Agricultural Water Management 257 (2021) 107161

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Application, adoption and opportunities for improving decision support systems in irrigated agriculture: A review

Iffat Ara[a,b], Lydia Turner[b], Matthew Tom Harrison[b,*], Marta Monjardino[c], Peter deVoil[d], Daniel Rodriguez[d]

[a] Agriculture Victoria Research, Department of Jobs, Precincts and Regions, Government of Victoria, Hazeldean Road, Ellinbank, VIC 3821, Australia
[b] Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, Hobart TAS 7001, Australia
[c] CSIRO Agriculture and Food, CSIRO Waite Campus, Waite Road, Urrbrae, SA 5064, Australia
[d] Queensland Alliance for Agriculture and Food Innovation (UQ-QAAFI), The University of Queensland, Gatton QLD 4343, Australia

ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:
Irrigation
Software
Scale
Socio-economic
Policy
Adoption

ABSTRACT

Decision support systems (DSS) have long been used in research, service provision and extension. Despite the diversity of technological applications in which past agricultural DSS canvass, there has been relatively little information on either the functional aspects of DSS designed for economic decisions in irrigated cropping, or the human and social factors influencing the adoption of knowledge from such DSS. The objectives of the study were to (1) review the functionality and target end-users of economic DSS for irrigated cropping systems, (2) document the extent to which these DSS account for and visualise uncertainty in DSS outputs, (3) examine tactical or strategic decisions able to be explored in DSS (with irrigation infrastructure being a key strategic decision), and (4) explore the human and social factors influencing adoption of DSS heuristics. This study showed that development of previous DSS has often occurred as a result of a technology push instead of end-user pull, which has meant that previous DSS have been generated in a top-down fashion rather than being demand-driven by end-user needs. We found that few DSS enable analysis of both tactical and strategic decisions, and that few DSS account for uncertainty in their outputs. We uncover a surprising lack of documented end-user feedback on economic DSS for irrigated cropping, such as end-user satisfaction with DSS functionality or future intentions to use the technology, as well as a lack of DSS application outside regions in which they were originally developed. Declining adoption of DSS does not necessarily imply declining adoption of DSS heuristics; in fact, declining DSS uptake may indicate that *knowledge* and *heuristics* extended by the DSS has been successful, obviating the need for use of the DSS per se. Future DSS could be improved through the use of demand-driven participatory approaches more aligned with user needs, with more training to build human capacity including understanding uncertainty and ability to contrast tactical and strategic decisions using multiple economic, environmental and social metrics.

1. Introduction

Irrigated cropping systems underpin *status quo* food security (Carruthers et al., 1997; Schultz et al., 2005) and will be increasingly important for ensuring consistent food supply in future. Irrigated croplands are more than twice as productive as rainfed croplands, and while only 16% of global croplands are irrigated, irrigated crops comprise around 36% of the global harvest per year. However, the extent to which irrigation is employed in any agricultural system is a function of manifold biophysical, economic, environmental and social factors. Biophysical factors include crop type, crop water-use efficiency, enterprise mix (Alcock et al., 2015; Bell et al., 2015; Harrison et al., 2012b, 2012d; Koech and Langat, 2018), physical factors may include water allocation/availability, irrigation infrastructure and effects of climate change (Bell et al., 2015, 2013; Harrison et al., 2017; Koech and Langat, 2018), economic factors include capital outlay, costs and commodity prices (Bjornlund et al., 2007), environmental factors may include anaerobic effects caused by waterlogging, risk of salinity (Beltrán, 1999; Lazaridou et al., 2019) and social factors may include management aspirations, peer and family values, succession plans, amongst others (Bjornlund et al., 2007; Bond, 1998; Caswell, 1991; Christie et al., 2018). Given this complexity, decision-makers are faced with multiple concurrent factors

---

* Corresponding author.
E-mail address: matthew.harrison@utas.edu.au (M.T. Harrison).

https://doi.org/10.1016/j.agwat.2021.107161
Received 1 June 2021; Received in revised form 26 August 2021; Accepted 27 August 2021
Available online 10 September 2021

to consider when deciding when irrigation should be used, if at all.

Decision support systems (DSS) have historically evolved to help users navigate and systematically disentangle some of the aforementioned issues. Appropriately contextualised DSS can be used to extricate the effects of irrigation on social, economic and environmental indicators through extension, service provision or participatory research (McCown, 2002). Early research defines DSS as computerised sources of knowledge, expertise and experience, providing accessible information to decision makers (Colomb, 1987). Unlike traditional techniques in operations research and optimisation, DSS rely on the judgement of the designer, from problem formulation to choosing relevant data, to selecting approaches to be used in generating solutions (Rausser and Yassour, 1978). Around four decades later, our modern definitions have changed little from those proposed in the 1970s, with Rinaldi and He (2014b) defining DSS as interactive software-based systems to help decision makers compile useful information from a combination of raw data, documents and personal knowledge to identify and solve problems and to optimise decisions (Olsson and Andersson, 2006; Van Meensel et al., 2012).

The application of and need for agricultural DSS in irrigated agriculture has increased substantially since the 1990s for different reasons around the globe. In developed countries, the use of DSS in agriculture by water management authorities has increased to help balance water use between the field and district levels. Agricultural DSS can also be used by decision-makers to more effectively manage the allocation of irrigation water to enhance crop or pasture water use efficiency and minimise environmental pollution while improving nutrient-use efficiencies (Christie et al., 2020; Ho et al., 2013; Rinaldi and He, 2014a). At the farm level, DSS have been promulgated for multiple tactical and strategic decisions (outlined further below), including contrasting of options for increasing productivity, better allocation of resources, climate change adaptation and for avoiding food waste (Chang-Fung-Martel et al., 2017; Ibrahim et al., 2018; Phelan et al., 2015, 2018; Zhai et al., 2020). Regional variation in the need for and use of agricultural DSS is explored in detail in the body of this review.

Temporal farm management decisions may be tactical (weekly) or strategic (over several years). Tactical decisions concerning irrigated cropping may include whether or not to apply water or fertiliser, repayment of debts or purchasing of operational supplies. Strategic decisions include enterprise choices and purchasing of machinery or irrigation infrastructure. Temporal decisions operate on a continuum from operational to strategic, with tactical and operational decisions being made in support of an overarching strategic vision. An appropriately designed DSS should facilitate decision-making at either tactical or strategic scales, helping transpose decisions from *reactive* to *proactive* (Chang-Fung-Martel et al., 2017; Phelan et al., 2018). A key purpose of the present paper was to review the extent to which previous DSS operate on tactical or strategic bases, because ultimately the combination of both short and long-term decisions contribute towards generation of economic wealth.

There are fewer agricultural DSS designed for strategic decision-making (Rinaldi and He, 2014c), even though strategic decisions may have greater impact on wealth compared with tactical decisions. More than two decades ago, Silva et al. (2001a) developed a DSS to improve strategic planning and management of large irrigation schemes in the Alentejo region of Portugal. The DSS allowed contrasting of crop types and systems, integrating socio-economic and biophysical data at the field level to analyse how a given irrigation scheme may be adopted by farmers. More recently, Khan et al. (2009) developed *WaterWorks*, a DSS designed to facilitate tactical and strategic irrigation decisions at the farm level to improve economic- and water-use efficiencies of farm businesses. A key strategic decision is the type of irrigation machinery and infrastructure to be purchased. Investment in irrigation infrastructure can represent a significant capital outlay that may be irreversible once new irrigation infrastructure is in situ. This can result in inflexible production systems that are unable to respond to future water scarcity, increasing investment risk by over six-fold, depending on the severity of drought (Adamson and Loch, 2014). Despite the potential impact of irrigation infrastructure on economic outcomes, few DSS appear to permit contrasting of economic factors associated with irrigation infrastructure.

Many DSS output (produce) values that have no variability, e.g. the profitability associated with a management intervention may be shown as a mean value, but the range, standard deviation or variability associated with the mean is not shown. This variability is known as 'uncertainty'. Outputs from any DSS or model carry implicit uncertainty associated with either (1) lack of knowledge or data used to build a DSS (Hardaker et al., 2015, 2004; Pembleton et al., 2016), (2) uncertainty in model inputs or internal parameters (Harrison et al., 2014, 2012c, 2012d), or (3) uncertainty in model algorithms and equations (Harrison et al., 2019). Uncertainty can be visualised through appropriate statistical measures that show ranges or statistical distributions of DSS inputs or outputs (Harrison et al., 2017; Ho et al., 2014; Kandulu et al., 2012; Monjardino et al., 2015). Despite the variety of methods with which uncertainty can be displayed graphically (e.g. Ho et al. 2014, Harrison et al. (2016b), the extent to which risk and risk metrics can be usefully interpreted by DSS users is not well known. There is also evidence to suggest that end-users often have little understanding of uncertainty implicit to DSS outputs or how uncertainty may affect their management decisions (Harrison et al., 2016a; Mowrer, 2000).

The extent to which DSS outputs are adopted is rarely measured and, anecdotally at least, is often considered to be limited (Bell et al., 2015; Harrison et al., 2012a; Inman-Bamber et al., 2007; McCown, 2001). Previous research on irrigation DSS has often focused on technology aspects but has not generally assessed how socio-economic aspects influence adoption. Pannell et al. (2006) describe the challenges of measuring these adoption-related attributes: even if resources were available to conduct surveys of end-users, such assessments tend to rely on indirect measurement through expert opinion. In most technical evaluations, there has been little consideration of the *attributes* of agricultural communities and households that support or hinder adoption (in contrast to the bulk of work on the *characteristics* of farm households). Pannell et al. (2006) indicate that innovations are more likely to be adopted when they have a high relative advantage and when they are readily trailable. To address this knowledge gap, the review discuss how economic, social and cultural factors influence application and adoption of irrigation DSS and DSS knowledge and illustrate pathways in which these factors should be considered in future DSS development.

In this review, we focus on economic DSS for agriculture that have graphical user interfaces (GUIs) that can be used to compare scenarios for tactical and/or strategic purposes. We examine the drivers of adoption of past agricultural DSS and DSS outputs/knowledge, discussing pathways to ensure economic DSS are relevant and contain actionable information for farm irrigation management. Specifically, the aims of this paper were to (1) review the functionality and intended end-users of previous and extant economic DSS for irrigated cropping systems, (2) document the extent to which these DSS account for and visualise uncertainty in DSS outputs, (3) examine tactical and strategic decisions that are able to be explored in DSS (with investment decisions in irrigation infrastructure being a key strategic decision), and (4) explore the human and social factors influencing adoption of DSS heuristics.

2. Methods

In this review we apply the following criteria to select economic DSS for inclusion: (1) the DSS includes a GUI in a form of web-based software/tool or as an app (not mathematical models in isolation or DSS without GUIs) which are flexible to operate/utilize by the end users, (2) the DSS includes output variables of either yield, water use or both and (3) the DSS allows contrasting of resources allocation and management across the whole farm. We define *end-users* as people who use DSS heuristics to action decisions, where a heuristic is the development of a problem-solving process that allows a short-term approximation to a problem. By way of example, a DSS heuristic could be gained by a farmer who uses trial and error processes to learn how a crop responds to a given seasonal climate outlook. Once the farmer has gleaned an appropriate mental model rom using the DSS, she/he may thus decide to jettison future use of the DSS. We define *next-users* as people who use DSS (and DSS heuristics) to provide advice to others but do not ultimately action decisions themselves (e.g., a farm advisor, agronomist or consultant may use the outputs from a DSS to provide information to a farmer; see Table 1). Decision time frames considered in this review include seasonal/annual or long term (5–20 years). Hereafter, economic decisions relating to seasonal/annual time frames are referred to as 'tactical' (e.g., crop sowing choices), and decision making relating to longer-term multi-year time frames are referred to as 'strategic' (e.g. decisions relating to irrigation infrastructure, climate change and transformational adaptation for longer term farm profitability). Following these guides, DSS designed for daily (or real-time) irrigation decisions including irrigation scheduling, precision irrigation or Geographic Information Systems (GIS) were considered out of scope. Instead, our primary objective was to review economic DSS that analyse farm systems on tactical or strategic bases, e.g., DSS designed to compute the economically optimal the proportion of farm productivity derived from irrigation. The review was conducted and structured as follows:

1. Literature search: based on the search criteria process outlined in Fig. 1, fourteen economic irrigation DSS were selected from the literature (Table 1, Section 2).
2. Extract information from selected DSS: each DSS was analysed in the context of our aims, including intended application and decision analysis (tactical and strategic economic decisions, including presence or absence of irrigation infrastructure), type of end-user, type of interface, biophysical and/or environmental metrics (e.g., yield, water use and water productivity), economic metrics (e.g., $/ML, $/ha) and ability to quantify uncertainty (Section 3).
3. Evaluate drivers of adoption of agricultural DSS and DSS heuristics and identify pathways for increasing the adoption of beneficial knowledge provided by economic DSS (Section 4).
4. Conclusions: summarise the major challenges, typical decisions made, outline criteria that would make DSS more useful for decision-makers, and identify opportunities for enhancing the effectiveness of extension processes that use DSS (Section 5)

The description of DSS in Section 3 is designed to facilitate insights into *technology deficits* related to DSS functionality (e.g., tactical and strategic decision making, uncertainty in outputs etc), whereas Section 4 is designed to address human and social factors related to end-user knowledge derived from DSS, including the attributes of DSS that influence adoptability.

3. Economic DSS for irrigated agricultural systems

3.1. Overview of DSS functionality

DSS shown in Table 1 facilitate tactical and strategic economic decisions considering the influence of climate on economic and risk outcomes, labour requirements, benchmarking, economic performance, selection and design of irrigation systems, irrigation management and investment assessment. Target end-users include farmers, irrigation managers, intermediaries (i.e., consultants, extensionists, advisors, and agronomists), and policymakers (Table 1). These DSS contained graphical user interfaces facilitating scenario comparison and use without coding (Christie et al., 2020; Pembleton et al., 2016; Tapsuwan et al., 2015; Watkiss et al., 2015), with software varying from web-based tools to apps and spreadsheets. Many DSS have been developed and tested as case studies (TRL level 2 in Table 1) but perpetuation of DSS into the long term appears to be a problem that most developers and scientists still grapple with (e.g., *DSS-EVIM* and *DSSIPM* were developed for research purposes and were not maintained; this example has been repeated historically *ad nauseum*).

Across regions, DSS have been developed for many different reasons. Most DSS aim to help users identify more profitable irrigation regimes (e.g. *AHP*, *DSSIR*, *DOMIS*, *Cotton WebApp*, *DSS-EVIM*), some have been developed for comparison of alternative farming systems and/or cropping diversity (*FEAT*, *Irrigation Optimiser*, *DSSIPM*) or water productivity and use-efficiency (*SIRMOD*, *Irrigation Optimiser*), while fewer have been developed for comparison of the profitability associated with adapting irrigation infrastructure (*WaterWorks*, *WHAT-IF*, *SADREG*). The majority of DSS facilitate comparisons of multiple crop types, which adds versatility and presumably utility to a broader range of end-users, though some focus only on one crop type (e.g. *Cotton WebApp*, *FEAT*). Most DSS have been designed for use by farmers, advisors and service providers at the farm scale, fewer DSS have been designed to facilitate decision-making at the regional and catchment scale, with exceptions of *DOMIS*, *DSSIR*, *DSSIPM*, *WHAT-IF* and *DSS-EVIM*.

Perhaps the most stark conclusion from Table 1 is that most DSS have been developed and applied only locally and are not available publicly: in the latter case, potential users need to contact developers to gain access to the DSS of interest. Localised development of DSS suggests that developers may prefer to construct new decision-support tools rather than adapt or share previous DSS. Such lack of transfer between regions may be due to multiple reasons, such as inability to access and modify source code, protection of commercial intellectual property, inadequate functionality of the existing DSS, improper complexity/suitability or even a simple lack of research into existing DSS at the outset. This is key area in which future DSS developers could significantly improve upon: the use and adaptation of existing DSS would be expected to facilitate collaboration, lead to greater support and maintenance of DSS, improve understanding of diverse agroecological and socio-economic systems and ultimately improve impact (adoption of DSS knowledge) in the environments in which they operate. More extensive sharing, increased public availability and advertising of DSS (either commercially or free of charge) would be also expected to improve awareness and uptake.

3.2. Tactical decisions

Tactical DSS are designed for shorter term, seasonal economic decisions. For instance, *WaterWorks* was developed to provide seasonal irrigation management decisions. In *WaterWorks* (Fig. 2), simulation and optimisation modules were considered at the farm level in Australia (Khan et al., 2009). WaterWorks is designed to help users evaluate water productivity, economic efficiency and environmental performance for pivot, drip, and surface irrigation systems to increase crop yield and profit for a farm business. Inputs include crops, cropped area, soil type, source of water (surface or groundwater), water trading, existing and proposed irrigation layouts. The main output of the DSS is optimised profitability at the whole farm-level, seasonal water allocation, overall crop water use efficiency, water trading price, crop price and crop yield. While WaterWorks was built using participatory approaches with end-users (trialling ease of use, flexibility and user-friendliness; Khan et al., 2009), there appears to be little documentation of user feedback on quality criteria of the DSS, such as information (semantic success), system (technical success) or service quality (use and effectiveness success) This observation suggests a need for further documentation of user feedback on both satisfaction and further intentions to use this DSS.

The DSS *SIRMOD* simulates the hydraulics of surface irrigation (border, furrow, and basin) at the field level and evaluates the economic implications of alternative field layouts, including differences due to topography, field size and length (Walker, 1993, 1998). *SIRMOD* helps users understand economically viable management practices such as seasonal water application and optimisation of surface irrigation (Wu et al., 2017; Zheng et al., 2009a, 2009b). The DSS allows comparison of

Table 1

Economic irrigation DSS supporting tactical and strategic decision making. Uncertainty was defined as the ability to quantify variability associated with DSS outputs. ‘Locality’ describes the region in which the DSS was developed. The definitions and descriptions of Technology Readiness Level (TRL) has been adopted from DST (2021) and each DSS has been scored based on available information in relevant literature/references. Abbreviations and definitions of TRL score are shown at the base of the table.

DSS[a]	Purpose	Crop	First release	Scale	End-user	Type of economic decision	Includes uncertainty	Cost	Locality	TRL[b]	User Interface	Developer	Public availability	Ref.
Expert Choice (AHP)	Selection of irrigation method by considering other socio-economic inputs/ scenarios	Multiple crops	2006	Farm	Farmer, Researcher	Strategic	Yes	N/A	Tested and validated in Iran	4	Software is known as ’Expert Choice’ based on multi-criteria decision making	Expert Choice, Inc	No	Karami (2006)
Cotton WebApp	Estimate profitability under center pivot irrigation in $AUD/Acre	Cotton	2013	Farm	Irrigation advisor	Tactical	No	N/A	Currently being used in Southern High Plains, USA	4	Web app based on CROPGRO-Cotton model	Agricultural Research Service, United States Department of Agriculture	No	Mauget et al. (2013a, 2013b)
DOMIS	Assess the cost of a micro-irrigation system in $ (Rs).	Multiple Crops	2018	Farm and Region	Irrigation advisor, policymaker	Strategic	No	N/A	Currently being used in India.	4	Webtool based on Hypertext Pre-processor and MySQL	Indian Government	No	Patel et al. (2018)
DSIRR	Measure farm profit in €/ha and water productivity (WP) in Eurocents/m^3 with alternative irrigation management	Multiple crops	2005	Catchment	Irrigation advisor, policymaker	Strategic	Yes	N/A	Applied as a case study in Cremona maize district of Po river basin, Italy	2	Software based on Microsoft Windows operating system	National Research Council, Italy	No	Bazzani (2005a)
DSSIPM	Assess possibilities of increased crop diversity and farmers income	Multiple crops	2001	Region	Farmer, irrigation advisor, Policymaker Researcher	Strategic	No	N/A	Previously used in Portugal. Currently not available	3	Software-based on Microsoft Visual Basic 4.0 and Microsoft Access 7.0	The University of Lisbon	No	Silva et al. (2001a),Silva et al. (2001b)
SADREG	Analyse alternative attributes to design and select surface irrigation systems	Wheat	1998	Farm	Irrigation advisor	Strategic	No	N/A	Used in Tentugal of the Lower Mondego Irrigation System, Portugal	3	Software built with Microsoft Access, Microsoft Visual Basic and Microsoft Visual C+ +	Agricultural Engineering Research Centre, Lisbon	No	Goncalves et al. (2007), Goncalves and Pereira (2009), Goncalves et al. (1998b), (1998a)
SIRMOD	Measure surface irrigation water productivity	Multiple crops	1993	Farm	Irrigation manager/ advisor Researcher	Tactical	No	N/A	Tested in many countries (USA, Egypt, Philippines etc)	3	Numerical the solution of the Saint-Venant equations	Utah State University, Utah, USA	No	Walker (1993, 1998), (Mehanna et al., 2015)
WaterWorks	Provide economic decisions in gross margin ($AUD)	Cereal crops	2010	Farm	Farmer	Tactical and Strategic	Yes	N/A	Tested and validated	4	Software based on Microsoft	Irrigated Cropping Forum and	No	Khan et al. (2008)

(*continued on next page*)

Table 1 (*continued*)

DSS[a]	Purpose	Crop	First release	Scale	End-user	Type of economic decision	Includes uncertainty	Cost	Locality	TRL[b]	User Interface	Developer	Public availability	Ref.
	and water productivity (ML/ ha)								in NSW, Australia.		Windows operating system	Coleambally Irrigation Cooperative Ltd, Australia		
WHAT-IF	Support economically viable strategies for water infrastructure investment	Multiple Crops	2019	Catchment	Policymaker Researcher	Strategic	Yes	Free	Currently being used in Zambezi River basin, Africa,	4	Webtool coded in the Python using the Pyomo modelling framework	Innovation Fund, Denmark	Yes	Payet-Burin et al. (2019)
DSS-EVIM	Calculate the economic value of irrigation water in LE/m^3	Multiple crops	2012	Region	Policymaker Researcher	Strategic	No	N/A	Applied as a case study in Egypt	2	Software based on Microsoft Access and ArcMap 9.3	National Water Research Centre, Cairo, Egypt	No	El-Gafy and El-Ganzori (2012)
E-Water	Provide information on resource allocation for water management	Multiple crops	2018	River basin	Farmer Researcher	Strategic	Yes	Free	Applied as a case study in the Mekrou river basin in West Africa	2	Software based on the EPIC model and regression modules	European Union (EU), Joint Research Centre (JRC), and Global Water Partnership (GWP)	Yes	Udias, Pastori et al. (2018)
FEAT	Estimate profit in $/ha with an alternative farming system	Sugarcane	2018	Farm	Farmer	Tactical	No	Free	Currently used in Australia	4	Spreadsheet	State of Queensland, Australia	Yes	FEAT (2016)
Irrigation Optimiser	Calculate profitability in $AUD/ha or $AUD /ML	Multiple crops	2010	Farm	Farmer and irrigation manager/ advisor	Tactical	No	N/A	Tested in Australia, currently no adoption	2	Windows XP; must be hosted on Internet Explorer	The University of Queensland and Queensland Government	Yes	Rodriguez and Doherty (2010)

AUD = Australian Dollar, LE = Egyptian pound, and Rs = Indian rupee

[a] DSS Abbreviation: AHP=Analytic Hierarchy Process, DOMIS=Design of Micro Irrigation Systems, DSIRR=Decision Support System for Irrigation, DSSIPM= Decision Support System to Improve Planning and Management, DSS-EVIM= Decision Support System for Economic Value of Irrigation Water Maps, GISDSS= Geographic Information Systems based Decision Support System, SIRMOD= Surface Irrigation Model, FEAT=Farm Economic Analysis Tool, SIMIS=Scheme Irrigation Management Information System.

[b] Definitions of the Technology Readiness Levels (TRL) used: (Level 1: Initial scientific research begins; Level 2: Initial practical applications are identified; Level 3: Proof of concept established; Level 4: Validation of the process)

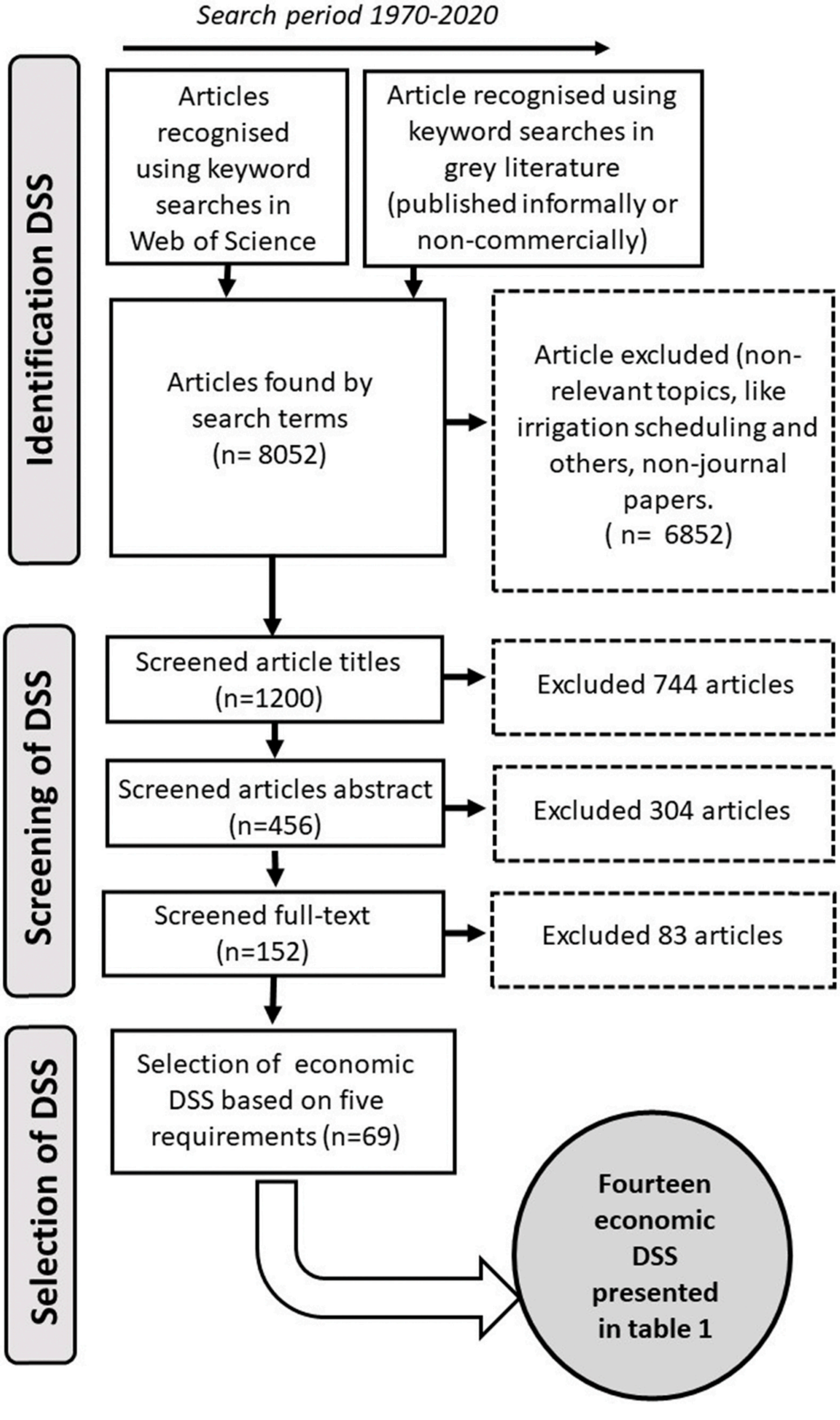

Fig. 1. The process of identification, screening and selection of the economic irrigation DSS used in this review.

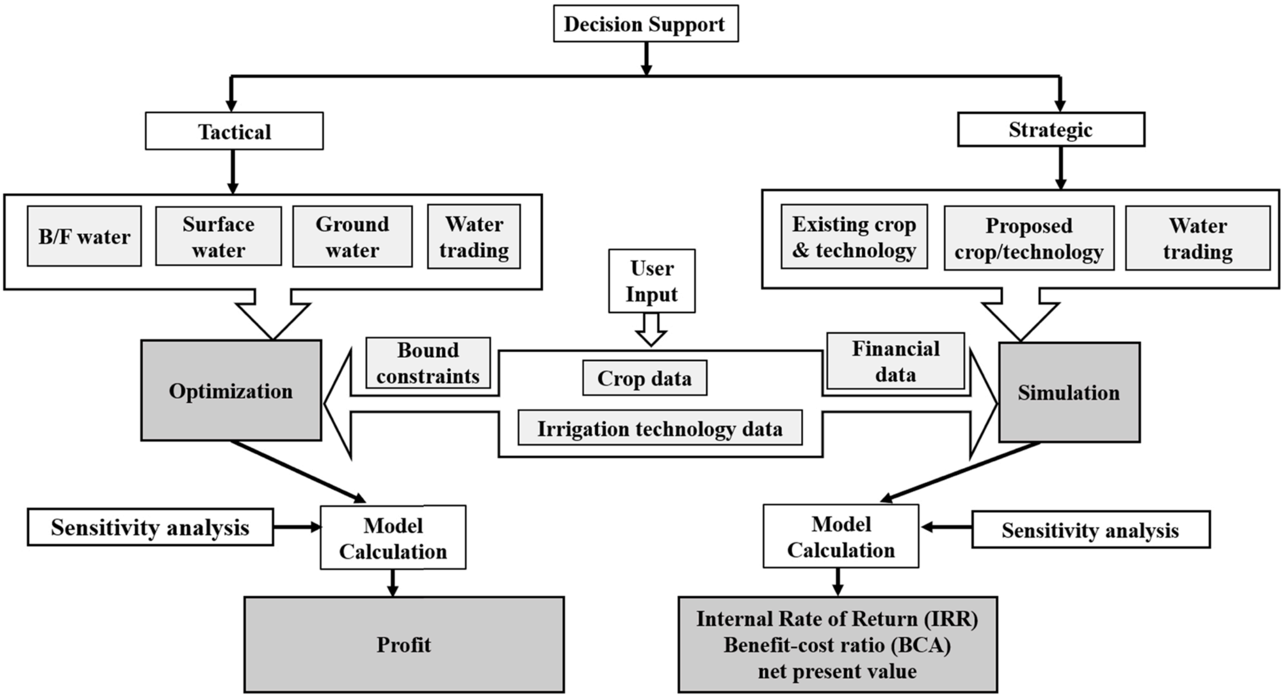

Fig. 2. *WaterWorks* execution process. B/F = carryover brought forward.
Adapted from Khan et al. (2009).

alternative seasonal surface irrigation design and management practices to irrigators and other decision makers (Abbasi et al., 2003; Hornbuckle et al., 1999; Raine and Walker, 1998). Hornbuckle et al. (2005) indicate that (1) the ease of data entry into the DSS, (2) type of platform (PC vs mobile device), (3) designing the DSS to better meet end-user needs and (4) cost benefit ratio as a result of using *SIRMOD* are key observations regarding potential uptake of the DSS. Despite the widespread use of this DSS, there appears to be little documentation of user uptake, learning or feedback on *SIRMOD*.

3.3. Strategic decisions

Strategic DSS facilitate insight into long-term economic decisions, such as adoption of a whole-farm plan for an irrigation system or development of a plan to establish irrigation infrastructure (Montagu et al., 2006). While many approaches have been used in the literature to assist decisions on managing water resources, the Multi-Criteria Analysis (MCA) or Multi-Criteria Decision Analysis (MCDA) are popular in comparing irrigation strategies with respect to long-term economic value. MCA and MCDA approaches evaluate trade-offs between the successes of alternative irrigation systems and their impacts on the process of decision making (Hajkowicz and Collins, 2007; Karleuša

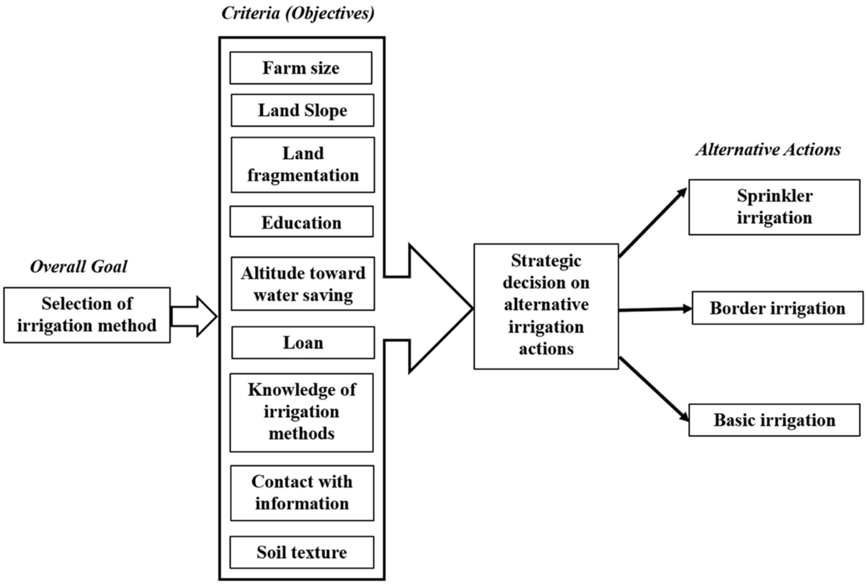

Fig. 3. Decision tree showing the selection of alternative irrigation methods in the *Analytic Hierarchy Process (AHP)*.
Redrawn from Karami (2006).

et al., 2019).

As shown in Fig. 3, the analytical hierarchy process (*AHP*) uses MCA to support strategic economic decisions at the farm level. The *AHP* was conceived in response to top-down transfer of technology, in which experts (e.g., scientists) perceived farmer problems and proposed solutions for these problems (Karami, 2006) but without first consulting farmers (as the end-users). As might be predicted, such top-down approaches often lead to poor adoption outcomes. Through a participatory process using *AHP* in the DSS 'Expert Choice', the end-user participants in the study of Karami (2006) agreed that the decision hierarchy should be (1) comprehensive, (2) relevant to extension programs for diffusion of irrigation methods and (3) include both technical and socio-economic factors. In using Expert Choice with four distinct groups of irrigation farmers, Karami (2006) clearly showed how *AHP* can help end-users better understand the characteristics of alternative irrigation systems but also identify the broader socio-economic factors contributing to farmer decisions underpinning whether or not to adopt a specific type of irrigation.

DSSIPM helps users assess cultivation options for irrigated agricultural systems and to identify constraints impacting crop choice and crop yields (Silva et al., 2001a). While outcomes from the work of Silva et al. (2001b) provide insights into the relative value of crop irrigation, *DSSIPM* was not designed to compare different irrigation systems. A similar MCA approach was used in the development of *SADREG,* which supports strategic decisions to design and select surface irrigation systems through comparison of alternative attributes (yield, cost of investment, operation, and maintenance, run-off, land levelling, soil erosion) (Goncalves et al., 2007, 1998b, 1998a; Goncalves and Pereira, 2009). *SADREG* has been previously used to understand the context of water-saving in relation to farm economics in Northeast Syria (Darouich et al., 2012), along with comparing surface irrigation with sprinkler irrigation and drip irrigation (Darouich et al., 2017, 2014).

El-Gafy and El-Ganzori (2012) used *DSS-EVIM* to produce economic maps at the regional level in Egypt for different crops to support strategic economic decisions on cropping patterns to maximise the value of irrigation water (but does not include irrigation infrastructure). In contrast, *DOMIS* estimates the cost of irrigation systems (i.e., drip irrigation, sprinkler, and micro-sprinkler) for different crops. *DOMIS* evaluates the economic feasibility of these systems considering the location, soil, groundwater, irrigation equipment, crop information, the regional profile of a given region accounting for water quality, rainfall, wind speed, solar energy, source of irrigation and agricultural land use. Despite its widespread use in India and current availability online (Patel et al., 2018), we find little evidence in the little of user feedback or evaluation on the system, service or information quality of this DSS.

While DSS are often used to make strategic economic decisions at the farm and regional levels (Langworthy et al., 2018); few catchment scale DSS account for irrigation infrastructure. Economic indicators associated with water infrastructure and policies in the water--energy-food–climate nexus were considered in the *WHAT-IF* DSS for the Zambezi River basin in Africa (Payet-Burin et al., 2019). This DSS centres on large-scale irrigation management strategic plans, including irrigation infrastructure development, agriculture production (farming zone, crop choices, irrigation and yield), crop and energy markets. Similar to *WHAT-IF*, *DSSIR* was designed to help users understand environmental, economic and social interdependencies of irrigated agriculture at the catchment scale, including employment, subsidies, gross domestic product and environmental pollution (Bazzani, 2005a). Irrigation systems in *DSSIR* comprise fixed and site-specific irrigation layout (furrows and drip) and mobile layouts (sprinklers and self-moving guns) to understand water-yield functions and rotations. Because most catchment level DSS have been designed for analyses of irrigation investment at a large scale, outcomes do not consider tactical decisions such as crop management and are thus not comparable with other tactical DSS. These findings underscore the need for consistent output metrics in DSS spanning multiple disciplines (social, economic and environmental) and ability to examine both tactical and strategic decisions.

Of the DSS analysed, only five (*AHP*, *DSIRR*, *WHAT-IF*, *WaterWorks*, *E-Water*) include uncertainty in output variables. This may be because (1) uncertainty in DSS outputs is often not intuitive to users, (2) variability associated with climatic, economic factors, implicit parameter uncertainty and error propagation can be difficult to quantify (Harrison et al., 2019), or (3) developers do not consider uncertainty as a high priority DSS output. We suggest that uncertainty in DSS outputs is a feature that should be given more consideration in future work, particularly in DSS that include climatic or market volatility. Assuming that an irrigation DSS has been designed to be compatible with users' sociocultural values and their need for innovation, including uncertainty in output variables would allow more informed assessments of the relative advantage of proceeding with DSS-based decisions.

3.4. *Irrigation infrastructure*

In general, few of the DSS reviewed accounted for irrigation infrastructure, although WaterWorks and SADREG are notable exceptions. Khan et al. (2009) use WaterWorks to compare yields of several crops under alternative irrigation systems (Table 2). In a case study of the feasibility of drip or pivot irrigation investment (Table 3), Khan et al. (2009) show that the capital cost of pivot irrigation ranges between AU $2771 and AU$3750/ha, while variable costs depended on the size of the pivot irrigators and crop type, seasonal conditions, soil types and groundwater level. The case study documented a scenario for maize grown over 40 ha, where shifting from surface to pivot irrigation increased yield by 0.5 t/ha, gross margin by AUD $115/ha, water use efficiency by 0.22 t/ML and reduced water use for irrigation by 0.65 ML/ha (Table 2). In general pivot irrigation led to higher gross margins associated with higher yields and water productivity, resulting in improved economic returns per unit irrigation water ($/ML). This result was consistent for grapes, maize, soybeans and wheat, suggesting that pivot irrigation systems would be a more profitable investment that surface irrigation in this context.

A limited number of studies have examined the agronomic and economic effects of irrigation infrastructure. Darouich et al. (2014) used SADREG and MCA and found an 11% reduction in cotton yield in surface and drip irrigation systems when comparing deficit irrigation with full irrigation. The same authors later compared border-check and sprinkler systems and found that wheat yields for border-check and sprinkler irrigation systems were 4511 kg/ha and 5200 kg/ha respectively, suggesting that flood-based systems had lower water-use efficiencies (Darouich et al., 2017). Maraseni et al. (2012) examined a range of irrigation systems in Southern Queensland, Australia, and showed that while irrigation efficiency was similar across irrigation systems, there was large variability in capital investment, labour, water savings and nitrogen input across infrastructure systems (Table 4). The highest capital cost was that associated with changing from sprinkler (hand-shift) to drip sprinkler (roll-line, $5000/ha) but this change in infrastructure also increased yield by 18%, reduced labour by 40% and saved 2 ML/ha in irrigation. Rollin and Scott (2018) compared irrigation infrastructure for rice, cotton, and maize in southern NSW and northern Victoria and showed that marginal rates of return varied due to depending on level of capital investment (Table 5). For instance, changes in irrigation system (from the contour system to terrace bankless) resulted in higher cropping intensity and reduced water use, but received the lowest return (14%) on capital invested. While these findings are useful, future work must go further and compare the biophysical (yield, water use etc) and economic (cost, profitability etc) associated with irrigation infrastructure systems across environments and production systems (ie crops able to be grown based on enterprise mix). These findings would facilitate improved development of future DSS (e.g., water-use efficiency parameters associated with different irrigation infrastructure) as well as end-user understanding of the most appropriate infrastructure,

Table 2
Comparison of surface and drip or pivot irrigation in grape, maize, soybean, and wheat in New South Wales, Australia using the DSS *WaterWorks*. WP represents water productivity.

	Grape		**Maize**		**Soybean**		**Wheat**	
	Surface	Drip	Surface	Pivot	Surface	Pivot	Surface	Pivot
Area (ha)	40	40	40	40	20	20	60	60
Irrigation (ML/ha)	9.0	7.5	7.15	6.5	6.0	5.4	3.9	3.3
Yield (t/ha)	14.0	15.0	10.0	10.5	3.0	3.2	5.0	5.3
Gross margin	3711	5304	682	797	381	468	325	379
WP (t/ML)	1.56	2.00	1.40	1.62	0.50	0.59	1.28	1.61
WP ($/ML)	412	707	95	123	64	87	83	115

Source:Source: Khan et al. (2009).

Table 3
Costs associated with alternative irrigation layouts appropriate to crop type calculated using *WaterWorks*.

	Drip irrigation Grape	**Pivot irrigation Maize**	**Pivot irrigation Soybean**	**Pivot irrigation Wheat**
Area (ha)	40	40	20	60
Capital costs				
Pivot (AU$/ha)	4500	2771	3750	2147
Soil moisture monitoring ($/ha)	62	62	62	62
Variable costs				
Maintenance (AU $/ha)	45	27	38	22
Power (AU$/ML)	45	15	13	19
Corner production losses (AU$/ha)	–	31	31	31

Source:Source: Khan et al. (2009).

accounting for their farming system, climate type and future management aspirations (Table 5).

3.5. Transparency in presenting uncertainty in DSS outputs

Previous work has shown that end-users of DSS often have little understanding of uncertainty (Mowrer, 2000). Uncertainty in DSS can be broadly classified into six categories: (1) inherent randomness in initial conditions, (2) measurement error, (3) systematic error (e.g. due to a bias in sampling), (4) natural variation (biological systems may vary in time and space), (5), model uncertainty and (6) selective judgment (uncertainty due to different interpretations of the data) (Uusitalo et al., 2015) Model uncertainty comprises DSS structure and DSS internal parameters; these factors are not independent because there is a trade-off between increasing complexity, improved model structure and increasing parameter error (Harrison et al., 2019; Passioura, 1996; Reynolds and Acock, 1985). Probability theory, inter- or intra-year climatic variability may also be used to quantify uncertainty (Harrison et al., 2017, 2016b, 2012b).

DSS that account for economic scenarios ideally should also account for uncertainty and risks (Alcock et al., 2015; Uusitalo et al., 2015) as this supports more informed user assessments of relative advantage and perceived superiority of alternative innovations. DSS considered here (Table 1) show limited scope in accounting for risk and/or uncertainty; only five DSS of those reviewed here quantify uncertainty. Uusitalo et al. (2015) suggest that evaluating uncertainty depends on the amount and quality of available information, scale of application and the purpose of the DSS. Many economic DSS are deterministic, wherein outputs are derived from a single computation such that no uncertainty is embodied in DSS outputs (Ho et al., 2014; Watkiss et al., 2015). In these cases, uncertainty could be shown by running multiple input values (e.g. market prices or costs) through a DSS to produce a distribution of outputs. This process is applied in *DSSIR* such that outputs in the DSS are presented as both means and associated variability (e.g. the range of irrigation water to be applied and the variability in water supply associated with climatic variability).

However, the development of uncertainty metrics in DSS involves considerable technical complexity, e.g., adequate mathematical accounting of error propagation, or the development of datasets that reasonably account for social, environmental and economic variability implicit to DSS datasets. These reasons may explain why many contemporary DSS do not account for uncertainty. As well, visualisation of risk in DSS outputs if often not intuitive to the layperson, and large variability in outputs of some DSS may result in a loss of trust in the software by some users. Similar to other functional aspects of DSS, quantification of uncertainty must be considered in the design phase and should be iteratively refined throughout the development and adoption phases in line with end-user feedback. Such refinement should be conducted using multi-disciplinary participatory approach that involves input from not only next- and end-users, but also software developers, scientists and other stakeholders throughout the life of the DSS. This process would be expected to increase the adoptability of the DSS heuristics by ensuring the aspirations and capacities of users and their communities are addressed, and that the DSS is compatible with users' sociocultural values, including their need for innovation.

To move forwards, uncertainty metrics in future DSS may be developed with participatory approaches and either (1) expert judgment, (2)

Table 4
Capital costs, changes in yield, water, nitrogen and labour associated with five irrigation infrastructure transition scenarios. Irrigation efficiency represents the extent to which irrigation water is used by plants in each scenario for both the old and new infrastructure. ML = megalitres.

Change in irrigation infrastructure	**Capital cost in AUD ($/ha)**	**Yield increase (%)**	**Labour savings (%)**	**ML water savings per ha (%)**	**Irrigation efficiency**	**Change in nitrogen inputs (kg/ha)**
Flood (furrow) to sprinkler (lateral move)	3250	18	20	2.0 (33)	90	-200
Flood (furrow) to sprinkler (centre-pivot)	1990	20	20	1.0 (20)	90	-100
Flood (furrow) to drip	1950	12	15	1.0 (17)	90	0
Sprinkler (hand-shift) to drip	5000	18	40	2.0 (52)	92	+ 200
Sprinkler (roll-line) to sprinkler (centre-pivot)	2400	36	40	8.0 (50)	90	0

Source:Sourced from Maraseni et al. (2012).

Table 5
Costs and gross margins associated with changing irrigation infrastructure.

Case Study	Irrigation system description[a]		Change	Benefit achieved	Area (ha)	Capital cost (AU $)	Average gross margin (AU $)	Marginal return on capital invested (%)	Discounted cashflow return, Net Present Value (NPV) (AU$)
	New	Existing							
Murrumbidgee 1	Furrow-Cotton/ Winter Crop (F-Co/WC)	Furrow-Cotton/Winter Crop (F-Co/ WC)	Automation and earthworks	Water-use efficiency, greater cotton area grown.	250	238,000	195,000	66	1713,000
Murrumbidgee 2	Furrow-Maize (F-M) + Contour-Rice double-crop (C-R/dc)	Terrace Bankless -Cotton (TB-Co)	Change from furrow and contour to Terrace Bankless	Greater labour and machinery efficiency	1600	3520,000	1144,000	26	3879,000
Murray 1	Contour-Rice double crop (C-R/dc)	Contour-Rice double-crop (C-R/dc) + Terrace Bankless - Cotton/Maize (TB-Co/M)	Add Terrace Bankless	Greater flexibility in crop rotations and crop diversity	150	454,000	129,000	23	490,000
Murray 2	Contour-Rice/ Winter Crop (C-R/WC)	Terrace Bankless -Rice double crop (TB-R/dc)	Change from Contour to Terrace Bankless	Higher cropping intensity, reduced water use	360	863,000	150,000	14	365,000
Victoria 1	Border-Check-Maize/Winter Crop (BC-M/WC)	Border-Check-Maize/Winter Crop (BC-M/ WC)	Re-lasered, channel upgrades, bigger border check	Greater cropping area, increased yield, reduced water use	550	1210,000	890,000	59	6358,000
Victoria 2	Border-Check-Maize/Winter Crop (BC-M/ WC)	Border-Check-Maize/Winter Crop (BC-M/ WC)	Re-lasered, total automation, infrastructure upgrades	Greater cropping area, increased yield, and reduce water use	250	675,000	123,000	15	754,000

[a] Irrigation systems- F = Furrow; TB = Terrace Bankless; C= Contour; BC = Border Check. Crops -Co = Cotton; WC = Winter Crop; M = Maize; R = Rice; dc = double crop
Source:Source: Rollin and Scott (2018).

model emulation (i.e. a statistical representation/low-order simplification of model outputs), (3) sensitivity analysis (e.g. via parameter perturbation), (4) temporal or spatial variability in model outputs, (5) use of multiple models, (6) use of multiple initial conditions and/or (7) probabilistic approaches, which may be conducted by rerunning a model with multiple sets of driving variables (e.g. climates/soil types). If the addition of uncertainty metrics to a DSS interface results in excessive variability that prevents a meaningful decision being made, then the addition of uncertainty will have served its purpose. Such cases would mean that the variability associated with a given value or treatment is so high that it is not significantly different from another treatment. Without showing uncertainty, end-users have no way of knowing if the difference between any two treatments is real or significant. Having the ability to distinguish between treatments is another key reason future DSS developers should consider implementing measures of uncertainty in as outputs of DSS.

3.6. Summary of functional aspects of previous and extant DSS

Economic DSS have been developed for multiple purposes, from comparisons of investment decisions in irrigation infrastructure, to analyses of agronomic effects on farm profit or costs, to strategies for increasing water-use efficiency or water productivity (Table 1). It is worth noting that the extent to which an intervention causes change very much depends on the initial conditions. For example, a crop is unlikely to respond to irrigation if the soil moisture profile is already full: thus, consideration of baseline conditions in any DSS is important. We found that many economic DSS have been developed with site-specific foci using case studies for validation, and that only one DSS (*SIRMOD*) has been actively tested and applied in multiple regions. This observation suggests that previous DSS have had limited transferability across environments. Such lack of transferability of DSS across regions may be due to many reasons, such as inappropriate DSS functionality, lack of extension, training support, or lack or research/awareness raising by previous DSS developers. Ongoing development and structural or software maintenance issues appear to be a key issue: we showed that many past DSS are no longer extant or in operation. Because the continued use of DSS outputs in research, policy and industry is critical to impact (increased profitability and sustainability), the following section examines adoption of previous DSS knowledge and outlines pathways for increasing adoption of future DSS heuristics. In the following section, we broaden our scope to all DSS in agriculture, since we examine the multitude of factors influencing the extension, adoption and impact of DSS in agriculture in general. We first cover the problem of implementation, then discuss factors influencing adoption and finally end with a discussion on participatory approaches.

4. Adoption and impact of DSS in irrigated agriculture

4.1. The 'problem of implementation'

There are many benefits of DSS for farmers and extension providers. Some of these benefits include confirmation or rebuttal of intuitive knowledge, improved awareness of direct and external issues impacting a given outcome, reduced uncertainty, improved ability to contrast multiple scenarios and utilise large datasets and proven science to make more informed decisions, and/or the use of DSS as proxies for conveying and understanding knowledge as part of extension frameworks. Despite this, many studies have shown that current agricultural DSS are not well adopted by farmers: this is termed the *problem of implementation* (Eastwood et al., 2012; Leeuwis, 2013; Lindblom et al., 2013; Mackrell et al., 2009; Matthews et al., 2008; McCown, 2002; Rossi et al., 2014; Van Meensel et al., 2012). Evaluating the number of users, mode and extent of use, and benefits to users has not historically been included in DSS research (Kerr, 2004; McCown, 2001; Rinaldi and He, 2014c). Indeed, many publications relating to irrigation DSS may infer the future relevance and benefits for end users of the system based on its characteristics, but research rarely extends to evaluating adoption once/if the DSS becomes publicly available.

An approach to examining adoption of irrigation DSS was carried out across 12 irrigation districts in Alberta, Canada (Wang et al., 2015). While 67% of the 199 participating farmers had adopted improved use of irrigation, the majority involved physical tools and observation - the use of a hand auger to dig up soil and direct assessment of the appearance and feel of soil moisture—to guide their decision making. Applying DSS-related methods to support irrigation decision making was 'near to or less than 1% for both adoption and level of intensity' (i.e. the percentage of total irrigated area on which it was used) (Wang et al., 2015). These findings highlight some of the key attributes of DSS compared with some physical on-farm practices that influence adoptability; the increased complexity, and reduced trialability of the DSS-related methods (viz. Phelan et al., 2018) in this instance reducing implementation compared with physical tools and observation.

A range of agricultural DSS have targeted the interface between farm management theory and actual practice (McCown, 2001). Payne et al. (2016) provide useful guidelines on the extent of support required for users to adopt different technologies, recognising the important role that human and social capital play in the process of adoption. Technologies that implement a 'technology push' or 'top-down' strategies tend to address simple (cause and effect) problems, provide readily experienced and observable benefits, are highly compatible with current practices and are relatively easy for farmers to implement independently. Some agricultural DSS in this category are relatively simple tools developed to assist farmers' tactical decisions (McCown, 2002; Stone and Hochman, 2004). A shortfall of these simple tools is that as users learn more about a situation, they may desire greater flexibility than the tool allows—namely, the opportunity to reduce decision uncertainty further and assess relative advantage to a greater extent by exploring different scenarios (Rose et al., 2016). Upon reaching the point at which the outputs and heuristics become readily predictable, users may discontinue use of such tools, even though they continue using the heuristics gained. Although somewhat intractable, future DSS research would benefit from documenting adoption of DSS heuristics, rather than DSS per se.

At the other end of the spectrum, Payne et al. (2016) describe the high level of co-learning required to develop and extend technologies that address complex problems and do not generally bring about rapid results. Strategic irrigation DSS designed to provide integrated recommendations for systems management fall within this high complexity category and are often associated with low levels of implementation. Stevens (2007) describes the ineffective scientific framework and linear knowledge pathways often used to convey information to farmers about irrigation decision making, instead of the deeper, learning-based approach required to support practice change.

A key reason for limited adoption by farmers is that many DSS have been created by scientists and software developers purely from a supply rather than a demand perspective (Lindblom et al., 2013). In such cases, development has proceeded as a result of technology push, instead of end-user pull to help solve a problem or improve a practice. Significant shortcomings of current agricultural DSS are a consequence of a lack of understanding of farmers' needs and decision-making in practice—a lack of compatibility. McCown (2001) and Mackrell et al. (2009) explain DSS have traditionally promulgated empirical, positivist paradigms with an underlying belief that the role of a DSS is to provide information to improve or even replace farmer decision making. Yet farmer decision making is a tacit and heuristic process and there is a disconnect between the farm management theory that forms the basis of modelled relationships and actual farm management in practice (Eastwood et al., 2012). When agricultural DSS are designed to provide recommendations for systems management and intended to act as proxies for a farmers' decision-making process, low adoption has been partly attributed to the resistance of farmers to give up their own decision-making processes (McCown, 2002).

Farmers' decision-making processes associated with adoption are influenced by a wide range of social factors (Vanclay, 1992). More innovative DSS development approaches take a less technical and analytical paradigm, acknowledging the importance of the social and individual views in farmer decision making. Vanclay (1992) highlighted that along with attributes of the technology itself, alignment of the technology with user aspirations (i.e., goals, values, beliefs, personality, culture, motivation) and capacity (human, social, natural, physical, financial) influence the extent of adoption. Rose et al. (2016) report fifteen factors influencing uptake and use of several agricultural DSS in the United Kingdom following semi-structured interviews with farmers and advisors, and these included characteristics of the technology, end-users and compliance landscape, such as performance, ease of use, trust, relevance to the user, level of marketing, IT education and farmer age (Fig. 4). Similar factors have also been identified and discussed to varying extents in other publications (Alvarez and Nuthall, 2006; Cox, 1996; Kerr, 2004; Tapsuwan et al., 2015; Van Meensel et al., 2012).

4.2. *Drivers of adoption*

4.2.1. *Technology*

The attributes of the technology itself—relative advantage, compatibility, complexity, trialability, observability (Rogers, 1)—are key factors that can be used to evaluate potential adoption pathways for existing irrigation DSS and to intentionally address in the development of future DSS. Van Meensel et al. (2012) summarised the success factors of agricultural DSS and the influential characteristics of the technology reflected the importance of compatibility (flexibility, perceived usefulness, credibility) and trialability (ease of use, see also Rose et al., 2016). DSS flexibility is the opportunity for end users to compare different scenarios and adapt the system to farm-specific situations, and this also allows assessment of the relative advantage of proceeding with DSS-based decisions. Relative advantage is also relevant for the initial decisions relating to investing in or using an irrigation DSS. Olivier and Singels (2004) listed uncertainty about actual benefits of investing in and using agricultural DSS for irrigation scheduling.

McCown (2002, p. 195) explains that 'farmers cease to care about (even credible) tools when they cannot see sufficient practical value for action resulting from the output, taking into consideration the costs, including managerial time and attention'. It is not uncommon for farmers to cease using a technology if they are able to learn and then apply the associated principles heuristically, and this mode of use can be viewed as successful adoption (McCown, 2002). There are also cases in which agricultural DSS shift from being used as goal-orientated tools towards learning aids (Schlindwein et al., 2015).

The web-based *DOMIS* DSS is reported to aid farmer decision making around the design and cost of micro-irrigation systems by providing different scenarios to consider and prioritise (Patel et al., 2018). Flexibility has been incorporated into the DSS design so that different levels of data can be entered depending on user knowledge, with the reduced complexity allowing it to be used without the aid of professional knowledge of agricultural engineering and micro irrigation system design. While an evaluation of adoption of *DOMIS* has not been published, Patel et al., (2018, p. 2247) state that this DSS 'is considered to be useful to farmers, industry, researchers and policy makers in agriculture and allied sectors' in India.

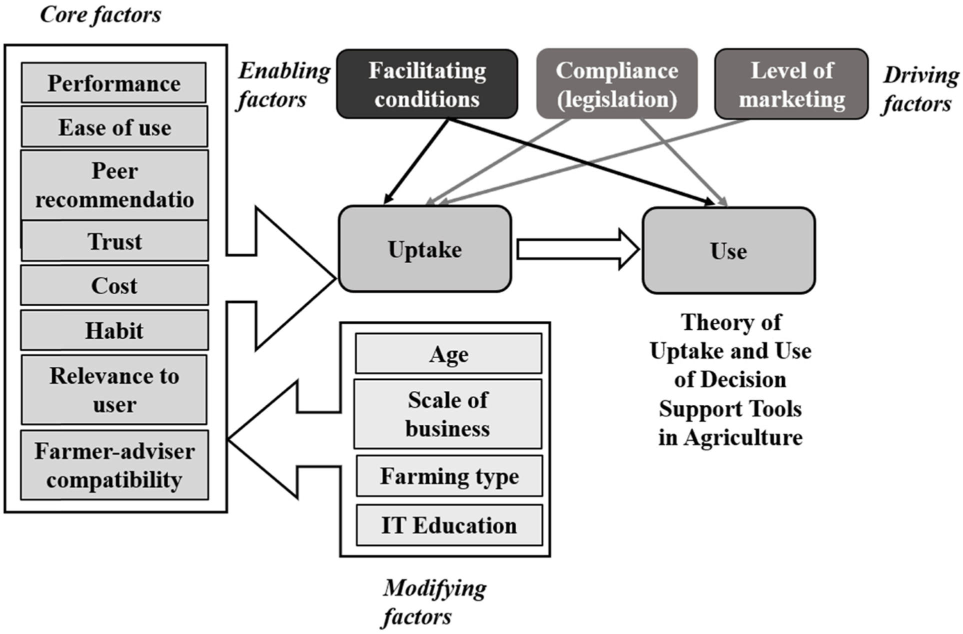

Fig. 4. Factors influencing uptake and use of agricultural DSS in the United Kingdom.
Source: redrawn from Rose et al. (2016).

A challenge for DSS that provide flexibility and credible representation of complex farming systems is ease of use. Kerr (2004) explains that many DSS are not implemented in small, owner-operated farming systems because they are too complex—requiring users to understand unfamiliar language and variables for basic input (for which they may not have the associated data) and possess existing knowledge and skills. For irrigation DSS, scientific complexity of the system and high requirements of inputs and parameters have limited adoption (Inman--Bamber et al., 2007; Olivier and Singels, 2004). In a review of DSS to manage irrigation in agriculture, Rinaldi and He (2014c) suggest that it is necessary to achieve a middle ground between simplicity in farmer use to encourage adoption and scientific complexity in the DSS to maintain rigour.

To encourage initial and continued implementation, DSS must also be easily maintained, with the capacity to be adapted with new information; an important yet challenging consideration for DSS funders and stakeholders (Rossi et al., 2014). DSS developers and funders must therefore consider alternative pathways to market after the build of the tool. DSS are generally constructed for a purpose, but their longevity must also be planned for to prevent outdated software and DSS redundancy. The tactical *Irrigation Optimizer* and strategic *DSSIPM and DSS-EVIM* are examples of economic irrigation DSS that are not available for use due to ceased development (Table 1). They are among many DSS that have showed promise or been successful for a period only to be discarded when their creators have ceased maintenance of the software, licencing and training manuals, or technology and science have advanced but the data within the tool have been superseded (e.g., DSS tools containing now defunct global climate model data, such as the SRES emissions scenarios).

4.2.2. *End-users*

When the attributes of the DSS has been tailored to favour adoption, the most likely users are the Innovator and Early Adopter farmer segments (McCown, 2002; Tapsuwan et al., 2015). Innovators are at the forefront of change and enjoy the process of trialling new practices, often without facilitated support (Howden et al., 1998; Rogers, 1995). They focus on continually improving their farm, with confident decision making often based on science and data. Turner et al. (2017) found that Innovator Australian farmers displayed strong economic and business orientations and were more likely than other segments to participate in benchmarking and other recordkeeping activities that align with the measuring and monitoring approach of DSS. Early Adopters take a proactive stance to change and are mostly viewed with respect by their industry peers when successfully implementing new practices (Rogers, 1995). However, McCown (2002) warns against the assumption that adoption of agricultural DSS by Innovators and Early Adopters (termed 'visionaries') will lead to adoption by the Early Majority (Rogers, 1995). The Early Majority are more pragmatic in their decision making, less open to innovation and change, and do not relate to the experience of the visionaries. Interviews with 30 irrigators in Georgia, USA, in relation to adoption of *Irrigator Pro*, revealed that on-farm contact and demonstrations would be needed to build the human and social capital required to support wider uptake, rather than relying on diffusion from Innovators to other farmer segments (Morrison, 2009). McCown (2002, p. 204) suggests that initial users of agricultural DSS:

> *'…are 'visionary' farmers, and the DSS fails to 'cross the chasm' to be used by the 'pragmatists'. By not crossing, an effort fails to achieve the critical market size that would retain funding and/or agency political support. This is the significance of the 'chasm': only about 15% of potential customers are comprised of visionaries on the left side of the 'chasm' – the left 'tail' of the bell curve.'*

Studies on farmer characteristics that influence adoption of DSS provide insights into the inter-related social factors associated with farmers' approaches to decision making (Alvarez and Nuthall, 2006; Rose et al., 2016). Alvarez and Nuthall (2006) investigated adoption in the context of New Zealand and Uruguay dairy farming and identified a suite of aspirations, and human and social capacity (farmer goals, personality, education, skills, current information processes, learning style and business size) as influential factors. Fig. 4 highlights the complexity of relationships between some of these factors in the United Kingdom context (Rose et al., 2016)—and the reality that in different contexts (e.g. cultures, farming systems, stages of community development, landscapes) the relative influence of these factors changes. The Adoption and Diffusion Outcome Prediction Tool (*ADOPT*) (Kuehne et al., 2017) can be used to estimate peak adoption rates of any agricultural technology and times to peak adoption. James and Harrison (2016) used *ADOPT* to examine a range of livestock greenhouse gas abatement techniques and predicted adoption rates from 34% to 95% and times to peak adoption of 3.9–14.9 years.

While farmers can be end users of the DSS *AHP, SIRMOD, WaterWorks, E-Water* and *FEAT*, the remaining DSS reviewed in this paper are targeted at next-users, including intermediaries (such as farmer advisors) and policy makers. Targeting intermediaries (i.e., consultants, extensionists, advisors and agronomists) may therefore help bridge the chasm and increase adoption rates of agricultural DSS. Design and development processes can be tailored accordingly if the goal is to create a DSS that will act as an adaptable simulator for an intermediary (most likely a consultant) in these interactions (McCown, 2002). Van Meensel et al. (2012) explains that intermediaries (i.e. next-users) can facilitate dialogue between farmers and agricultural DSS and the exchange of ideas about management practices that are relevant to the farmers. Indeed, given the need for advisors to contrast multiple scenarios (across perhaps multiple farms), it could be expected that farm advisors tent to be more receptive to DSS than the majority of farmers. A worthwhile avenue for future research would be the impact gained by conducting participatory work with advisors (as an intermediary to farmers) versus the impact gained by working with farmers themselves. Here again we return to our earlier sentiment that practice change primarily occurs when end-users learn and apply heuristics: these heuristics could be gained through direct interaction with a DSS or via an intermediary that passes down the heuristics.

Advisory support is particularly important where irrigation DSS are developed to investigate future production potential in large irrigation schemes, such as *DSIRR* in Italy (Bazzani, 2005a), *WHAT-IF* in the Zambezi River Basin in Africa (Payet-Burin et al., 2019), *E-Water* in the Mekrou River Basin in West Africa (Udias et al., 2018) and *Cotton WebApp* in the US Southern High Plains (Mauget et al., 2013). Not only are advisors likely to be the most effective next-users of this type of DSS, the recommended changes to farming systems as a result of use can be extensive, such that adoption of recommendations would be limited without additional agronomic advice to build human capital. *E-Water* is an example of a DSS that aids decision making about irrigation and fertiliser management to optimise food crop production, improve food security and efficiently use natural resources at a river basin level (Udias et al., 2018). While case study research showed that *E-Water* could identify promising site-specific management strategies for the Mekrou river basin in West Africa, the future impact of the DSS will rely on the capacity of intermediaries to use and understand the software, and the extent that farmers across the region are willing and able to adopt the resulting recommendations.

4.3. Participatory approaches: challenging yet essential

Lindblom et al. (2013) state that the ‘single unifying predictor of success or failure’ of a DSS is the extent to which end users are involved in its development. This aligns with the reality that the adoption process involves users continually re-evaluating whether the attributes of management practices contribute to their aspirations within the constraints of the assets available (Lindblom et al., 2013). Therefore, a development process that aims to understand end user aspirations, capacities and innovation needs, and aligns the attributes of the irrigation DSS with these, would be expected to achieve greater impact.

Jakku and Thorburn (2010) and Van Meensel et al. (2012) illustrate effective participatory approaches that developed DSS deemed useful by farmers. They emphasise the role of co-learning by a range of stakeholders involved in the participatory process, with farmers considered experts in their domain and scientists recognising the need to prioritise understanding over technicality. Agricultural innovation is viewed as a complex, interactive and iterative process of review, act and reflect, as opposed to scientists creating a technology and the adoption pathway simply focused on persuading farmers to implement it.

Key factors influencing the success of the participatory approach carried out by Van Meensel et al. (2012) include: (1) selection of appropriate stakeholders and a high level of transparency among them, (2) constructive collaboration among stakeholders and common goals for the DSS, and (3) flexibility in the development process, respecting the available time and scope but accepting adaptation during the process and not following a priori road map. Richards et al. (2008) describes another example of extensive industry and user consultation in the development of *Hydro-LOGIC* to deliver a simple, focussed irrigation DSS with ‘intermediate’ (rather than complex) and therefore accessible software. Following its initial release in Australia in 2003 there was ongoing system development in response to continued research and evaluation of end use, and in 2007 a survey of registered users revealed 30% implementation by farmers for irrigation management decisions.

Jakku and Thorburn (2010) suggest stakeholders involved in DSS development consider four potential outcomes of participatory DSS development: (1) ongoing use of the technology; (2) co-creation of management recommendations; (3) improved understanding but no practice change; and (4) rejection of the technology. While Outcome 1 is traditionally viewed as successful adoption, the evaluation of all outcomes paints a wider picture of the extent of uptake and use of the technology; indeed, “success” can be viewed through many lenses. Jakku and Thorburn (2010) evaluated the outcomes of participation in co-creating the *WaterSense* DSS and considered actions consistent with Outcomes 2 and 3 to be a success. This approach aligns with Wilkinson (2011), who describe adoption as a non-linear process that may be gradual, step-wise and/or may result in only partial implementation or even dis-adoption (as described above). Marianne et al. (2012) show that DSS can be used to characterise the diversity of uses and user situations to identify the need for flexibility in a DSS, as well as identification of new concepts. Through a series of workshops with designers and users, Marianne et al. (2012) co-created the *CETIOM* DSS and attributed “success” of their work to the iterative processes in which the prototype tool was tested and refined with end-users (in line with point 2 above). Lynch and Gregor (2004) highlighted the need to broaden the constructs of both participation and adoption “success”. Along with Mackrell et al. (2009), they noted that structured survey methods are insufficient to capture the resulting range of outcomes, and that qualitative, interpretative studies must be factored into funding and activity timelines. In our experience, end-users often learn as much through the participatory co-learning process as they do in using DSS per se, suggesting that the DSS provide a platform in which different agricultural paradigms can be proposed, contrasted and debated. In many cases, “success” could even be defined as dis-adoption of a DSS, because the heuristics have been learnt and can be applied mentally by end-users without support from the DSS.

Although participatory approaches are vital to success, the size of the end-user population to be surveyed and the number of proposed iterations requires careful consideration at the outset. Further, if a wide range of end-users are involved in the design of a DSS, their views and needs often vary (e.g., Harrison et al., 2017). Selecting the most common viewpoint arising from participatory approaches may address the needs of the largest part of the target population of end-users but may not necessarily have the greatest impact (Harrison et al., 2017, 2016a). Further work is required to determine which views arising from participatory processes, surveys, semi-structured interviews and other information gathering processes are the most important and/or will maximise future adoption of the DSS.

5. Conclusions

The objectives of this review were to (1) review the functionality and intended end-users of economic DSS for irrigated cropping systems, (2) document the extent to which these DSS account for uncertainty in DSS outputs, (3) examine tactical or strategic decisions able to be explored in DSS (with irrigation infrastructure being a key strategic decision), and (4) explore the human and social factors influencing adoption of DSS heuristics.

We showed that many DSS have focussed on either tactical or strategic decision-making, but only the DSS *WaterWorks* accounted for both tactical and strategic decision making. We found that few DSS show measures of uncertainty in their outputs (e.g., standard deviation associated with a mean), though reasons for this are unclear. It is possible that uncertainty is not well understood by end-users or is unable to be adequately quantified and intuitively displayed by DSS developers. We suggest that simple statistics shown in an intuitive and transparent fashion (e.g., standard deviations, ranges or percentiles) would go a long way towards helping end-users understand potential variability associated with DSS outputs.

We also found that only *WaterWorks* allowed contrasting between alternative forms of irrigation infrastructure; a lack of DSS comparing economic implications of alternative irrigation systems and investment may be a reflection of the limited experimental data comparing yields and profitability of alternative forms of irrigation in the field. Our findings suggest that *WaterWorks* is perhaps most developed in terms of the functional aspects of our aims.

Another key conclusion of our work was that very few DSS have been applied in multiple regions; the vast majority of DSS have been applied only in the regions in which they were developed. This observation may be underpinned by either (1) a lack of willingness to use or adapt existing DSS in new environments, (2) a lack of extension or awareness of existing DSS, (3) the presence of socio-economic or cultural barriers preventing adoption of existing DSS or (4) combinations of these reasons. Lack of widespread use of DSS across regions is another area deserving of further study.

Importantly, the clear distinction should be made between the adoption of DSS per se vs the adoption of DSS *heuristics*. Adoption and perpetual use of DSS does not necessarily indicate cumulative adoption of a given heuristic or paradigm promulgated by a DSS; in fact, disuse of DSS may indicate that knowledge transfer has been entirely successful, wherein the knowledge extended by the DSS is no longer required by the end-user.

Improving the adoption of future DSS heuristics may require addressing socio-economic and cultural problems associated with implementation, including the limited alignment of DSS features with end user aspirations (viz. historical top-down approaches), capacities and innovation needs, perceived relative advantage of an innovation, reversibility, trialability and training to build the human and social capacity required to build trust and confidence in the technology. To address these issues, future design and development of DSS should be *demand-driven* and be conducted in an *iterative participatory learning process*, providing manifold ways in which stakeholders can learn from and choose to implement the knowledge, technology or skills gained through such dialogue.

CRediT Authorship Contribution Statement

MTH conceived the study. IA, LT and MTH wrote the manuscript. All authors contributed to the revisions of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was funded by the Grains Research and Development Corporation (research investment UOT1906–002RTX) with support from the University of Tasmania, the University of Queensland, the Department of Primary Industries and Regions South Australia (PIRSA) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Competing interests

The authors declare that they have no competing interests.

References

Abbasi, F., Shooshtari, M.M., Feyen, J., 2003. Evaluation of various surface irrigation numerical simulation models. J. Irrig. Drain. Eng. 129, 208–213.

Adamson, D., Loch, A., 2014. Possible negative feedbacks from 'gold-plating'irrigation infrastructure. Agric. Water Manag. 145, 134–144.

Alcock, D.J., Harrison, M.T., Rawnsley, R.P., Eckard, R.J., 2015. Can animal genetics and flock management be used to reduce greenhouse gas emissions but also maintain productivity of wool-producing enterprises? Agric. Syst. 132, 25–34.

Alvarez, J., Nuthall, P., 2006. Adoption of computer based information systems: the case of dairy farmers in Canterbury, NZ, and Florida, Uruguay. Comput. Electron. Agric. 50, 48–60.

Bazzani, G.M., 2005a. A decision support for an integrated multi-scale analysis of irrigation: DSIRR. J. Environ. Manag. 77, 301–314.

Bell, M.J., Eckard, R.J., Harrison, M.T., Neal, J.S., Cullen, B.R., 2013. Effect of warming on the productivity of perennial ryegrass and kikuyu pastures in south-eastern Australia. Crop Pasture Sci. 64, 61–70.

Bell, L.W., Harrison, M.T., Kirkegaard, J.A., 2015. Dual-purpose cropping–capitalising on potential grain crop grazing to enhance mixed-farming profitability. Crop Pasture Sci. 66 (i-iv).

Beltrán, J.Mn, 1999. Irrigation with saline water: benefits and environmental impact. Agric. Water Manag. 40, 183–194.

Bjornlund, H., Nicol, L., Klein, K.K., 2007. Challenges in implementing economic instruments to manage irrigation water on farms in southern Alberta. Agric. Water Manag. 92, 131–141.

Bond, W.J., 1998. Effluent irrigation—an environmental challenge for soil science. Soil Res. 36, 543–556.

Carruthers, I., Rosegrant, M.W., Seckler, D., 1997. Irrigation and food security in the 21st century. Irrig. Drain. Syst. 11, 83–101.

Caswell, M.F., 1991. Irrigation technology adoption decisions: empirical evidence. The Economics and Management of Water and Drainage in Agriculture. Springer,, pp. 295–312.

Chang-Fung-Martel, J., Harrison, M.T., Rawnsley, R., Smith, A.P., Meinke, H., 2017. The impact of extreme climatic events on pasture-based dairy systems: a review. Crop Pasture Sci. 68, 1158–1169.

Christie, K.M., Smith, A.P., Rawnsley, R.P., Harrison, M.T., Eckard, R.J., 2018. Simulated seasonal responses of grazed dairy pastures to nitrogen fertilizer in SE Australia: pasture production. Agric. Syst. 166, 36–47.

Christie, K.M., Smith, A.P., Rawnsley, R.P., Harrison, M.T., Eckard, R.J., 2020. Simulated seasonal responses of grazed dairy pastures to nitrogen fertilizer in SE Australia: N loss and recovery. Agric. Syst. 182, 102847.

Colomb, R., 1987. Knowledge-based decision support systems: a background to expert systems. Rev. Mark. Agric. Econ. 55 (2), 162–166.

Cox, P., 1996. Some issues in the design of agricultural decision support systems. Agric. Syst. 52, 355–381.

Darouich, H., Cameira, M.R., Gonçalves, J.M., Paredes, P., Pereira, L.S., 2017. Comparing sprinkler and surface irrigation for wheat using multi-criteria analysis: water saving vs. economic returns. Water 9, 50–69.

Darouich, H., Gonçalves, J.M., Muga, A., Pereira, L.S., 2012. Water saving vs. farm economics in cotton surface irrigation: an application of multicriteria analysis. Agric. Water Manag. 115, 223–231.

Darouich, H.M., Pedras, C.M., Gonçalves, J.M., Pereira, L.S., 2014. Drip vs. surface irrigation: a comparison focussing on water saving and economic returns using multicriteria analysis applied to cotton. Biosyst. Eng. 122, 74–90.

DST, 2021. Technology Readiness Levels Definitions and Descriptions. ⟨https://www.dst.defence.gov.au/sites/default/files/basic_pages/documents/TRL%20Explanations_1.pdf⟩. Accessed 15 Aug 2021.

Eastwood, C., Chapman, D., Paine, M., 2012. Networks of practice for co-construction of agricultural decision support systems: case studies of precision dairy farms in Australia. Agric. Syst. 108, 10–18.

El-Gafy, I., El-Ganzori, A., 2012. Decision Support System for economic value of irrigation water. Appl. Water Sci. 2, 63–76.

Goncalves, J.M., Muga, A., Darouich, H., Pereira, L.S., Universidade Fernando, P., 2007. The Decision Support System SADREG: application to improve wheat surface irrigation. Novas Perspect. Em Sist. Tecnol. Inform. Vol Ii, 15–26.

Goncalves, J.M., Pereira, L.S., 2009. Decision Support System for surface irrigation design. J. Irrig. Drain. Eng. 135, 343–356.

Goncalves, J.M., Pereira, L.S., Sousa, P.L., 1998a. Environmental criteria in a decision support system for surface irrigation design. In: Pereira, L.S., Gowing, J. (Eds.), Water and the Environment: Innovative Issues in Irrigation and Drainage. 111–119.

Goncalves, J.M., Pereira, L.S., Sousa, P.L., 1998b. Decision support system for surface irrigation design. In: Zazueta, F.S., Xin, J. (Eds.), Computers in Agriculture, 1998, pp. 138–145.

Hajkowicz, S., Collins, K., 2007. A review of multiple criteria analysis for water resource planning and management. Water Resour. Manag. 21, 1553–1566.

Hardaker, J.B., Lien, G., Anderson, J.R., Huirne, R.B., 2015. Coping with Risk in Agriculture: Applied Decision Analysis, 3rd edn.,. British Library, London, UK.

Hardaker, J.B., Richardson, J.W., Lien, G., Schumann, K.D., 2004. Stochastic efficiency analysis with risk aversion bounds: a simplified approach. Aust. J. Agric. Resour. Econ. 48, 253–270.

Harrison, M.T., Christie, K.M., Rawnsley, R.P., Eckard, R.J., 2014. Modelling pasture management and livestock genotype interventions to improve whole-farm productivity and reduce greenhouse gas emissions intensities. Anim. Prod. Sci. 54, 2018–2028.

Harrison, M.T., Cullen, B.R., Armstrong, D., 2017. Management options for dairy farms under climate change: Effects of intensification, adaptation and simplification on pastures, milk production and profitability. Agric. Syst. 155, 19–32.

Harrison, M.T., Cullen, B.R., Rawnsley, R.P., 2016a. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agric. Syst. 148, 135–148.

Harrison, M.T., Cullen, B.R., Tomkins, N.W., McSweeney, C., Cohn, P., Eckard, R.J., 2016b. The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems. Anim. Prod. Sci. 56, 370–384.

Harrison, M.T., Evans, J.R., Dove, H., Moore, A.D., 2012a. Recovery dynamics of rainfed winter wheat after livestock grazing 1. Growth rates, grain yields, soil water use and water-use efficiency. Crop Pasture Sci. 62, 947–959.

Harrison, M.T., Evans, J.R., Dove, H., Moore, A.D., 2012b. Recovery dynamics of rainfed winter wheat after livestock grazing 2. Light interception, radiation-use efficiency and dry-matter partitioning. Crop Pasture Sci. 62, 960–971.

Harrison, M.T., Evans, J.R., Moore, A.D., 2012c. Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing 1. Model derivation and coefficient calibration. Field Crops Res. 136, 116–126.

Harrison, M.T., Evans, J.R., Moore, A.D., 2012d. Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing 2. Model validation and effects of grazing management. Field Crops Res. 136, 127–137.

Harrison, M.T., Roggero, P.P., Zavattaro, L., 2019. Simple, efficient and robust techniques for automatic multi-objective function parameterisation: case studies of local and global optimisation using APSIM. Environ. Model. Softw. 117, 109–133.

Hornbuckle, J., Christen, E., Faulkner, R., 1999. Improving the Efficiency and Performance of Furrow Irrigation Using Simulation Modeling in South–Eastern Australia. Environmental Engineering Department, University of New England, Armidale,, New South Wale, Australia, pp. 1–18.

J. Hornbuckle E. Christen R. Faulkner Use of SIRMOD as a quasi real time surface irrigation decision support system. In Proceedings of International Congress on Modelling and Simulation Papers 2005, MODSIM 2005. Modelling and Simulation Society of Australia and New Zealand Inc., pp. 217–223.

Howden, P., Vanclay, F., Lemerle, D., Kent, J., 1998. Working with the grain: farming styles amongst Australian broadacre croppers. Rural Soc. 8, 109–125.

Ho, C., Jackson, T., Harrison, M., Eckard, R., 2014. Increasing ewe genetic fecundity improves whole-farm production and reduces greenhouse gas emissions intensities: 2. Economic performance. Anim. Prod. Sci. 54, 1248–1253.

Ho, C., Newman, M., Dalley, D., Little, S., Wales, W., 2013. Performance, return and risk of different dairy systems in Australian and New Zealand. Anim. Prod. Sci. 53, 894–906.

Ibrahim, A., Harrison, M., Meinke, H., Fan, Y., Johnson, P., Zhou, M., 2018. A regulator of early flowering in barley (*Hordeum vulgare* L.). PLoS One 13, 0200722.

N. Inman-Bamber S. Attard S. Verrall W. Webb C. Baillie. A web-based system for scheduling irrigation in sugarcane. In: Proceedings of the International Society of Sugar Cane Technologists Congress, 2007 International Society of Sugar Cane Technologists, pp. 459–464.

Jakku, E., Thorburn, P., 2010. A conceptual framework for guiding the participatory development of agricultural decision support systems. Agric. Syst. 103, 675–682.

James, A.R., Harrison, M.T., 2016. Adoptability and effectiveness of livestock emission reduction techniques in Australia's temperate high-rainfall zone. Anim. Prod. Sci. 56, 393–401.

Kandulu, J.M., Bryan, B.A., King, D., Connor, J.D., 2012. Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. Ecol. Econ. 79, 105–112.

Karami, E., 2006. Appropriateness of farmers' adoption of irrigation methods: the application of the AHP model. Agric. Syst. 87, 101–119.

Karleuša, B., Hajdinger, A., Tadić, L., 2019. The application of multi-criteria analysis methods for the determination of priorities in the implementation of irrigation plans. Water 11, 501–521.

Kerr, D., 2004. Factors influencing the development and adoption of knowledge based decision support systems for small, owner-operated rural business. Artif. Intell. Rev. 22, 127–147.

Khan, S., Mushtaq, S., Chen, C., 2009. A decision support tool for irrigation infrastructure investments. Irrig. Drain. 59 (4), 404–418. https://doi.org/10.1002/ird.501.

Khan, S. and Chen, C. and Mushtaq, S. (2008) WaterWorks: a decision support tool for irrigation infrastructure decisions at farm level. In: 2008 Western Pacific Geophysics Meeting, 29 July - 1 Aug 2008, Cairns, Australia.

Koech, R., Langat, P., 2018. Improving irrigation water use efficiency: a review of advances, challenges and opportunities in the Australian context. Water 10, 1771–1788.

Kuehne, G., Llewellyn, R., Pannell, D.J., Wilkinson, R., Dolling, P., Ouzman, J., Ewing, M., 2017. Predicting farmer uptake of new agricultural practices: a tool for research, extension and policy. Agric. Syst. 156, 115–125.

Langworthy, A.D., Rawnsley, R.P., Freeman, M.J., Pembleton, K.G., Corkrey, R., Harrison, M.T., Lane, P.A., Henry, D.A., 2018. Potential of summer-active temperate (C3) perennial forages to mitigate the detrimental effects of supraoptimal temperatures on summer home-grown feed production in south-eastern Australian dairying regions. Crop Pasture Sci. 69, 808–820.

Lazaridou, D., Michailidis, A., Trigkas, M., 2019. Socio-economic factors influencing farmers' willingness to undertake environmental responsibility. Environ. Sci. Pollut. Res. 26, 14732–14741.

Leeuwis, C., 2013. Communication for Rural Innovation: Rethinking Agricultural Extension. John Wiley & Sons,.

Lindblom, J., Rambusch, J., Ljung, M., Lundström, C., 2013. Decision making in agriculture-farmers' lifeworld in theory and practice. Ext. Educ. Worldw. 177–182.

Lynch, T., Gregor, S., 2004. User participation in decision support systems development: influencing system outcomes. Eur. J. Inform. Syst. 13, 286–301.

Mackrell, D., Kerr, D., Von Hellens, L., 2009. A qualitative case study of the adoption and use of an agricultural decision support system in the Australian cotton industry: the socio-technical view. Decis. Support Syst. 47, 143–153.

Maraseni, T.N., Mushtaq, S., Reardon-Smith, K., 2012. Climate change, water security and the need for integrated policy development: the case of on-farm infrastructure investment in the Australian irrigation sector. Environ. Res. Lett. 7 (3), 034006, 1-17.

Marianne, C., Jeuffroy, M.-H., Prost, L., Jean-Marc, M., 2012. Participatory design of agricultural decision support tools: taking account of the use situations. Agron. Sustain. Dev. 32.

Matthews, K., Schwarz, G., Buchan, K., Rivington, M., Miller, D., 2008. Wither agricultural DSS? Comput. Electron. Agric. 61, 149–159.

Mauget, S., Leiker, G., Nair, S., 2013. A web application for cotton irrigation management on the US Southern High Plains. Part II: application design. Comput. Electron. Agric. 99, 258–264.

McCown, R., 2001. Learning to bridge the gap between science-based decision support and the practice of farming: evolution in paradigms of model-based research and intervention from design to dialogue. Aust. J. Agric. Res. 52, 549–572.

McCown, R.L., 2002. Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agric. Syst. 74, 179–220.

Van Meensel, J., Lauwers, L., Kempen, I., Dessein, J., Van Huylenbroeck, G., 2012. Effect of a participatory approach on the successful development of agricultural decision support systems: the case of Pigs2win. Decis. Support Syst. 54, 164–172.

Mehanna, H., Abdelhamid, M., SABREEN, K., ABDEL-SALAM, E., 2015. SIRMOD model as a management tool for basin irrigation method in calcareous soil. Int. J. Chem. Technol. Res. 0974–4290.

Monjardino, M., McBeath, T., Ouzman, J., Llewellyn, R., Jones, B., 2015. Farmer risk-aversion limits closure of yield and profit gaps: a study of nitrogen management in the southern Australian wheatbelt. Agric. Syst. 137, 108–118.

Montagu, K., Thomas, B., Thomas, G., Christen, E., Hornbuckle, J., Baillie, C., Linehan, C., Smith, P., Gallo, F., North, S., 2006. Understanding irrigation decisions: from enterprise planning to the paddock. Land Water Aust.

Morrison, M., 2009. Encouraging the adoption of decision support systems by irrigators. Rural Soc. 19, 17–31.

Mowrer, H.T., 2000. Uncertainty in natural resource decision support systems: sources, interpretation, and importance. Comput. Electron. Agric. 27, 139–154.

Olivier, F., Singels, A., 2004. Survey of irrigation scheduling practices in the South African sugar industry. Proc. S. Afr. Sug. Technol. Assoc. 239–244.

Olsson, J.A., Andersson, L., 2006. Possibilities and Problems with the Use of Models as a Communication Tool in Water Resource Management. Integrated Assessment of Water Resources and Global Change. Springer,, pp. 97–110.

Pannell, D.J., Marshall, G.R., Barr, N., Curtis, A., Vanclay, F., Wilkinson, R., 2006. Understanding and promoting adoption of conservation practices by rural landholders. Aust. J. Exp. Agric. 46, 1407–1424.

Passioura, J.B., 1996. Simulation models: science, snake oil, education, or engineering? Agron. J. 88, 690–694.

Patel, N., Rajput, T.B.S., Dinkar, D.K., Ram, S., Singla, S.K., 2018. DOMIS: a decision support system for design and cost estimation of micro-irrigation systems. Curr. Sci. 115, 2240–2248.

Payet-Burin, R., Kromann, M., Pereira-Cardenal, S., Strzepek, K.M., Bauer-Gottwein, P., 2019. WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water-energy-food-climate nexus. Hydrol. Earth Syst. Sci. 23, 4129–4152.

T. Payne J. Turner K. Rijswijk A. McDermott R. Wakelin. Informing extension project design: the right tool for the job. Hill Country Symposium. Grassland Research and Practice Series. 2016. pp. 33–38.

Pembleton, K., Cullen, B., Rawnsley, R., Harrison, M., Ramilan, T., 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. J. Agric. Sci. 154, 1131–1152.

Phelan, D.C., Harrison, M.T., Kemmerer, E.P., Parsons, D., 2015. Management opportunities for boosting productivity of cool-temperate dairy farms under climate change. Agric. Syst. 138, 46–54.

Phelan, D.C., Harrison, M.T., McLean, G., Cox, H., Pembleton, K.G., Dean, G.J., Parsons, D., do Amaral Richter, M.E., Pengilley, G., Hinton, S.J., Mohammed, C.L., 2018. Advancing a farmer decision support tool for agronomic decisions on rainfed and irrigated wheat cropping in Tasmania. Agric. Syst. 167, 113–124.

S. Raine W. Walker A decision support tool for the design, management and evaluation of surface irrigation systems In: Proceedings of the National Conference. 1998 Irrigation Association of Australia, Citeseer pp.19–21.

G.C. Rausser J. Yassour. Construction of decision support systems for agriculture marketing boards and other public agencies in less developed countries: parts 1 and 2 1978.

Reynolds, J.F., Acock, B., 1985. Predicting the response of plants to increasing carbon dioxide: a critique of plant growth models. Ecol. Model. 29, 107–129.

Richards, Q., Bange, M., Johnston, S., 2008. HydroLOGIC: an irrigation management system for Australian cotton. Agric. Syst. 98, 40–49.

Rinaldi, M., He, Z., 2014a. Decision Support Systems to manage irrigation in agriculture. Adv. Agron. 123, 229–280.

Rinaldi, M., He, Z., 2014b. Decision Support Systems to manage irrigation in agriculture. Adv. Agron. 123, 229–279.

Rinaldi, M., He, Z., 2014c. Decision Support Systems to Manage Irrigation in Agriculture. Advances in Agronomy. Elsevier,, pp. 229–279.

Rogers, E.M., 1995. Diffusion of Innovations. Simon and Schuster,, New York.

M. Rollin F. Scott Maximising on-farm irrigation profitability: economic analysis report. Department of Primary Industry Australia. 2018.

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., Dicks, L.V., 2016. Decision support tools for agriculture: Towards effective design and delivery. Agric. Syst. 149, 165–174.

Rossi, V., Salinari, F., Poni, S., Caffi, T., Bettati, T., 2014. Addressing the implementation problem in agricultural decision support systems: the example of vite. net®. Comput. Electron. Agric. 100, 88–99.

Schlindwein, S.L., Eulenstein, F., Lana, M., Sieber, S., Boulanger, J.-P., Guevara, E., Meira, S., Gentile, E., Bonatti, M., 2015. What Can Be Learned about the Adaptation Process of Farming Systems to Climate Dynamics Using Crop Models? Sustainable Agriculture Research 4 (4), 122–131. https://doi.org/10.5539/sar.v4n4p122 (4) (PDF) Adoption of the Agricultural Decision Support System CropSAT in Extension: Incentives and Needs. Available from: https://www.researchgate.net/publication/319243982_Adoption_of_the_Agricultural_Decision_Support_System_CropSAT_in_Extension_Incentives_and_Needs [accessed Sep 08 2021].

Schultz, B., Thatte, C.D., Labhsetwar, V.K., 2005. Irrigation and drainage. Main. Contrib. Glob. Food Prod. Irrig. Drain. 54, 263–278.

Silva, Md.L., Park, J., Keatinge, J., Pinto, P., 2001a. I. A decision support system to improve planning and management in large irrigation schemes. Agric. Water Manag. 51, 187–201.

Silva, Md.L., Park, J.R., Keatinge, J.D.H., Pinto, P.A., 2001b. II. The use of the DSSIPM in the Alentejo region of southern Portugal. Agric. Water Manag. 51, 203–215.

Stevens, J.B., 2007. Adoption of irrigatio scheduling methods in South Africa. Univ. Pretoria.

Stone, P., Hochman, Z., 2004. If interactive decision support systems are the answer, have we been asking the right questions, New directions for a diverse planet. Proc. 4th Int. Crop Sci. Congr.

Tapsuwan, S., Hunink, J., Alcon, F., Mertens-Palomares, A.N., Baille, A., 2015. Assessing the design of a model-based irrigation advisory bulletin: the importance of end-user participation. Irrig. Drain. 64, 228–240.

Turner, L., Wilkinson, R., Kilpatrick, S., 2017. Boundaries to change: insights into the change process of beef and sheep farmers. Rural Ext. Innov. Syst. J. 13 (1), 9–18.

Udias, A., Pastori, M., Dondeynaz, C., Moreno, C.C., Ali, A., Cattaneo, L., Cano, J., 2018. A decision support tool to enhance agricultural growth in the Mékrou river basin (West Africa). Comput. Electron. Agric. 154, 467–481.

Uusitalo, L., Lehikoinen, A., Helle, I., Myrberg, K., 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ. Model. Softw. 63, 24–31.

Vanclay, F., 1992. The barriers to adoption often have a rational basis. Proc. 7th Int. Soil Conserv. Organ. Conf., Syd. 452–458.

Walker, W., 1993. SIRMOD, A Surface Irrigation Model. Utah State University Depart of Biol. and irrig. Engin. UTAH State University Logan UT,, 84322-84105.

Walker, W., 1998. SIRMOD–Surface Irrigation Modeling Software. Utah State University,, Logan.

Wang, J., Klein, K.K., Bjornlund, H., Zhang, L., Zhang, W., 2015. Adoption of improved irrigation scheduling methods in Alberta: An empirical analysis. Can. Water Resour. J. / Rev. Can. Des. Ressour. Hydr. 40, 47–61.

Watkiss, P., Hunt, A., Blyth, W., Dyszynski, J., 2015. The use of new economic decision support tools for adaptation assessment: A review of methods and applications, towards guidance on applicability. Clim. Change 132, 401–416.

Wilkinson, R., 2011. The many meanings of adoption. Chang. Land. Manag.: Adopt. N. Pract. Rural Land. 39–49.

Wu, D., Xue, J., Bo, X., Meng, W., Wu, Y., Du, T., 2017. Simulation of irrigation uniformity and optimization of irrigation technical parameters based on the SIRMOD model under alternate furrow irrigation. Irrig. Drain. 66, 478–491.

Zhai, Z., Martínez, J.F., Beltran, V., Martínez, N.L., 2020. Decision support systems for agriculture 4.0: Survey and challenges. Comput. Electron. Agric. 170, 105256.

Zheng, H., Shi, H., Cheng, M., Zhu, M., JoséManuel, G., 2009a. Analysis of irrigation efficiency and water use efficiency of border irrigatio. Trans. Chin. Soc. Agric. Eng. 25, 1–6.

Zheng, H., Shi, H., Zhu, M., Liu, H., José Manuel, G., 2009b. Estimation of infiltration parameters for border irrigation based on SIRMOD method and modelling of border irrigation. Trans. Chin. Soc. Agric. Eng. 25, 29–34.