Modelling water allocation in community irrigation using multi-agent system

A thesis
submitted in partial fulfilment
of the requirements for the Degree of
Doctor of Philosophy

at
Lincoln University
by
KItti Chiewchan

Lincoln University
2021

Declaration

Parts of this thesis have been submitted (with slight alterations dependent on journal requirements) and accepted for publication and/or presented in advance of submission of this thesis.

Paper published

1. Chiewchan K., Anthony P., Samarasinghe S. (2019) Agent Based Irrigation Management for Mixed-Cropping Farms. In: Alfred R., Lim Y., Ibrahim A., Anthony P. (eds) Computational Science and Technology. Lecture Notes in Electrical Engineering, vol 481. Springer, Singapore. https://doi.org/10.1007/978-981-13-2622-6_46

2. Chiewchan K., Anthony P., Birendra K.C., Samarasinghe S. (2020) Improving Water Allocation Using Multi-agent Negotiation Mechanisms. In: Jezic G., Chen-Burger YH., Kusek M., Šperka R., Howlett R., Jain L. (eds) Agents and Multi-agent Systems: Technologies and Applications 2019. Smart Innovation, Systems and Technologies, vol 148. Springer, Singapore.

3. Chiewchan K., Anthony P., Birendra K.C., Samarasinghe S. (2021) Improving water distribution in a multi-agent system using fixed multiunit first-price sealed-bid auction, accepted for Agent and Multi-agent systems: Technology and applications (KES-AMSTA-21) and will be published by Springer as book chapter in a volume of the KES Smart Innovation Systems and Technologies series.

Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy.

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by

Kitti Chiewchan

Insufficient water for irrigation is a common problem in New Zealand, particularly in the Canterbury region, where the use and demand have been steadily increasing over the past 20 years (PCE, 2004; The Parliamentary Commissioner for the Environment, 2004). As a limited resource, there are restrictions around its use. While farmers who need water for irrigation can apply for consent through Environment Canterbury, the process takes a long time and is expensive. As a result, only those with large farms or those who will be able to realise greater financial benefits and higher levels of productivity tend to apply. Instead, most farmers apply to a community irrigation scheme such as Central Plain Water Limited (CPWL) who sells water to individual farmers. As a farmer must pay for each unit of water that s/he uses, s/he needs to have a good irrigation plan in place to ensure they obtain the maximum profit from their investment.

In New Zealand, most farmers use computer programmes to estimate their irrigation requirements. The two most common programmes in New Zealand are IrriCalc and OVERSEER. However, both have some limitations: they can only be used to calculate the water needs of an individual farm and neither can prioritise crop water needs during periods of water scarcity. To deal with this problem, we designed an agent-based irrigation management system that can be used to optimise water allocation around the farm which is particularly useful during periods of water scarcity by taking into account the crop types and prioritising them based on the crop utility value. As it calculates the water savings based on each crop's growth stage and prioritises it in terms of its potential sales price, this agent-based system provides a way to increase farmers' profitability and to enables them to thrive during periods of water scarcity.

During the water reduction exercise, most farms suffer from water shortages. However, there are farmers (who may have overestimated their water needs) who will have excess water. Recognising this situation, we developed a multi-agent system to improve water allocation within a community of water users (where each individual agent represents a farm) and investigated the efficiency of water distribution mechanisms among farms. Farmers can use the proposed multi-agent water management system to negotiate with each other to buy and sell water among themselves. One of the most well-known and simplest methods to achieve this is by using an auction. The choice of an auction was deliberate as it allows agents to buy water at a price, they are comfortable with. An agent must consider how much they are willing to pay for a specific volume of water to ensure their farm remains profitable. This study considered three-auction types and compared the results of each auction in terms of fair water distribution, profit for the sellers and reductions in losses for bidders. We found that the pay-per-bid auctions (discriminatory and uniform) are the best strategies for water distribution that balance between water distribution and gaining profit in water community. In addition, we also investigated how varying behaviours of sellers and buyer affect the outcome of the auction.

Keywords: water allocation, crop water need, agent and multi-agent system, auction mechanism

Acknowledgements

The completion of this thesis would not have been possible without the support and encouragement of many people. I am deeply grateful to my supervisor Associate Professor Patricia Anthony, for her excellent supervision. She provided me with invaluable advice and guidance during my study. Moreover, she always encouraged me to develop my ideas. I would also like to express my gratitude to my associate supervisors, Professor Sandhya Samarasinghe and Dr Birendra K.C. Thank you for your support and your invaluable comments on my drafts.

Thank you to Douglas Broughton and Tracey Shields for their administrative assistance and making my time at Lincoln University so much easier. Special thanks to Dr Rebecca Kambuta who edited my work and provided me with suggestions to improve my writing.

Thank you to the Bansomdejchaopraya Rajabhat University for supporting my PhD study.

I would like to thank my colleagues and friends at Lincoln University who have assisted me in various ways. Thank you to Kiatikorn for sharing your knowledge with me. Thank you to Jumtip and Mina who always cheered up me and helped me to overcome various obstacles.

I dedicate this thesis to my family. I am deeply grateful for my parents' love and unconditional support. I am particularly grateful to my sisters who inspired and encouraged me to complete this thesis.

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Chapter 1

Introduction

1.1 Background of research

Due to population growth, demand for agricultural production has been increasing constantly since the second half of the 20th century. A Food and Agriculture Organization (FAO) report shows an increase of 30% in per capita food consumption in developed countries (Food and Agriculture Organization, 2010). To feed the projected population of 2050, current food production will have to double. This will require two times the amount of water (Birendra, Schultz, & Prasad, 2011). As an activity, agriculture uses the most water on the globe: Seventy percent of all water used by humans is used in agriculture (Food and Agriculture Organization, 2010). However, as urbanisation increases, so too does the domestic and industrial need for water thus meaning there is less water for agriculture. This means that farmers today must produce more food using less water.

Birendra. et al. (2019) have shown that it is possible to feed a growing (global) population using less water through improved water management practices. Improvements in irrigation efficiency not only help improve food production, but also reduce the environmental deterioration caused by overland flow and deep percolation (Anthony & Birendra, 2018).

Environmental problems associated with inefficient irrigation are common around the world. This is the case in New Zealand, where ground and surface water resources have been degraded due to nitrate leaching through drainage (Birendra, 2016). Computer programmes such as IrricalC, OVERSEER, and APSIM seek to improve farm irrigation management practices. These tools enable farmers to calculate their irrigation requirements (Keating et al., 2003; Mateos, López-Cortijo, & Sagardoy, 2002; Wheeler & Bright, 2015). However, these programmes have their limitations: they can only calculate irrigation requirements for a single crop on a single farm: in other words, they cannot be used on a farm which has multiple crops. In addition, they do not support water sharing between users.

This research applies computer techniques to estimate irrigation needs for farms which have multiple crops, each with varying watering requirements. Moreover, the proposed computer programme supports water sharing mechanisms between users which optimises the use of water without compromising on yields and having a negative impact on the environment.

1.2 Agriculture and irrigation in Canterbury

The Canterbury region which is located in the South Island of New Zealand, has the largest area of irrigated land and thus uses the largest proportion of water (58% of country's total water allocation): it represents 70% of the country's total irrigated land (Birendra, 2016; Housen, 2015). In this region, areas under irrigation have been progressively increasing over the past 13 years: from 240,778 ha in 2002 to 478,143 ha in 2017 (refer to Figure 1.1). Numerous dryland farms has been converted to irrigated land (Jenkins, 2015). Consequently, water use and water demand have steadily increased over the past 20 years, resulting in insufficient water availability. Insufficient water availability may become a problem in the future. New Zealand water usage data shows that in the agriculture sector, water usage has been on the rise: 55% per decade since 1965 (The Parliamentary Commissioner for the Environment, 2004). This increasing demand for water has directly affected the water allocation scheme in Canterbury. This means that there is not enough surface water for agriculture.

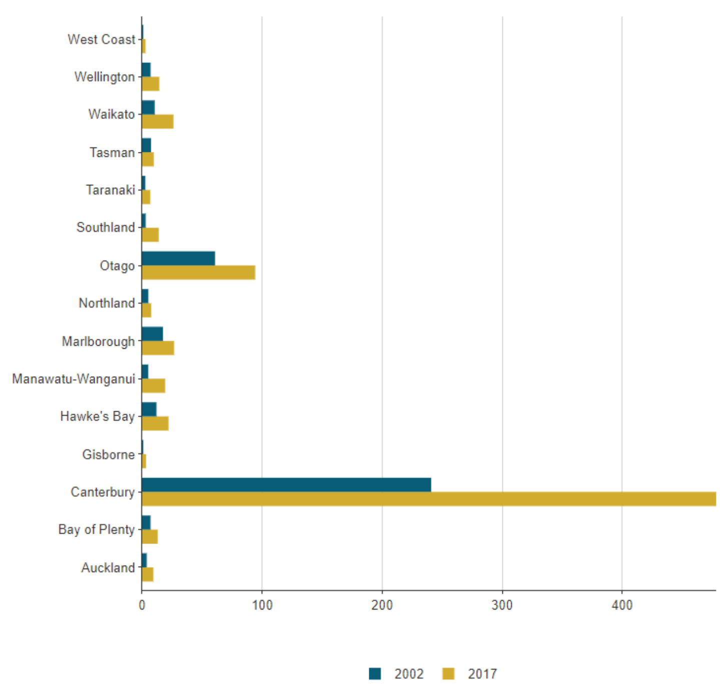


Figure 1.1 Total irrigated land area (Hectare per km^2) (2002 - 2017)
Source: https://www.stats.govt.nz/indicators/irrigated-land

1.3 Canterbury climate

The New Zealand climate varies across regions. It has been broadly categorised into three types: subtropical; warm-temperate; and cold-temperate (Chappell, 2013; Macara, 2014). The North Island is considered a subtropical region. This area is the warmest part of the country and tends to be humid. During the planting season (from November to April) temperatures range between 15˚C and 30˚C. The main crops grown in the North Island are wheat and potatoes (Macara, 2014). The warm-temperate region (the middle) is cool in winter and warm in summer. Temperatures range from 10 ˚C in spring to 25˚C in summer. The main growing season is from September to May/June. The main crops are onions, broccoli, broad beans, and eggplants (Macara, 2014). The cold-temperate region (the South) has no humidity. This region is cold in the winter and warm in the summer. Cold winters are ideal for crops that need winter chilling. The main growing season is from October/November to April/ May, with the main crops being pasture, peas, wheat and radishes.

Figure 1.2 Canterbury regional map
Source: http://www.localcouncils.govt.nz/lgip.nsf

Figure 1.2 shows that Canterbury falls into the cold-temperature category. This region lies on the Southern Alps where the annual rainfall is low and long dry spells can occur, especially during summer (see Figure 1.2). The rainfall and Reference Evapotranspiration (ET_0) data show that from September to April the ET_0 is greater than rainfall (refer to Figure 1.3). Evapotranspiration (ET) is the rate of water extraction from the bare soil is known as evaporation (E). The sum of evaporation and plant transpiration is called evapotranspiration (ET) (Brouwer, Goffeau, & Heibloem, 1985; Brouwer, Prins, Kay, & Heibloem, 2013). This means that there is the potential for water shortages over September to April. Thus, farmers may need to apply supplementary irrigation during this period. Crop water needs vary each month depending on the rainfall. Due to high water usage, there are often water shortages and/or restrictions during the summer season (Macara, 2014).

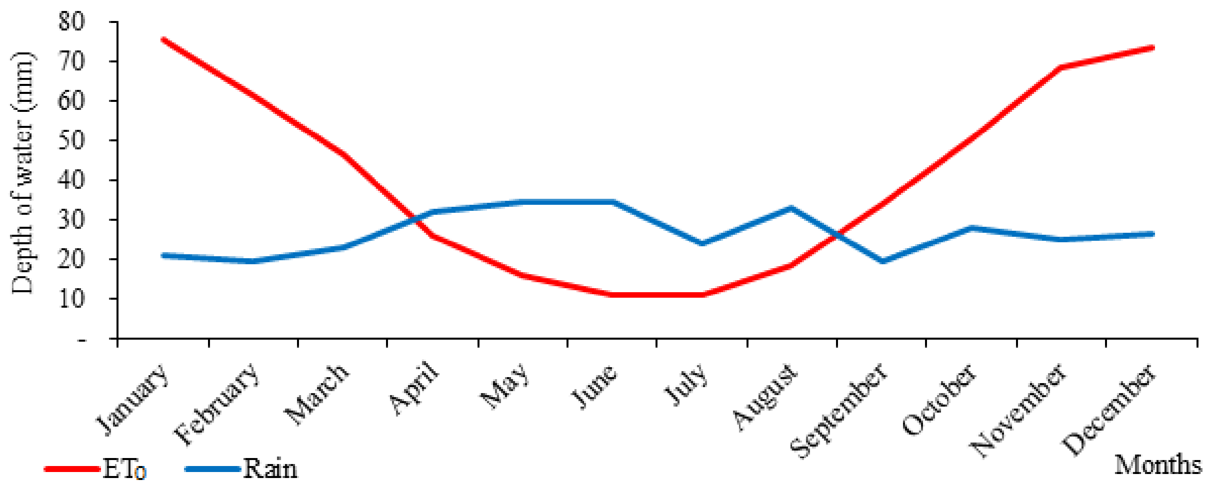


Figure 1.3 Average monthly reference evapotranspiration (ET_0) and rainfall data based on 16 years (2000 – 2015) of values, recorded at Broadfield weather station (Birendra, 2016)

1.4 Irrigation in Canterbury

In terms of surface water, Canterbury has three types of rivers. The first of these, the alpine rivers with their upper reaches in Ka Tiritiri o te Moana (the Southern Alps), are snow-and alpine-rain fed. The second, the foothill rivers, are rain-fed catchments where water flow peaks during winter. The third type, the lowland streams, are spring-fed from the groundwater (Environment Canterbury, 2012; Jenkins, 2018).

Currently, many catchments such as the Hawke's Bay, Wairarapa, Marlborough, the Tasman, Canterbury, and Otago are heavily allocated and are expected to face further pressure due to increasing land use intensification, particularly from irrigated dairy farming (Environment Canterbury, 2012). In order to support this growing need for water, farmers must use the available water more efficiently.

In Canterbury, the irrigation season generally starts in September and ends in April (Birendra, 2016). In Canterbury, there are many different irrigation systems, including centre pivot systems, rotorainer, k-line and long lateral. The centre pivot is the most popular irrigation system in New Zealand and in particular, in Canterbury where 44% of the total irrigated area is under centre pivot (as shown in Figure 1.4) (Canterbury, 2016). The centre pivot has a high level of automation and farmer can programme it to apply a certain amount of water per second or to a particular depth. The water application rate varies along the length of pivot: At the centre, it will be a low application rate (a light drizzle) while at the end span, it has a higher application rate (a heavy downpour). The long lateral and k-lines are used in areas which are not covered by centre pivot systems, such as the corners of a paddock (McIndoe, 2002).

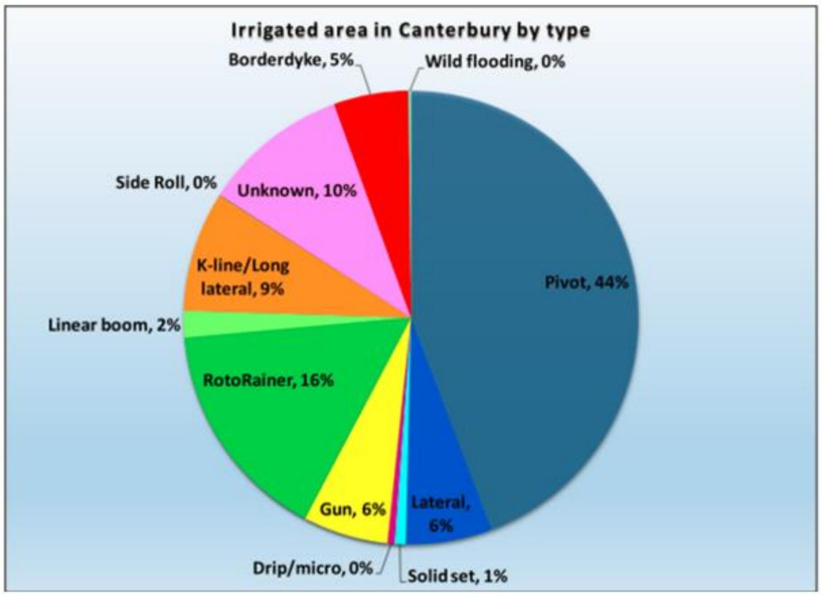


Figure 1.4 Type of irrigation (Canterbury)
Source: Guide to good irrigation: Part 1 (DairyNZ, 2015)

Farmers determine irrigation needs based on their crop, soil moisture, and soil type. Any irrigation system needs to programme the water flow based on irrigation need estimation before applying water rate to soil surface to ensure the efficient use of water. Farmers need to schedule maintenance for their irrigation systems (Dairy NZ, 2011).

Agricultural crops require irrigation to meet their water requirements and ensure the production of high-quality crops. To maximise irrigation efforts, farmers should have control over the actual application of water (Agriculture Victoria, 2018). A good farm irrigation management system is useful for irrigation planning to determine when a good time is to irrigate and how much water is needed. Too much water can drown the plants and kill them. Equally, a lack of water can severely stress the plants and may lead to reduced growth (Armstrong, 2020).

1.5 The main agriculture crops in Canterbury

The main crops that are grown in Canterbury include pasture, wheat, barley, oats, field peas, and potatoes. Most of the farmland under the water consent is related to pasture (76%). New Zealand farm systems can be classified into two categories: stock farming and mixed farming. Stock farming is predominantly grass-fed and includes sheep, cows, and pigs. Mixed farming can be further divided into two groups: 1) sheep and crop and 2) intensive cropping. Mixed crop farms produce both pastures to feed sheep and other crops on the same farm. Intensive cropping includes wheat, barley, oats, and peas (Evans, 2004).

All farms need to have good nutrient, waterway, and irrigation management. Nutrient control involves managing the fertiliser inputs and taking into account all nutrient sources. Waterway management involves identifying the risk of overland flow of sediment into water resources. Crop water irrigation management includes controlling the timing of irrigation inputs and plant water demand management to minimise the risk of leaching and water runoff.

1.6 Water use consent mechanisms in Canterbury

Currently, in Canterbury water management policy is governed by the Resource Management Act 1991 (RMA 1991) and the Local Government Act 2005 (LGA 2005). The RMA is a primary piece of legislation that outlines how natural resources, water included, should be managed. This is a sustainable management policy that affects environmental activities now and in the future when making resource management decisions. While the RMA is focused on the sustainable management of natural resources the LGA enables the local government to make decisions for their community's benefit. The RMA requires local governments which included regional, district and city council to create plans that help them manage natural resources within their boundaries. These plans outline the rules and conditions associated with resources use. After the local government approves a plan, they release the RMA that contains guidelines for freshwater management to regional, city and district councils. Generally, resource consent includes information on how much water a consent holder can use on daily, weekly and monthly basis and under what minimum river flow conditions.

The local government monitors the utilisation of resources within its area. For example, Environment Canterbury (ECAN) monitors river flow and water levels for 155 rivers and lake sites in Canterbury. It updates this information on its website daily at 3 pm. Farmers need to check the water level data before applying water on their farms. Farmers are responsible for understanding the minimum flow conditions imposed under their water consent (ECAN, 2010).

In terms of water consents, ECAN's records show that there were 150,000 ha of land consented for irrigation in Canterbury in 1985. By 2006 it had reached 560,000 ha (Jenkins, 2018). This massive increase in the number of consents means that there is a great need to reduce water usage on farms. At the moment, the maximum amount of water that a farmer who does not have a consent can use is less than 5 litres per second; this figure represents a significant reduction from the 20 litres per second allowed in 2011 ("Measuring and reporting water takes: An introduction to the Resource Management," 2010). This shows that insufficient water to meet irrigation demands may become a problem in the future.

Canterbury currently has an oversubscribed water consent problem. It has been reported that potentially millions of litres of water are used illegally. The data shows that approximately 400 large-consent holders are still not measuring water usage. It is difficult to obtain a consent for water usage and the irrigation water is inadequate for all users. Farmers can obtain water use consents from ECAN or they can purchase water from community irrigation schemes such as the Central Plain Water Limited (CPWL). This kind of community irrigation scheme can offer large irrigation consents to individual farmers (Is et al., 2014).

1.6.1 Individual water consents

The RMA requires councils permitting for a controlled water permit based on ECAN plan. To use water, farmers must prepare and submit an application to ECAN to obtain approval. They must provide farm information such as land size, water needs, and their farming plan. In addition, the application should include a brief description about the site, location and impact on the environment. Farmers can consult with ECAN, but must pay extra for these consultations. (Kaye-Blake, Schilling, Nixon, & Destremau, 2014). The consent process takes a long time and is expensive. Applying for consent is only really suitable for farmers who own large pieces of land (Environment, 2004) and as a result of irrigation will be able to realise greater financial benefits and productivity.

1.6.2 Water use consent through the Central Plains Water Limited (CPWL)

The CPWL is the owner and operator of the Central Plains Water Enhancement Scheme which is located in the Central Plains of Canterbury (Figure 1.5). The CPWL has obtained approval for water diversion, damming, reticulation, and irrigation to 60,000 hectares. The scheme takes water from the

Rakaia and Waimakariri rivers which are linked by a 56 kilometres headrace canal running around the foothills. The CPWL Scheme was established over three stages, based on the geographical location (Thorpe & Global, n.d.). Stage 1 covers 23,000 hectares of irrigation land which lies between the Rakaia and Selwyn rivers. Stage 2 covers 20,000 hectares between the Selwyn and Waimakariri rivers. The Sheffield scheme covers 4,100 hectares lying at the western margin of the CPWL irrigation area. It utilises water from the Waimakariri and Kowhai rivers (Thorpe & Global, n.d.).

The CPWL provides services to its shareholders. The water price is a fixed price per hectares based on location and the CPWL construction stages. Farmers can ask for a quote directly from CPWL. It is a good option for farmers to buy water from CPWL rather than applying for ECAN consent because it can reduce the water consent application process and cost in case of small/medium farming sector. However, if a farmer chooses to change their cropping strategies this may lead to changes in their water requirements. Situations like these mean that there is a need to manage irrigation more wisely and/or allow users to share their water.

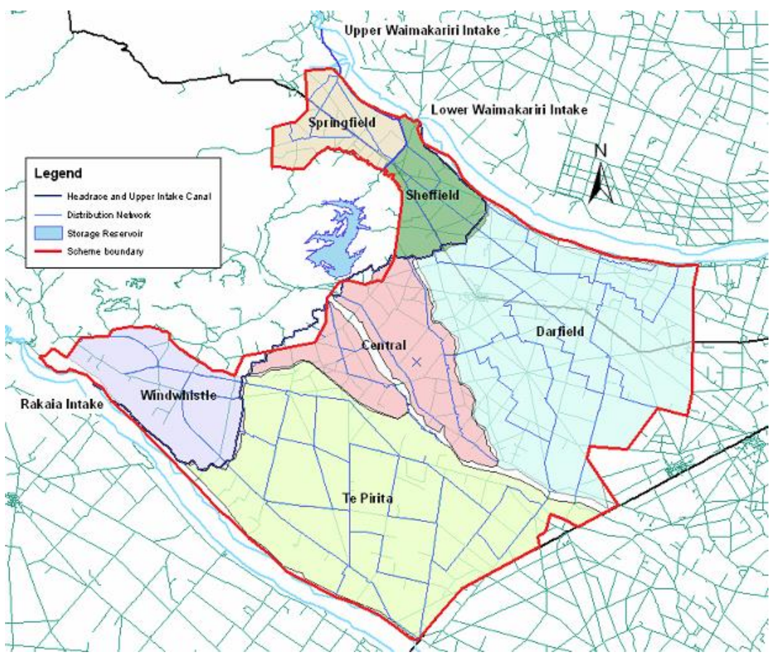


Figure 1.5 CPWL enhancement scheme area
Source**:** https://www.cpwl.co.nz

1.7 Main irrigation issues in Canterbury

1.7.1 Water sharing

Drought is a major problem for farmers. Reduced water leads to a loss of productivity and stock/crops. In 2014, it was reported that there was a 20% decrease in production when farmers were asked to reduce their usual water usage in December by 50% (Sharpe, 2015). During the drought season, ECAN issues water restrictions. Farmers must adhere to these water restrictions which makes water distribution worse. Restrictions essentially mean depriving crops of water, which in turn, leads to a loss in productivity. To maintain productivity, there must be a reliable method to determine the actual water requirements for each individual crop based on their type, growth stage and the soil moisture level. If a farmer knows how much water his crop/s require, it is possible to ensure that they only get what they need and thus avoid wastage. In addition, during drought conditions, it is crucial to prioritise by irrigating high yield crops first to minimise financial losses.

Although farmers are knowledgeable enough to determine their water requirements, there is the need for a flexible mechanism which can deal with day-to-day fluctuations in plant water requirements due to changing weather conditions (van Iersel, Burnett, & Kim, 2010). Farmers need to have a plan in place which outlines which crop they will irrigate in times of drought (Anthony & Birendra, 2018).

Once consent has been granted (it is valid for 10 to 12 years), it is difficult to reduce one farmer's water take rate so that another's take rate can be increased (Mitchell, 2016). However, ECAN provides a water sharing portal between consent holders by joining water user groups. The Land and Water Regional committee defines a water user group as one designed to manage the water allocation. It is a voluntary group that is authorised to take and manage water resources among members of a particular group. The member of a water user group can allocate water between themselves during periods of water restrictions as long as they follow the water user group's rules. Members who need to buy water can contact other members directly. They can negotiate between themselves to determine how much water they need and what price they are willing to pay. They then provide this information to ECAN (Thorpe & Global, n.d.).

The CPWL allows shareholders to take and use water for irrigation depending on how much water they are allowed to use. The CPWL also provides a water sharing portal on their website. All CPWL member can access this portal and share their requirements (offers to buy or sell). They can then negotiate the price and sharing volume directly. Like with the ECAN scheme, they must report to the CPWL on any deals made. However, there is no mechanism which enables users to share and distribute excess water to others particularly in the case where most of the shareholders have a deficit. Moreover, if such a mechanism was available, how would it best distribute excess water so that everyone would benefit from it? This situation has received very little scholarly attention and requires greater understanding. Based on this setting, this thesis aims to describe how to distribute the excess water and optimise the total additional profit in water user community.

1.7.2 Limitations with current irrigation management tools

Using a computer programme to estimate irrigation requirements is a popular option. The two most common computer programmes used in New Zealand are IrriCalc and OVERSEER. IrriCalc is a water balance model designed to estimate irrigation water requirements. It can determine seasonal irrigation water needs. OVERSEER, owned and supported by the Ministry for Primary Industries, uses daily soil water content data to calculate daily water drainage. Irricalc and OVERSEER require users to enter factors such as the selected month, farm location, and irrigation system, to calculate daily water needs. However, these programmes can only be used on a single farm with a single crop. Chapter 2 discusses these programmes in greater detail.

1.8 Agent-based solution

The current irrigation management programmes do not support irrigation estimates for multiple crops on a single farm (Anthony & Birendra, 2018). To deal with this problem, this research has developed an irrigation system which can be used to manage irrigation both on single/multiple crops on individual farms and within a community, using an agent-based approach to optimally allocate water, in particular under conditions of water scarcity or restrictions. Agent-based Programming (AP) is a software paradigm that uses concepts from Artificial Intelligence (AI). The agent-based system has an advantage over other approaches because it can work with uncertain factors. It also supports non-linear data. Moreover, it is flexible and autonomous in complex situations. It can make decisions in an unexpected situation and is suitable for software development, which requires dynamic behaviour.

Agent-based software is applied to solve complex problems. Researchers can build a single or multi-agent depending on their problem. Our irrigation management system can manage irrigation both on individual farms and within a community of farmers during periods of water scarcity. This programme helps allocate water more efficiently. With the proposed system it is possible to apply a single agent to estimate crop water needs and crop water allocation in periods of water scarcity. It makes decisions about water allocation based on farm factors which include potential crop yields, crop drought sensitivity, crop growth stage, soil type, soil moisture levels and irrigation systems. The agent can harness the maximum potential of agent on water allocation in community when we apply them to work together as multi-agent system to optimize the water distribution between water users in community. However, the single agent cannot handle complexity of water distribution in water user community which has different farming behaviours. Therefore, multi-agent system is more effective to deal with this problem.

A Multi-Agent System (MAS) is a computation system composed of multiple interacting agents. It solves problems that are difficult to solve using the single agent scheme. It can model complex systems and introduce the possibility of conflicting goals in complex problem statements (Bellifemine, Caire, & Greenwood, 2007; Garro et al., 2018). The multi-agent system can be applied to many types of modelling with varying agent behaviours. It can learn and adapt itself to meet its objective (Bellifemine et al., 2007; Le Bars, Attonaty, & Pinson, 2004). In MAS, an agent can negotiate/collaborate/coordinate with another agent/s to achieve common goals. Moreover, an agent can operate independently and intelligently, while at the same time working with other agents to achieve a larger goal without compromising their own goal.

MAS has been applied to solve resource and water allocation problems. For example, the agent based model was applied to capture collective problems in water infrastructure provisions (Berger, Birner, Díaz, McCarthy, & Wittmer, 2006). The problems are collected by learning and understanding the complexity of water use by MAS simulation. MAS has been used to understand the behaviour of different water users (representing them as agents). The results from the interactions of these agents have been used to develop water management policies (Berger et al., 2006). Giuliani et al. (2015) applied the MAS simulation model to demonstrate a hypothetical water allocation problem. The simulation model created several active and passive agents to investigate the tradeoff between efficiency-acceptability. The results were used to support the design of a distributed solution.

Gregg and Walczak (2006) proposed an auction mechanism which has the ability to ensure maximum profit on both seller and bidder. Several research have proposed that the auction mechanism is useful for water and resource allocation (Gregg & Walczak, 2006). Yamamoto & Tezuka (2007) compared three types of auctions in an electric supply auction to analyse how these large generator bids can maximise their profits and how auction impacts the closing price and the winning bids. Hailu and Thoyer (2005) proposed a multi-unit auction mechanism for water reallocation between users.

Accordingly, this thesis extended the single agent water management to multi-agent system to improve water allocation and investigate the efficiency of water distribution mechanism among farms. Farmers can use the proposed multi-agent water management system to negotiate with each other (where each farmer is represented as an agent) on how excess water should be distributed among themselves. One of the most well-known and simplest methods to achieve this is using an auction. The choice of an auction was deliberate as it allows agents to buy water at a price they are comfortable with. An agent must be clever as to how much they are willing to pay for a particular volume of water because they need to consider their own goals. This research considered three-auction types and compared the results of each auction in terms of fair water distribution and additional profit for sellers as well as reductions in losses for bidders. We found that the auction mechanism is useful for allocating excess water. Chapter 3 explains the auction techniques and mechanisms used in this research.

1.9 Research objectives

This research has following main and sub-objectives:

Main objective

To develop a multi-agent-based irrigation management system to manage irrigation on individual farms and within a community during periods of water scarcity.

Sub-objective

a) To design and develop a water allocation algorithm to allocate water more efficiently on an individual farm.
b) To implement a multi-agent system to facilitate water sharing within a community of farmers.
c) To investigate varying strategies that can be used to optimise water sharing within a community of farmers.
d) To assess how agents' behaviour may affect water sharing within the community.

1.10 Thesis structure

The thesis is structured in the following way:

- Chapter 1 describes the research background. It provides an overview of irrigation in Canterbury and explains key issues farmers face with respect to irrigation and water management. The chapter also discussed aims and objectives of the research.
- Chapter 2 broadly describes irrigation management and planning. It includes calculations for crop water needs (which are based on factors such as soil moisture and weather data), farm costs and profit estimates. It also describes related works on water management using various computing techniques and current irrigation management programmes.
- Chapter 3 describes our irrigation management system which can be used to manage water on a single farm and within a community of farmers. It also explains water sharing mechanism related to various auction mechanisms for finding the best water allocation strategies.
- Chapter 4 presents the experimental results for the performance of the irrigation management for a single farm.
- Chapter 5 investigates how excess water can be distributed within a community irrigation using different water sharing mechanisms.
- Chapter 6 summarises the research and provides suggestions for future work.

Chapter 2

Literature Review

This chapter describes factors related to irrigation planning and management. As such, it explains crop water needs and water estimation procedures in detail. It also discusses existing irrigation tools used to estimate farm water requirements. In addition, this chapter reviews related work on agent-based water allocation and other resources associated with agent-based technologies. It summarises various computing techniques used for resource and water allocation. The chapter concludes by identifying research gaps.

2.1 Irrigation planning and management

Irrigation planning involves scheduling irrigation to achieve a desired goal. Irrigation management is the day-to-day work which needs to be completed in order to achieve that goal. The goal of irrigation planning and management is to ensure more efficient use of water. Some factors that need to be taken into consideration in irrigation scheduling and management include soil temperature, soil moisture status, the weather forecast and water restrictions. These are summarised in Table 2.1 (DairyNZ, 2011).

Table 2.1 Some key factors affecting irrigation planning and management

Factor	**Issues**
Soil temperature	The soil temperature varies with crop type, climate and planning season. The crop growing rate will slow down when it is too hot (above 35ºC) or when it is too cold (below 6ºC) (DairyNZ, 2011).
Soil moisture status	The soil moisture level must be between refill point and field capacity in order to ensure optimal crop growth (Birendra, 2016).
Weather forecast	The weather forecast provides information on rainfall that can be used when making irrigation plans.
Water restrictions	Checking water supply restrictions include annual volume allocation limits or water delivery rosters.

Some of the key factors to be considered in irrigation planning and management are described in further detail in the next section.

Soil type

Soil is a natural storage tank. It holds water for plants. Soil can be categorised into different types based on its water holding capacity (WHC), which is the amount of water that a soil can hold expressed in millimetres of water per metre depth of soil (mm/m) (DairyNZ, 2011). Crop water needs can be estimated using the WHC of the soil within the crop root zone. For example, the structure of clay soil means that it sits closely together. It has a high WHC value (190 – 195 mm/m), meaning that it holds water well. While this soil type is wet and contains a lot of water, it is not desirable for growing crops. Sandy soil is soil with small pieces of eroded rock. It has a gritty texture. It is usually dry and has a low WHC value (45 – 55 mm/m). Sandy soil is usually dry and fast draining. On farms, soils change even within a single metre. Therefore, it is essential to consider spatial variations in the application of irrigation (K.C. et al., 2019)

Crop growth is related to soil water levels. Soil can be categorised based on its water content; it can be saturated, have reached field capacity, the refill point or permanently wilting (shown in Table 2.2). Saturation level refers to when the soil is totally saturated and is unable to hold any more water. This will also result in a loss of excess water to deep drainage and surface ponding may occur. Field capacity refers to the saturation level of moisture content that a soil can hold. If there is no rainfall and irrigation, soil moisture goes down from the field capacity and reaches a point below which plants need to use a certain amount of energy to absorb water. This is called the refill point. If there is still no rainfall and irrigation, soil moisture keeps decreasing. It reaches a point where plants cannot absorb water at all: this is called a permanent wilting point. Farmers need to apply irrigation before soil moisture drops to a refill point and fills up to the field capacity, leaving some room for potential rainfall (Birendra, 2016).

Table 2.2 Effective soil moisture for plant growth

Soil moisture status	Soil moisture levels	Plant growth
Saturation	The soil is totally saturated and unable to hold any more water. Excess water is lost to deep drainage. Surface ponding may occur.	Plant growth is restricted through a lack of oxygen and nutrient loss.
Field capacity	The optimum level of soil moisture. All water is available to plant.	Ideal for plant growth.
Refill point	Soil becoming drier.	Plant under stress, growth might be impaired (survival mode).
Permanent wilting point	Soil is very dry	Plant dies.

Plant type and its development stages

Crops receive water via the root zone. Different crops and pasture types have different root depths. The plant root zone is the surrounding root area which contains soil and oxygen near the plant. The depth of the plant root affects the water available for the plant. Deep rooting crops can absorb more water than those with a shallow root (DairyNZ, 2011; Pierret et al., 2016; Savva & Frenken, 2002). The plant root depth is used for crop water estimations in irrigation schedules. We explain root depth data associated with crop water estimations and daily irrigation schedules in Chapter 3.

To obtain maximum crop productivity, a farmer must apply irrigation, or the right amount of water at the right time to suit the plant's growth stage; different crop growing stages require different amounts of water. Farmers need to estimate water usage for each stage of the plant's growth. According to Brouwer et al. (1985) the crop growing period can be divided into four stages (refer to Table 2.3). While crops use a lot of water in the initial stage, in the last stage, they need less water. Therefore, farmers need to align the irrigation with the crop growth stage. Every crop has different growing stages, and every stage has different water needs.

Table 2.3 Crop growth stages

Crop stage	Description
1) Initial stage	This is the period from sowing or transplanting until the crop covers approximately 10% of the ground cover.
2) Crop development stage	This period starts at the end of the initial stage and lasts until the ground is nearly fully covered (ground cover 70 - 80%): it does not necessarily mean that the crop is at its maximum height.
3) Mid-season stage	This period starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain-setting.
4) Late-season stage	This period starts at the end of the mid-season stage and lasts until the last day of the harvest; it includes ripening.

Climate

The plant growing process is affected by the climate. The major climate factors that are related to crop growth are rainfall and evapotranspiration (Food and Agriculture Organization, 2012). Figure 2.1 shows the inputs and outputs for the crop. The input water sources are rainfall, irrigation and capillary rise. Water is reduced through transpiration (loss from the leaves), evaporation (lost from the soil), surface run-off and deep percolation. The rate of water extraction from the bare soil is known as evaporation (E). The sum of evaporation and plant transpiration is called evapotranspiration (ET) (Brouwer et al., 1985, 2013). Transpiration is the movement of water within a plant and the subsequent loss of water as vapour by leaf. The ET rate depends on the season. For example, the ET rate is higher in the summer as the plant needs more water to grow and maintain a consistent temperature. The ET rate is lower during winter; irrigation is not required as rainfall alone is enough to meet crop water needs. Irrigation scheduling in autumn and spring depends on the rainfall which varies with location.

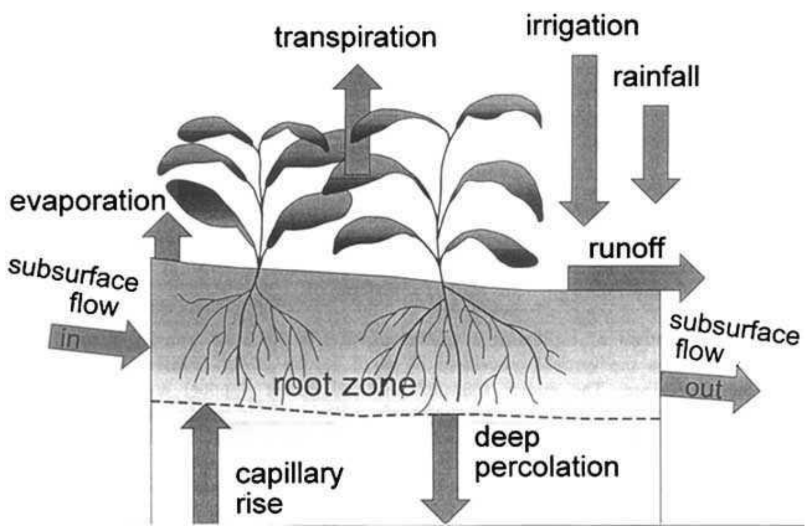


Figure 2.1 Water input and outputs in the plant root zone

Source: (Allen & Pereira, 2009)

Irrigation system capabilities

Different irrigation systems have different application capabilities which affect irrigation planning and management. There are four key factors which need to be considered in irrigation planning (Table

2.4). These irrigation processes are based on the application depth, application rate, distribution uniformity and soil infiltration rate. The different irrigation systems provide different levels of irrigation efficiency (DairyNZ, 2011).

Table 2.4 Description of the irrigation process

Irrigation process	**Description**
Application depth	How deep must the water penetrate? For example, farmers generally apply 5 mm of water for pasture.
Application rate (or application intensity)	How fast the water is applied to the irrigated field. This is measured using water depth in fixed time (mm/ ha). The standard rate is 1 litre/m^2 or $10m^3$/ha.
Distribution uniformity	The evenness of irrigation application. For a centre pivot, this is generally 70 – 90%.
Infiltration	The rate of water movement from the surface into the soil: water must soak into the soil without causing run-off or ponding. Infiltration rates vary according to the soil type and slope.

2.2 Estimating crop water needs

Water requirement for crops are estimated using the water requirement for a reference crop. The daily water need indicates the daily water requirement for a particular crop. This value varies with different factors, such as temperature. For example, in locations that have a high temperature or dry climate the recommended water requirement is 10 mm per day. This means that the crop needs a water layer (rain or irrigation) around 10 mm over the whole area every day. The crop water need estimates are shown in Table 2.5 (Brouwer et al., 1985). Using Table 2.5, if a standard grass crop in each area needs around 5.5 mm of water per day, then, maize will need 10% more water and nuts will need 20% more water. In the case of maize, $10\%\ \text{of}\ 5.5\ \text{mm.} = \frac{10}{100} \times 5.5 = 0.55\ \text{mm}$. This means that maize needs: 5.55 + 0.55 = 6.05 mm per day. A crop's water needs for a growing period can be calculated by multiplying daily water need and crop growing period (days).

Table 2.5 Crop water needs compared to a standard grass

Crops needing the same amount of water as grass	Crops which need 10% more water than standard grass	Crops which need 20% more water than standard grass
Carrots, cabbage, cauliflower, broccoli, lettuce, onions, peanuts, grass, clean cultivated nuts & fruit trees	Barley, beans, maize, small grains, tomatoes, eggplant, lentils, oats, peas, potatoes, soybeans, sunflowers, wheat	Nuts and fruit trees with cover crops

Since crop water needs vary according to development stages, we need to know the different crop growth stages. Data on crop growing periods, provided by the FAO, is shown in Table 2.6. Crop water needs are defined by their evapotranspiration (ET_{crop}) and can be calculated using the following formula (2.1):

$$ET_{crop} = ET_0 \times K_C \qquad (2.1)$$

where: ET_{crop} = Crop evapotranspiration

ET_0 = Reference evapotranspiration

K_C = Crop coefficient

Reference evapotranspiration (ET_0)

ET_0 is the amount of water a crop needs to ensure optimal growth. It can be affected by major climatic factors which are sunshine, temperature, humidity, and wind speed. Table 2.7 shows the effect of major climatic factors on crop water needs (Brouwer et al., 1985). The highest water need for crops is found in hot, dry, windy and sunny conditions. The lowest need is found in cool, humid and cloudy conditions.

Table 2.6 Crop growing periods (days)

Crop name	Min/max	Total	Initial	Crop development	Mid-season	Late season
Barley/oats/wheat	Min	120	15	25	50	30
	Max	150	15	30	65	40
Beans/green	Min	75	15	25	25	10
	Max	90	20	30	30	10
Beans/dry	Min	95	15	25	35	20
	Max	110	20	30	40	20
Cabbages	Min	120	20	25	60	15
	Max	140	25	30	65	20
Carrots	Min	100	20	30	30	20
	Max	150	25	35	70	20
Tomatoes	Min	135	30	40	40	25
	Max	180	35	45	70	30
Grains/small	Min	150	20	30	60	40
	Max	165	25	35	65	40
Lentils	Min	150	20	30	60	40
	Max	170	25	35	70	40
Maize, sweet	Min	80	20	25	25	10
	Max	110	20	30	50	10
Maize, grain	Min	125	20	35	40	30
	Max	180	30	50	60	40
Onions/green	Min	70	25	30	10	5
	Max	95	25	40	20	10
Onions/dry	Min	150	15	25	70	40
	Max	210	20	35	110	45
Peanuts/groundnut	Min	130	25	35	45	25
	Max	140	30	40	45	25
Peas	Min	90	15	25	35	15
	Max	100	20	30	35	15
Potatoes	Min	105	25	30	30	20
	Max	145	30	35	50	30
Sorghum	Min	120	20	30	40	30
	Max	130	20	35	45	30
Soybeans	Min	135	20	30	60	25
	Max	150	20	30	70	30
Spinach	Min	60	20	20	15	5
	Max	100	20	30	40	10
Squash	Min	95	20	30	30	15
	Max	120	25	35	35	25
Sunflower	Min	125	20	35	45	25
	Max	130	25	35	45	25

Table 2.7 Effect of major climatic factors on crop water needs

Climate factors	Crop water needs	
	High	**Low**
Temperature	Hot	Cool
Humidity	Low (dry)	High (humid)
Wind speed	Windy	Little wind
Sunshine	Sunny (no clouds)	Cloudy (no sun)

ET_0 can be estimated using several methods including the pan evaporation method and the Blaney- Criddle method. Pan evaporation is a measurement that combines the effects of several climate elements (humidity, temperature, rainfall, solar radiation, and wind). However, this method requires many processes for measuring data (Allen & Luis S., 1998). The Blaney- Criddle method is more popular because it is calculated using a theoretical method that does not require measured data (Allen & Luis S., 1998). The Blaney-Cridle method is simple, especially because it only requires temperature data.

The Blaney-Criddle formula

$$ET_0 = p\ (0.46\ T_{mean} + 8) \qquad (2.2)$$

where: ET_0 = Reference crop evapotranspiration (mm/day) as an average for a one-month period

T_{mean} = mean daily temperature (°C)

p = mean daily percentage of annual daytime hours

To determine the value of T_{mean}, requires the monthly temperature values from the local metrological station. p is determined by taking the mean daily temperature and the latitude of the area (as shown in Table 2.8). For example, T_{mean} for latitude of -25° in April is 25.5°C. As Table 2.8 shows, p is 0.26. To work out the ET_0:

$$ET_0 = 0.26[(0.46 \times 25.5) + 8] = 0.26(11.73 + 8) = 0.26 \times 19.73 = 5.12\ mm/day$$

Table 2.8 Mean daily percentage (p) of annual daytime hours for different latitudes

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°		0.15	0.20	0.26	0.32	0.38	0.41	0.40	0.34	0.28	0.22	0.17	0.13
55°		0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
50		0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.2	0.18
45°		0.2	0.23	0.27	0.3	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.2
40°		0.22	0.24	0.27	0.3	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35°		0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.3	0.28	0.25	0.23	0.22
30°		0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.3	0.28	0.26	0.24	0.23
25°		0.24	0.26	0.27	0.29	0.3	0.31	0.31	0.29	0.28	0.26	0.25	0.24
20°		0.25	0.26	0.27	0.28	0.29	0.3	0.3	0.29	0.28	0.26	0.25	0.25
15°		0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.25
10°		0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
5°		0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27
0°		0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

The ET calculation can be calculated using several methods such as Penman−Monteith, Shuttleworth−Wallace, Makkink methods etc. which depend on the different weather information. Based on the correlations between the model results, Pereira and FAO-56 models agreed the most to the pan evaporation measurements included Bleney-Cradle method (Rácz, Nagy, & Dobos, 2013).

Crop coefficient (K_c)

The crop coefficient (K_c) is the ratio of ET_{crop} to ET_0 (Jensen, 1968). It indicates the propensity of a crop to loose water through transpiration. Higher the K_c the greater the water loss. It varies with different crops and their development stages. Table 2.9 shows K_c values for some crops at different growth stages. It shows that K_c increases gradually up to mid-season and then drops in the late season, following the crop growth pattern and corresponding water needs.

Table 2.9 K_c value for each crop stage

Crop	Initial	Crop development	Mid-season	Late season
Barley/oats/wheat	0.35	0.75	1.15	0.45
Beans, green	0.35	0.7	1.1	0.9
Beans, dry	0.35	0.7	1.1	0.3
Cabbages/carrots	0.45	0.75	1.05	0.9
Eggplants/tomatoes	0.45	0.75	1.15	0.8
Grain/small	0.35	0.75	1.1	0.65
Lentils/pulses	0.45	0.75	1.1	0.5
Maize, sweet	0.4	0.8	1.15	1
Maize, grain	0.4	0.8	1.15	0.7
Onions, green	0.5	0.7	1	1
Onions, dry	0.5	0.75	1.05	0.85
Peanuts/groundnut	0.45	0.75	1.05	0.7
Peas, fresh	0.45	0.8	1.15	1.05
Potatoes	0.45	0.75	1.15	0.85
Soybeans	0.35	0.75	1.1	0.6

Many researchers use a K_c = 1 value for pasture. However, Birendra et al. (2018) have found that it varies significantly with different growth stages due to changing canopies represented by pasture height (as shown in Table 2.10).

Table 2.10 Crop coefficients of pasture estimated for different growth stages for a grazing rotation.

Pasture	Crop coefficient (K_c) at the following pasture height (cm).					
	5	10	15	20	25	30
	0.5	0.6	0.7	0.8	0.9	1.0

Source: (Birendra et al., 2018)

Example of crop water needs for tomatoes:

Let us assume an average daily ET_0 during different months as shown in the following table (Table 2.11).

Table 2.11 The ET_0 reference data with difference month

Month	Jan	Feb	Mar	April	May	June	July
ET_0	4.0	5.0	5.8	6.3	6.8	7.1	6.5

Using tomato data from Tables 2.6, 2.9 and 2.10 (shown in Table 2.12).

Table 2.12 Period of tomato growth stage base on planting date

Data/stage	Date	K_C
Planting date	1 Feb	
Initial stage (35 days)	1 Feb – 5 Mar	0.45
Crop development stage (40 days)	6 Mar – 15 April	0.75
Mid-season stage (50 days)	16 Apr – 5 Jun	1.15
Late season stage (25 days)	6 Jun – 30 Jun	0.8
Last day of the harvest	30 Jun	0.80

Table 2.13 shows a detailed calculation of the crop water need for tomatoes.

Table 2.13 Total crop water needs for the whole growing season: Tomatoes

Month	Crop stage	K_c	ET_{crop} (mm/day)	Total monthly water need
February	Initial (30 days)	0.45	$5 \times 0.45 = 2.25$	67.5
March	Initial (5 days) Crop development 25 days)	$\left(\frac{5}{30} \times 0.45\right) + \left(\frac{25}{30} \times 0.75\right) = 0.69$	$5.8 \times 0.69 = 4$	120
April	Crop development 15 days) Mid-season (15 days)	$\left(\frac{15}{30} \times 0.75\right) + \left(\frac{15}{30} \times 1.15\right) = 0.96$	$6.3 \times 0.96 = 6.1$	183
May	Mid-season (30 days)	1.15	$6.8 \times 1.15 = 7.82$	234.6
June	Mid-season (5 days) Late season (25 days)	$\left(\frac{5}{30} \times 1.15\right) + \left(\frac{25}{30} \times 0.8\right) = 0.85$	$7.1 \times 0.85 = 6.04$	181.1
			Total	787.70

As can be seen in Table 2.13, the crop water needs for the whole tomato growing season is 788 mm/ha. We can estimate water requirements for any crop using this process. In the case of a farm with multiple crops, we can estimate water requirements for each crop and add them together to obtain the farm's total water requirements. In summary, crop water needs are influenced by K_c, ET_0, the crop growth stage and the duration of crop growth.

Using a crop water need estimate, a farmer can determine their total crop water need for the year when buying water from providers like ECAN or CPWL. A farmer must consider the cost of water in terms of the farm's total expenditure to ensure maximum profit. To estimate total expenditure, a farmer must consider several factors, including water costs, seeds, fertilisers, and cultivation costs. The following section discusses farming cost estimation in detail, including the reference of farm budget in New Zealand context.

2.3 Farming cost estimates

The previous section discussed water usage estimation and the related factors that need to be considered in farm irrigation estimates. A farmer's main objective is to achieve the highest total profit by maximising farm productivity. The total farm profit is calculated using Equation 2.3 (Faris, 2010).

$$P(x) = R(x) - C(x) \qquad (2.3)$$

where:

$P(x)$ = Total farm profit

$R(x)$ = Total revenue

$C(x)$ = Total cost

Total revenue refers to the summation of each crop's sale price (dollars per ton). The total cost varies and may include the cost of fertilisers, pesticides, irrigation, and labour charges. Figure 2.2 shows the total cost and profit per hectare for wheat. This estimated figure is based on data obtained from a financial budget manual (Askin & Askin, 2012). The irrigation cost is approximately $303.33 out of $1,684 of total direct costs or approximately 18% of the total direct costs. Data used in this manual was collected from hundreds of sources in New Zealand and is updated every year.

WHEAT GROSS MARGIN							
(Autumn sown feed)							
INCOME:							
Per tonne	9	t/ha	@	$380.00	/tonne		$3,420.00
Straw	0		@	$25.00	bale		$0.00
TOTAL INCOME - assumes wheat straw is normally burnt							**$3,420**
EXPENDITURE (per hectare):							
Cultivation -							
115 kW Tractor	1.5	hrs	@	$118.54	/hour		$177.82
(Running and Fixed costs)							
Seed -	120	kg/ha	@	$1,110.00	/tonne		$133.20
Fertilizer -							
Sulphur Super 15	250	kg/ha	@	$364.40	/tonne	$91.10	
Urea	350	kg/ha	@	$860.00	/tonne	$301.00	$392.10
Weed, Pest and Disease -							
Cougar	0.75	l/ha	@	$66.60	/litre	$49.95	
Glean	15	g/ha	@	$0.63	/gram	$9.45	
Opus	0.5	l/ha	@	$9.00	/litre	$4.50	
Amistar	0.75	l/ha	@	$100.87	/litre	$75.65	
Applications	3		@	$20.00		$60.00	$199.55
Irrigation	260	mm	@	$1.17	mm		$303.33
Straw baling	0		@	$15.00	/bale	$0.00	
Harvest -				$280.00	/ha	$280.00	$280.00
(in silo; contract)							
Freight -	9	t	@	$22.00	/tonne		$198.00
(silo to port 60 km)							
TOTAL DIRECT COSTS							**$1,684**
GROSS MARGIN per hectare							**$1,736**

Figure 2.2 The cost of wheat in a single season

Source: (Askin, Askin, Askin, David, & Virginia, 2013)

2.4 Existing tools for irrigation planning and management

In New Zealand, farmers often use computing tools such as IrriCalc and OVERSEER to assist with irrigation planning.

IrriCalc is a soil water balance model that estimates irrigation requirements using effective rainfall and actual crop requirements. It was developed by Aqualinc Research Limited, New Zealand (Wheeler & Bright, 2015). Effective rainfall refers to total stored water in the crop's root zone. IrriCalc applies the rainfall, spatial information and climate data from the National Institute of Water & Atmospheric Research (NIWA). The actual crop water need is calculated using the multiple reference evapotranspiration (ET_r) and crop coefficient (K_r). The ET_r value is estimated using the Peaman-Monteith method (Birendra, 2016) and is based on daily weather data. Using this information, IrriCalc estimates daily, monthly and seasonal crop water needs. IrriCalc only works for a single crop. It also does not support water reductions during periods of water scarcity.

OVERSEER is a farming strategic management software that supports farmers to improve farming performance. It was originally developed as a farm management programme to calculate nutrient loss using a rule-based setting. It uses daily soil water content data to calculate daily water drainage and nutrient losses (Dunbier et al., 2013; Murray, Read, Park, & Fietje, 2016). OVERSEER applies an irrigation water demand model which is similar to IrriCalc. The core of the OVERSEER model is a nutrient budget table or a table of inputs and outputs for nutrient that depicts the relationship between crop and other factors (fertilisers and supplements) by basic derivation. The OVERSEER sub-model was extended to estimate crop water need with a modified input-output table. The data required to calculate the crop water need includes soil type, soil moisture level, climate data, and rainfall data. The output calculation contains the nutrient budget and the monthly crop water need (Wheeler, 2016; Wheeler & Bright, 2015).

IrricalC and OVERSEER are similar in that they are both single-layer soil water balance models and require the same input data for crop water need estimates which are farm size, farm location, soil moisture level, the irrigation system and crop types. However, the climate data that is applied for these models are different. While Irricalc uses NZ seasonal climate data, OVERSEER uses annual average climate data (yearly) and devolves this down to monthly data. Furthermore, OVERSEER and IrriCalc use different canopy cover values in the model. The canopy cover value refers to the percentage of soil surface shaded by plant cover at midday (Allen & Pereira, 2009). IrriCalc applies the seasonal adjustable value on the canopy cover which is 0.8 on average. OVERSEER assumes the 'full canopy' cover (a value of 1) (Wheeler & Bright, 2015).

There are other computing programmes such as the Agricultural Production Systems Simulator (APSIM) and AquaTRAC. APSIM is a comprehensive model that was developed to simulate biophysical processes for the agricultural sector. It allows users to specify the management rules and provides a set of modules (physical process in the farm, farm management rules and the simulation engine) to support the higher order goal of farming simulation. The set of modules includes climate, genotype, soil, crop characteristic and management factors. APSIM requires various data to be input, such as crop type and crop stage, farm location, and soil moisture. A simulation engine simulates the result by following specific management rules. The APSIM model calculates crop water needs based on the FAO reference and was developed using a set of biophysical modules on each crop based on a C# programming framework. Each module allows the user to specify the intended management rules (schedule plan, soil type, and weather data), and simulate the farming process (Adam et al., 2012; Brown, Huth, & Holzworth, 2018).

AquaTRAC is a software that was developed by the New Zealand Foundation for Arable Research (FAR), to assist cropping farmers with their irrigation scheduling. It calculates when and how much irrigation to apply to optimise yield for each crop. It includes factors that influence crop water needs such as crop type, soil moisture, weather, irrigation levels, and irrigation system. The irrigation water need is calculated using the FAO's equation which is based on rainfall data, evapotranspiration and drainage (FAR, 2010). AquaTRAC estimates crop water needs (mm/Ha/day) and generates a farm irrigation schedule. To prioritise the crop water need list, the software compares the stress levels of each plant, the potential yield value, and soil moisture data. It calculates the yield loss rate value to compile a prioritised list based on the potential yield.

APSIM and AquaTRAC require different input data than IrriCalc and OVERSEER. APSIM and AquaTRAC require weather data, specific farm location, soil type and rainfall data as input. They work with multiple paddock sizes and can provide multiple farm crop water estimation. However, they cannot support the distribution of water between farms in a water sharing scheme.

In summary, these irrigation programmes can help farmers with proper irrigation planning based on soil moisture monitoring for a fixed period of time followed by the crop water need estimation model. IrriCalC and OVERSEER do not support multiple crops on a single farm. While APSIM and AquaTRAC have features which support multiple crops in irrigation scheduling they do not take into account differences in crops' water requirements at different growth stages (Anthony & Birendra, 2018; Brown et al., 2018; Keating et al., 2003).

2.5 Related work

This section discusses work related to water allocation using agent and multi-agent systems. It also explains other computer techniques used to solve resource and water allocation problems.

2.5.1 Agent-based water allocation

Agent-based Programming (AP) is a software that uses concepts from Artificial Intelligence (AI). An agent's behaviour is dependent on what it is tasked to do. AP is a microscale model that simulates operations and interacts with other agents to predict the emergence of complex phenomena (Bellifemine et al., 2007; Kravari & Bassiliades, 2015). Moreover, the agents are able to exhibit goal-directed behaviour by taking initiative while ensuring that it achieves its goal. It can learn and adapt itself to fit its environment and to fulfil the users' desires. An agent is essentially a special software component that can operate without the direct intervention of humans. Researchers can build a single or multi-agent system depending on the nature of the problem. A single agent is often limited in what it can do, but these agents can work together collaboratively to solve more complex problems by way of a multi-agent system. In a multi-agent system environment, each agent is autonomous and is able to make their own decisions. They are able to communicate with each other using Agent Communication Language (ACL). This allows them to negotiate and collaborate in order to achieve a common goal (Caire, 2009; Soklabi, Bahaj, & Bakkas, 2013).

MAS has been used to solve resource allocation problems. It has the potential to manifest self-organisation as well as self-direction and other control paradigms and related complex behaviours to find the optimal solution (Bellifemine, Poggi, & Rimassa, 2001; Soklabi et al., 2013).

Chu et al. (2009) proposed an agent-based social simulation model to calibrate and capture residential water usage behaviour. They disaggregated total water demand to the end-users. They considered several factors, including market penetration of water saving technology, regulatory policies, economic development and social consciousness and preferences in their investigation of consumer responses to water. They evaluated different water usage policies and tried to find potential water saving for infrastructure development planning using a multi-agent model. In this model, they defined three types of agents: a regulator (responsible for establishing the structure and the water prices), the water appliance market (which collects and synthesises information for households) and the household/s (social water user). Using this model, a user can quantify dynamic patterns of residential water use. This information can be used to design effective demand management policies and infrastructure planning strategies. J. Cai & Xiong, 2017 proposed an agent-based simulation of the water sharing formation of cooperation in using irrigation. The simulation model is developed based on the understanding of the farmers' behaviour who are participating in water resource cooperation. This research applied the cooperation rule on irrigation as agents' behaviour and government water management mechanism to optimize the water usage between users in community.

Berger, Birner, Díaz, McCarthy, and Wittmer (2006) proposed a multi-agent programming model to capture social and spatial interactions between individual farms in Chile. They used MAS to better understand water users and water use complexity within sub-basins. The MAS implemented several sub-models such as crop growth, economic decisions and water runoff. The outcome of the research showed that multi-agent simulation can provide support for policymakers and stakeholders, particularly in water resource trading and small/large scale infrastructure provisions. An agent-based model is developed to find a solution for irrigation and drainage network to reduce the water usage from the water demand request by considering the social conditions of farmer in Iran. This research proposed two main group of agents that are policy maker and farmer to optimize the balancing of water resource policy and water requirement from farmer (Ghazali, Honar, & Nikoo, 2018).

Nouri, Saghafian, Delavar, Mohammad, & Bazargan-Lari (2019) proposed the crop pattern optimization using agent -based approach. This research applied the agent behavior based on farming behaviour and self-learning their own behaviour to optimize their crop pattern for the next season. The farmer agent interacted with government agent which imposes its policies in the form of scenarios. The result shows that agent-based optimisation is useful to help farmer with crop pattern optimization based on the water policy. The assessment of irrigation schemes and production scenarios can be optimised by an agent-based model agricultural system. Lopez-Jimenez, Quijano, & Vande Wouwer (2021) proposed the dynamic crop model underlying each agent to consider the negative effect of water excess in soil and making simple optimization strategy based on soil characteristics.

Ding, Erfani, Mokhtar, and Erfani (2016) investigated how to tackle the unfair distribution of water resources among the northern African countries within the Nile basin. They implemented agent-based modelling to simulate the interactions between water users located in the Nile riparian states. They investigated three solutions: a centralised solution, a decentralised solution and a re-allocation solution. With a centralised solution, the aim is to maximise the total benefits for all water users. This can be obtained from the fitness function (the aggregated benefit) of all the countries (agents). In the decentralised solution, each agent is separate from the rest of the agents and they maximise their own economic function. Each agent uses a parallel evolutionary algorithm to solve their local optimisation problem while communicating with other agents. The re-allocation solution reallocates the system revenue from the perspective of fairness by combining information obtained from the centralised and the decentralised solutions. Using this framework, it was found that the re-allocation of revenue guarantees fair and efficient water allocation for all users.

Becu, Perez, Walker, Barreteau, and Le Page (2003) used a multi-agent model (CATCHSCAPE) to simulate the Mae Uam catchment in Northern Thailand in order to understand the impact of upstream water management on the viability of downstream farming systems. The simulation comprised of farmer agents and canal manager agents. Each farmer owned paddy plots. Each plot belonged to a canal which is managed by a canal manager. The model also included information related to the environment including crops, rivers, canals and villages. The model was used to simulate the hydrological system based on distributed water balance, irrigation scheme management and crop and vegetation dynamics and capture individual farmer's decision. Using this model, a variety of scenarios can be explored over a period of time from different perspectives: an economic perspective, an environmental perspective, a landscape perspective, a water management perspective and an individual farmer's perspective.

Le Bars et al. (2004) proposed Agent-Based Modelling (ABM) as a negotiation tool to address water sharing conflicts in France. The model consists of farmers and water suppliers as cognitive agents and information suppliers, crops and climate as reactive agents. Each farmer is expected tand communicates with other agento establish their cropping plan and water needs for the year and privately sends this request to the water supplier agent. These water requests are compiled by the water supplier agent who decides how much water to allocate to each farmer based on the water allocation rules. They conducted a preliminary experiment to analyse the outcome of the water distribution using three types of water allocation rules, with two types of farmers/agents (greedy and selfish). Other rules are also possible. In this work, the actual negotiation between agents were not implemented. The water allocation process was dictated by the agents and the water allocation rules.

Barreteau, Garin, Dumontier, Abrami, and Cernesson (2003) applied an ABM to simulate water allocation for the Drome River in France. This model was compared against a more classical approach, programmed using Excel macros. The ABM model consists of several classes of agents: A farmer's association, individual farmers, and the Local Water Commission (CLE), as well as Crop and Plot. This model was used to support negotiations and to determine limitations around water use based on behavioural factors (resource capacity, a set of individual water use rules, and a set of collective rules). They also evaluated the complexity of water and land use via the agent-based system. They found three major benefits associated with the use of ABM as negotiation support tools. Firstly, the negotiation tools were relevant to the negotiation stakes. Secondly, the field of information was extended through multi-level viewpoints on the system dynamics. Finally, it uncovered hidden interconnected topics in the discussion. These results strongly indicate that ABMs are efficient in supporting the negotiation process in irrigation management.

Management of water resources often results in conflicts among water users as they have to compete for a limited water supply. One potential solution involves using an agent-based model to simulate the behaviour and interactions of parties in a conflict scenario. Akhbari and Grigg (2013) developed an agent-based model to simulate the process of encouraging conflicting parties to cooperate. This method was also useful in determining the effectiveness of various social and institutional enhancements designed to reduce conflict levels. The model included three types of agents; the water diversions/farmers, regulators and the environmental sector. Each of these agents varies in their behaviour based on the problem and their perception of the system. Diversion agents can be cooperative or non-cooperative. The conflicting agents often waited as long as possible. This forced other agents to cooperate because they realised it was more beneficial for them. This research confirms that ABM is a powerful tool that can be used to establish rules and scenarios associated with the timing of flows, water demands and environmental concerns.

Cai et al. (2011) studied water rights trading within an integrated economic-hydrologic modelling framework for the Yellow River Basin (YRB) in China. They used Yang et al.'s (2010) MAS. The MAS consists of 52 general agents, 5 reservoir agents and 3 ecosystem agents. The authors evaluated three water management scenarios for the YRB: the de facto water allocation (baseline), unmanaged water allocation and market-based water allocation. In terms of unmanaged water allocation, it was found that the basin water consumption was higher than the basin gross domestic product (GDP) which was lower than in the baseline scenario. The basin gross domestic allocation, however, was lower than the baseline. In the market-based water allocation scenario, the MAS recorded lower water consumption and higher basin GDP. The water trading scenario was able to improve the agent’s net benefit and the efficiency of the overall basin water use.

Anthony and Birendra (2018) proposed a preliminary design of an agent-based irrigation management tool that manages water allocation in mixed crop farms. The agent-based tool can reason and make intelligent decisions based on several farming factors such as crop type, crop value, and soil type. The proposed system generates an irrigation plan which considers the drought sensitivity of the crop, the crop’s growth stage, the soil type and the crop’s efficiency during periods of water scarcity. The programme achieved farm water savings without compromising farm productivity. The proposed solution also shows that it is possible to maximise water usage by prioritising each crop's water needs during periods of water scarcity so that the high yield crops do not suffer from a lack of water which may result in a lower yield. This tool can be used during periods of water scarcity (such as during the drought season). However, the calculation method for the crop water need is not accurate, as it did not include irrigation system data. Moreover, it does not address the need to reduce water when there is adequate water, nor does not it support sharing water between different community users. This ABM system can be extended to a MAS that allows agents to interact for the purpose of sharing water in drought conditions. As each agent represents a single farm, the programme should be able to determine the water need for a given farm and identify whether a farm has an excess of water or a shortage of water. The agent can then engage in negotiations (agents have the ability to communicate and collaborate with other agents to achieve a common goal), with other agents in the water community scheme to buy or sell based on the most efficient auction mechanism within the multi-agent framework. This will ensure that excess water in the community is consumed by other farmers who are facing a shortage of water. The research in this thesis aims to follow in this direction to produce a MAS for optimal water sharing.

Barbalios et al. (2012) applied MAS to simulate realistic water-sharing scenarios for assessing an ecosystem's viability. They considered environmental and socio-economical parameters. The proposed model was implemented in a real ecosystem (Koronia Lake in Greece), for a community of farmers using the lake. This research made several assumptions. First, each farmer had no knowledge of the exact number of farmers in the community and how much water each farmer used. Second, farmers did not interact with each other. Third, all farmers planted the same crops. The farmers were represented as agents and every day they decided how much water to take from the lake. These farmers interact with the environment which is a self-contained reservoir of water that contains a certain amount of water. This reservoir provides the farmers with water as requested until a certain threshold is reached. Once the threshold is reached, the reservoir will supply the same predefined amount to the farmers. To examine the farmers' behaviour, the researchers developed five level of greediness: from low to high. The farmer's objective is to take as much water as possible. This decision is based on a self-adaptive learning algorithm. The model's performance was investigated using three different policies: a non-rational policy (resembling the current behaviour of the farmers living near the lake), a profit driven policy (profit is the most important factor), and an environmental friendly policy (water preservation is the most important factor). The profit driven policy fared badly in terms of economic survival and resource preservation. While the environmentally friendly policy ensured the preservation of resources it prevented farmers from taking enough water to make a profit. With the introduction of a self-adaptive algorithm, farmers cooperated to achieve a common goal and were able to preserve their resources and achieve a higher profit.

Kanta and Berglund (2015) developed a Complex Adaptive System (CAS) to evaluate the performance of demand side strategies in an urban water supply system in Arlington, Texas. The model was used to simulate changes in consumers' water consumption which in turn affect the operational policies and long-term resource planning. In this model, consumers were represented as agents. They used an evolutionary computation-based multi-objective methodology to explore tradeoffs in cost, inconvenience to customers and environmental impact. In addition to consumer agents, the researchers included two additional components in the model: a policymaker agent and a mechanistic water resources model. The authors explored two optimisation scenarios in order to generate optimal management policies for the Arlington Water System.

2.5.2 Use of auctions to distribute and share goods

As mentioned in Chapter 1, one of the thesis' research objectives is to implement a MAS to facilitate fair water distribution in the community. This involves striking a balance between maximising profits and ensuring efficient and fair water allocation. Auctions have been used widely for resource allocation problems. Izakian et al., (2010) developed a continuous double auction (CDA) method for resource allocation in a computational grid. A computational grid consists of resource consumers and resource providers. Consumers look for resource providers who can deliver resources to run their computational-intensive jobs and are willing to pay for them. Resource providers are willing to rent their computational resources for profit. In a CDA setting, the resource consumers publish the amount they are willing to pay for the service (based on the remaining time and remaining resources), and the resource providers publish the amount they are willing to sell their service for (based on their workload). Their results suggest that the proposed auction mechanism is efficient for both the resource providers and the resource consumers.

Huang, Han, Chiang, & Poor (2008) have studied the use of an auction in a spectrum allocation problem which was subject to an interference temperature constraint. In this research, users wanted to purchase a local, short term data service from private companies or government agencies. This research used two auction mechanisms: The first one was an auction in which users are charged for receiving Signal to Interference Noise Ratio (SINR) and the second one involved charging users for power. Their research showed that both auction mechanisms are optimal for a large system (with limitations) with co-located receivers.

Lin, Lin, and Wei (2010) proposed a dynamic auction mechanism to allocate computation capacity in a cloud computing environment. A second-price auction was applied to determine the price of computation capacity allocation from cloud service provider (CPS). CPS will increase the fixed cost amount if the total input into background tasks goes over the threshold. A cloud server provider will also sell its residual resources to cloud users after deciding how much resources will be distributed to the background task. The experiment results showed that the proposed auction mechanism can optimise profits and allocate computational resources efficiently.

Rassenti, Smith, and Bulfin, (1982) applied a sealed-bid combinatorial auction for the allocation of airport time slots that the airports offer take-off and landing price packages – so airlines can pay money to get prime take-off and landing times. The proposed algorithm was used to price packages for the winner at levels guaranteed to be no greater than the bid amount. These packages were based on three criteria: resource (slot for airline), package (set of valuable slots for the airline), and logical constraints. Moreover, they proposed a secondary market, which consisted of an oral auction where airlines were able to buy additional units or sell units from excess slots after an auction was finished.

Zaman and Grosu (2013) improved the virtual machine resource allocation for a cloud computing provider using combinatorial auction-based allocation mechanisms. They argued that fixed-price allocation mechanisms (which favour allocation and pricing for virtual machine resource allocation on cloud computing) have some disadvantages: they are economically unproductive and do not reflect the equilibrium between supply and demand. They applied two combinatorial auction mechanisms: the first one considered a combinatorial auction problem where a user can include, at most, one item of a particular type in their request bundle. The second one extended the greedy mechanism which determines the allocation of user valuations and requested item in total from bidder. The simulation result showed that the proposed auction techniques were better for virtual machine allocation in the cloud.

One study used an auction-based algorithm to allow users to fairly compete for a wireless fading channel (Sun, Modiano, & Zheng, 2006). They used a second-price auction which adopts the Nash equilibrium strategies for general channel state distribution to allocate bandwidth for users based on user payment. The Nash equilibrium strategy of this auction was used to analyse the average money constraints on each user's strategy. The user submits a bid according to the channel condition revealed to it. The transmitter chooses the one with the highest bid and the winning user pays the second highest bidder's bid. They found that the proposed auction leads to an allocation at which total data throughput is increased.

Budde and Minner (2014) investigated a news vendor-type retailer problem where there is a dominant retailer and several competing and identical suppliers. The main objective was to find the least costly supplier where there was asymmetric information. They used combinations of different simple auction formats and risk sharing supply contracts (push and pull). The retailer and suppliers were either risk averse or risk neutral. The authors found that the first price push auction for a risk neutral retailer was superior.

2.5.3 Other work on water allocations

Scholars have used other approaches to water allocation including dynamic programming, linear programming and genetic algorithms. For example, Gu, Guo, and Huang (2013) explored uncertainty in water resource allocation in China using dynamic programming. The main purpose of the study was to deal with flood control and water conservation problems. They implemented interval multistage joint-probability programming (IMJP) to deal with water resource allocation under uncertainty and to handle economic expenditure resulting from regional water shortages and flood control. This method was applied to water resources allocation in Shandong, China, and was used to assist the water resource manager to identify desired system designs under various conditions. Ayvaz & Elçi (2013) implemented a simulation model to minimize the cost of groundwater pumping. They integrated a heuristic search algorithm to solve pumping cost minimisation problems. They included the pumping rates and the locations of additional new wells as the decision variables. The proposed simulation-optimisation model obtained acceptable responses for the different parameters which led the authors to conclude that the model was an effective way of solving the pumping cost-minimisation problem.

Khare, Jat, and Sunder (2007) explored the potential of the conjunctive use of ground and surface water for irrigation during the drought season for one of the proposed link canals in India. They used linear programming to optimise crop patterns and identify water resource availability (both surface and groundwater) in situations of water scarcity. They found that conjunctive use planning is beneficial as a large quantity of surface water can be saved. This water can be redistributed to other areas that have a limited supply. Freire-González, Decker, & Hall (2018) applied a multi-objective linear programming input-output method to generate plans for water supply allocations during the drought season in the UK. They aimed to assess how water allocation decisions interact with other policy goals to determine the economic impacts of a drought. They proposed water supply allocations to determine the minimum profit impact during periods of water scarcity with different water allocation policies to illustrate how choices made about water allocation can minimise economic production losses.

Barlow et al. (2003) applied linear programming to evaluate trade-offs between depleted streamflow and groundwater for sustained yields of alluvial- valley stream- aquifer systems in the United States. This model evaluated the trade-offs between groundwater withdrawal and streamflow depletion for assessing hydrologic variability on minimum streamflow requirements. The proposed model reduced the water depletion rate by approximately 10% during the summer season. Yamout and El-Fadel (2005) used linear programming to manage water supply rates from various water sources. They applied a linear model in the Greater Beirut area to optimise water allocation patterns to provide the highest net return above water use while fulfilling the main constraints such as water availability and water requirements. The results obtained from the various scenarios indicated that the optimal net return from water used and the corresponding optimal allocation in different sectors differ from one objective to the other. Guo, Chen, Li, and Li, (2014) applied a fuzzy chance-constrained linear programming to support multiple uncertainties around water resource allocation on different farms. The proposed approach was implemented in an agricultural water resources management system for farms with multiple crops. The result of the simulation showed that crop water reduction affects the total benefit on the farm because crop cannot get maximum productivity if do not have enough water. This analysis can help farmers to decide on plants with less water demand to keep the maximum productivity during water scarcity.

Li, Fu, Singh, Ma, and Liu (2017) implemented a multi-objective non-linear programming model to examine water allocation for irrigation in Qing‘an, China. They wanted to determine how to allocate limited water resources to rice based on its growth stage. Using multi-objective programming, the model was able to quantitatively solve multiple problems, including crop yield increases, blue water savings and water supply cost reductions. The model also considered the combination of dry and wet conditions for water availability and precipitation. The results obtained can be used to generate a range of water allocation schemes that can assist decision makers to determine the irrigation water resources allocation policy under uncertainty. This model can be applied to a single farm irrigation during periods of water shortage.

Interval multistage joint-probabilistic left-hand-side chance-constrained programming (IMJLCP) was developed to address the complexity and uncertainty of agricultural water management (Zhang, Li, & Guo, 2017). The proposed model applied probability distribution to address uncertain factors to optimise water allocation for different crop growth stages in the Heihe River Basin, China. It also took into account groundwater and surface water in its decision making. The programme was used to investigate six scenarios. Managers' attitudes to economic benefit are represented in the different levels of constraint violation. This model also assists managers to determine the best water allocation plan (whether to utilise ground water or surface water), based on the crop type and the farming location.

Similarly, Benli and Kodal (2003) applied a non-linear optimisation model to determine the optimum cropping pattern, including water supply conditions and farm income. They compared water allocation models using both linear programming (LP) and non-linear programming (NLP) techniques based on a crop water-benefit function. The result showed that the NLP technique generated higher farm income values compared to LP on different water reduction schemes. Dursun and Özden (2017) applied a genetic algorithm (GA) and an artificial neural network (ANN) to reduce the number of soil moisture sensors and to determine the best location for these sensors in the farms. While ANN was used to estimate soil moisture, GA was used to find the optimum energy and water consumption in the system. At the end of the irrigation period, it was found that the application rate was more homogeneous than the traditional irrigation systems. There was a 32% decrease in daily energy and water consumption. The moisture rate was kept at a desired range. Ramakrishnan et al., (2010) wanted to see what effect it would have if a farmer replaced a peanut crop with rice or changed the crop growing season in Sathanur, India. Water for irrigation is collected in the reservoir during the monsoon period and used in the cultivation of crops during the rainy season. They proposed a GA based crop calendar adjustment model to determine a suitable crop period to maximise crop water needs during a period of water scarcity while reserving drinking water as a priority. GA was used as an optimisation tool to drive near-optimal operating strategies for water allocation in the UK (Rao, Debski, Webb, & Harpin, 2010). The initial population consists of the discharged water flow from each reservoir. Each chromosome was evaluated based on the value of its fitness function in finding the optimal solution. These studies demonstrate that the fitness function and the selection method must be accurate in order to obtain the optimal solution.

In summary, dynamic programming is useful when the same subproblem occurs in the calculation process. It can reduce calculation time and memory resource capacity because the system stores the previous result and reuses it (this process is called "memorisation") (Skiena, 2008). DP is very powerful when the same subproblem is formulated. DP divides the problem into multiple subproblems and saves the results for each subproblem in local memory. If the same subproblem occurs, DP will use the old reference from the previously calculated subproblem. However, it takes a lot of memory to store the calculated result and there is no guarantee that the stored value will be utilised.

The LP technique has the same advantages as dynamic programming. It is applied to optimal decision analysis in a linear inequalities form. It is applied to those problems that require maximisation because of its easy formulation and application (Kuo & Liu, 2003). For example, IrriCalc uses the LP model to estimate water needs based on farming location and daily data (Wheeler & Bright, 2015). The LP technique is easy to formulate and apply. In linear programming, an objective function needs to be defined. However, it needs to define a specific objective function for complex problems such as water resource allocation. It is hard to develop mathematical formulas because there are many factors that must be considered. In addition, the LP specific objective is based on assumption that inputs and outputs have linear relations. Unfortunately, input and output data are not linear in real-life situations (Skiena, 2008). Moreover, crop factors are not well-defined as these are non-linear factors: thus, these issues cannot be solved using LP techniques. The NLP model does not perform better than the LP model. It is applied in cases where some of the constraints or the objective functions are non-linear (Chambers & Fletcher, 2001). However, the extreme points which is the Intersection graph of multivariate equations that represent the balance of the equation. may not determine an optimal solution (Bradley, Stephen ; Hax, Arnoldo ; Magnanti, 1977).

A genetic algorithm (GA) is a computer algorithm which applies metaheuristic to provide a good solution for an optimisation problem. The GA is inspired by the principle of genetics and natural selection where the best generations live and the bad ones die (Goldberg & Holland, 1988; Haupt & Haupt, 2004). However, the GA has some limitations in terms of finding an optimal solution because the method selection must be appropriate and the fitness function must be accurate.

In summary, every technique has advantages, depending on the nature of the problems that it is trying to solve. The agent-based system has advantages over other approaches because it can work with uncertain factors. It can also support non-linear relationships which is a common data for crop water estimation model. Moreover, it is flexible and autonomous in complex situations. It can make decisions in unexpected situations and is suitable for solving complex problems (Singh, 2014).

2.6 Gaps in the literature

The literature review has shown that there is a lot of work on resource allocation and in particular, various computing techniques. Many studies contend that MAS modelling has the potential to solve water allocation problems as it is flexible and can be modified to reflect varying user behaviours. It is able to negotiate with other agents and the environment. Moreover, MAS can be implemented to simulate a variety of scenarios in order to determine the best decision. MAS can be used to determine the best irrigation plan based on the current environment (weather, crop types, soil moisture, and economic factors). Based on the reviews discussed in this chapter, the literature has identified the following gaps:

- Existing tools that are commonly used in agriculture such as IrriCalc and OVERSEER cannot prioritise crop water needs during periods of water scarcity.
- There is limited research on the development of negotiation tools for water resource allocation (for examples, see Barreteau et al., 2003; Le Bars et al., 2004). In these studies, agents were not able to communicate with each other and hence negotiate with each other.
- While auctions have the potential to be used as a mechanism for fair water distribution and would help meet different objectives (such as profit, community benefit or a balance of both), there has been no research on using them in community irrigation schemes.
- Most of the pre-existing literature focuses on capturing water requirements and responding using optimisation methods based on current water resource capacity. They do not consider how to manage excess water once the allocation process is complete.

In response to these gaps, this research develops an agent-based irrigation management system that can be used by individual farmers to generate irrigation plans on a daily basis. This system generates optimised irrigation plans based on specific information such as crop type, crop growth stage, soil moisture and the weather conditions. During periods of water scarcity, these agents can negotiate with other agents in the community to buy or sell water as needed, with the objectives of maximising profit, minimising loss and the fair distribution of water. The outcomes of these negotiations are dependent on the behaviour of the agents in the community (greedy, neutral, or generous).

Chapter 3

Methodology

This chapter discusses the architecture of our multi-agent-based irrigation management system that is designed to manage water on a single farm and within a community of farmers. Firstly, we briefly describe agent and multi-agent systems, the architecture of these systems and their applications. Secondly, we describe the Java Agent Development Environment (JADE) which is the platform used to develop our multi-agent-based irrigation management system. Thirdly, we discuss the algorithm used by the single agent to calculate an individual farm's water needs. Fourthly, we explain the various auction mechanisms that a farmer can use to buy and sell water. We then describe the architecture of the multi-agent system which facilitates the interaction between agents in the farming community. Finally, we explain strategies that can be used to distribute excess water in a farming community.

3.1 Agent and multi-agent systems

An agent or a software agent is a special software component that provides an interoperable interface to an autonomous system like a human agent that works with a client to achieve a particular goal. An agent can work as a solitary agent within a particular environment or interact with other agents if necessary (Wooldridge & Jennings, 1995). Agents have been widely used in several technologies such as artificial intelligence (AI), database, and computer networks (Niazi & Hussain, 2011). An agent is *autonomous*, *social*, *proactive*, *and reactive*. Autonomous means that agents can interoperate without human intervention. An agent has control over its actions and internal state. Social means that an agent can work with other agents or humans to achieve their tasks. An agent is reactive because it can perceive and automatically respond to changes in its environment. An agent is proactive not only because it acts in response to its environment, but also it can exhibit goal-directed behaviour by taking initiative (Bellifemine et al., 2007).

As discussed in Chapter 2, agent-based software can be used to solve complex problems. Researchers can build a software agent or multi-agent system depending on the nature of the problem. When the problem is complex, the software agent may require the cooperation of several agents, each with different capabilities. In this research, we develop an irrigation management system which can determine water needs irrigation in individual farm and interact and work together with other farmers within a community of farmers during water scarcity. The water distribution within the farming community is a complex problem because each individual agent (who works on behalf of a farmer) needs to determine the water needs for the farm (based on many factors) and negotiate with other agents in the farming community to secure more water (within their purchasing capability) in order to ensure that it obtains the maximum profit for the farm. Moreover, factors that affect a farm's water needs are dynamic: they change from time to time. These factors include crop growth stages (crops require different amounts of water depending on their growth stage), temperature (which changes on a daily basis), and the season (during periods of drought there are often water restrictions). Moreover, each farm has different water requirements due to varying crop types, soil types, farm location, and farm size.

3.1.1 Agent-based architecture

Agent architecture can be divided into one of four categories based on the agent's behaviour: 1) logic-based (symbolic); 2) reactive; 3) belief, desire, intention (BDI); and 4) layered architecture (Bellifemine et al., 2007; Soto, 2007)

Logic-based architecture

Logic-based architecture uses reasoning mechanisms based on human knowledge. Logic is used for encoding and to find the optimal solution. In other words, a human can easily understand the agent's logic. However, it is difficult to produce an accurate symbolic representation and it takes more time to execute.

Reactive architecture

Reactive architecture maps the situation to set of actions. This architecture is based on responsive data that is triggered by sensors. It is not like logic-based architecture because it does not have a central symbolic model. The key idea of this architecture is that it makes a decision through goal-directed behaviour. Reactive architecture uses a simple design: on or off stage allows an agent/s to respond faster in a dynamic environment. One limitation with this type of architecture is that it is very hard to develop reactive agents with specific behaviour because the agent's action is simple.

Belief, Desire, Intention (BDI)

BDI is probably the most popular form of agent architecture. It uses logic theory which defines the mental attitudes of belief, desire, and intention using a logic model. Beliefs represent information about the agent' s environment. Desires represent an agent' s allocation tasks and corresponding objectives or goals. Intention represents the result or decision that an agent has committed to achieving.

Layered architecture

Layered architecture allows agents to engage in both types of behaviour: reactive and deliberate. This architecture subsystems, arranged as layers of hierarchy, are utilised to accommodate agent behaviours. The layers enable flexibility in the agent communication process (Ferguson, 1992; Müller, Pischel, & Thiel, 1995).

This research uses hybrid agent architecture to develop a water sharing scheme. We use a logic-based form of architecture for the open auction process which depends on the agent's goals. We use reactive architecture to facilitate the auction, process bids and determine the winner/s. Each agent is motivated by his/her individual goal (efficient water allocation) and multiple agents work together to achieve fair distribution of water and ensure the community, as a whole, profits.

3.1.2 The multi-agent system

The multi-agent platform has been developed on the availability of appropriate technology (Bellifemine et al., 2007). We chose object-oriented language because the agent concept is similar with object oriented model such as encapsulation, inheritance and message passing (Bordini et al., 2006). Agents communicate with each other using standard agent communication language (ACL). One of the most popular forms of ACLs is FIPA-ACL which was developed by the Foundation for Intelligent Physical Agents (FIPA). FIPA is an industry body which develops and establishes computer software standards for heterogeneous and interacting agents and multi-agent communication. There are several software frameworks that support FIPA standards which can be used to develop agents and multi-agent-based system such as Agent Services Layer (ASL), Java-based Intelligent Agent Componentware (JIAC), Bee-get and Java Agent Development Environment (JADE).

Agent Services Layer (ASL) is a multi-agent platform developed by Broadcom. This platform has independent language support systems that allow an agent to be implemented in several languages such as JAVA and C++. The key concept of ASL is authority. There is a controlling agent who creates and deletes agents of various types in the system. It works with other agents as local name servers that resolve any active agent request and which allows it to discover agents based on role and name (Ferguson, 1992; Hayzelden & Bigham, 1999; Kerr, O'Sullivan, Evans, Richardson, & Somers, 1998).

JIAC is an agent framework that supports the design implementation and development of a software agent system. In JIAC, an agent platform consists of one or more nodes that represent an agent's runtime environment. The agent node runs in the Java Virtual Machine (JVM) and communicates with other agents with the encapsulation in the agent bean. The agent bean, which works as an authority device, defines the possible service of the agents (Kuster, Küster, Lützenberger, & Albayrak, 2014; Lützenberger, Küster, Konnerth, & Masuch, 2014).

Bee-gent, an agent software framework developed by Toshiba, provides two type of agents: a wrapper agent and a mediator agent. The wrapper agent works as a coordinator. It communicates with others by handling messages through an XML/ACL message which follows FIPA standards. The mediator agent is a mobile agent. It identifies other agents in the environment by name and service (Bellifemine et al., 2001; Tanaka, Funabiki, & Nabae, 2002).

JADE is a software platform that provides middleware- layer functionalities (Bellifemine et al., 2007; Caire, 2009). It is implemented using a well- known Java programming language which provides a simple and friendly Application Programing Interface (API). JADE offers a middleware agent: it provides a set of services which fulfil FIPA standards. It supports interoperability. Moreover, JADE provides several graphic tools for debugging and testing. It can be adapted for use on mobile devices and communicate between agent environments (Bordini et al., 2006). JADE provides two agents: the Agent Management System (AMS) and a Directory Facilitator (DF). AMS performs platform management actions which include starting and killing agents (Caire, 2009). DF works as yellow pages service that can be used to publish the services provided by agents and to find agents who provide specific services (Bellifemine et al., 2007, 2001; Caire, 2009).

ASL and Bee-gent were both developed by private companies. They work only with specific devices. Neither are open-source software. In contrast, both JIAC and JADE are open source frameworks. However, JADE is a full FIPA-compliant agent framework. This means that JADE's architecture and performance have been well-tested to ensure agent interoperability (Soklabi et al., 2013). JADE is a more popular platform than others because it is developed fully in Java and supports different operating systems on the web (Hayzelden & Bigham, 1999; Kravari & Bassiliades, 2015). It is for these reasons that we chose to develop our system using the JADE platform.

3.1.3 Java Agent Development Environment (JADE)

The main components of JADE are: 1) a container and platforms and 2) an agent management system and a directory facilitator (see Figure 3.1).

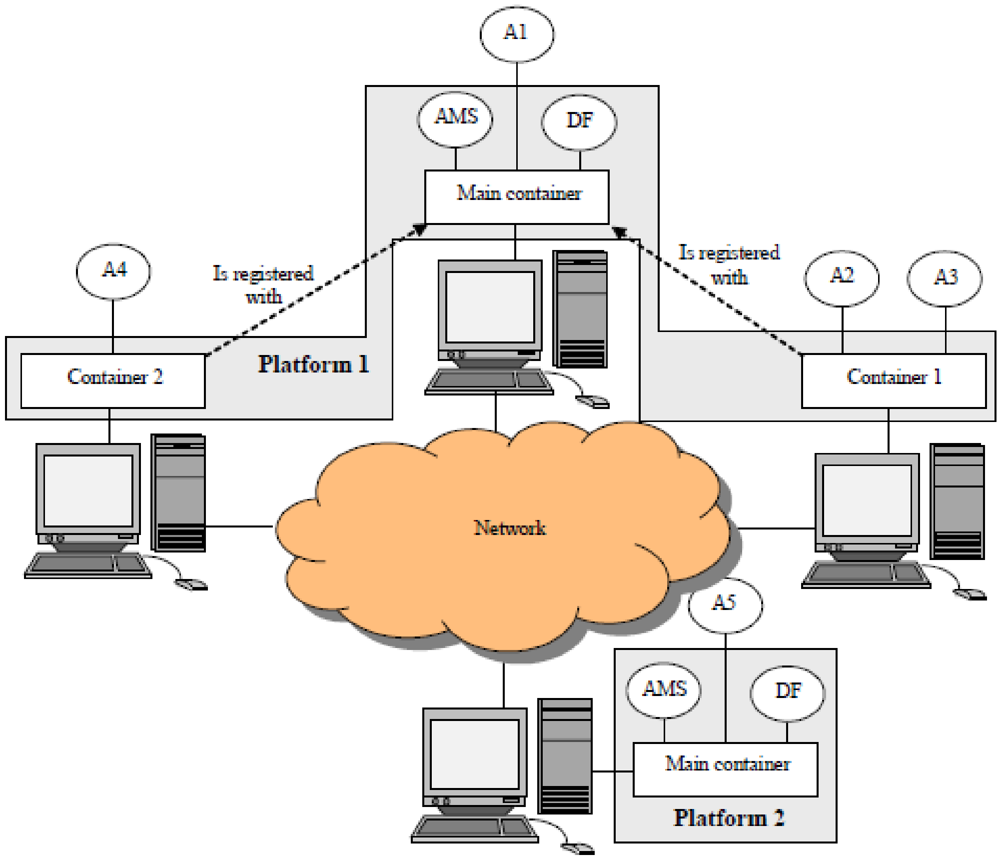


Figure 3.1 JADE's container and platforms
Source: (Bellifemine et al., 2007)

Containers and platforms

The container runs instances of the JADE runtime environment. It can contain several agents and a set of active containers called a platform. The main container is a single special container and must always be active in the JADE environment platform. Every container needs to register with the main container. If another main container is started somewhere in the network, it constitutes a different platform (new normal containers can register to this platform). Figure 3.1 shows how agents can communicate with other agents in the same container (A2 and A3), different containers in the same platform (A1 and A2) or in different platforms (A4 and A5).

Agent Management System (AMS) and Directory Facilitator (DF)

AMS and DF are special agents that are launched after the main container is established. AMS provides a naming service and represents a platform authority designed to manage agents on remote containers. DF acts like a yellow page. If agents want to find another agent service, they will use the DF. Overall, JADE technology is flexible and able to solve complex problems. The JADE framework is a dynamic environment. It has features to support a changing agent behaviour scheme and add external factors to the processing scheme. Changing an agent/s' behaviour allows a user to determine its effect on the current situation. Agents in a multi-agent environment may need to negotiate with each other in order to achieve a certain goal. This research focuses on negotiations between agents who are buying or selling water using a variety of auction rules.

3.2 The irrigation management agent (a single agent)

In our system, each farm is represented by a single agent whose main role is to calculate the farm's water needs based on crop type/s, moisture on the ground and farm type (whether it is a grazing pasture or mixed crop farm). The agent generates an irrigation plan to determine how much water each crop needs. During periods of water restriction, the agent must consider several factors, including the crop's potential yield, its sensitivity to drought and the farm's soil type, to generate an effective irrigation plan. As discussed, the proposed irrigation management agent is an extension of Anthony & Birendra (2018) original work.

3.2.1 Conceptual design

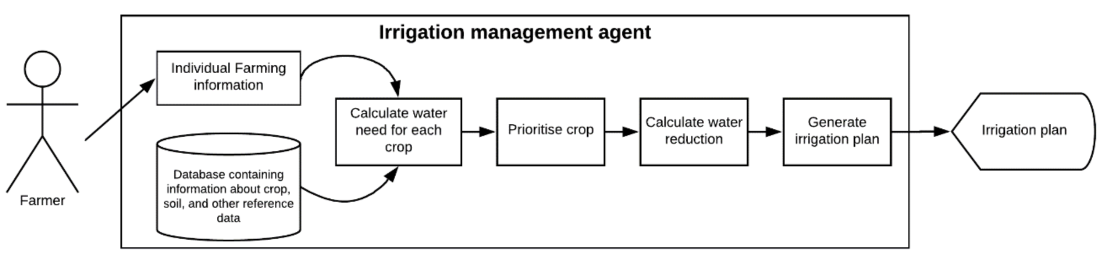


Figure 3.2 Conceptual framework

Figure 3.2 shows the conceptual design of the single agent. The main purpose of the single agent is to optimise water allocation around the farm which is particularly useful during periods of water scarcity (water restriction). As described in Chapter 2 (Section 2.1), crop water need is calculated based on crop evapotranspiration and the crop coefficient (crop type and the growth stage). Most crops have four growing stages (initial, development, mid-season, late-season). Pasture has three stages (after grazing, development, and late-season). Our software agent assumes that each type of crop is planted in a certain sized plot. This means that the water need for a particular crop is calculated using a particular plot size.

An agent represents a single farm. Each farm may grow a single crop or many different crops. The agent must determine the irrigation plan for the farm for a given planting season. During a period of water scarcity (such as during a drought), the agent will develop an irrigation plan that will prioritise crop irrigation needs based on the prevailing conditions. The crop information database contains up-to-date information about the state of the farm, including information about each crop, its growth stage, its location, plot size, and soil type. During periods of water scarcity, a user needs to enter the percentage of water reduction as required by the local authority. The agent will then calculate the water need for each crop on the farm, calculate the expected utility for each crop, decide which crops have higher water needs by prioritising them and determine how much water should be reduced for each crop on the farm. This prioritisation is based on the crop's expected utility, which takes into account the potential yield of the crop, its sensitivity to drought (low, medium, and high where crops with high sensitivity to drought are given priority), the crop’s growth stage, and the farm’s soil type (light, medium, heavy where heavy soil can absorb more water and so it has low irrigation priority). For example, if the farm contains high yield crops, more importance will be placed on the crop's yield to ensure that the farm’s revenue is not compromised. If the farm does not have a high yield crop, then the other two factors can be considered.

3.2.2 Water reduction plan

In a normal situation, the proposed algorithm calculates the farm’s total water requirement based on the FAO’s crop water need calculations (as discussed in Chapter 2). During periods of water scarcity, the water reduction plan is generated once the water requirement calculation process is complete. The algorithm to generate the water reduction plan is shown in Figure 3.3. First, the user keys in the required water reduction percentage. It is assumed that the water reduction is set by the water authority. If there is no water reduction in place, the proposed algorithm calculates the total water requirement of each crop using a zero water reduction percentage. Second, the agent retrieves the crop information from the database, the influence of crop type on crop water need (K_c) value for each crop stage, and the reference ET_0 data.

```
Begin
   get water reduction percentage
   retrieve crop information from crop database
   calculate the water requirement for each crop
   calculate total water requirement on farm
   calculate expected utility for each crop
   prioritise crops based on expected utility
   calculate water reduction for each crop
   generate water reduction plan for a farm
End
```

Figure 3.3 The pseudocode of the irrigation management agent

The K_c and ET_0 are used to calculate the actual crop's water requirements. The ET_0 value is retrieved from the New Zealand weather data, and the K_c value is based on the FAO data reference. All data references are stored in the crop database which are collected from multiple sources: for example, weather data from the National Institute of Water & Atmospheric Research (NIWA) and total income (from a New Zealand Financial Budget manual book).

While the main idea for the proposed algorithm is the same as the original work of Anthony & Birendra (2018), we have made several improvements to the existing algorithm. This includes improving the accuracy of the crop water needs calculation by adding soil moisture level and irrigation system as factors that can be used to determine crop water needs. These factors are useful for optimising the total water requirements on farm as different crops need different amounts of water depending upon their growth stage. Another improvement is the extension of this single agent to a multi-agent systems to allow for water sharing negotiations among the farmers in the community irrigation.

An agent calculates the individual crop water needs and the total water requirement for the whole farm (this is the sum of all the water needs for all the crops in the farm). The algorithm then calculates how much water a farmer can save. The agent will attempt to save water by checking the growth stage of each crop, paying particular attention to those crops in the late season stage (or close to harvest). At this stage, crops do not need as much water so the agent can reduce the amount by a certain percentage (Anthony & Birendra, 2018). This process results in a detailed estimate of potential water reduction efforts to make more efficient use of water in total. Next, the agent calculates the farm's water reduction requirements based on the percentage of required reductions entered by the user. It calculates the expected utility for each crop based on its properties. Once the crops are prioritised, the agent will determine the percentage of water reduction that should be applied to each crop. The proposed system will prioritise those crops that need water the most. The proposed system does not prioritise water needs if there is sufficient water. However, the algorithm will still try to reduce the farm's water needs based on each crop's growth stage. Finally, the agent generates an individual irrigation reduction plan for the farmer. These processes are detailed in the following sections.

Crop information database

The crop information database is designed to calculate irrigation water needs. It contains information about each crop and other relevant information from multiple data sources (see Figure 3.4).

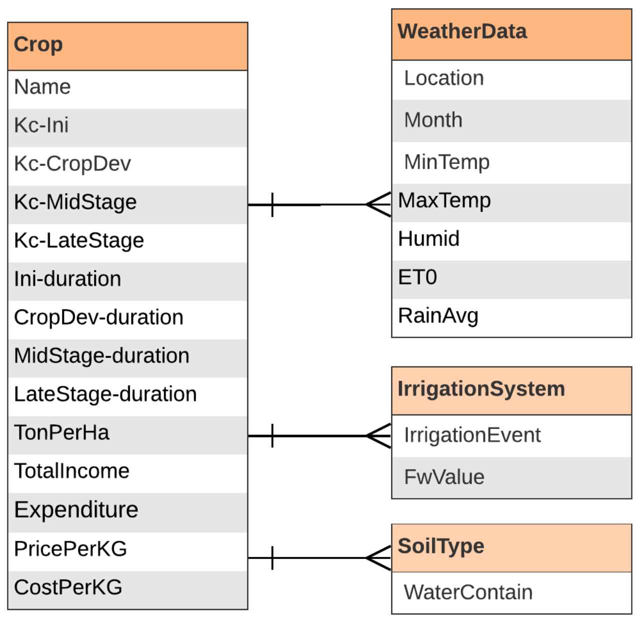


Figure 3.4 ER diagram for crop information database

The database contains multiple tables that contain crop information, weather data, irrigation system, and soil type. The crop information includes the crop growth stage and also crop evapotranspiration (ET_{crop}). As shown in Chapter 2 (see Tables 2.6, 2.9 and 2.10), each crop has a name, growth stage (referenced from the FAO and (Birendra et al., 2016)). The weather data table contains weather information from multiple weather stations in Canterbury. It also captures the ET_0 value, where ET_0 is calculated using weather data and New Zealand geographical data, including geographical location (latitude and longitude), and the average monthly temperature value (°C), crop period (indicating the duration of each stage, as shown in Table 2.6), and the irrigation system. The revenue and cost table contains information about the crop value, including the price per kilogram, productivity per hectare, and the total revenue per hectare which is taken from a New Zealand farm budget manual (Askin et al., 2013).

The soil type table contains various types of soil as identified by their water holding capacities (Birendra et al., 2019).

The irrigation system contains reference data from the FAO's water management method (Brouwer et al., 2013). As shown in Table 3.1, the typical values for soil surface wetted (f_w) are from a mixture of irrigation and precipitation in the same area on the same day. This value is based on a weighted average of the f_w for precipitation (f_w = 1) and the f_w for the irrigation system. It is approximately proportionate to the infiltration depths from each water source. These values are used to calculate crop water needs.

Table 3.1 Common values of fraction f_w of soil surface wet by irrigation or precipitation

Wetting event	$\boldsymbol{f_w}$ **(mm/day)**
Precipitation	1.0
Sprinkler irrigation	1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.75
Furrow irrigation (every furrow), wide bed	0.5
Furrow irrigation (alternated furrows)	0.4

Calculating crop water needs

The proposed model modified the standard calculation for crop water needs from Equation (2.1 in Chapter 2) which was based on crop water needs on a daily basis. This new equation takes into account the soil moisture and the farm's irrigation system. We applied the FAO's dual crop coefficient model to calculate crop water needs, which include the wetting system and soil moisture level. This procedure is conducted on a daily basis and improved the accuracy of K_C by estimation (Allen & Luis S., 1998; Allen & Pereira, 2009). As shown in Equation 3.1, this calculation requires ET_0 and K_C.

$$ET_{Crop} = (K_{cb} + K_e) \times ET_0 \qquad (3.1)$$

Where ET_{Crop} = Crop evapotranspiration (mm/day)

K_{cb} = Base crop coefficient value

K_e = Soil evapotranspiration coefficient

ET_0 = Reference evapotranspiration value

This represents a slight variation from Equation 2.1 in that the original K_c value is added with K_e to accommodate the soil evapotranspiration (Allen & Luis S., 1998). The modified formula is more accurate than the previous model for irrigation water needs. In this case, the K_{cb} is the crop coefficient value from the standard K_c based on crop stage. K_e describes the soil evaporation coefficient. The $K_e$value is maximal when the topsoil is wet and zero when the soil surface is dry. The K_e is calculated as follows (Testa, Gresta, & Cosentino, 2011):

$$K_e = K_r\left(K_{c_{max}} - K_{c_b}\right) \leq f_{ew} \cdot K_{c_{max}} \quad (3.2)$$

where K_r = Soil evapotranspiration reduction coefficient

K_c = Soil evapotranspiration coefficient

K_{c_b} = Base value of crop coefficient

$K_{c_{max}}$ = Maximum value of K_c (following the remain irrigation)

f_{ew} = Exposed and wetted soil fraction

K_e calculation includes the soil evapotranspiration reduction coefficient (K_r) and the exposed and wetted soil fraction (f_{ew}). The K_r is the evapotranspiration from the exposed soil, which can be replaced with the soil moisture level. The maximum value is 1 if the soil surface is wet. The K_r value is zero when the total amount of water that can be evaporated from the topsoil is depleted (Testa et al., 2011). K_e is used to compare the $f_{ew} \times K_{c_{max}}$. The maximum K_e is less than or equal to $f_{ew} \times K_{c_{max}}$. The f_{ew} value is essentially defined as $(1 - f_c)$, where f_c is the average fraction of soil surface covered by vegetation and $(1 - f_c)$ is the approximate fraction of soil surface that is exposed. The f_c formula is shown in Equation 3.3.

$$f_c = \left[\frac{K_{c_b} - K_{c_{min}}}{K_{c_{max}} - K_{c_{min}}}\right]^{(1+0.5h)} \quad (3.3)$$

where Kc_b = Based crop coefficient value

Kc_{min} = Minimum crop coefficient

Kc_{max} = Maximum crop coefficient

h = Crop height

In irrigation systems where only a fraction of the ground surface is wet by irrigation, f_{ew} is limited to f_w, the fraction of the soil surface wetted by the irrigation system. As shown in Table 3.1. f_{ew} can be calculated using Equation 3.4.

$$f_{ew} = \min\,(1 - f_c, f_w) \qquad (3.4)$$

where $1 - f_c$ is the average of exposed soil fraction not covered (or shared) by vegetation [0.01 – 1]. The f_w value is the average fraction of soil surface wetted by irrigation or Precipitation [0.01 – 1]. The f_{ew} function selects the lowest value of $1 - f_c$ and f_w values.

Example of crop water needs calculation

The steps to calculate the crop water needs for potatoes to be planted in February with a soil moisture rate of 0.3, using a sprinkle irrigation system, are shown below. Table 3.2 shows the ET_0 for potatoes for January – July.

Table 3.2 ET_0 reference data for crop water needs (potato)

Month	**Jan**	**Feb**	**Mar**	**April**	**May**	**June**	**July**
ET_0	4.0	5.0	5.8	6.3	6.8	7.1	6.5

The potato data obtained from Table 2.9 and Table 2.10 is shown in Table 3.3.

Table 3.3 The potato K_c and period

Data/ Stage	**K_C**	**Period**
Initial stage	0.45	25
Crop development	0.75	30
Mid-season stage	1.15	30
Late season stage	0.85	20

1. The values of $K_{c_{max}}$ and $K_{c_{min}}$ are determined.

The $K_{c_{max}}$ = 1.15 and $K_{c_{min}}$ = 0.45

2. Work out f_c (the average fraction of soil surface covered by vegetation).

$$f_c = \left[\frac{K_{c_b} - K_{c_{min}}}{K_{c_{max}} - K_{c_{min}}}\right]^{(1+0.5h)} = \left[\frac{0.75 - 0.45}{1.15 - 0.45}\right]^{(1+0.5*0.5)} = 0.35$$

3. Determine f_w.

f_w value with sprinkle system is 1.0, as shown in Table 3.1.

4. Calculate f_{ew}.

$f_{ew} = \min(1 - f_c, f_w) = \min(0.65, 1)$ ➔ 0.65

5. Calculate K_e.

K_e is then calculated using $K_e = K_r\left(K_{c_{max}} - K_{c_b}\right) \leq f_{ew} \cdot K_{c_{max}}$

$K_e = 0.3(1.15 - 0.45) \leq (0.65 \cdot 1.15)$ ➔ 0.21. This value is lower than $f_{ew} \cdot K_{c_{max}}$ which follows the irrigation system calculation.

6. Calculate K_c for each crop stage.

Finally, K_c that includes soil moisture calculation is $K_e = K_{cb} + K_e = 0.75 + 0.21 = 0.96$. Then,

calculating the potato new K_C value on every crop stage as shown in Table 3.4 and the total crop water need with new K_C can be calculated as shown in Table 3.5.

Table 3.4 Comparison between K_c reference and new K_c calculation

Crop stage	K_c reference	K_C includes soil moisture
Initial	0.45	0.96
Crop development	0.75	0.87
Mid-season	1.15	1.15
Late-season	0.85	0.94

7. Then, using the new K_c value, the crop water need for potatoes in each stage can be calculated using Equation 2.1.

Table 3.5 Total crop water needs for the whole growing season with new K_C

Month	Crop stage	K_c (new)	ET_{crop} (mm/day)	ET_{crop} (mm/month)
February	Initial (30 days)	0.96	$5 \times 0.96 = 2.3$	144.00
March	Crop development (30 days)	0.87	$5.8 \times 0.87 = 4$	151.38
April	Crop development (5 days) Mid-season (25 days)	$\left(\frac{5}{30} \times 0.87\right) + \left(\frac{25}{30} \times 1.15\right)$ =1.103	$6.3 \times 1.103 = 6.1$	208.53
May	Mid-season (25 days) Late season (5 days)	$\left(\frac{25}{30} \times 1.15\right) + \left(\frac{5}{30} \times 0.94\right)$ =1.117	$6.8 \times 1.117 = 7.82$	227.87
June	Late season (25 days)	0.94	$7.1 \times 0.94 = 6.67$	166.85
			Total	690.10

Crop water needs can be calculated daily, monthly or for the whole season. This water need value can be multiplied by the plot size to determine the total water requirements for a given crop. For example, the crop water needs for the entire potato growing season is 690.1 mm/Ha. So, assuming that the potato plot size is 10 hectares, the total crop water requirement (C_{wrq}) is 6,901 mm. This is calculated as:

$$C_{wrq} = ET_{crop} \times C_{plot} \tag{3.5}$$

where C_{wrq} is the total crop water requirement for the whole growing season, ET_{crop} is the water requirement for potatoes for the whole growing season and C_{plot} is the size of the plot used for planting potatoes. If the farm grows a variety of crops, the farm's total water requirement can be calculated by adding up the water requirements for each crop.

3.2.3 Prioritising irrigation water needs for multiple crops

To prioritise irrigation water needs for multiple crops, the agent uses three determinants: drought sensitivity and the growth stage, the potential crop yield, and the soil type (Anthony & Birendra, 2018). Each determinant is associated with a utility function that indicates the importance of that crop (the higher the value, the higher the irrigation priority). These utility functions (based on a crop's potential yield, drought sensitivity and growth stage and soil type) are defined as follows:

$$f_{PY} = (C_{plot} \times C_{yield}) \times C_{price} \quad (3.6)$$

$$f_{DS} = C_{stage} \times D_{val} \quad (3.7)$$

$$f_{ST} = S_{type} \times C_{plot} \quad (3.8)$$

where:

f_{PY} = Crop's potential yield function

C_{yield} = Yield amount of crop area

C_{price} = Price per kilogram

f_{DS} = Crop's drought sensitivity function

f_{ST} = Soil type function

C_{stage} = Crop stage

D_{val} = Drought sensitivity value

C_{plot} = Plot size of crop

S_{type} = Soil type

To prioritise crop water need, the water reduction process considers three factors (drought sensitivity, crop potential yield for different crop stages, drought sensitivity and soil type). We divide crops into two categories: pasture and crops. Crops have four growth stages (see Table 2.3). Pasture only has three stages: after grazing, development, and late season (Anthony & Birendra, 2018). Drought sensitivity is divided into three levels: low, medium and high. Drought sensitivity is related to irrigation priorities. A high sensitivity to drought requires a higher irrigation priority (Cavin & Jump, 2017). The soil types are divided into three levels: light, medium and heavy. As described in Chapter 2, the WHC value is high for clay soil which that has a heavy texture. Sandy soil, which has the lowest WHC, has a light texture (Bodner, Nakhforoosh, & Kaul, 2015; DairyNZ, 2011). This work considers high-value crops; crop yield can be estimated based on the total planting area and price per kilogram. High yield crops have a higher irrigation priority as they generate more money.

To determine the expected utility (EU) for each crop, the agent combines the three utility functions by allocating weights to denote their relative importance. Thus, the expected utility of each crop is calculated as follows:

$$EU_{crop} = \sum_{j\epsilon c} w_j f_j \qquad ;\ 0 \leq w_j \leq 1\ and\ \sum_{j\epsilon c} w_j = 1 \qquad (3.9)$$

where C is the set of determinants which the agent uses to calculate the crop priority value, f is the utility function for each determinant, and j is the individual parameter. At any time, the agent can consider the three utility functions to determine irrigation priority, depending on what it sees as being important at that moment.

For example, in an all pasture farm, the crop's drought sensitivity and growth stage determinants are the most important because the potential yield of the crop is the same (pasture only). If the farm is a mixed crop which has high yield crops, then the crop's potential yield is more important because it affects the farm's productivity and income. Thus, a higher weight will be applied to the crop's potential yield function.

Determining water reductions for each crop during periods of water scarcity

The percentage of water reduction is the key determinant for water reduction. In New Zealand, the average water reduction is around 95% of water supply reliability (Anthony & Birendra, 2018). However, the agent needs to consider the worst dcase scenario as well. The maximum water reduction should not be over 20% for crops because it will lead to low productivity and a decline in their value (Brouwer et al., 2013). We also consider different crop growth stages as at each stage, crops have different water requirements. Anthony and Birendra (2018) note that it is possible to reduce water by 50% during the late season stage for crops and late season stage for grazing pasture.

All reductions are performed in two stages. First, the software calculates the percentage of water reduction for each individual crop based on the crop growth stage. The software divides the crops into two types: crops and pasture. As described in Section 3.2.2, crop water is reduced from 30 to 50% for the late season stage, 15% for the mid-season stage, 20% for the development stage and 10% for the initial stage. In terms of pasture, water reductions in the late season stage are reduced from 30 to 50%, 20% for the development stage and 10% for the after grazing stage. These reductions are performed from the bottom of the prioritised crop list. This process continues up the list until the required water reduction level is reached. Using this strategy, we can ensure that the top priority crop is least affected. In the second stage, if the total required water reduction for all the crops is still less than the required amount, then each crop's water requirement is reduced by the percentage of water reduction.

The outcome of the water reduction exercise is, in most farms, obviously a shortage of water. However, there are farmers (who may have overestimated their water needs or farmers who originally planned to plant more crops but decided not to), who will have excess water. In short, farmers may want to buy water or sell water within the water community scheme. It would be beneficial for those farmers with excess water to distribute it to those who need it in an optimal manner. This would mean that farmers with excess water are able to make more profit and those who do not have enough water are able to purchase water to reduce their losses. To maximise/minimise their profits/losses, we need an optimal marketplace to ensure that everyone obtains the maximum benefits from the exchange of water. In this research, we explore how auction-based negotiations can be used to optimise water sharing within a community of farmers during periods of water scarcity.

3.3 The negotiation process and auction mechanisms

The negotiation process involves dialogue between two or more people with the aim of reaching an agreement. The outcome of the negotiation is an important factor in determining whether the negotiations are successful (De Dreu, 2014; Hopmann, 1995). Negotiations are commonly used to solve labour issues, to resolve conflict and in market bargaining. Figure 3.5 shows a simple negotiation process between a seller and a buyer. A buyer can join a group and find products or services offered by a seller. A buyer may contact and negotiate with a seller who can provide compatible value and/or specialist services. Sellers and buyers can negotiate an agreed price for a services/items. A successful negotiation will result in a sale/trade (De Dreu, 2014; Gates, 2012).

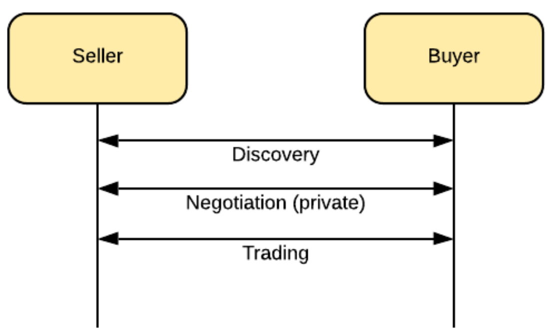


Figure 3.5 Simple negotiation process

Negotiation between a seller and a buyer is very important. Both sellers and buyers are keen to maximise their benefits. In general, negotiations can be divided into two categories: 1) distributive negotiations and 2) integrative negotiations. Distributive negotiations operate under zero-sum conditions that one person is going to win and other bidders will lose. Integrative negotiation attempts to create total value from the course of the negotiation using “win-win negotiation.” A seller is interested in obtaining a good price for the item/service that he is trying to sell; equally, the buyer/bidder is keen to receive a bargain. This form of negotiation is called an auction (Krishna, 2010).

An auction is a process of buying and selling goods/services that involves several steps. Multiple buyers want the same item; however, they are aware that they may not win the negotiation process. Buyers need to make sure that they do not bid more than their private valuation (the maximum price they are willing to pay for the item being negotiated), and estimate the best bidding price so that they can win the auction (Gates, 2012). Sellers want to sell their item at a price equal to or above their reserve price. There are four standard auction types: an ascending-bid auction, a descending-bid auction, a first-price sealed-bid auction, and a second-price sealed-bid auction (Klemperer, 1999).

An ascending-bid auction is often called an English auction. It is the most prevalent form of auction. At the beginning of the English auction, the seller sets a starting price for the item to be auctioned. Bidders compete to buy the item, with each bid being higher than the last. This process goes on until there is a single bidder left who is holding the highest bid. In the online variation, there is a fixed time: when the time is up, the winner is the one who has offered the highest bid. A bidder cannot re-join an auction once s/he decides to quit the auction. Sometimes, in online auctions, bidders wait until the last minute before making a bid. If this happen, the time is often extended. When an auction closes, if the winning bid is lower than the reserve price, then the seller can choose not to sell the item (Anthony, 2003; Pinker, Seidmann, & Vakrat, 2003).

A descending-bid auction works in the opposite way. The auctioneer starts the auction with highest price. The price lowers in steps until a bidder accepts the current price. The winner pays that price for the item. This auction is called a “Dutch auction” because it is used to sell flowers in the Netherlands. Sometimes, if there are a lot of the same product from the same seller, bidders call out to buy some of the available lots and the rest are re-auctioned (Klemperer, 1999).

In the first-price sealed-bid auction, a bidder cannot see anyone else’s bids. They can only submit one bid price. When the auction period closes, the seller opens all bids and sells their goods/services to the person who has offered the most money. The winner pays for their bid. This type of auction is used widely in the sale of artworks, real estate and government mineral rights (Jank & Shmueli, 2010; Krishna, 2010). The second-price sealed-bid auction has the same rules and process as the first-bid auction. However, the winner pays the second-highest bid price. This auction is called a Vickrey auction after William Vickrey who wrote a paper on auctions (Anthony, 2003; Klemperer, 1999). Sellers can use these different types of auctions to sell a single item or trade multiple units of a product (see Table 5.3). The multiunit auction is used for selling multiple units of the same item (Krishna, 2010).

Table 3.6 Comparison table for standard auction types

Type	Bidding rule	Clearing rule	Unit of goods
Ascending-bid auction	Seller announces the starting price and bidders are free to raise the price successively	Expiration of bidding period or when no new bids are received. Winner is the bidder who made the last/highest bid.	Single/multiple
Descending-bid auction	Bidders submit bids without any knowledge of what other potential buyers bid	Expiration of bidding period. Winner is the highest bidder. They pay a price equal to the highest bid.	Single/multiple
First-price sealed-bid auction	Bidder submit bids privately (price) Seller proposes to sell a single unit/volume.	Expiration of bidding period. Winner is the highest bidder. They pay the price equal to the highest bid.	Single/multiple
Second-price sealed-bid auction	Bidders submit bids without any knowledge of what other potential buyers bid.	Expiration of bidding period. Winner is the highest bidder. They pay a price equal to the second highest bid.	Single/multiple

Source: (Anthony, 2003)

The multiunit auction is designed for people who want to sell multiple units of a particular good/service at the same time. The multiunit uniform auction is an auction where multiple units can be sold at the same price. In contrast, the multiunit discriminatory auction is an auction where multiple units can be sold with varying prices depending on the bid price.

In a multiunit uniform auction, bidders may submit single/multiple bids which specify the number of units and price per unit. These bids are sealed and are not revealed to the other bidders until the auction closes. The auctioneer serves the highest bidder as the first priority and gives them the requested number of units. The auctioneer then serves the second highest bidder using the same process until all the items are sold. All bidders pay the same price per unit, which is the lowest winning bid. In this auction, the winners pay the price equal to the lowest winning bid (Engelbrecht-Wiggans & Kahn, 1998).

The multiunit discriminatory auction differs slightly from the multiunit uniform auction. This kind of auction is used to sell multiple homogeneous items at difference prices (Binmore & Swierzbinski, 2000). The bidding process is the same (bidders submit the number of units and how much s/he is willing to buy). After the auction closes, the auctioneer serves the highest bidder as the first priority. Each bidder pays the price they offered.

In summary, the multiunit uniform and multiunit discriminatory auctions have the same sequential bidding process. In water distribution, the bidder specifies the volume of water s/he needs. However, the sale price depends on the type of auction used. In a multiunit uniform price auction, the winners pay the lowest winning bid price, whereas in a multiunit discriminatory auction, the bidders pay the price they offered. These auctions are described in greater detail in Section 3.5.3.

There is a wide range of applications for auctions. According to Yamamoto & Tezuka (2007), in England and Wales, the discriminatory auction has been used to balance the market in electricity trading arrangements. The uniform auction is used to balance benefit on the difference size of electric company that has difference electric volume to sell because the big company can dominate the price in the market. Sheikholeslami and Navimipour (2018) showed that auctions are useful for solving resource allocation and pricing problems. Izakian, Abraham, and Ladani (2010) applied agent-based and multiunit discriminatory auctions for computational grid resource sharing. This enables resource owners and resource consumers to make autonomous scheduling decisions. The auction technique is applied to regulate the supply and demand of resources. This method motivates participants to consider multiple factors such as budget and the service quality requirements.

3.4 The multi-agent mechanism

As mentioned, each agent calculates their farm's total water requirements, prioritises the crops to be irrigated, and calculates water reductions for each crop. An agent is able to decide whether to buy or sell water and negotiate with other agents. During periods of water scarcity, it is anticipated that there will be farms who do not have enough water and there will be farms that have excess water. It would be useful for those farms with excess water to share water with other farms in the community. This practice would enable those facing water shortages to reduce their potential losses. One of the objectives of this research is to investigate efficient water sharing mechanisms that can be used by a community of farmers. To simulate this community of water users, we have developed a multi-agent system which consists of multiple agents that represent farmers in the community. These agents are able to communicate with each other and negotiate to buy or sell water. We propose a range of water sharing mechanisms: a first-price sealed-bid auction format, a multiunit discriminatory auction format, and a multiunit uniform auction format. We use an auction format because they are an efficient allocation mechanism (Budde & Minner, 2014; Izakian et al., 2010; Mailler, Lesser, & Horling, 2003; McAfee & Mcmillan, 1987; Sheikholeslami & Jafari Navimipour, 2018).

Figure 3.6 shows the multi-agent environment and the algorithm for the multi-agent water management system. The system can be explained in two parts; 1) A single farm's total crop water needs and 2) the negotiation process among the agents using auction mechanisms. We discussed crop water needs calculations in Section 3.2. Each individual agent is able to estimate their crop water needs on a daily basis. Based on this calculation, agents who have excess water will be categorised as seller agents. Agents who have a shortage of water are categorised as buyer (bidder) agents. The seller agents will auction their excess water and bidder agents will participate in these auctions. As shown in Figure 3.6, the algorithm from Figure 3.3 is extended to include the agent's decision to participate in the marketplace as a buyer or seller. The agent decides on the reserve price/private valuation for the water to be sold/bought based on the farm's total marginal profit. In any given farm, the total marginal profit can be calculated as follows equation 3.10.

$$P = \sum CV_i - \sum FC_j \tag{3.10}$$

Here, P represents the total marginal profit in the farm, CV is the total crop value, and FC is the total farming cost, i is the crops planted in the farm, and j is the farming cost factors for each crop.

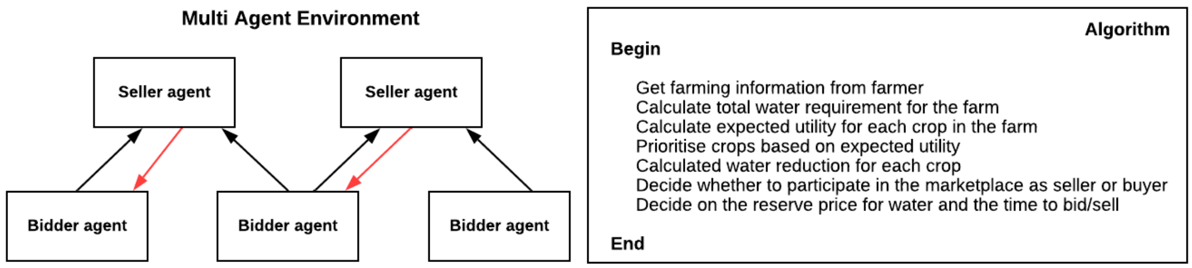


Figure 3.6 Pseudo-code for multi-agent irrigation management system

Before excess water is auctioned, the seller agent needs to determine the reserve price (the minimum price it is willing to sell the water), for its water (the price per cubic metre). A buyer agent sets a private valuation (the maximum price it is willing to pay for water), which is dependent on the farm's expected profit. The water pricing equations are shown in Equations 3.11, 3.12, and 3.13. The water price for various agents differs depending on the farm's expected profit. While it is assumed that the profit will decrease during periods of water scarcity, the total farm cost will remain the same. As shown in Equation (3.11), in this situation, the farming profit value will decrease if a farmer does not have enough water for the farm. If the farmer has more water than s/he require, he can gain additional profit by selling water to others (see Equation (3.12)). The expected profit function is shown in Equation (3.13) where x is the profit changed value (in dollars), $f(y)$ is the total farm cost function, and $f(z)$ is the utility function for water pricing. $f(z)$ is used as a maximum price (reserve price) for the bidder agent and a minimum price (reserve price) for the seller agent. The auctions begin once the reserve prices for seller agents and private valuation for the bidder agents have been decided. The auctions have an expiry date/time (this is dependent upon the seller's requirement). The auction can be started in parallel, but a bidder agent can only participate in a single auction and only a single bid is required. The auction duration is fixed. Bidders must submit their bids within this time. When the time is up, the winner is determined according to the type of auction. During the auction period, agents can contact each other using FIPA–ACL message protocol. The agent standard protocol includes different message types and standard descriptions to show the sequence of the auction process. The MAS is implemented on JADE platform: sellers and agents can communicate using standard agent communication language. At the conclusion of the auction, the winner leaves after receiving the product. The other agents standby for new auctions to open.

$$P - x = f(x)_{income} - f(y)_{farm\ cost} \quad (3.11)$$

$$P + x = f(x)_{income} - f(y)_{farm\ cost} \tag{3.12}$$

$$f(z) = \begin{cases} \sum CV_i - \sum FC_j - x & ;seller\ stage \\ \sum CV_i - \sum FC_j + x & ;buyer\ stage \end{cases} \tag{3.13}$$

3.4.1 Negotiation messages and specifications

JADE architecture

A JADE platform is composed of agent containers that are distributed over the network. Agents live in containers that provide all services for hosting and executing agents. Agents communicate with other agents using FIPA-ACL message standards. There is a message stack that provides a transport envelope that comprises the set of parameters that details the agent communication. The communication protocol can be separated into four sub-layers: transport information, encoded messages, message parameters, and message content (see Figure 3.7).

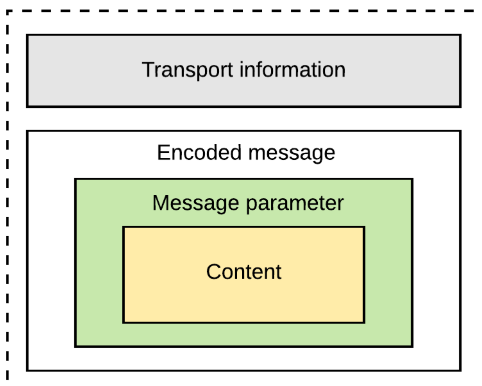


Figure 3.7 FIPA message structure

The transport information is used on the internet protocol standard. There is Hypertext Transfer Protocol (HTTP), which is the foundation of data communication on the internet (Fielding, Irvine, & Gettys, 1999). Encoded messages use a simple byte-encoded message. This layer is intended for communication between agents over low bandwidth connections. The message parameter is specified independently. This level contains the necessary parameters for agent communication based on FIPA ACL message standards, as shown in Table 3.6 (Bellifemine et al., 2007; Caire, 2009). The message content can be in any text form which follows general logical formulas in FIPA-SL content language specification (Bagherzadeh

& Arun-Kumar, 2006; Juneja, Jagga, & Singh, 2015). Once the JADE environment is opened, the main container is launched, and all the agents are registered following a standard FIPA message structure.

Table 3.7 FIPA communicative acts

FIPA communicative act	Description
Call for Proposal (CFP)	Service and behaviour advertising message.
Accept proposal	The action of accepting a previously submitted proposal to perform an action.
Inform	The sender informs the receiver that a given proposition is true.
Failure	The action of telling another agent that an action was attempted, but the attempt failed.
Propose	The action of submitting a proposal to perform a certain action, given certain preconditions.
Refuse	The action of refusing to perform a given action and explaining the reason for the refusal.
Accept proposal	The action of accepting proposals to perform the action during the negotiation process.
Reject proposal	The action of rejecting a proposal to perform some action during a negotiation.
Request	The sender requests the receiver to perform some action.

Message interaction and protocol specification

In FIPA message standard, there is the FIPA Contract Net Interaction Protocol (IP) which describes the negotiation between the initiator agent and participant agents (see Figure 3.8). The sequence diagram describes the agent message. There are two types of agents: initiators and participants. The initiator sends the Call for Proposal (CFP) to all participants. Participants will decide whether to reply, propose, or refuse the message. The participant will propose its service if the CFP description is matched, otherwise it will send a refuse message. The initiator evaluates the received proposals and selects the best agent to perform the accept-proposal. The initiator will send an accept-proposal to the selected participant and reject-proposals to the others. The initiator sends an inform message to the selected participant/s. Upon receiving an accept-proposal message, the participant will send an inform message.

Negotiation between agents can take many forms, including auctions. The action mechanism is discussed in the next section.

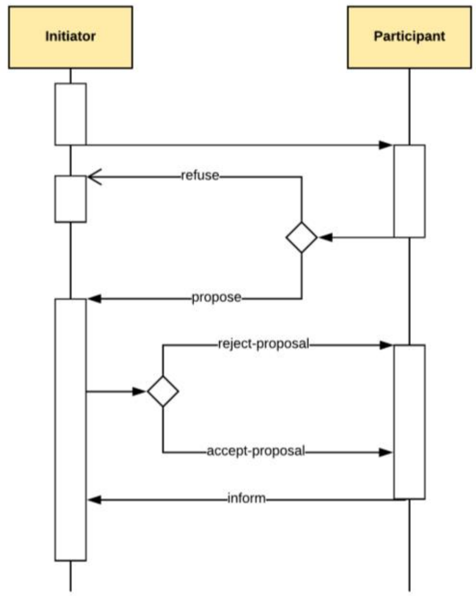


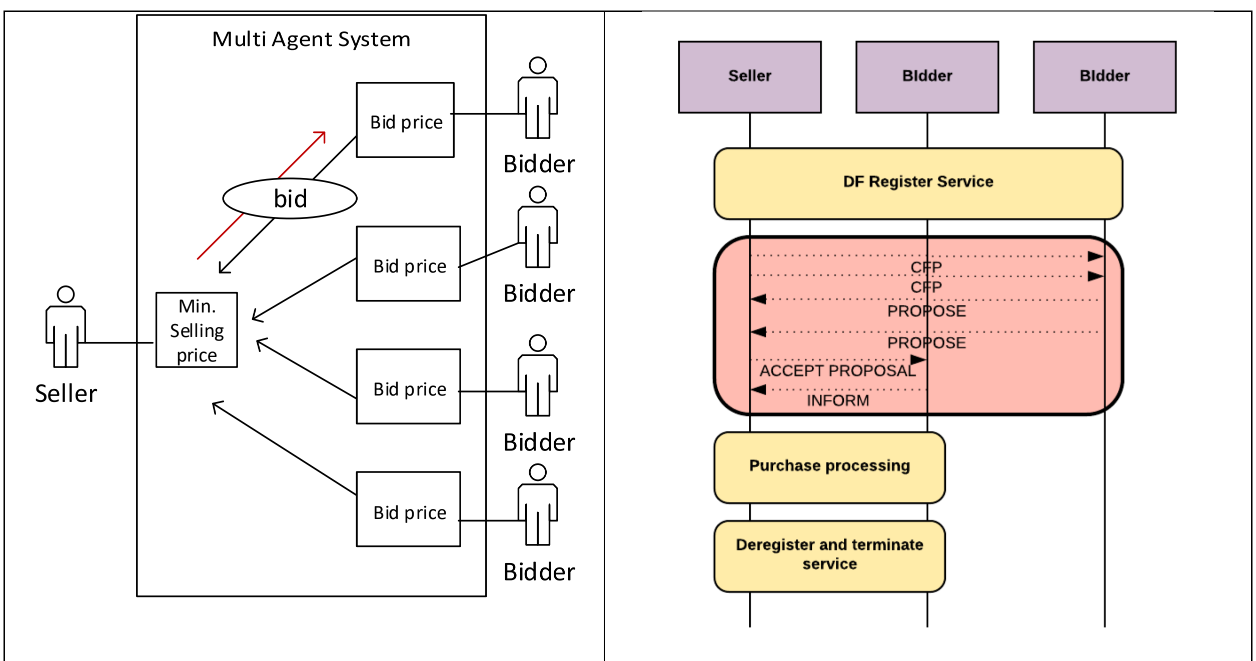
Figure 3.8 Request interaction between agents

3.5 Auction mechanisms and process

Before an auction can take place, each agent must calculate their individual farm's crop water requirement. Once it has done so, it decides whether to act as a seller or bidder agent. Auctions begin only if there are bidder agents who can bid in any of the auctions. At the conclusion of the auction, the winner is determined and the affected seller and bidder agents will calculate and update their profit margin. In this research, we offer four bidding strategies: the single unit first-price sealed-bid, the multiunit first-price sealed-bid, the multiunit discriminatory and multiunit uniform auction. The first-price sealed-bid is an auction where the bidder submits their bids for a specified volume of water (the seller determines the amount of available water). The multiunit first-priced sealed-bid is where a seller splits the available water into smaller volumes. For example, if the volume of excess water is 5,000 cubic meters, a seller can conduct five independent auctions, each consisting of 1000 cubic metres. A single unit first-price sealed-bid is where the seller will auction off the 5,000 cubic metre in a single auction. A multiunit first price sealed-bid auction increases a seller's chance of selling and allows bidders to bid for a smaller unit of water as it is possible that the volume of water traded as a single unit may be more than what they need. Bidders can bid for multiple units to fit their needs. However, this strategy may also be risky as they will need to bid in multiple auctions and they may not win all the auctions that they participate in.

3.5.1 The single unit first-price sealed-bid auction

The first-price sealed-bid is a common type of auction. The seller advertises a minimum selling price and volume to the agent environment. Once the auction has begun, all bidder agents submit their bids. The bids are private and hidden from the other bidders: they are opened at the end of the auction, where the bidder with the highest bid wins and pays the bid price he submitted (see Figure 3.9(a)) (Krishna, 2010; McAfee & Mcmillan, 1987). The first-price sealed-bid is a single round auction and all users have a single round to propose a bidding price and volume to the seller. The duration of the auction was set to 300 milliseconds: bidders must submit their bids within this period. This duration simulates what happens in the real world where auctions last for a specific period of time. If there are no bids received during this time, no winner will be declared. If there are multiple bidders with the same highest bid, then the first one who submitted the bid is declared the winner. The sequence diagram (based on the JADE and FIPA), is shown in Figure 3.9(b). The seller sends a CFP message that contains information about the reserve price and the volume of water that is being auctioned to all bidder agents. The interested bidder agents send a propose message with their bid. Once the time is up, the seller evaluates all the bids and selects a winner. This winner will be notified after the auction is concluded.



(a) Conceptual design | (b) Sequence diagram

Figure 3.9 Conceptual design and sequence message for the first-price sealed-bid auction

In this auction, the bidder's objective is to purchase water at the lowest possible price. In contrast, the seller is seeking a bidder who can offer the highest price. Although the literature (Krishna, 2018; Mcafee et al., 2018) suggests that the best strategy for bidders in this type of auction is to bid below the private valuation, in our setup, a bidder should bid the true valuation to increase his/her chance of winning. This will also indirectly reduce the losses associated with having insufficient water. When the auction closes, the winning bidder is the one who submitted the highest bid. If the highest bid is lower than the seller's reserve price, no winner will be declared, and the excess water will be re-auctioned in the next round.

The first price sealed-bid auction has several limitations. Often the volume of excess water being traded does not match the bidders' requirement (it is either too much or too little). Moreover, it is not beneficial for bidders to buy more than what they need as they will incur additional costs and wastage. To maximise the sellers' chance of trading their excess water, a bigger volume of water can be divided into smaller units and be auctioned off individually to allow more bidders to purchase it. In this way, buyers can choose to participate in several auctions based on the volume of water they need. The fixed multiunit first-price sealed-bid auction offers a solution to this problem.

3.5.2 Fixed multiunit first-price sealed bid auction

This auction is a variation of the single unit first-price sealed-bid auction. Instead of selling excess water as a single unit, the seller splits the water into smaller units and sells them using several auctions. The seller predetermines the volume of water for each auction. Figure 3.10 shows that excess water can be split into two equal parts. In this setting, bidders may bid in multiple auctions if the water needed is more that the individual lot being traded. The auction process is the same as before but this time there are more auctions in the marketplace. The winner is chosen in the same way as the previous form of auction. However, the same bidder can win more than one auction if s/he has bid in multiple auctions. As before, there is no auction winner if the highest bid is lower than the reserve price.

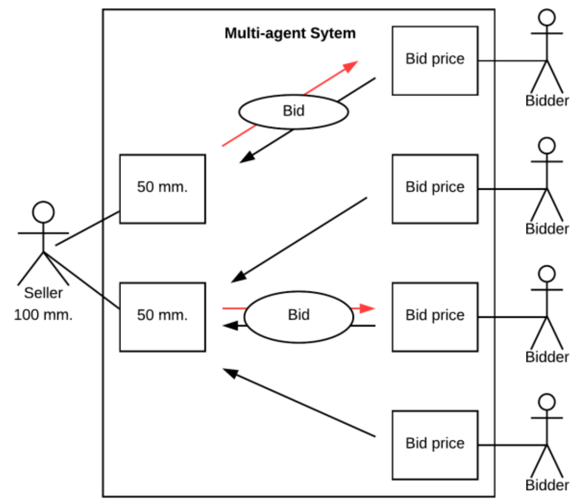


Figure 3.10 Conceptual design for fixed multiunit first-price sealed bid auction

By splitting the excess water into many lots, a seller may be able to obtain higher offers from the bidder. Likewise, bidders have more opportunities to bid in more than one auction. A bidder will also be able to buy the right amount of water (or closer to the volume that they need). Hence, there is less wastage and less cost. Even though this mechanism represents an improvement on the previous one, there is still no guarantee that all the excess water can be traded, as the water volume per auction is fixed. A better solution would be to allow the bidder to specify how much water s/he needs and how much s/he is willing to pay for it. The next section describes the multiunit auction.

3.5.3 The multiunit auction

In section 3.5.2, we proposed that splitting the water volume into smaller units is useful. However, there may be difficulties associated with this approach; for example, knowing how much to split and how many units to split it into. The multiunit auction type provides a better solution to deal with this problem. This type of auction can be applied to water trading as buyers can specify the exact volume of water required and what price they are willing to pay. In terms of the auction process, the multiunit discriminatory and multiunit uniform auction has the same sequential task, but the selling prices are different. Figure 3.11 shows the interactions between bidder agents and the seller agents in a multiunit auction.

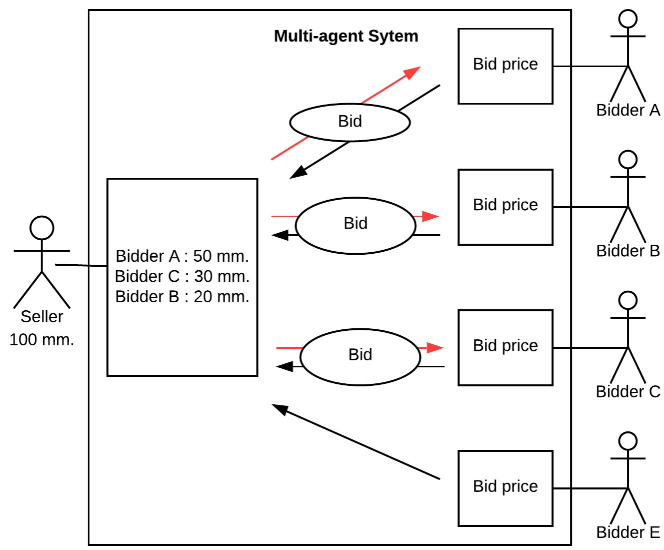


Figure 3.11 Conceptual design and for a multiunit auction

At the start of the auction, the seller advertises the volume of excess water to be auctioned off to all the bidders. Each interested bidder submits a bid which contains the volume of water needed and the price that s/he is willing to pay. At the end of the auction, the seller determines the winning bidders using the following algorithm:

```
Preprocessing:
        SET array[i] = 0
        GET all offers from bidders (B1, B2, … ,Bn)
        ADD Bi to array[i]
On the arrival of the Bn:
        SET array[x]=0
        SET v = selling volume: v′=0
        Sort array[i] in ascending order of offering price
        FOR i=0 to array[i] length -1
                GET value from array[i]
                IF (v′ < v) then
                        ADD array[i] to array[x]
                        v′ = v′ + value of array[i]
                ENDIF
        ENDFOR
        RETURN array[x], v – v′
```

Figure 3.12 The multiunit auction algorithm

Figure 3.12 shows the seller agent algorithm for the multiunit auction process. First, the seller reads each offer and determines the actual price. Then, all offers are sorted in ascending order (lowest to highest price). After that, the bidder with the highest price is served, followed by the second highest bidder. This process is repeated until all units have been offered. The seller will reply to all winning agents, stating the accepted volume and the price. The difference between those two auctions is the price that the bidder must pay. In the uniform auction, the bidders all pay the lowest price offered. Once the auction is over, all winners pay the same price. In contrast, in the discriminatory auction, those who are successful must pay the price they offered. Figure 3.13 shows the reply message that is sent once the auction is complete (the multiunit discriminatory auction is shown in (a)) and the multiunit uniform is shown in (b)). In the multiunit discriminatory auction, the seller offered the winning bidders (A, B, and C) 50mm, 30mm, and 20mm of water at $12.50, $10.00, and $9.50 respectively. All three bidders accepted the offers. Bidder D was sent a reject message which s/he acknowledged. In the multiunit uniform auction, the seller offered all the winners the same price: the lowest winning bid ($9.50).

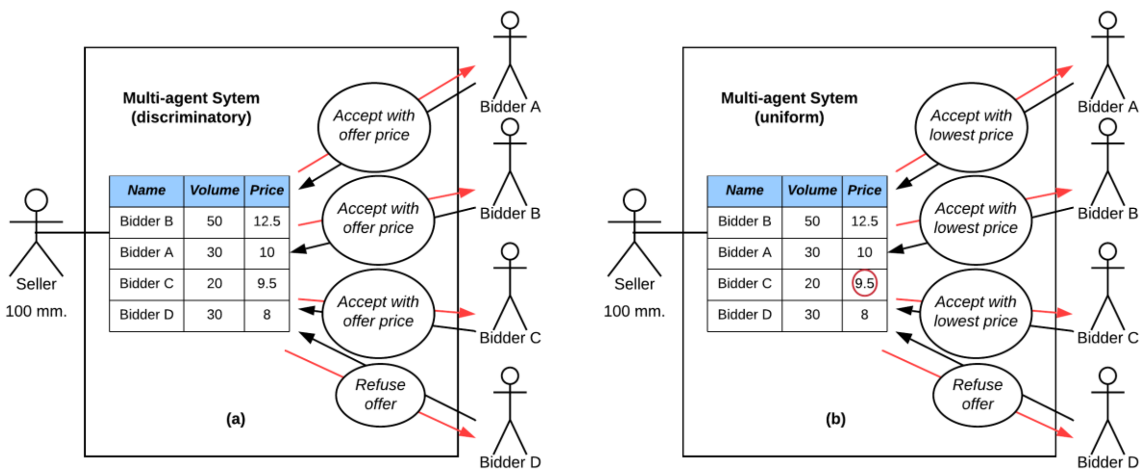


Figure 3.13 The interaction messages between agents for multiunit discriminatory and multiunit uniform auctions

These proposed auction techniques are designed to optimise water sharing within a farming community. Table 3.8 provides a comparison of the auction techniques. The table includes the bidding and clearing rules for each auction. The first price sealed-bid is a simple auction which determines its winner based on the highest bid. The highest bidder is awarded the item at a price equal to the bid amount. However, in this auction, the buyer must buy all of the water. This form of auction does not guarantee the highest profit for all participants because a buyer may end up buying more water than s/he needs. The fixed multiple units first price sealed-bid provides bidders with the opportunity to bid in smaller lots closer to the volume of water needed. The multiunit discriminatory and multiunit uniform price auctions offer a more efficient way of distributing excess water as bidders are able to buy the required volume of water. The bidder can bid on demand and the seller has a better chance of selling all their excess water. While both proposed auction techniques use the same bidding process, the sale price is determined differently. In the case of a multiunit discriminatory auction, winning bidders will pay based on their offer. In contrast, winners in a multiunit uniform auction all pay the same price (the lowest winning bid price).

Table 3.8 Comparison table for all auction techniques

Type	Bidding rule	Clearing rule	Unit of goods
Fixed multiunit first price sealed-bid auction	Bidder submits bids privately (price) Seller separates single selling volume to multiple groups and auctions them simultaneously. Each auction is treated as a single first price sealed-bid auction	Uses the same rule as the first-price sealed bid auction	Single/multiple
Multiunit discriminatory auction	Bidders place bids for a specific volume of water along with the offer price.	Seller collects offers and chooses the highest bid price until all the volumes of water are traded. There are multiple winners. Each pays a different rate depending on their bid values.	Single / Multiple
Multiunit uniform auction	Bidders place bids for a specific volume of water along with the offer price	Seller serves the highest bidder first, giving them the number of units requested, then the second highest bidder and so forth until all the water is sold. . All bidders then pay a per unit price equal to the lowest winning bid.	Single/multiple

3.6 Agent behaviour

Sellers and bidders may behave differently when participating in online auctions. Agents can be neutral, greedy, or generous (see Table 3.8). As prior research has shown, the agents' varying behaviours may lead to different auction outcomes (Hailu & Thoyer, 2005; Zuo, Brooks, Wheeler, Harris, & Bjornlund, 2014)

Table 3.9 Description of agent behaviour

Agent behaviour	Description
Greedy	The agent wants to buy the water with the cheapest price.
Generous	The agent wants to distribute water to others and does not care about making a profit. The seller is motivated to share the excess water.
Neutral	The agents buy water based on how much they can afford.

In this water trading scenario, the bidders display one of two behaviours: (greedy and neutral). Similarly, the sellers can be greedy, generous, or neutral). In this research, we analyse varying agent behaviours and assess their impact upon the auction results. We assume that different agent behaviours will result in different water distribution patterns and reserve prices. In this setting, we are interested in studying the effect of water sharing in the community and the economic effect of water trading.

A neutral bidder agent is an agent who behaves in a neutral manner. S/he will offer bids which reflect the true value of the water that they need. A greedy bidder agent is an agent who is willing to take a risk by bidding less than the water's true value, with the objective of reducing their potential losses.

In terms of selling, a neutral seller is one who sets the actual reserve price at the same price as the water consent cost. They are not looking to make a profit but want to share unused water with community members and simply get some of their money back. A generous seller is one who wants to share all of his/her excess water and does not care about the income s/he receives from selling it. This means that the seller's main concern is to distribute all of his/her excess water. Thus, the seller does not impose any reserve price which means that excess water will be auctioned off to the bidder/s with the best offer. A greedy seller will set a slightly higher reserve price to try and gain higher profit.

Having outlined the methods used in this research, the next two chapters discuss the experimental evaluations used to assess the performance of single agents and to determine which auction mechanisms are best suited for trading and distributing water in a community of users. The effect of varying bidder and seller behaviours will also be discussed.

Chapter 4

Irrigation management agents: Experimental evaluations and discussions

This chapter presents and examines in detail all the experimental results for the irrigation management agent. The objective of the experimental evaluation is to analyse the performance of the irrigation management agent. As explained in the previous chapter, a farmer can use this software to calculate their farm's water requirement and water reductions during periods of water scarcity. The experiment is divided into two stages. First, we validate the crop water needs estimation model and utility function for the priority list. Second, we evaluate the performance of the proposed irrigation management algorithm using two scenarios: during normal conditions when the farm has sufficient water and during periods of water scarcity. We compare the performance of our software to a control agent from an existing irrigation calculation tool.

4.1 Validating the model

4.1.1 The crop water reduction model

A farm's total water needs depend on several factors, including the farm's location, the planting schedule, the weather conditions, and the type of crops grown. During periods of water scarcity, it is important to consider each crop's growth stage, as their water needs vary from one stage to another. The proposed irrigation management agent takes all of these factors into account when determining an irrigation plan for periods of water scarcity. The agent's water need calculation is based on a 95% supply reliability for the average target in New Zealand irrigation scheme as well as the wilting point. The wilting point refers to the situation where the soil's water content has been exhausted by the crop and, as a result, the crop wilts and cannot be revived. At this point, the crop will die (FAR, 2010; Savva & Frenken, 2002). The soil is considered to be at wilting point when the potential of soil moisture level is at or below -1.5 Mean soil moisture potential (Mpa) (Rai, Singh, & Upadhyay, 2017). Anthony and Birendra (2018) have shown that the lowest point for crop water usage (the plant will die if the applied water is lower than this point) is approximately 80% of the maximum need. In the late season stage, water usage can be reduced to around 50%. In this experiment, it is assumed that the maximum water reduction is 20% based on the wilting point.

The model's accuracy needs to be validated. We do this by comparing the agent-based water calculations and the author's desk calculations based on crop water need equations from the FAO. We collected the water usage estimates (mm/sec/Ha) from three farming categories: pasture only, crops only, and mixed crops farms. The farm was located in Lincoln in Canterbury, New Zealand. The farm has a fixed soil moisture level, soil type and drought sensitivity value.

Crop water need: Pasture

The steps to calculate water need for pasture planted in summer is shown below. Before calculating, we must note the following factors. The pasture is now in the late-season stage and has 30 cm of pasture height. It has a moisture rate of 0.3 using sprinkle irrigation system.

1. The Kc_{max} and Kc_{min} values are determined. The data from Table 2.10 shows Kc_{max} = 1.0 and Kc_{min} = 0.5.

2. Calculate f_c (the average fraction of soil surface covered by vegetation).

$$f_c = \left[\frac{K_{c_b} - K_{c_{min}}}{K_{c_{max}} - K_{c_{min}}}\right]^{(1+0.5h)} = \left[\frac{1.0 - 0.5}{1.0 - 0.5}\right]^{(1+0.5*0.3)} = 1$$

3. Determine f_w.

f_w value with sprinkle system is 1.0 as shown in Table 3.1.

4. Calculate f_{ew}.

$f_{ew} = \min(1 - f_c, f_w) = \min(0, 1)$ ➔ 0

5. Calculate K_e.

K_e is then calculated using $K_e = K_r\left(K_{c_{max}} - K_{c_b}\right) \leq f_{ew} \cdot K_{c_{max}}$

$K_e = 0.3(1.0 - 1.0) \leq (0 \cdot 1)$ ➔ 0. This value is equal to $f_{ew} \cdot K_{c_{max}}$ which follows the irrigation system calculation.

6. Calculate K_c for the late-season stage. The K_c that includes soil moisture calculation is $K_e = K_{cb} + K_e = 1 + 0 = 1$.

7. Calculate the pasture water need (daily). The ET_0 on average in summer is 3.99. Then, the daily water need for pasture is $ET_{crop} = ET_0 \times (K_C + K_e)$ ➔ 3.99 × 1 = 3.99 mm.

Using these steps, we calculated the water requirement for pasture and other crops and compare this value with the agent-based calculation for verification and validation as shown Tables 4.1 – 4.3.

Table 4.1 Comparison between author's calculations and irrigation management agent: Pasture only

Crop name	Crop stage	Drought sensitivity	Soil type	Water requirement (mm.)	
				Author's calculation	Agent-based
PastureA	After grazing	High	Light	3.97	3.97
PastureB	Development	High	Light	3.89	3.89
PastureC	Late season	High	Light	3.99	3.99

Table 4.1 shows the comparison between the author's calculations for pasture water requirements and agent-based water management. The planting season is summer. The rainfall data is from NIWA. Each crop is in a different crop growth stage. The values obtained using the author's desk calculation is identical to the agent's calculation.

Tables 4.2 and 4.3 show the water needs calculation for a mixed crop farm and a mixed crop and pasture farm. In both tables, the author's calculations and the values generated by the irrigation management agent are identical. This result indicates that the agent's calculations are accurate.

Table 4.2 Comparison between author's calculation and irrigation management agent: Mixed crop

Crop name	Crop stage	Drought sensitivity	Soil Type	Water requirement (mm)	
				Author's calculation	Agent-based
Wheat	Initial	High	Light	4.31	4.31
Wheat	Late-season	High	Light	4.27	4.27
Maize	Crop development	High	Light	4.59	4.59
Maize	Mid-season	High	Light	4.45	4.45
Peanut	Crop development	High	Light	4.19	4.19
Peanut	Late-season	High	Light	3.95	3.95

Table 4.3 Comparison between author's calculation and irrigation management agent: Mixed crop and pasture

Crop name	Crop stage	Drought sensitivity	Soil Type	Water requirement (mm)	
				Author's calculation	Agent-based
Peanut	Crop development	High	Light	3.95	3.95
Maize	Crop development	High	Light	4.59	4.59
Wheat	Initial	High	Light	4.31	4.31
Oil seed	Mid-season	High	Light	4.25	4.25
Pasture	Development	High	Light	3.89	3.89
Pasture	After grazing	High	Light	3.97	3.97

4.1.2 Calculating the utility function and prioritising crops

In this section, we show how we have validated the utility function and crop prioritisation calculations. Table 4.4 provides descriptions for PastureA, PastureB and PastureC which include information about the crop stage, planting season, rainfall, soil type and plot size. In this setup, PastureA should be given the highest priority as it is in its initial stage (after grazing). Based on prior literature, a crop in the initial stage of growth requires more water than crops in either the development or late-season stage.

Table 4.4 Input model validation: Crop stage and soil type

Crop type	Crop stage	Planting season	Rainfall (mm)	Soil type	Plot size
PastureA	After grazing	Summer	630	Light soil	100 m^2
PastureB	Development	Summer	630	Medium	100 m^2
PastureC	Late-season	Summer	630	Heavy soil	100 m^2

Table 4.5 shows the calculations for drought sensitivity (f_{DS}), soil type (f_{ST}), potential yield (f_{PY}) and the final utility value. To calculate the final utility value for each crop, the value of each function is multiplied by its weight (this indicates its relative importance). These are then added together. Here, the weights for f_{DS} and f_{ST} are set to 0.5, as both the drought sensitivity and the soil type factors are equally important. The potential yield is not considered here as this is an all pasture setting. As shown in Table 4.5, PastureA has the highest utility followed by PastureB and PastureC. This is as expected, since pasture at the initial stage needs the most water.

Table 4.5 Prioritised list based on the utility function: Pasture only

Crop type	f_{DS}	f_{ST}	f_{PY}	Utility value	Prioritised list
PastureA:	30	300	928,000	92.95	1
PastureB:	20	200	928,000	92.90	2
PastureC:	10	100	928,000	92.85	3

This prioritisation list is used to determine how much water should be reduced for each crop based on the algorithm defined in Chapter 3.

Table 4.6 Simulated data validation: Other Crops farm

Crop type	Crop stage	Planting season	Rainfall (mm)	Soil type	Plot size
Oil seed	Late-season	Summer	630	Light soil	100 m^2
Wheat	Mid-season	Summer	630	Medium	100 m^2
Maize	Initial	Summer	630	Heavy soil	100 m^2

Table 4.6 shows an example for other crops farm. The water requirements for oil seed, wheat and maize are 4377.18, 3219.12 and 4576.85 m^3, respectively. The farm's total water need is 13,073 m^3. Wheat is considered a high value crop and more water is required in the mid-season stage than the late season and initial stage.

Table 4.7 Prioritised list based on the utility function: Other Crops

Crop type	f_{DS}	f_{ST}	f_{PY}	Utility value	Prioritised list
Wheat:	20	200	597,000	59.80	1
Maize:	40	300	537,000	53.85	2
Oil seed:	10	100	260,000	26.05	3

Table 4.7 shows the calculation for the utility function and the prioritisation of each crop. Using this example the weights are changed to 0.2, 0.2, 0.6 for f_{DS}, f_{ST} and f_{PY} respectively as we considered yield as more important in a farm with varying crops. Here, we considered all three factors, but placed more importance on the potential yield. As expected, wheat is at the top of the priority list. Then, the result of priority list is used for the water reduction plan based on the percentage of water reduction requirement as discussed in Section 4.3. Overall, the validation result shows that our model can accurately calculate the crop water need based on the FAO reference data. The proposed water reduction behaved as expected.

4.2 The experimental setup

To evaluate the proposed agent's performance, we need to prove that the irrigation management agent can generate the best possible solution for users, particularly in prioritising water usage on the farm with different water reduction schemes. We consider two scenarios: when water is available and when water restrictions are in place. In the first scenario, we are interested in investigating how much water can be saved using the irrigation management agent as opposed to other software that does not consider different crop stages in water requirement calculations (such as IrriCalc and Overseer). In the second scenario, we investigate a scenario where there is water scarcity. We consider the potential savings that can be gained by using an irrigation management agent. In both cases, we observe the amount of water than can be potentially saved and the change in the farm's profit by taking into account the crop yields and the cost of water.

To test the performance of our irrigation management agent, we conducted three experiments using three farm setups: a grazing pasture only farm, other crops only farm and a mixed crops farm (which consists of pasture and other crops). These setups are common in New Zealand. For each experiment, we randomly generated 100 farms with varying crop properties. For the pasture only farm, we set the crop type to pasture and randomized the growth stage to three different stages. In the other crops farm, we randomized the crop type and the growth stage to four different stages. The setup for the mixed crops farm is also similar to the other crops farm. However, we included pasture as the additional crop. We fixed the farm size to 250 hectares based on the average New Zealand farm size (The Law Foundation, 2018).

In the first scenario, it is assumed that there is sufficient water on the farm. We are interested in investigating how much water is actually needed and how much water can be saved by using an irrigation management agent. We compare this agent's performance to a control agent, which exhibits similar behaviour to an existing irrigation management tool. We also compared the proposed water need generated by our agent during a period of water scarcity (based on a 10% water reduction scheme) with the control agent.

The second scenario investigates how much water can be saved when using the water management agent. It is based on four water reduction schemes: 5%, 10%, 15%, and 20%. This is to align with the real-world setting where the water authority defines the water reduction percentage during periods of water scarcity. We did not test the agent with a reduction scheme higher than 20% as the water reduction scheme is usually capped at 20%. In Chapter 3, we proposed the utility function, which includes a crop's potential yield function (f_{PY}), crop's drought sensitivity function (f_{DS}) and soil type function (f_{ST}). The utility function weights are based on the real life scenario which focuses on the crop yield and productivity as first priority to get maximum profit in the farm. In the pasture only farm, we set the weight for the three determinants as (f_{PY}=0.2, $f_{ST} = 0.5, f_{DS} = 0.3$) to indicate the importance of the growth stage and drought sensitivity. On the other crops farm, we set the weight to favour the productivity outcome, which is a farmer's first priority. The soil type and drought sensitivity are the second and third priorities, respectively. The weight for the utility function for a mixed crops farm is set as (f_{PY}=0.5, $f_{ST} =$

$0.3, f_{DS} = 0.2$). The same weight distribution was applied to the mixed crops farms. Other weights can be considered as well, depending on what the farmer considers to be important at that point in time.

4.3 Result

4.3.1 Comparisons between an existing tool and irrigation management agent when there is sufficient water on the farm

In the next two sections, we compare the water requirements generated by the irrigation management agent and the control agent. We use an existing water allocation calculator called Irricalc as our control agent. As described in Chapter 2, Irricalc is a soil water balance model that estimates irrigation requirement from effective rainfall and actual crop requirements (Wheeler & Bright, 2015). Irricalc's estimations only work for a single crop. So, to estimate multiple crops, a user must calculate water requirements for each individual crop. To use Irricalc, the user must enter the address of the farm, the crop (the user can select from a drop down list which consists of pasture, apples, avocadoes, grapes, kiwifruit, stone-fruit, arable, and others) (see http://mycatchment.info/), plant available water and irrigation method. The software estimates the irrigation requirements for each month of the whole year.

Table 4.8 compares the pasture water requirement from the control agent and the irrigation management agent. The planting season is summer, and the rainfall data was obtained from NIWA. The crop stages vary. The water requirements recommended for all pastures by the control agent are 40.22 mm/sec/hectare whereas the values recommended by the agent vary depending on the crop stage. The differences in calculations were expected because the agent took into account the growth stage of the pasture and incorporated it into the water needs calculations. These values are lower than those recommended by the control agent (reducing the total water need by 11.98%).

Table 4.8 Irrigation management agent vs. the control agent: Pasture only

Crop name	Crop stage	Drought sensitivity	Soil type	Water requirement (mm/sec/hectare)	
				IrricalC	Agent-based
PastureA	After grazing	High	Light	40.22	32.67
PastureB	Development	High	Light	40.22	39.46
PastureC	Late-season	High	Light	40.22	34.07
			Total	**120.66**	**106.2**

Table 4.9 shows the water requirement for other crops farm. As before, the water requirement calculated by the irrigation management agent is less than that recommended by the control agent. The values generated by the irrigation management agent vary from one crop to another based on each crop's

growth stage. The irrigation management agent's total proposed water requirement is 16.40% lower than that of the control agent. As seen in Table 4.10, the total water requirement for a mixed crops farm generated by the irrigation management agent is 13.95% lower than the control agent's value.

Table 4.9 Water requirement from irrigation management agent vs. control agent: Other crops

Crop name	Crop stage	Drought sensitivity	Soil type	Water requirement (mm per hectare)	
				IrricalC	Agent-based
Wheat	Initial	Low	Heavy	40.22	33.07
Wheat	Late-season	Low	Heavy	40.22	34.66
Maize	Development	Low	Heavy	44.24	40.26
Maize	Mid-season	Low	Heavy	44.24	33.87
Peanut	Development	Low	Heavy	44.24	37.06
Peanut	Late-season	Low	Heavy	44.24	36.26
			Total	**257.4**	**215.18**

Table 4.10 Water requirement from irrigation management agent vs. control agent: Mixed crops and pasture

Crop name	Crop stage	Drought sensitivity	Soil type	Water requirement (mm per hectare)	
				IrricalC	Agent-based
Peanut	Development	Low	Heavy	44.24	32.27
Maize	Development	Low	Heavy	44.24	33.87
Wheat	Initial	Low	Heavy	40.22	34.66
Oil seed	Late-season	Low	Heavy	40.22	38.85
Pasture	Development	Low	Heavy	40.22	35.87
Pasture	After grazing	Low	Heavy	40.22	39.06
			Total	**249.36**	**214.58**

In summary, the irrigation management agent calculated lower water requirements as it used the modified formula to calculate K_c, It also took into account the crop growth stage.

4.3.2 Comparison between an existing tool and the irrigation management agent when there is insufficient water on the farm

When there is sufficient water on the farm, the irrigation management agent's water need calculations were lower than the control agent's estimates. This means that the agent can achieve additional water savings even when there is sufficient water. Reducing usage becomes more important when water is scarce, especially during the drought season.

Table 4.11 shows the water reduction results from the control agent and the irrigation management agent for a pasture only farm using a 10% water reduction scheme. Since the control agent does not provide functionality that can be used during water scarcity, we apply a standard 10% reduction to the actual water requirements. This means that for a 40.22 mm/sec/Ha, the proposed reduction for the control agent is 36.20 (40.22 – 4.022). The total water requirement for the control agent is 108.60. This figure is higher than the irrigation management agent's water requirement estimate (90.09). The water requirement for PastureC is very low as the pasture is in the late season and less water is required (the control agent reduced the water usage around 50% of water usage). The agent-based proposed 36.20 mm/sec as opposed to 18.01 mm sec proposed by the agent. PastureB needs more water than PastureA and PastureC because it is in the development stage and needs more water for pasture growing. In total, the irrigation management agent's water requirement estimate is lower than that proposed by the control agent. The control agent does not provide an irrigation water need calculation based on the crop growth stage. In fact, the crop water needs estimate is calculated based on the average of water needs for the entire planting period. In contrast, the irrigation management agent estimates crop water need based on the crop growth stage, season and soil moisture data for the farm.

Table 4.11 Water reduction irrigation management agent vs the control agent: Pasture only

Crop name	Crop stage	10 % of water reduction (mm/sec/Ha)	
		IrricalC	**Agent-based**
PastureB	After grazing	36.20 (10%)	32.67 (-)
PastureA	Development	36.20 (10%)	39.46(-)
PastureC	Late season	36.20 (10%)	18.01 (-50%)
	Total	**108.60**	**90.09**

Similar results are observed for the other crops farm and the mixed crops farm. Table 4.12 shows the water reduction results for other crops for a 10% of water reduction. Since the control agent is not able to prioritise crop water needs, it is assumed that a water reduction of 10% is applied to all crops. In this setting, the pea (field) is in late season and water usage can be reduced to 50% of the normal water need. The maize's water can also be reduced by 15%. The agent's total water reduction is approximately 16.80% which is much higher than the control agent's proposed reduction of 10%. Similarly, the irrigation management agent proposed greater water reductions than the control agent for the mixed crops farm. Table 4.13 shows that the water reduction from the irrigation management agent is around 19.58% for mixed crops without compromising the crops and pastures as the reductions are based on the crop priority list. The oil seed and PastureB water requirements are reduced by 50% because they are in the late season stage. In summary, the water reduction algorithm ensures that the reduction is applied from the crop with the lowest priority to the crop with the highest priority: notably, the required reduction is fulfilled before getting to the top of the crop priority list. This process is discussed further in the next set of experiments.

Table 4.12 Water reduction from irrigation management agent vs. the control agent: Other crops

Crop name	Crop stage	10 % of water reduction (mm/sec/Ha)	
		IrricalC	**Agent-based**
Barley	Initial	39.82 (10%)	34.66 (-)
Peanut	Development	39.82 (10%)	37.06 (-)
Oil seed	Mid-season	36.20 (10%)	38.26 (-)
Wheat	Mid-season	36.20 (10%)	36.66 (-)
Maize	Mid-season	39.82 (10%)	28.79 (-15%)
Pea (field)	Late-season	39.82 (10%)	17.33 (-50%)
	Total	**231.68**	**192.76**

Table 4.13 Water reduction from irrigation management agent vs. control agent: Mixed crops

Crop name	Crop stage	10 % of water reduction (mm/sec/Ha)	
		IrricalC	**Agent-based**
Maize	Initial	39.82 (10%)	33.87 (-)
PastureA	After grazing	36.20 (10%)	39.06 (-)
Wheat	Development	36.20 (10%)	36.66 (-)
Peanut	Mid-season	39.82 (10%)	37.06 (-)
PastureB	Late-season	36.20 (10%)	18.01 (-50%)
Oil seed	Late-season	36.20 (10%)	15.73 (-50%)
	Total	**224.44**	**180.49**

4.3.3 Water scarcity: Varying reduction schemes

This experiment investigates how much water can be saved when using the irrigation management agent based on four water reduction schemes: 5%, 10%, 15%, and 20% for a pasture only farm, other crops farm and mixed crops farm. For each reduction scheme, we observe the actual reduction proposed by the irrigation management agent. All crop types and crop stages are generated randomly, based on commonly found crops on a dairy farm in the Canterbury region.

Grazing pasture only

In this experiment, it is assumed that the farm has different types of pastures at different growth stages planted in varying soil conditions with same plot sizes (see Table 4.14).

Table 4.14 Information for pasture only

Crop name	Crop growth stage	Drought sensitivity level	Plot size (Ha)	Yield (kg/ha)	Price ($/kg)	Soil type
PastureA	Late-season	Low	50	2,000	2.32	Light
PastureB	Development	Low	50	2,000	2.32	Medium
PastureC	Development	Low	50	2,000	2.32	Heavy
PastureD	After grazing	Low	50	2,000	2.32	Heavy
PastureE	Late-season	High	50	2,000	2.32	Heavy

Table 4.15 Irrigation priority list and water reduction for different reduction rates for pasture only

	Water reduction (m^3)			
Priority	**5%**	**10%**	**15%**	**20%**
PastureD	0	0	0	194.12
PastureC	0	0	0	194.12
PastureB	0	0	386.25	386.25
PastureA	0	376.27	376.27	376.27
PastureE	900.74	900.74	900.74	900.74
Actual water requirement	9,536.53	9,536.53	9,536.53	9,536.53
Actual reduction	476.83	953.65	1,430.48	1,907.31
Proposed reduction	900.74	1,277.01	1,663.26	2,055.51
Proposed reduction (%)	**9.45**	**13.39**	**17.44**	**21.55**

Table 4.15 shows the irrigation management agent's proposed water reduction plan. PastureE has the lowest priority because it in the late growth stage and soil contains a lot of water with a heavy soil type. PastureA is the second lowest priority due to its light soil type which needs more water than PastureE. In the 5% water reduction scheme, only PastureE's water need is reduced. The rest of the pastures do not require any water reductions since the proposed water reduction of 5% has already been fulfilled. In the 10% water reduction scheme, only Pasture E (50%) and PastureA (50%) are subject to water reductions. This is because PastureE and PastureB are both in the late season stage. In the 15% reduction scheme, PastureE (50%), PastureA (50%) and PastureB (20%) are subject to reductions. With a 20% reduction scheme, all pastures are subject to water reductions, with PastureC and PastureD having the lowest reductions as they are the top two in the prioritised list. The actual water requirement is 9,536.53 m^3. Using this model, the proposed reductions are greater than what is required: at 5% the agent is able to reduce the water by 9.45%, at 10% by 13.39%, at 15% by 17.44% and at 20% by 21.55%. These results show that the actual water reductions for all schemes proposed by the agent are actually higher than the proposed reduction schemes.

Other crops (without pasture)

In this scenario, we assume that the farm has multiple crops, which are peas, oil seed, barley, wheat and a hybrid carrot seed. As shown in Table 4.16, they are all at different crop growth stages. The weight was set with productivity value as the first priority (f_{PY}=0.5). Soil type and drought sensitivity are equally weighted ($f_{ST} = 0.25, f_{DS} = 0.25$).

Table 4.16 Information for other crops

Crop name	Crop growth stage	Drought sensitivity levels	Plant size (Ha)	Yield (kg/ha)	Price ($/kg)	Soil type
Wheat	Initial	Low	50	15,000	0.4	Light
Oil seed	Mid-season	High	50	4,000	0.65	Medium
Barley	Development	Medium	50	7,500	0.39	Medium
Maize	Development	High	50	12,500	0.43	Light
Peanut	Late-season	Low	50	4,500	0.46	Heavy

Table 4.17 shows the irrigation priority for these scenarios. Wheat is the highest priority as it has the highest yield, followed by maize, barley, oil seed and peanuts. Peanuts has the lowest priority because it is in the late-season stage and the crop value is low. Hence, the water usage can be reduced to 50% of the actual water needed. The proposed reduction recommended is 9.13% for a 5% water reduction scheme. At a 5% reduction scheme, no water reduction is required for wheat, maize, barley and oil seed. In the 10% reduction scheme, the recommended water reduction is 13.03% and wheat, maize and barley are not subject to water reductions. With the 15% water reduction scheme, the proposed water reduction is 16.42% and wheat and maize are not subject to water reductions. Likewise, in the 20% water reduction scheme, the proposed water reduction is 21.51%, where wheat and maize are subject to a 10% and 20% water reduction. Based on this result, the proposed water reductions were more than the actual reduction requirements, which are 9.13% at 5%, 13.03% at 10%, 16.42% at 15% and 21.51% at 20%.

Table 4.17 Irrigation priorities and water reductions for different reduction rates on other crops farm

	Water reduction (m^3)			
Priority	**5%**	**10%**	**15%**	**20%**
Wheat	0	0	0	173.68
Maize	0	0	0	344.38
Barley	0	0	344.38	344.38
Oil seed	0	397.28	397.28	397.28
Peanut	928.30	928.30	928.30	928.30
Actual water requirement	10,171.52	10,171.52	10,171.52	10,171.52
Actual reduction	508.58	1,017.15	1,525.73	2,034.3
Proposed reduction	928.3	1,325.58	1,669.96	2,188.02
Proposed reduction (%)	**9.13**	**13.03**	**16.42**	**21.51**

Mixed crops (pastures and other crops)

In this experiment, we included a combination of crops (maize, wheat, oil seed) and pastures (PastureA and PastureB) as shown in Table 4.18. The agent placed equal weight on drought sensitivity and soil type (0.25) but allocated a heavier weight (0.5) to the crop value.

Table 4.18 Information for the mixed crops farm

Crop name	Crop growth stage	Drought sensitivity levels	Plant size (Ha)	Yield (kg/ha)	Price ($/kg)	Soil type
PastureA	Late-season	Medium	50	2,000	2.32	Light
PastureB	After grazing	Medium	50	2,000	2.32	Light
Maize	Mid-season	Medium	50	12,500	0.13	Heavy
Wheat	Initial	Low	50	15,000	0.176	Light
Oil seed	Mid-season	High	50	4,000	0.43	Light

Table 4.19 shows the irrigation priority for these crops and the proposed water reductions at different water reduction percentages. Wheat is marked as the highest priority as it is a high value crop followed by maize, PastureB, PastureA and oil seed. Oil seed is the lowest priority because it has the lowest productivity value. In the 5% reduction scheme, only oil seed and PastureA are subject to water reductions. In a 10% water reduction scheme, oil seed, PastureA and PastureB are subject to water reductions. Outcome is the same when a 15% water reduction scheme is applied. All the crops and pastures are subject to water reductions in a 20% water reduction scheme, but wheat and maize are subject to the lowest water reductions as they are the top two crops. The agent system's proposed water

reductions are more than the actual reduction requirements: 6.38% at 5%, 15.24% at 10% and 15% and 21.52% at 20%.

Table 4.19 Irrigation priorities and water reductions for different reduction rates on a mixed crops farm

	Water reduction (m^3)			
Priority	**5%**	**10%**	**15%**	**20%**
Wheat	0	0	0	173.68
Maize	0	0	0	438.21
PastureB	0	863.41	863.41	863.41
PastureA	196.64	196.64	196.64	196.64
Oil seed	425.23	425.23	425.23	425.23
Actual water requirement	9,747.23	9,747.23	9,747.23	9,747.23
Actual reduction	487.36	974.72	1,462.08	1,949.45
Proposed reduction	621.87	1485.28	1485.28	2,097.17
Proposed reduction (%)	**6.38**	**15.24**	**15.24**	**21.52**

Based on these experiments, it can be concluded that the proposed system was able to prioritise the crops' water needs based on predetermined constraints. The greater reductions can be achieved for lower % reduction schemes, and at higher % schemes, the agent still can achieve a marginal increase in water saving. For 10% and 15% of water reduction scheme, the agent-based proposed the same water reduction which is around 15.24% because the proposed system reduced the water usage to its maximum.

In this chapter, we have discussed the performance of the irrigation management agent on an individual farm. We have validated the agent's water need requirements by comparing the values obtained using a manual calculation based on the FAO formula. The water need calculations were also compared with the values obtained from a control agent - an existing water calculator - in two settings (when the farm has sufficient water and when the farm has insufficient water). In both cases, the irrigation management agent proposed a lower water need rate than the control agent. We then applied the proposed model to several scenarios, which are grazing pasture only, other crops and mixed crops and found that it was able to reduce water more than the required reduction. Moreover, some of experimental result shows the satisfying water reduction plan. These results show that the proposed system can be used by a single farm to help with irrigation management on an individual farm during a normal season and during periods of water scarcity. The next chapter presents and discusses the results of the water sharing experiment.

Chapter 5

Multi-agent irrigation management system: Experimental evaluations and discussion

This chapter describes the experiments used to evaluate various auction mechanisms employed to distribute excess water within the community. The main objective of this experimental evaluation is to investigate how excess water can be distributed to a community using four different auction techniques. The experiment has three parts. The first part of the experiment is designed to establish whether the use of auctions is better than direct negotiation. Here, we compare how much excess water is left for bidders, sellers and the community at the end of the negotiation process. The second part of the experiment compares the performance of different auction techniques in terms of excess water and profits/losses. Finally, we report the impact of sellers and bidders' behaviour on the auction outcomes and the distribution of excess water.

5.1 Experimental setup

To determine the number of sellers and bidders in the marketplace we compare different situations with respect to the number of auction participants: 1) small (two sellers and 20 bidders) 2) medium (five sellers and 50 bidders), and 3) large (10 sellers and 100 bidders). We run each distribution 100 times and conduct statistical analysis using ANOVA (see Table 5.1).

Table 5.1 Statistical significance of closing price for four auction mechanisms and three auctions' scenarios with ANOVA.

Size of the experiment	2 sellers and 20 bidders	5 sellers and 50 bidders	10 sellers and 100 bidders	Statistical test		
	Mean	Mean	Mean	Sum-of-squares		F - statistic
				Between group	Within group	
First price sealed bid auction	16.84	18.84	18.90	66.70	237.97	8.409*
Fixed multi-unit first price sealed bid auction	18.79	19.55	19.76	7.29	12.08	17.207*
Multiunit discriminatory auction	19.21	18.67	19.71	10.40	389.07	0.722
Multiunit uniform auction	18.78	19.07	18.90	0.95	107.02	0.268

Note: * indicates significance at the 5% level.

Table 5.1 shows the closing prices for auction techniques based on the various distributions of sellers and bidders. The mean closing price from the single unit first-price sealed-bid and fixed multiunit first-price sealed-bid auction differ significantly across the three distributions. However, the mean closing price from the multiunit discriminatory and multiunit uniform auction are not significant across the three distributions. We apply a histogram to examine the spread of the closing prices, including the peaks, spread, and symmetry as shown in Figure 5.1.

Figure 5.1 Closing price histogram on the different of auction size

It shows that the frequency of the closing price on small, medium and large bidding experiments from the single unit first-price sealed-bid and fixed multiunit first-price sealed bid auction is such that approximately 85% of the frequency data is the highest price on every size of experiment. This result indicates that the closing prices for all auctions are not significantly different. As the statistical analysis shows that different numbers of sellers and bidders do not affect the closing price, we opted to use a medium distribution (five sellers and 50 bidders).

To conduct the experiments, we establish a simulated environment consisting of 55 farmers. Within this group there are five sellers and 50 buyers. Each farmer is represented by an irrigation management agent (as described in Chapter 4). Each agent must calculate their farm's water requirements and decide whether to bid or sell water. They must also determine a private valuation/reserve price for the water they want to buy or sell. For each experiment, we generate varying crop properties based on a Canterbury farm. Crop properties are randomised based on the crop growth stage, and crop type/s. The farm size is fixed to 250 hectares which is the average farm size in New Zealand. The agents display varying behaviours. They have access to relevant farm information. This information is based on Canterbury crop types. The cost and expense values are based on the Financial budget book: Volume 40 (Askin et al., 2013). Information about each individual farm is generated individually and depends on whether it is a mixed crop and/or pasture farm. This environment can be configured to run multiple types of auctions with different numbers of sellers and bidders.

Table 5.2 Agent characteristics in the water sharing scheme

	Seller	**Bidder**
Excess water	Yes	No
Productivity loss	No	Yes
Reserve price	Yes	No
Private valuation	No	Yes

In the first and second part of the experiment, all the agents have neutral behaviour. The agents' characteristics are shown in Table 5.2. In the last part of the experiment, the bidders and sellers have varying behaviours (generous, greedy and neutral). We use four auction techniques: the single unit first-price sealed-bid, the fixed multiunit first-price sealed bid, the multiunit discriminatory auction, and the multiunit uniform auction. Each experiment is run 100 times. The excess water, the seller's total income ($), bidders ($) and community ($) are calculated and averaged at the conclusion of each auction.

5.2 Comparing direct negotiation and the auction mechanisms

The purpose of this experiment is to investigate the suitability of auctions in distributing excess water to the community. In CPWL, sellers can sell their excess water via direct negotiation with any interested buyer. A seller broadcasts the volume to be sold and the reserve price on the marketplace (provided by CPWL). The auctions are conducted on a 'first come first serve'd basis. Any interested buyers will contact the seller directly. When there are multiple buyers who are interested, the water will be offered to the buyer who makes the first offer. As indicated in the literature, an auction is an efficient mechanism for selling goods. In this experiment, we compare two negotiation mechanisms (direct negotiation and a single unit first-price sealed-bid auction) for distributing excess water. We compare the performance of the two mechanisms, focusing on how much excess water from seller is sold and distributed (Chiewchan, Anthony, Birendra, & Samarasinghe, 2020). It is assumed that all agents participating in this experiment have neutral behaviours.

Table 5.3 shows the total excess water for sellers, bidders and the community at conclusion of the auctions. Using direct negotiation, the total excess water is reduced from 100% to 59.29% for sellers. The total excess water increases from 0% to 13.82% for the bidders. For the community, the total excess water is reduced from 100% to 73.11%. This means that only 27.89% of the excess water is distributed to the community. Using a first-price sealed bid auction, the total excess water in the community is reduced from 100% to 62.25%, a figure higher than what is that traded through direct negotiation. This means that 37.75% of the excess water is distributed to the community. This figure represents an improvement of 10.86%. As Table 5.3 shows, a part of the excess water has now been transferred to the bidder. The bidder must purchase the water as a single unit which means that the volume might be more than what s/he needed. However, purchasing water helps to increase the bidder's marginal profit (see Table 5.4). Table 5.4 shows the percentage of total additional marginal profit once the water trading is complete. By trading the excess water, sellers, bidders and the community as a whole can gain additional marginal profit. This additional gain is higher when the auction is used as the trading mechanism (0.54% using direct negotiation and 0.58% using a first price sealed bid auction). In addition, sellers gain more profit from using an auction (1.05%) compared with direct negotiation (0.75%).

Table 5.3 Total excess water after water trading

	Total excess water (%)					
	Seller		**Bidder**		**Community**	
	Before	**After**	**Before**	**After**	**Before**	**After**
Direct negotiation	100%	59.29%	0%	13.82%	100 %	73.11%
Single unit first-price sealed-bid	100%	48.12%	0%	9.07%	100%	62.25%

Table 5.4 Total additional marginal profit ($) after water trading

	Additional margin profit (%)					
	Seller		**Bidder**		**Community**	
	Before	**After**	**Before**	**After**	**Before**	**After**
Direct negotiation	0%	0.75%	0%	0.52%	0%	0.54%
Single unit first-price sealed-bid	0%	1.05%	0%	0.52%	0%	0.58%

As Tables 5.3 and 5.4 show, by using an auction to distribute their excess water, farmers are able to gain additional marginal profit. The additional profit is calculated from the crop yield calculation. As discussed in the previous chapter, the water management agent calculates the total crop water need based on reduction scheme. When the total crop yield is reduced, it will affect the total profit for a farm.

In this experiment, we use a first price sealed bid auction, where bidders have to bid for the water as a single unit; there are no options for the bidders to buy the exact volume of water they need. We explore different types of auctions to discover the best water distribution model that both maximises marginal profits and minimises excess water.

5.3 Comparing auction techniques

5.3.1 Single unit first-price sealed-bid auction

In this experiment, like the previous one, the marketplace is populated with five sellers and 50 bidders. In this auction, each bidder submits their bid privately during the auction. At the end of the auctions, the sellers evaluate all the bids and the winning bidders are announced. Here, there are five units of water that are for sale and there are potentially five winners (with the highest winning bids). Each winner pays for the water based on the winning bid. However, if the winning bid is lower than the seller's reserve price, there will be no winner and the water is re-auctioned. We run the auction 100 times and, at the end of the auctions, average the excess water and additional profit for the sellers, bidders and community.

Table 5.5 Single unit first-price sealed-bid auction: Summary result

	Excess water		
	Before	**After**	**%**
Seller	3,596.40	1,000.45	27.82
Bidder	-	336.05	9.34
Community	3,596.40	1,337.49	37.19

	Additional margin profit ($)		
	Before	**After**	**%**
Seller	3,582,701.99	3,631,387.70	+1.36
Bidder	26,553,969.39	27,073,635.91	+1.96
Community	30,136,671.38	30,705,023.61	+1.89

Table 5.5 shows water distribution once the auctions have concluded. Before the auctions, the amount of excess water in the community is 3,596.40m^3. At the conclusion of the auctions, the sellers still have 1.000.45m^3 excess water. The bidders now have 336.05m^3 (bidders have apparently bought more water than necessary due to the nature of the auction), resulting in the community having excess water of 1,337.49 m^3. Some sellers are left with excess water: it was not auctioned off as there were no offers from the bidders and/or the winning bid was lower than the seller's reserve price. At the end of the auction, over 70% (72.18%) of the total excess water has been distributed, thereby increasing the sellers' profits by 1.36%. The bidders now have an excess of 336.05 litres, since they have to buy the total volume offered. In short, they are unable to specify how much water they actually need. Overall, 62.81% of the excess water has been distributed to the community, representing an additional profit of 1.89%.

Details of the auction rounds are shown in Tables 5.6, 5.7 and 5.8. While Seller 5 was not able to sell his excess water, the other four sellers were able to trade their water at a higher price than their specified reserve: as shown in Table 5.7 they gained 71.21%, 63.11%, 20.19% and 17.76%. Sellers who sold their excess water via an auction obtained a higher price for their water in contrast to those who sold it via direct negotiations where sellers received offers based on their reserve price. In short, the first price sealed bid auction technique is a good option for the sellers because they can sell most of their water and make additional profit. Unfortunately, buyers end up purchasing more water than they need. As shown in Table 5.8, all four bidders have excess water. However, they were still able to recover some of their losses (10.83% for Bidder 27, 4.63% for Bidder 26, 50.8% for Bidder 17 and 10.27% for Bidder 22).

Table 5.6 Single unit first-price sealed-bid result: Seller

Seller name	Total income			Excess water	
	Before	After	%	Before	After
Seller1	508,265.55	517,757.66	+1.87	483.81	-
Seller2	689,198.80	705,845.15	+2.42	955.56	-
Seller3	987,283.53	1,001,574.88	+1.45	736.38	-
Seller4	583,978.16	592,234.01	+1.14	419.19	-
Seller5	813,975.95	813,975.95	-	1,001.45	1,001.45

Table 5.7 Winner reserve price

Winner name	Reserved price		
	Before bidding	After bidding	%
Bidder27	11.46	19.62	71.20
Bidder26	10.68	17.42	63.11
Bidder17	16.15	19.41	20.19
Bidder22	16.72	19.69	17.76

Table 5.8 Single unit first-price sealed-bid results: Winner

Winner name	Total income			Total income			Excess water	
	Volume Purchase (mm)	Purchase price ($)	Water need	Before bidding	After bidding	%	Without bidding	After bidding
Bidder27	483.81	19.62	469.60	786,029.69	871,151.69	+10.83	-	14.22
Bidder26	955.56	17.42	781.82	630,176.57	659,331.02	+4.63	-	173.74
Bidder17	736.38	19.41	670.81	563,341.59	849,505.56	+50.80	-	65.57
Bidder22	419.19	19.69	336.68	584,784.42	644,853.62	+10.27	-	82.52

5.3.2 Fixed multiunit first-price sealed bid auction

As observed in the previous experiment, a single unit first-price sealed-bid helps to distribute excess water to those who need it. Unfortunately, the excess water is sold as a single unit (in some cases, the water is a large volume), and bidders are not able to specify the volume they require. This is the main reason why the sellers were not able to auction off their excess water. To avoid such a problem, a seller may choose to sell their water in multiple units or by splitting it into smaller volumes. This provides bidders with more options and results in less water wastage. In this experiment, the marketplace is set up to run multiunit first-price sealed-bid auctions: this auction is a modified version of the single unit first-price sealed-bid auction. However, in this case the seller can now split excess water into several smaller units. This means that each seller will run several auctions depending on the number of water units they wish to sell. This also means that if bidders need to buy more water than they can get in a single unit, they will need to bid in multiple auctions.

Table 5.9 Fixed multiunit first price sealed bid: Summary results.

	Excess water				Additional profit		
	Before	**After**	**%**		**Before**	**After**	**%**
Seller	3,596.40	1,171.64	32.58	Seller	3,582,701.99	3,625,744.86	+1.20
Bidder	-	153.4	4.27	Bidder	26,553,969.39	26,958,604.65	+1.52
Community	3,596.40	1,325.04	36.84	Community	30,136,671.38	30,584,349.51	+1.49

Table 5.9 shows the outcome of water distribution at the conclusion of the auction. Before the auction, the amount of excess water in the community is 3,596.40m^3. At the conclusion of all the auctions, the sellers still have excess water of 1,171.64m^3. The bidders now have 153.4m^3 meaning that the community has excess water of 1,325.04 m^3. The fact that the sellers still have excess water indicates that this water was not auctioned off: there were no offers from the bidders. Moreover, the cost of the water was higher than bidders' private valuations. The possibility of selling this water decreased with multiple units. The sellers distributed 67.42% of their excess water which increased their profits by 1.2%. The excess water from the bidders was approximately 153.4 litres. This is due to the fact that in this type of auction, the bidders have more bidding options. Overall, 63.16% of the excess water has been distributed to the community, meaning an additional income of 1.49%.

The details of the auction rounds are shown in Tables 5.10 and 5.11. Each seller (five in total) has two units of water to sell. They offer buyers two different volumes to choose from. For example, Seller 1 splits his 483.81 litres into two units (200 litres and 283.81 litres). Similarly, Seller 2 splits his water into two units (455.56 litres and 500 litres). This means that there is a total of 10 auctions: five sellers each hold two auctions. This also means that bidders now have more auctions to participate in. Seller 1, Seller 3 and Seller 5 were not able to sell all of their excess water. However, they were able to auction off one unit of their water to Bidder14 and Bidder 27 and for this they gained profits of 0.71%, 0.64% and 1.21% respectively. Both Seller 2 and Seller 4 were able to trade all their excess water at a higher price than their reserve price: they gained a percentage of income around 2.18% and 1.41%, respectively. Bidder 14 and Bidder 22 won bids in two separate auctions. Bidder14 purchased 550 litres of water (8.94 litres more than what s/he needed). Bidder 22 won both of Seller 4's auctions. S/he bought a total of 419.19 litres of water which was 82.51 litres more than s/he needed.

In summary, a fixed multiple units first price sealed bid auction is a good option for bidders because they have more auctions to choose from. However, they may have to bid in more than one auction as the volume sold in each auction might be smaller than what they need. Furthermore, there is no guarantee that they will win all the auctions that they participate in. The bidders were able to recover some of their losses (3.33% for Bidder32, 45.85% for Bidder 16 and 10.27% for Bidder 22, 6% for Bidder14 and 10.79% for Bidder27). Some of the sellers were not able to sell all of their excess water which resulted in reduced profits. Moreover, sellers need to conduct multiple auctions.Table 5.10 Fixed multiunit first-price seal-bid result: Sellers

Seller name	**Total income**			**Excess water**		**Reserved price**		**Winner**
	Before bidding	**After bidding**	**%**	**Before bidding**	**After bidding**	**Without bidding**	**After bidding**	
Seller1	508,265.55	511,879.55	+0.71	283.81	283.81	11.46	0	
				200	0.00	11.46	18.07	Bidder14
Seller2	689,198.80	704,239.31	+2.18	455.56	0.00	10.68	15.74	Bidder16
				500	0.00	10.68	15.74	Bidder32
Seller3	987,283.53	993,608.03	+0.64	386.38	386.38	16.15	0	
				350	0.00	16.15	18.07	Bidder14
Seller4	583,978.16	592,232.01	+1.41	219.19	0.00	16.72	19.69	Bidder22
				200	0.00	16.72	19.69	Bidder22
Seller5	813,975.95	823,785.95	+1.21	501.45	501.45	11.07	0	
				500	0.00	11.07	19.62	Bidder27

Table 5.11 Fixed multiunit first price sealed bid: Winners

Winner name	Total Income			Total income			Excess water	
	Buying volume	Purchase price	Water need	Before bidding	After bidding	%	Without bidding	After bidding
Bidder32	500	16.6	482.52	853,608.80	882,037.10	+3.33	-	17.48
Bidder16	455.56	15.74	441.49	418,619.53	610,562.51	+45.85	-	14.07
Bidder22	200 219.19	19.69 19.69	200 136.68	584,784.42	644,855.62	+10.27	-	82.51
Bidder14	200 350	18.07 18.07	200 341.06	656,735.32	696,124.01	+6	-	8.94
Bidder27	500	19.62	469.6	786,029.69	870,833.80	+10.79	-	30.4

5.3.3 Multiunit discriminatory auction

Using a fixed multiunit first price auction provides bidders with more auctions to choose from. They can select the appropriate auction based on the volume of water they need. However, sellers must decide how best to split the excess water (what volume and how many units). They must also manage multiple auctions. Likewise, bidders may need to bid in multiple auctions to obtain the actual volume of water they require. A better approach is to use a multiunit auction. The multiunit auction allows bidders to specify how much water they want to buy and how much they are willing to pay for it. As discussed in Chapter 3, there are two variations of this auction: the multi-unit discriminatory auction and the multi-unit uniform auction. These two auctions differ in terms of how the final price is determined. In a multi-unit discriminatory auction the winning bidders pay what they bid. In contrast, in a multi-unit uniform auction, the winning bidders pay the same amount as the lowest bid from the pool of winning bidders.

Table 5.12 Multiunit discriminatory auction: Result

	Excess water		
	Before	After	%
Seller	3,596.40	1218.3	33.88
Bidder	-	-	-
Community	3,596.40	1,218.30	33.88

	Additional profit		
	Before	After	%
Seller	3,582,701.99	3,625,046.34	+1.18
Bidder	26,553,969.39	26,959,688.05	+1.53
Community	30,136,671.38	30,584,734.39	+1.49

Table 5.12 shows the distribution of water post-auction. Before the auction, the amount of excess water in the community is 3,596.40m^3. At the conclusion of the auctions, the sellers still have excess water of 1,218.30m^3. There is no excess water on the bidders' side because bidders only bought what they need. The total excess water is thus whatever volume of water is not sold by the sellers (1,218.30 m^3). This

remaining excess water was not auctioned off as there were no offers from bidders or the received offers were below the sellers' reservation prices. At the conclusion of the auction, 66.12% of total excess water has been distributed, increasing the sellers’’ profit by 1.19%. Overall, the community’s total income increased by 1.49%.

The details of the auctions are shown in Tables 5.13 and 5.14. Seller 2 was not able to sell his/her excess water. The other four sellers were able to trade their water at a higher price than their reservation price: they gained 61.69% (Seller1), 66.76% (Seller3), 17.76% (Seller4) and 60.25% (Seller5) respectively. The sellers were able to sell most of their water and made additional income from these sales. In this type of auction, a bidder can bid for the volume of water they need at the desired price. They do not need to buy more water than they require. Moreover, the number of winners at the end of the auction process is more than the previous two auctions as this type of auction promotes bidding on demand. The bidders are still able to recover some of their losses: as shown in Tables 5.13 and 5.14 this is approximately 10.98% in total. Significantly, there is no excess water on the bidders’ side as they only purchase water as needed, resulting in zero wastage. A total of eight bidders were able to buy and use the excess water and reduce their losses. The multi-unit discriminatory auction is a good option for sellers and bidders because the reserve price is based on the bidding offer.

Table 5.13 Multiunit discriminatory result: Seller

Seller name	**Total income**			**Excess water**		**Reserved price**		%	**Winner name**
	Before bidding	**After bidding**	**%**	**Before bidding**	**After bidding**	**Before bidding**	**After bidding**		
Seller1	508,265.55	516,482.08	+ 1.62	483.81	-	11.46	18.53	61.69	Bidder4, Bidder41
Seller2	689,198.80	689,198.80	-	955.56	955.56	10.68	-	-	-
Seller3	689,198.80	706,109.80	+ 2.45	955.56	-	10.68	17.81	66.76	Bidder35 Bidder23 Bidder 20
Seller4	583,978.16	592,234.01	+ 1.41	419.19	-	16.72	19.69	17.76	Bidder5, Bidder40
Seller5	813,975.95	823,679.72	+ 1.19	1,001.45	501.45	11.07	17.74	60.25	Bidder22

Table 5.14 Multiunit discriminatory results: Winners

Winner name	Total income			Total income			Excess water	
	Before volume	Purchase price	Water need	Before bidding	After bidding	%	Before bidding	After bidding
Bidder4	231.70	18.53	231.70	407,082.22	425,143.45	+ 4.44	-	-
Bidder5	315.03	18.15	315.03	635,058.93	700,893.79	+ 10.37	-	-
Bidder41	252.12	15.56	288.60	374,226.12	386,038.06	+ 3.16	-	-
Bidder35	360.90	17.81	360.90	302,963.60	421,558.33	+ 39.14	-	-
Bidder23	405.17	17.74	405.17	794,292.43	876,415.81	+ 10.34	-	-
Bidder20	189.5	17.39	267.64	304,266.53	337,724.48	+ 11.00	-	-
Bidder40	287.01	16.96	287.01	291,187.52	305,327.75	+ 4.86	-	-
Bidder22	336.68	19.69	336.68	584,784.42	646,478.77	+ 10.55	-	-

5.3.4 Results: Multiunit uniform auction

In this experiment, the marketplace was set up to run five multiunit uniform auctions. This auction is a variation of the multiunit discriminatory auction in that each bidder bids by specifying the volume of water they want to purchase and how much they are willing to pay for it.

Table 5.15 The multiunit uniform auction: Result

	Excess water		
	Before	After	%
Seller	3,596.40	1,159.26	32.23
Bidder	-	-	-
Community	3,596.40	1,159.26	32.23

	Additional profit		
	Before	After	%
Seller	3,582,701.99	3,625,577.73	+1.20
Bidder	26,553,969.39	26,987,060.37	+1.63
Community	30,136,671.38	30,612,638.10	+1.58

Table 5.14 shows the distribution of water at the conclusion of the auctions. Before the auctions, the amount of excess water in the community is 3,596.40m^3, contributed by the sellers. At the conclusion of the auctions, the sellers still have excess water of 1,159.26m.^{3} However, as in the multiunit discriminatory auction, there is no excess water on the bidders' side because the bidders only bid for the amount of water that they need. At the end of the auction, the community's profits increased by 1.58%.

The details of the auction rounds are shown in Tables 5.16 and 5.17. Seller 4 was not able to sell his/her excess water. The other four sellers were able to trade their water at a higher price than their reserve price: Seller1 gained 51.75%, Seller3 gained 45.97%, Seller4 gained 17.76% and Seller5 gained 60.25%. The multiunit uniform auction achieved similar results to the multiunit discriminatory auction. The sellers were able to sell most of their water and made additional income from these sales. Bidders are able to propose the exact volume they need and the price they are willing to pay. They were able to buy the exact amount of water that they need. The bidders were able to recover some of their losses: approximately 11.43% as shown in Table 5.17.

Table 5.16 Multiunit uniform result: Seller

Seller name	Total income			Excess water		Reserved price		%	Winer name
	Before bidding	After bidding	%	Before bidding	After bidding	Before bidding	After bidding		
Seller1	508,265.55	516,920.24	+ 1.70	483.81	0	11.46	17.39	51.75	Bidder5, Bidder20
Seller2	689,198.80	689,198.80	-	955.56	955.56	10.68	-	-	Bidder22 Bidder48 Bidder 33
Seller3	689,198.80	706,109.80	+2.45	955.56	0	10.68	15.59	45.97	Bidder4 Bidder35
Seller4	583,978.16	592,234.01	+1.41	419.19	-	16.72	19.69	17.76	-
Seller5	813,975.95	823,679.72	+1.19	1,001.45	501.45	11.07	17.74	60.25	Bidder23

Table 5.17 Multiunit uniform results: Winners

Winner name	Total income			Total income			Excess water	
	Buying volume	Purchase price	Water need	Before bidding	After bidding	%	Before bidding	After bidding
Bidder5	315.03	17.39	315.03	635,058.93	701,134.06	+ 10.40	-	-
Bidder20	168.78	17.39	267.64	304,266.53	334,067.13	+ 9.79	-	-
Bidder22	336.68	15.59	336.68	584,784.42	647,860.10	+10.79	-	-
Bidder48	417.29	15.59	417.29	324,796.51	353,275.09	+ 8.77	-	-
Bidder33	201.60	15.59	374.61	434,449.53	461,165.20	+ 6.15	-	-
Bidder4	231.70	17.81	231.70	407,082.22	425,309.43	+ 4.48	-	-
Bidder35	360.90	17.81	360.90	302,963.60	421,558.33	+ 39.14	-	-
Bidder23	405.17	17.74	405.17	794,292.43	876,415.81	+ 10.34	-	-

5.3.5 Comparing auction techniques

Tables 5.18 and Figure 5.2 shows the performance of the different auction techniques in terms of reductions in excess water and profit. The result shows that, first-price seal-bid auction resulted in the highest excess water among the bidders. This type of auction also brought in the most profit for the sellers and the community. While breaking the volume into smaller units leads to a slight improvement in the distribution of excess water it results in a slight reduction in the community's profit. The multiunit discriminatory auctions and the multiunit uniform auctions both perform well: they record the least excess water post auctions (1,218.30 liters and 1,159 liters respectively). According to the result, it does not have the excess water on bidder side in multiunit discriminatory and uniform auction as show in Figure 5.2) because the multiunit auction rule selling on the product on demand which suitable for the water distribution scheme.

Table 5.18 Comparing auction techniques in terms of excess water (excess water after finished auction)

	Seller		Bidder		Community	
	Before bidding	After bidding	Before bidding	After bidding	Before bidding	After bidding
First price sealed bid auction	3,596.40	1,001.45	-	336.05	3,596.40	1,337.49
Fixed multi-unit first price sealed bid auction	3,596.40	1,171.64	-	153.40	3,596.40	1,325.04
Multi-unit discriminatory auction	3,596.40	1,218.30	-	-	3,596.40	1,218.30
Multi-unit uniform auction	3,596.40	1,159.26	-	-	3,596.40	1,159.26

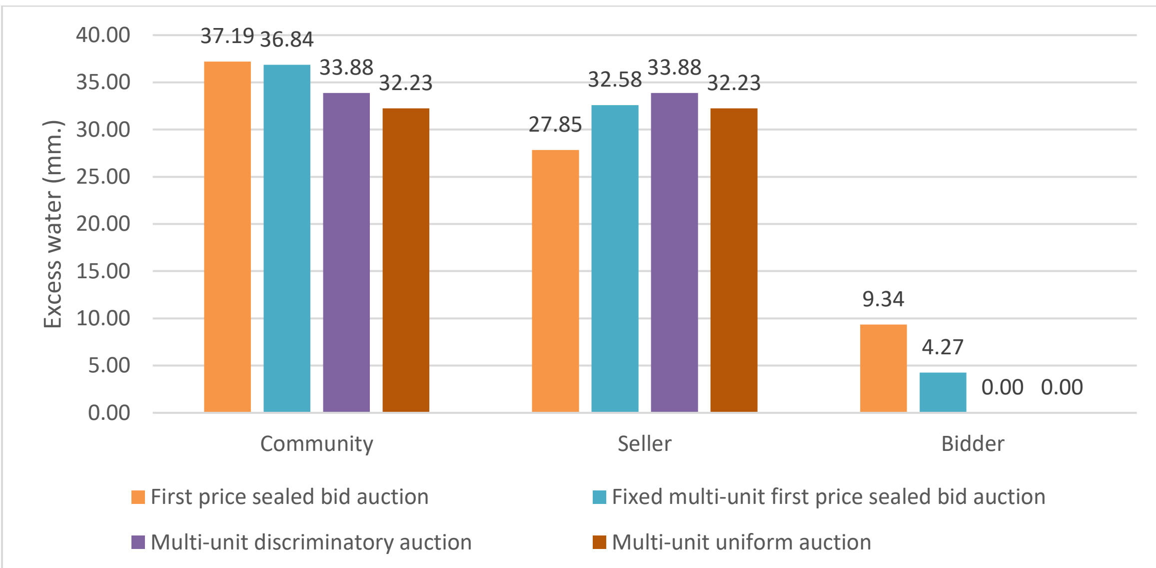


Figure 5.2 Comparing the percentage of excess water

Table 5.19 and Figure 5.3 shows the total income obtained by both auctions is also acceptable, lower than the first price single unit sealed bid but higher than first-price multiunit sealed-bid auction. When taken all auctions result together, the multiunit uniform auction is able to distribute the most excess water while generating an acceptable level of income. This result seems to suggest that using a multiunit uniform auction is better than using a multiunit discriminatory auction. Winners of the auction pay the same amount for their water (the lowest winning bid). As Table 5.19 shows, both sellers and bidders gain higher profits using a multiunit uniform auction. This type of auction also proves the best in regard to community profits. These findings indicate that the multiunit uniform auction should be used if the ultimate goal is to ensure that the community benefits from the water sharing as bidders only buy what they need meaning that there is no wastage. A single unit first-price sealed-bid auction only benefits the seller: while they may receive a better price for their water, the winning bidders may end up having excess water. Our experiment results show that the pay-per-bid auctions (discriminatory and uniform auction types) are the best strategies for water distribution. The multiunit uniform auction performs the best in terms of distributing the most excess water and gaining the most profit.

Table 5.19 Comparing profit value change between auction techniques (additional profit after finished auction)

	Seller		Bidder		Community	
	Before bidding	After bidding	Before bidding	After bidding	Before bidding	After bidding
First price seal bid auction	3,582,701.99	3,631,387.70	26,553,969.39	27,073,635.91	30,136,671.38	30,705,023.61
Fixed price first price seal bid auction	3,582,701.99	3,625,744.86	26,553,969.39	26,958,604.65	30,136,671.38	30,584,349.51
Multi-unit discriminatory auction	3,582,701.99	3,625,046.34	26,553,969.39	26,959,688.05	30,136,671.38	30,584,734.39
Multi-unit uniform auction	3,582,701.99	3,625,577.73	26,553,969.39	26,987,060.37	30,136,671.38	30,612,638.10

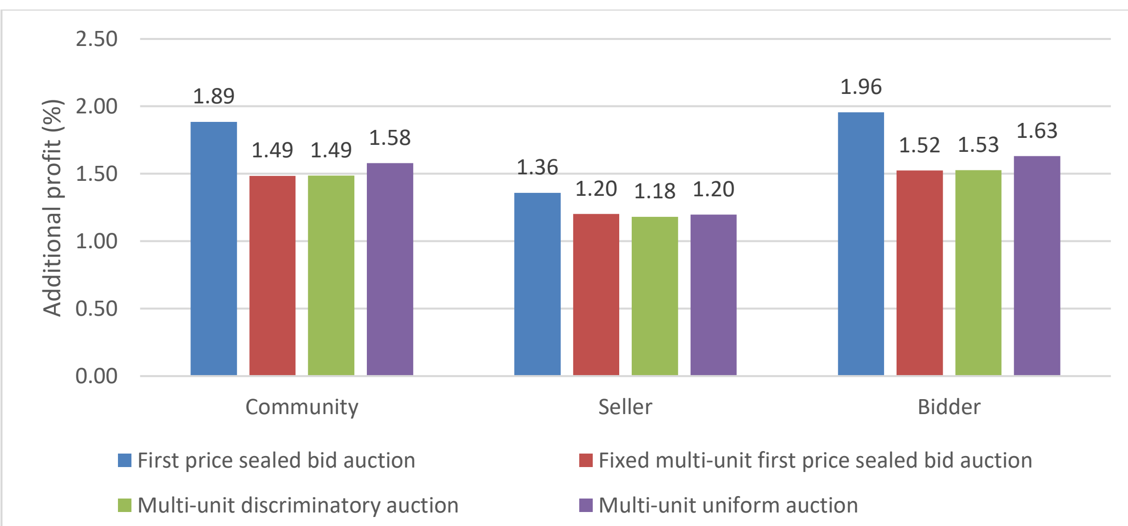


Figure 5.3 Comparing the percentage of profit value change

5.4 Agent behaviour

As the results in Section 5.3 show, auctions provide a good mechanism for trading water. We found that the multiunit auctions, the multiunit discriminatory and multiunit uniform auctions, are particularly good for redistributing excess water. However, in a real-world situation, sellers and bidders may behave differently. This experiment investigates the effects of different agents' (both sellers and bidders) behaviours on water distribution and community profit. In this experiment, we limit our experiment to multiunit uniform auctions as this auction performed best in the previous experiment. In Chapter 3, we outlined three agent behaviours: neutral, generous, and greedy. In this experiment, there are four different situations, based on the agents' behaviours. For a seller, being generous means that an agent's first priority is to distribute the excess water. S/he does not care about making a profit. They will not fix a minimum price; they will sell all excess water at any price. A neutral agent will sell the water at cost price. The seller will accept any offers equal to, or more than, what they paid for their water. A greedy seller will set the reserve price higher than the price they paid for the water in the hopes of obtaining additional profit. In this experiment, the greedy agents increase the price by approximately 10 – 15% more than the actual price of their water. The bidders' behaviours are similar to the sellers in that a neutral bidder will bid based on their actual private valuation. Greedy bidders will bid at a price below their private valuation. It does not make sense to have generous bidder(s), as bidders need to recover their losses. It is also not a good idea for an individual to pay more than what s/he can afford. In the water trading marketplace, all bidders join the bidding process with the same goal: to purchase additional water. We outline the various scenarios in Table 5.20 below.

Table 5.20 Agent behaviours in the four situations

Scenario	Seller		Bidder	
	Numbers	Behaviour	Numbers	Behaviour
			50	Neutral
Generous seller	5	Generous	50	Greedy
			50	Neutral / Greedy
			50	Neutral
Neutral seller	5	Neutral	50	Greedy
			50	Neutral / Greedy
			50	Neutral
Greedy seller	5	Greedy	50	Greedy
			50	Neutral / Greedy
			50	Neutral
Mixed seller behaviours	5	Generous / Neutral / Greedy	50	Greedy
			50	Neutral / Greedy

As before, there are five sellers and 50 bidders in the marketplace. As shown in Table 5.20, there are four different situations. These are: 1) generous seller 2) neutral seller 3) greedy seller and 4) mixed seller behaviours. All scenarios contain three sub-scenarios, with all neutral bidders, all greedy bidders and neutral/greedy bidders. We use a multiunit uniform auction for all the experiments. The results are shown in Table 5.21.

Table 5.21 Varying agent behaviours

	Excess water (%)					
	Seller		Bidder		Community	
	Without bidding	After bidding	Without bidding	After bidding	Without bidding	After bidding
			Generous seller scenario			
Neutral bidders	100	20.45	-	-	100	15.61
Greedy bidders	100	15.61	-	-	100	20. 45
Greedy and neutral	100	19.32	-	-	100	19.32
			Neutral seller scenario			
Neutral bidders	100	30.60	-	-	100	30.60
Greedy bidders	100	63.79	-	-	100	63.79
Greedy and neutral	100	57.26	-	-	100	57.26
			Greedy seller scenario			
Neutral bidders	100	39.58	-	-	100	39.58
Greedy bidders	100	70.58	-	-	100	70.58
Greedy and neutral	100	70.47	-	-	100	70.47
			Mixed seller scenario			
Neutral bidders	100	31.28	-	-	100	31.28
Greedy bidders	100	54.27	-	-	100	54.27
Greedy and neutral	100	52.89	-	-	100	52.89

The percentage of excess water in the community is at its lowest if all sellers behave generously. Significantly, if all greedy bidders are present in this environment, there is more excess water left in the community. The best combination is where the marketplace is populated with all generous sellers and all neutral bidders (in which case there is 15.61% excess water left in the community). In short, it is not beneficial for bidders to be greedy. The percentage of excess water in the community is at its highest if all the sellers are greedy. The worst scenario involves a marketplace populated by all greedy sellers and all greedy bidders: in this scenario only 30.42% of the excess water is distributed to the community (there was 70.58% excess water left in the community). The observations for all neutral sellers and mixed sellers are similar and expected. In the case of both all neutral and mixed sellers, the worst distribution is when the marketplace is populated by all greedy bidders. Similar results are found when there are greedy and neutral bidders (9% lower). This outcome was expected, since a greedy seller will set a higher price. Some of the bidders will withdraw because the reserve price is much higher than their private valuations. The result suggests that for water to be distributed fairly, sellers should be generous and bidders should be neutral. Table 5.22 shows the additional profit obtained, based on the varying agent behaviours.

Table 5.22 Additional profit with varying agent behaviours

	Additional profit (%)					
	Seller		Bidder		Community	
	Without bidding	After bidding	Without bidding	After bidding	Without bidding	After bidding
			Generous seller scenario			
Neutral bidders	100	101.31	100	101.96	100	101.89
Greedy bidders	100	100.88	100	102.07	100	101.94
Greedy and neutral	100	100.95	100	101.90	100	101.80
			Neutral seller scenario			
Neutral bidders	100	101.24	100	101.93	100	101.86
Greedy bidders	100	100.53	100	101.07	100	101.01
Greedy and neutral	100	100.65	100	101.25	100	101.18
			Greedy seller scenario			
Neutral bidders	100	101.09	100	101.86	100	101.77
Greedy bidders	100	100.47	100	101.94	100	100.89
Greedy and neutral	100	100.44	100	100.04	100	100.98
			Mixed seller scenario			
Neutral bidders	100	101.20	100	101.88	100	101.84
Greedy bidders	100	100.55	100	101.40	100	101.31
Greedy and neutral	100	100.67	100	101.30	100	101.23

The sellers make the most profit when the marketplace is populated with all generous sellers and neutral bidders. This result indicates that the additional profit gained by the generous sellers is driven by bidders' behaviour: in this case, having a mixture of greedy and neutral bidder is more favourable for generous sellers. Similar results can be seen in the marketplace populated with all neutral sellers and mixed sellers. However, in the marketplace populated with all greedy sellers, more profit can be gained if all the bidders are neutral. This means that for all types of seller(s), neutral bidders provide the most profit as shown in Table 5.22. It can be seen that the sellers want more profit, but the bidders want to buy water at the lowest possible price. This result was as expected as it is in line with human behaviour.

Bidders obtain the highest profit (102.07%) when the market is populated with all generous sellers and greedy bidders. The lowest profit (100.04%) is obtained when the market is populated with all greedy sellers and a mixture of greedy and neutral bidders. When all experiments are taken into account, the community's profit is at its highest when the marketplace is populated with all generous sellers and all greedy bidders (101.94%). The lowest (100.89%) is when there are all greedy sellers and greedy bidders. This result shows that sellers do not gain much by displaying greedy behaviour. It is more beneficial for them to be generous. The reverse is true for bidders; greedy bidders make profits for themselves in only 2 scenario which are greedy and generous sellers. A greedy bidder tries to obtain water at a price lower than his/her private valuation. This is sensible behaviour as the bidders' ultimate goal is to reduce his/her losses as much as possible. In summary, when additional profit is desired in community, the marketplace should be populated with generous sellers and greedy bidders. When water distribution is the primary concern, sellers should behave generously, and bidders should be neutral. Also, sellers do not lose much profit by being greedy or neutral as shown in the 1st column of Table 5.22. Only thing is that they have more excess water than when they are generous. In the next auction round they can sell or get rid of it by being generous if they wish and make additional profits. In general, the results show that generous sellers will result in additional profit for the community while they themselves do not gain as much.

5.5 Summary

In this chapter, we have discussed the results of the experiments designed to fulfil the research objectives. This research investigates how excess water can be distributed in a community of farmers using different water sharing mechanisms. We have evaluated four types of auctions. The results showed that the pay-per-bid (discriminatory and uniform) auctions are the best for distributing excess water. The multiunit uniform auction performed the best in terms of distributing the most excess water and gaining the most profit. This chapter has also reported the results of varying seller and buyer behaviours. The results indicate that if profit is the primary concern then the best combination is generous sellers and greedy bidders. When equitable water distribution is the key goal, then the marketplace needs to be populated with generous sellers and neutral bidders. Having explained the results, the final chapter summarises the work, revisits the research objectives, outlines the research's key contributions and provides suggestions for future work.

Chapter 6

Conclusions and Future Work

In this chapter, the summaries of all the chapters are discussed. The research findings are described and discussed with respect to the research objectives. In addition, the novel contributions of this work are detailed and finally the future directions of this work are described.

6.1 Summaries of the Chapters

In Chapter 1, we described the motivation of the work by describing some of the main issues in irrigation management in Canterbury which was contributed by the increasing water demand and shortage of water particularly during the drought season. The chapter also discussed the objectives of the research.

In Chapter 2 we presented the overview of irrigation planning and management which included the crop water need calculation based on FAO. We discussed factors that affect irrigation planning, irrigation management tools and their limitations. In addition, related works that employed various computing techniques are discussed in some detail. Finally, the research gaps are identified and elaborated.

Chapter 3 described the design of the irrigation management agent which can be used in a single farm. We described the water need calculation, the water reduction algorithm and how crops water needs are prioritised. To facilitate the water sharing in the community, the MAS design is discussed along with the auction mechanisms used to allocate water within the community of farmers.

In Chapter 4 the experimental evaluation for a single agent is discussed. First the model is validated, followed by a comparison in performance in terms of water saved with a control agent. This is followed by a discussion on the results obtained when water reductions scheme are in effect.

Chapter 5 discusses the water allocation within a MAS setting to simulate the water allocation in a farming community. Four auction mechanisms were evaluated based on the remaining excess water left in the community and the profit gained/reduction of losses by the sellers and buyers. The effect of varying the sellers and seller behaviours are also discussed.

6.2 Research findings

The main objective of this research is to develop a multi-agent based irrigation system to manage irrigation in an individual farm and within a community of farmers during water scarcity. In order to achieve this objective, several sub-objectives were defined. These are:

RO1: To design and develop a water allocation algorithm to allocate water efficiently in a farm.

RO2: To implement a multi-agent system to facilitate water sharing within a community of farmers

RO3: To investigate varying strategies that can be used to optimize water sharing within a community of farmers.

RO4: To assess how varying behaviour of the agents may affect water sharing within the community.

In this research, we have developed a multi-agent based irrigation management system than can be used by individual farm(s) to calculate the water needs based on the crop types, crop growth stages, soil types and climate on a daily basis. Each farm is represented by an irrigation management agent which has the ability to negotiate with other irrigation management agents to achieve an optimized water sharing mechanism. In Chapter 3, we described the design of the irrigation management agent and we evaluated the water allocation efficiency in terms of water saving in Chapter 4. These were the findings:

- The agent based irrigation management system proposed a lower water need than the control agent for all three types of farms (pasture only, other crops and mixed crops).
- The proposed system reduces water usage in farm both during normal situation and when water is insufficient. The water reduction during water scarcity is made based on the crop water need priorities as well as the growth stages of the crops and motivated by maintaining the maximum profit of the farm.

Based on these findings, we can confirm that RO1 has been achieved.

We extended the single irrigation management agent by setting up a multi-agent system to represent a community of water users during water scarcity. Each agent represents a farm and is able to make a decision on whether to buy or sell water. These agents are also able to negotiate with each other on how the water sharing should proceed through the implementation of auctions. Four auction mechanisms were investigated and the performance of these different auctions were investigated in terms of how much excess water was left in the community and how much profit/loss was gained/reduced at the end of the auction. These were the major findings of this experiment:

- First-price sealed-bid proposed the highest profit gain for the seller and community. However, it has a highest excess water in the community after the auctions are completed.
- Fixed multiunit first price sealed bid that separates the water volume to smaller units is an improvement from the first-price sealed bid auction in that it further reduced the excess water in the community and gain the additional profit at the conclusion of the auctions.
- The multiunit discriminatory auction can distribute the most excess water with acceptable income. On the other hand, the multiunit uniform auction recorded the most efficient water sharing (least excess water in the community) and also resulted the highest gain in community's profit at the conclusion of the auctions.
- The pay-per-bid auctions (discriminatory and uniform) are the best strategies for water distribution that balance between water distribution and gaining profit in water community.

Based on these findings, we can confirm that RO2 and RO3 have been achieved.

We recognized that sellers and buyers may possess varying behaviours in the auctions which will directly affect the outcome of the auction in terms of how much excess water is left in the community and how much profit can be gained by the sellers and how much loss can be reduced by the bidders. Hence, we designed the seller agents to possess three types of behaviours; generous, neutral and greedy and the bidder agents to possess two types of behaviours; neutral and greedy. We populated the marketplace with varying seller and bidder behaviours and we observed the outcome of the auctions. These were the major findings of this experiment:

- The excess water in community is the lowest if all sellers behaviour is generous. On the other hand, excess water is the highest if sellers and bidders are greedy.

- The suggestion for fair water distribution is that seller should be generous and bidder should be neutral.

- The highest profit recorded by the sellers is when the marketplace is populated with generous sellers and neutral bidders.

- The highest profit for bidders is when the market is populated with all generous sellers and greedy bidders.

- The community's profit is at its highest if the marketplace is populated with all generous sellers and all greedy bidders. On the other hand, the community's profit is lowest when there are all greedy sellers and greedy bidders.

- Sellers gain more profit when they are generous (no reserve price on the price of the water to be traded) and bidders gain more profit when they are greedy (they bid below their private valuation).

These findings support RO4.

6.3 Novel Contributions

In this research, we proposed a multi-agent based irrigation management framework that can work out the water requirement in the farms based on certain factors. The proposed agent can work as a single agent which works out the water requirement in the individual farm. Moreover, it can make the decision whether to sell or buy water and participate in an auction in a multi agent framework to deal with the water distribution in community.

The proposed agent estimated the water requirement with the goal of reducing water even when there is sufficient water in the farm. In terms of water scarcity, it is able to prioritise crop water needs based on its yield and participates in auctions to buy water (when there is water shortage) or sell water (when there is excess water).

The proposed framework provides an environment that can facilitate fair and equitable water distribution in the community during water scarcity through online auctions depending on the motivation (to gain extra profit, to help other farmers, or a combination of both). Moreover, we investigated the effect of water distribution with varying seller and bidder behaviours and analysed the outcome of having such behaviours in terms of community profit, sellers profit, bidders profit and how much excess water is left in the community.

The framework is also flexible in that we can modify the design of each agent, add additional agent behaviour and increase/decrease the number of agents in the marketplace. The negotiation mechanisms can also be configured to include other types of auctions or other negotiation techniques.

6.4 Future work

There are a number of open issues of this work and a number of extensions which can be applied to the existing framework. It can be divided into three categories: 1) applying other auction strategies, 2) improving the single agent mechanism and 3) extension of auction environments.

6.4.1 Applying other auction strategies

We described that the auction mechanism can improve the efficiency of water sharing and gain additional profit to the community in total. We applied four types of auctions to deal with water distribution, but each auction technique has limitations that can be improved. Our results showed that, excess water is not reduced if there are no matching offer during the auction period. It would be useful to explore other auction mechanisms that can be used in the second round of auction to improve the water distribution such as continuous double auction (CDA) as this type of auction is also based on supply and demand.

6.4.2 Improving the single agent mechanism

The single agent can work with the several factors (crop growth stage, soil type, productivity) in the calculation of the utility function. It can prioritise crop water need during water scarcity. However, the utility function can be improved by adding additional factors that might affect the crop water needs.

6.4.3 Extending the irrigation management framework

This research proposed an irrigation management system that can be applied in Canterbury region in New Zealand as it used localized data such as weather data, soil type and irrigation system. The framework can be extended to other locations by changing the information related to crops, the weather and potentially adding new information such as water usage policy. For example, in Thailand the water problem is dissimilar to New Zealand. It has a long drought season, two seasons only, farming behaviours are different, and the water usage policy is different.

Appendix A

A.1 Copy of the paper published in conference proceeding

Agent Based Irrigation Management for Mixed-Cropping Farms

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Abstract. This paper describes the development of an intelligent irrigation management system that can be used by farmers to manage water allocation in the farms. Each farm is represented as a single agent that can work out the actual water required for each crop in the farm based on the crop's drought sensitivity, growth stage, the crop coefficient value and the soil type. During water scarcity, it can be used to prioritise irrigation allocation to different crops on a farm and generates an irrigation plan based on the predetermined water reduction. Our initial experiment showed that using the irrigation management system, the farm can achieve a consistent water reduction which is more than the required reduction. The results showed that the agent consistently recorded an average water reduction higher than the actual reduction required by the water authority. This significant reduction means that more water can be conserved in the farm and reallocated for other purposes.

Keywords: agent-based model, water allocation, utility function, water reduction.

1 Introduction

Water use and water demand have increased steadily in New Zealand over the last 20 years resulting in insufficient water availability. The water usage data [13] shows that Canterbury water allocation makes up 58% of the New Zealand's total water allocation where it contributes 70% of the New Zealand irrigated land. It is expected that water demand will become a problem in the future because the irrigated areas in Canterbury have been increasing for the last 13 years (from 300,000 ha in 2002 to 500,000 ha in 2015) [7]. This demand directly affects the water allocation scheme in Canterbury. Currently, the water usage policy is based on "first in, first served", which means request for water consents are processed and determined in the order they are received. This policy worked in the past because water capacity and farming areas are in equilibrium. Unfortunately, "first in, first served" system is not the most efficient way to manage water. This is due to the fact that even though water demand has increased over the years, water capacity remains unchanged [13]. As the irrigation is based on estimate, there is a possibility that crops received more water than necessary leading to wastage. Water needs become more serious during drought season and so it is very important to conserve water and prioritise crop water need such that high yield crops get the highest priority so as not to affect productivity. If farmers can decide on the irrigation plan that is dependent on the importance of the crops, they can reduce water need in the farm and reduce the loss in productivity during water restriction [2].

To assist in the irrigation planning, farmers often used computing tools and two of the most common ones are OVERSEER and IrriCalc. IrriCalc is an irrigation management tool for irrigation water requirement. It can determinate the irrigation water need due to seasonal planning [6]. OVERSEER is owned and supported by the Ministry for Primary Industries. OVERSEER's model uses daily soil water content data to calculate the daily water drainage. IrriCalc and OVERSEER require input such as selected month, farm location, and type of irrigation system for daily water need calculation. However, IrriCalc and OVERSEER use different models to calculate climate data.

OVERSEER assumes full 'canopy' cover (value of 1) whereas IrriCalc uses a seasonally adjustable value, with an average value of 0.8 [16]. There are other computing tools such as APSIM (Agricultural Production Systems Simulator) and AquaTRAC. APSIM is a modeling framework that contains a suite of modules to enable simulation of agricultural systems. It provides a set of modules (physical process in farm, farm management rule, simulation engine) to support higher-order goal of farming simulation. It provides accurate predictions of crop production based on climate, genotype, soil and management factors. On the other hand, AquaTRAC is a software program developed by Foundation for Arable Research (FAR) which assists cropping farmers with their irrigation scheduling. It calculates when and how much irrigation to apply to optimise yield for each crop by including data on crop type, soil type, weather and irrigation levels [10][16]. However, these tools are limited to calculating water requirement for a single crop in a farm and is unable to address water requirement for farm with multiple crops. Hence, there is a need for a better irrigation management that can accurately estimate and manage irrigation water on the farm either for single crop farms or multi-crop farms. This paper proposes an agent-based irrigation management system that can be used to allocate water efficiently in the farm based on the farm's characteristics. The remainder of the paper is organised as follows. Section 2 describes the irrigation management and its application in New Zealand, the crop water needs calculation and related works on agent-based irrigation management. The proposed agent-based model for intelligent irrigation management system is discussed in Section 3. We present the experiment and result in Section 4 and finally Section 5 concludes and discusses future works.

2 Related Works

2.1 Irrigation scheme and the process

There are three stages in the cycle of crop growth; 1) soil preparation 2) irrigation process and 3) after irrigation process. During the soil preparation, farmers need to decide the location of the irrigation, the water capacity and the irrigation schedule to prepare for planting [15]. During the irrigation process, farmers need to check and work out their irrigation plan for the whole agriculture areas by making references to the weather, season and water policy. The after irrigation process cycle focuses on improving soil quality after the irrigation season and improving irrigation for the next seasons. The Evapotranspiration Rate (ET) is an important variable in irrigation which relates to land location, soil type, and planting season in the farm. ET is the summation of evaporation and plants transpiration from soil to atmosphere. To ensure that each crop gains the highest yield, maximum water need must be applied. This irrigation water need can be estimated using ET and another variable called the crop coefficient (K_c). The value of K_c is determined based on the crop growth stages which are initial state, crop development stage, mid-season stage and late season stage. The water need for each crop varies from one crop stage to another.

2.2 Calculating Crop Water Need

The irrigation water need is defined as the depth of water needed to meet the loss through evapotranspiration (ET). Crop water need can be calculated by using the following formula [9]:

$$ET_{crop} = ET_0 \times K_C \qquad (1)$$

Where: ET_{crop} = Crop water need
ET_0 = Influence of climate on crop water need
K_C = Influence of crop type on crop water need

Some of the tools commonly used in irrigation management (such as OVERSEER, IrriCalc, APSIM, AquaTRAC) follow this formula to estimate crop water need in the planting season. However, these tools do not consider the drought sensitivity of different crop and drought sensitivity based on crop growth stages. Drought sensitivity is a crop characteristic under drought stress where they need more water for every growth stage to ensure maximum productivity such as paddy rice and potato. If various crops are grown on an irrigation scheme, it is advisable to ensure that the most drought sensitive crops get the highest priority.

2.3 An agent-based approach to irrigation

Agent-based Programming (AP) is a software paradigm that uses concepts from Artificial Intelligence (AI). Agent's behavior depends on what it is tasked to do and gathers information about the environment to make a decision. AP has been used to solve resource allocation problems [17]. A software agent is essentially a special software component that can operate without the direct intervention of a human. These agents when grouped together, form a multi-agent system that can be used to model and solve complex systems as it has the ability to introduce conflicting goals and act upon it. An agent senses and reacts to the changes in the environment. An agent is able to exhibit goal-directed behavior by taking initiative while ensuring that its goal is achieved. The agent can learn and adapt itself to fit its environment and to the desires of its users [5]

Agent-based programming has been used in water resource allocation. For example, [8] used agent-based modeling to simulate the interaction between farmers who are stakeholders in transboundary Nile River. This simulation generated farmer agent and water sharing scheme from water usage behavior. This model was developed to optimize allocated water for each user with different water requirement to find a fair water allocation for stockholders at Nile river basin.

An agent-based model was applied to investigate the history of irrigated agriculture in Spain. The purpose of this study was to study the influence of farmers' characteristics on land-use change and associated groundwater over-use [12]. They showed that agent-based model can be utilized to enhance this understanding even when data is scarce and uncertain. An agent-based model was used to simulate irrigated system in Senegal River Valley to find the limitation of water used based on behavioral factors (resource capacity, a set of individual water used rule, and a set of collective rules) [3]. The focus of this work was to verify that MAS is a suitable architecture that can be used to theoretically study irrigated systems' viability. Using MAS, they designed and developed virtual irrigated systems as alternative to real labs.

A simulation based on multi-agent system was developed to study and analyse the collective action when a certain water policy is changed [4]. This model was able to capture collective action problems in water markets in small-large scale infrastructure provision. The system was also used to simulate the behavior of different water users to represent social and institutional relations among users. This work demonstrated how MAS can be used to better understand the complexity of water uses and water users within sub-basins.

[1] proposed an agent-based model that simulated the behaviors of different water users/stakeholders of a system as well as their reactions to different management scenarios. They simulated the behavior and interactions of the conflicting parties and modeled it as a game. This model was used to explain the interactions between parties and to enable decision making among the stakeholders.

Giuliani et al. [11] developed a multi-agent system to design mechanism for water management. The agent-based model represents the interactions between the decision makers to demonstrate a hypothetical water allocation problem, involving several active human agents and passive ecological agents. They used different regulatory mechanisms in three different scenarios of water availability to investigate efficiency-acceptability tradeoff. The results obtained showed that this approach was able to support the design of distributed solution.

Zhao et al. [18] compared the water user behavior under the administered system and market-based system by developing an agent-based modeling framework for water allocation analysis. Their analysis showed that the behaviors of water users were dependent on factors such as transactions, administrative cost and costs.

Overall, irrigation management is a complex problem because it is hard to determine the water need in the farm as there are many dynamic factors that need to be considered. For example, crops growth are in different stages, temperature changes on a daily basis, the soil moisture varies, and sometimes there is a prolong drought season. Moreover, different farms have different water requirements because of the varying crop type, soil type, farm location, and farm size. Agent-based programming has advantage over other software approaches because it can work with uncertain factors and supports non-linear data. Moreover, it is flexible and autonomous under complex situations.

3 Agent-based model for irrigation management

3.1 Conceptual design

This study focuses on using agent-based approach to optimise water allocation in mixed-cropping farms. The crop water need is calculated based on many factors such as crop water requirement, moisture on the ground, and farm types. It is assumed that an agent represents a single farm where each farm may have a single type of crop or mixed types of crop. The agent is able to estimate the crop water need on a daily basis based on the current state of the farm's characteristic (i.e. crop types, crop stage, soil type, etc.). The agent will also be able to work out the irrigation plan for the farm for a given planting season. During water scarcity (such as drought season), the agent will work out an irrigation plan that will prioritise crop water needs based on the prevailing condition.

The agent will be able to generate the irrigation plan on a daily basis, weekly or for the whole season. The crop information database contains an up-to-date information about the state of the farm including information about each crop, its growth stage, its location, size of the plot and soil type. During water scarcity, user may enter the percentage of water reduction required by the authority. The agent will then calculate the water need for each crop in the farm, calculate the expected utility for each crop, decide which crops have higher water need by prioritizing them and determine how much water should be reduced for each crop in the farm. This prioritization is determined based on crop's expected utility which takes into account the potential yield of the crop, the drought sensitivity and growth stage and the soil type. For example, if the farm contains high yield crops, more importance will be placed on the crop's yield to ensure that the revenue of the farm is not compromised. On the other hand, if there is no high yield crop on the farm, the other two factors can be considered.

Crops type can be divided into 2 categories: grazing pasture and other crops. High yield crops are crops that generate higher revenue for the farm. Examples of high yield crop include tomato, sugar cane and sugar beet. Most crops have four growing stages (germination, development, mid-season, late-season). Pasture has three stages (grazing, development and late-season). There are 3 types of drought sensitivity (low, medium, and high). Crop with high sensitivity to drought requires higher irrigation priority. Crops can be planted in plots with varying soil type (light, medium, heavy). Heavy soil can absorb more water and so it has low irrigation priority. On the other hand, light soil has bigger pores and absorbs less water. Therefore, light soil has higher priority over medium and heavy soil because of its inability to retain moisture in the soil moisture potential yield [14]. It is assumed that each type of crops is planted in plot of a certain size. This means that the water need for a crop is calculated to cover the plot that has been planted with that particular crop.

```
begin
   get water reduction percentage
   retrieve crop information from crop database
   calculate the water requirement for each crop
   calculate total water requirement on farm
   calculate expected utility for each crop
   prioritise crops based on expected utility
   calculate water reduction for each crop
   generate water reduction plan for a farm
end
```

Fig. 1. The pseudocode of the irrigation management agent

The pseudo code for the water reduction calculation is shown in Fig.1. First, the user keys in the percentage of water reduction required to the system. The agent retrieves the crop information from the database, K_c value for each crop stage, and reference ET_0 data. Equation 1 is used to calculate the actual crop water requirement. The ET_0 value is retrieved from the New Zealand weather data and the K_c value is based on the FAO data reference. Agent will work out the individual crop water need and the total water requirement for the whole farm (this is the summation of individual crop water requirement). Next, the agent calculates the water reduction requirement for the farm based on the percentage of required reduction entered by the user. Then, the agent calculates the expected utility for each crop based on its properties. Once the crops are prioritized, the agent will then determine the percentage of water reduction that should be applied to each crop. Finally, agent generates irrigation reduction plan as the output to the farmer.

3.2 Prioritising irrigation water need to multiple crops.

To calculate water requirement, agent uses ET_{crop} and plot size on each crop (C_{plot}) as follows:

$$C_{wrq} = ET_{crop} \times C_{plot} \quad (2)$$

To prioritise irrigation water need to multiple crops, the agent used three determinants namely the drought sensitivity and the growth stage, the potential yield for crops and the soil type [2]. Each determinant is associated with a utility function that indicates the importance of that crop (the higher the value, the higher the irrigation priority). These utility functions (based on crop's potential yield, drought sensitivity and growth stage and soil type) are defined as follows:

$$f_{PY} = (C_{plot} \times C_{yield}) \times C_{price} \quad (3)$$

$$f_{DS} = C_{stage} \times D_{val} \quad (4)$$

$$f_{ST} = S_{type} \times C_{plot} \quad (5)$$

Where:

f_{PY}	=	crop's potential yield function
f_{DS}	=	crop's drought sensitivity function
f_{ST}	=	soil type function
C_{yield}	=	yield amount of crop area
C_{price}	=	price per kilogram
C_{stage}	=	crop stage
C_{plot}	=	plot size of crop
D_{val}	=	drought sensitivity value
S_{type}	=	soil type

To determine the expected utility (EU) of each crop, the agent combines the three utility functions by allocating weights to denote their relative importance. Thus, the expected utility of each crop is calculated as follows:

$$EU_{crop} = \sum_{j \epsilon c} w_j f_j \quad ; \ 0 \leq w_j \leq 1 \ and \ \sum_{j \epsilon c} w_j = 1 \quad (6)$$

where C is the set of determinant when agent works out the crop priority value, f is the utility function for each determinant and j is the individual parameter. At any time, the three utility functions can be considered by the agent for irrigation priority depending on what it sees as being important at that point in time.

For example, in an all pastures farm, the crop's drought sensitivity and growth stage determinant are the most important because the potential yield of the crop is the same (pasture only). On the other hand, if the farm is a mixed crops farm that has high yields crops, then the crop's potential yield is more important because is affect the productivity and farming income. Thus, a higher weight will be applied to the crop's potential yield function.

4 Experimental Evaluation

4.1 Experimental setup

To test the performance of our intelligent irrigation management system, we conducted three experiments using three farm setups, grazing pasture only farm, other crops only farm and mixed crops farm (which consists of pasture and other crops). These setups are common in New Zealand's farms. For each experiment, we randomly generate 100 farms with varying crop properties. For the pasture only farm, we set the crop type to pasture and randomise the growth stage to three different stages. In the other crops farm, we randomise the crop type and the growth stage to four different stages. The setup for the mixed crop farm is also similar to the other crop farm. However, we included pasture as the additional crop. The farm size is fixed to 200 hectare and the water capacity to 15,000 m^3. To validate the accuracy of our crop water need, we manually calculated the crop water need the actual water need is calculated based on FAO's formula for calculating crop water requirement [9]. and compared this value with the value generated by our irrigation management system.

We run this experiment using four water reduction schemes at 5%, 10%, 15% and 20% and calculated the average difference between the actual reduction and the proposed reduction. This is to align with the real world setting where the water authority defines the water reduction percentage during water scarcity. We did not test it with reduction scheme higher than 20% as the water reduction scheme is usually capped at 20%. In the pasture only farm, we set the weight for the three determinants as (f_{PY}=0.2, $f_{ST}=0.5, f_{DS}=0.3$) to indicate the importance of growth stage and drought sensitivity. In the other crops farm, we set the weight as (f_{PY}=0.5, $f_{ST}=0.3, f_{DS}=0.2$) and in the mixed crops farms the weight were set to (f_{PY}=0.5, $f_{ST}=0.3, f_{DS}=0.2$).

5 Results and Analysis

The proposed water reduction by the system is shown in Table1 and Fig.2. In grazing pasture only farm, the average water reduction is much higher than the actual reduction for all cases. Our proposed irrigation management system recorded a reduction percentage of 9.36%, 11.79%, 16.70% and 20.81% for 5%, 10%, 15% and 20% reduction scheme. It can be seen that the agent was able to propose a higher water reduction than the actual reduction. In the other crops farm, the average water reduction is similar with all pasture farm for all cases (10.01%, 12.39%, 16.70% and 21.96% respectively). The result for the mixed crops farm, also recorded a higher reduction percentage compared to the actual reduction. It recorded a reduction percentage of 9.36%, 20.46%, 20.46% and 21.96% for 5%, 10%, 15% and 20% reduction scheme. The results for the three types of farm are consistent across all the reduction schemes where all three recorded a higher than the actual reduction percentage. Based on this result, we can conclude that our proposed agent-based irrigation management system was able to consistently propose a significantly higher water reduction than the actual reduction required.

Table 1. The average proposed water reduction for difference reduction schemes.

	Water reduction (m^3)							
	5% of reduction		10% of reduction		15% of reduction		20% of reduction	
	m^3	%	m^3	%	m^3	%	m^3	%
Actual water requirement	15,000	100	15,000	100	15,000	100	15,000	100
Actual reduction	750	5	1,500	10	2250	15	3000	20
Proposed reduction (pasture)	1,404.52	**9.36**	1,768.92 .	**11.79**	2,504.5	**16.70**	3,121.46	**20.81**
Proposed reduction (multiple crops)	1,500.81	**10.01**	1,859.21	**12.39**	2,332.5	**16.70**	3,294.92	**21.96**
Proposed reduction (crops and pasture)	1,404.52	**9.36**	3,068.92	**20.46**	3,068.92	**20.46**	3,294.92	**21.96**

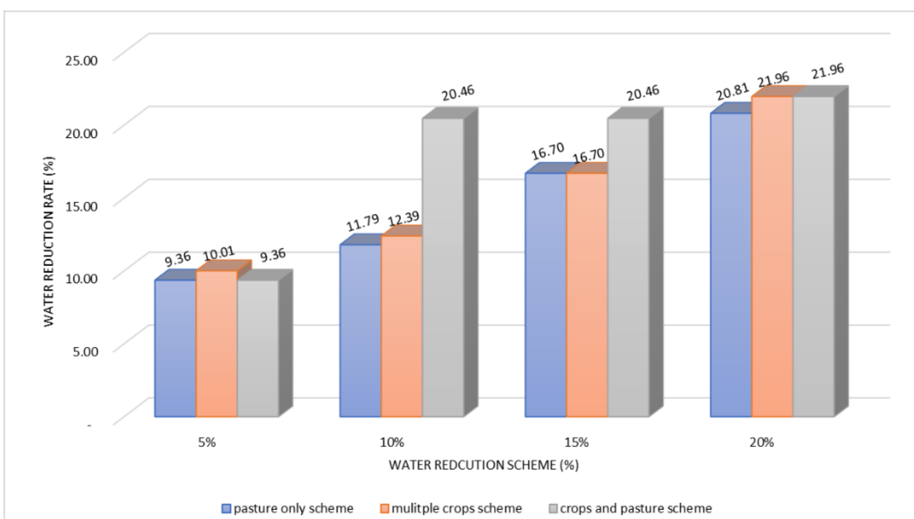

Fig. 2. The average water reduction based on water reduction scheme

6 Conclusion and discussion

In this paper, we describe an intelligent irrigation management system that makes water allocation decision based on the crop potential yield, the crop drought sensitivity and growth stage and the soil type. This tool is especially useful during water scarcity when farmers are required to make water reduction in the farm. Based on experimental result, it can be seen that the proposed model was able to save water even when water reduction is in place. It consistently proposed a water reduction plan that is higher than the actual reduction. For future work, we plan to extend this work by creating a community of agents that can work together to optimize water allocation in a community irrigation scheme. If each agent can accurately work out its crop water requirement in the farm, then it is quite possible that there is excess water that can be used for other purposes such as trading it with the other farmers in the community who might not have sufficient water. This will help the authority to maximize the allocation of water across the region. This water trading mechanism will also need to be further investigated.

Improving Water Allocation using Multi-Agent Negotiation Mechanisms

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Abstract. This paper describes a multi-agent irrigation management system that can be used to distribute water efficiently among farmers in a community irrigation scheme during water scarcity. Each farm is represented as an agent that can calculate how much water is needed in the farm and hence estimate the marginal profit for the farm based on how much water is available. During water scarcity such as drought, some farmers would face water shortages and some would have excess water for irrigation. To ensure efficient water distribution, those farmers with excess water should share their water with other farmers needing water. In this study, we used auction mechanism to distribute water efficiently among the farmers with the objective of maximizing the farmer's expected utility (profit margin). Our preliminary experiments showed that water distribution using auction mechanism yielded higher profit margin for all farmers in a community irrigation scheme when compared to direct negotiation strategy with a fixed price.

Keywords: multi-agent negotiation, water allocation, auction mechanism, water scarcity.

1 Introduction

Water demand for irrigation in Canterbury has been increasing in the last 20 years. The New Zealand statistic data shows that irrigated areas in Canterbury have increased by 200,000 ha from 2002 to 2015(Dairy NZ, 2015). It is expected that water demand will affect the water allocation scheme in this region in the future. Currently, access to water is controlled by the government. However, farmers can apply for water consent to irrigate their areas. Water consent requests are processed and determined in the order they are received (on a first come first serve basis). This policy has worked in the past because the water demand and the total irrigated area were in equilibrium. However, the processing method based on first come first serve is no longer efficient as the demand for water has increased but the water capacity in Canterbury remains unchanged(Environment, 2004). Moreover, where water availability is not sufficient, this approach cannot ensure water allocation to most productive use. Therefore, community irrigation scheme are in practice, where farmers get water with high reliability and flexibility. Under this scheme, water is distributed to shareholders through piped system and water consent is obtained by the community irrigation scheme. Shareholders have to pay for their shares based on the size of the farm and water charges on annual basis. However, request for required irrigation must be done one day in advance. This scheme provides water to the shareholders based on their demand provided that there is enough water to meet the demand. If available water is not sufficient to meet 100% of the demand, then the distribution is reduced proportionally.

Since farmers need to estimate their water usage for farming and pay for it, they need to consider many aspects in the farm such as the size of the farm, the crops to be planted as well as the soil condition. If farmers overestimate, they risk paying more for the water and they will have unused excess water. If they underestimate, then they may run into water shortages which will result in poor crop yields which in turn affect their profit. This becomes more serious during drought season when water is scarcer. Ideally, if farmers can decide on the irrigation plan that is dependent on the importance of the crops, they can keep their productivity and profit margin during water restriction(Anthony & Birendra, 2018). In a community irrigation scheme, during water scarcity, there are farmers who have excess water and farmers who have water shortages and it would be beneficial if farmers with excess water can extend this water to their counterparts who are facing water shortages. Unfortunately, these farmers do not have an efficient mechanism for selling or buying water from others when the situation arises.

In our previous work, we have developed an agent-based water management system that can be used by farmers to calculate the water requirement in the farm based on the types of crop, the soil condition and the size of the farm. However, this application can only be used for a single farm (Anthony & Birendra, 2018). In this paper, we described the extension of this work to a multi-agent system to improve water allocation and to investigate efficient water distribution mechanisms among the farmers in a community irrigation scheme. Each farm is represented as an intelligent agent that can work out the actual water needed for that farm at any given time. The agent can also work out the water shortage/excess for that farm as well as the marginal profit of that farm at any particular time (in this case, during drought season when water distribution is reduced). Each agent makes a decision on behalf of the farmer whether to buy or sell water and at what cost. These agents negotiate with each other to buy and sell water with the aim of maximizing their profit margins. In this preliminary experiment, we compared two negotiation strategies (the direct negotiation with fixed price and first price sealed-bid auction) and observed the additional profit obtained by the sellers and the total loss reduction for all the farmers in the community. This work advances the state of the art as it proposes a multi-agent irrigation management system that can allocate water efficiently in a farming community. This system consists of multiple agents that can make decision on behalf of the farmers whether to buy or sell water and negotiate with each other using negotiation strategies with the objective of maximizing their own profit margin. The remainder of this paper is organized as follows. Section 2 describes the overview of irrigation system and water requirement estimation, auction process and agent irrigation management. The proposed multi-agent for irrigation management is discussed in Section 3. The initial experiment and results are discussed in Section 4. Finally, Section 5 concludes and discusses future works.

2 Related Works

2.1 Irrigation water need and tools

There are three stages in the cycle of crop growth; 1) soil preparation 2) irrigation process and 3) after irrigation process. Farmers needs to work out an irrigation plan based on crop evapotranspiration (ET) and crop coefficient (K_c) (The Parliamentary Commissioner for the Environment, 2004). ET is the summation of plant transpiration and evaporation from soil. The K_c value is determined based on the crop's growth stage. Currently, there are computing tools that use ET and K_c factors to estimate irrigation water need and crop planning. The most popular ones are Irricalc and OVERSEER. The irrigation water need formula is defined by the Food and Agriculture Organization (FAO)(Testa et al., 2011). Both OVERSEER and IrriCalc follow the crop water need formula (1) to estimate the crop water need. However, both tools can only be used to calculate for a single crop farm and they do not provide an option for multiple crops water calculation(Testa et al., 2011)(Wheeler & Bright, 2015). The crop water need calculation is as follows:

$$ET_{crop} = ET_0 \times K_C \quad (1)$$

In this equation, ET_{crop} is the crop water need, ET_0 is the influence of climate on crop water need and K_C is the influence of crop type on crop water need. Based on the crop water need, farmers can then estimate the water requirement and the cost of water for their yearly farming schedule. Farmer can also estimate the total profit for their farm. During water restriction scheme, they make decision on which crops should have higher irrigation priority (usually based on which crops yield higher profit).

2.2 Margin value and crop value

The profit margin for crop productivity can be calculated using the following formula(Klos & Nooteboom, 2001).

$$V_{profit} = Total\ Revenue - Total\ Cost \quad (2)$$

V_{profit} is total profit in the farm which is calculated by subtracting the farming cost (Total Cost) from the crop revenue (Total Revenue). The crop revenue varies by plot size, value of crop (price per kilogram) and harvesting season. The farming cost includes the water consent fee, purchases of fertilizers (dollar/hectare), labour charges, etc. The goal is to obtain as much profit as possible.

2.3 Multi-agent approach and auction system

Multi-agent agent system has been applied to solve complex problems such as resource allocation problems(Jennings, 2002). Agent can be adapted to many types of modelling with varying agent behaviors (Le Bars et al., 2004). When the environment changes, agent can learn and adapt itself to the desires of its users(Bellifemine et al., 2007). Agent based model has also been implemented in water resource allocation. For example, agent based model was used for capturing the collective problems in small and large scale water infrastructure provision. This is done by simulating the different behaviors of water users to learn and understand the complexity of water use at Maule river basin(Berger et al., 2006). Giuliani et al.(Giuliani et al., 2015) proposed a multi-agent system to demonstrate a hypothetical water allocation problem. This model involved several active agents and passive agents under the same environment to investigate efficiency-acceptability tradeoff. The results were used to support the design of a distributed solution. In terms of water policy analysis, multi-agent can be used to create simulation model for improved policies. For example, uncertainty analysis was applied in agent-based model for optimising complexity of residential water use in Beijing, China. The multi-agent can evaluate the consumer responses on water and provide insights to seller agency to develop water usage policy(Chu et al., 2009). (W. Huang, Zhang, & Wang, 2011) developed a water resource allocation in China using multi-agent and complex adaptive system. In this work, multi-agent was used to verify rules of internal stage and behavior of the agent based on government policy. The results showed that the typical characteristics from agent changed based on the situation and can be used to improved water management policies. (Ding et al., 2016) used agent-based modeling to understand the interaction between stakeholder's in transboundary Nile River. This work generated farmers and water sharing scheme with the intention to optimize allocated water for each user and finding optimal water allocation method for stockholder's at basin based on crop types and user behaviours (Ding et al., 2016). Multi-agent modelling was implemented to optimize the trade-policies of inter basin water restriction in Texas, USA. The multi-agent model and complex adaptive system was developed to simulate consumer agents and were encoded to represent the interaction between consumers and policy maker agents to evaluate the performance of demand-side strategies (Krishna, 2010).

An auction is a process of buying and selling goods or services. The most popular auction protocol is the English auction which is an ascending-price auction. The auctioneer begins with lowest acceptable price and proceeds to finding the highest bidder. The auction is considered complete when no one increases their bid price and the item is sold to the bidder with the highest price (Krishna, 2010)(Mcafee et al., 2018). Another popular auction protocol is the first-price sealed bid auction where all bidders simultaneously submit sealed bids within a specified period of time and they have no knowledge of what the others bid. The winner is the one with the highest bid and he pays the price he submitted. There are many applications that apply auction mechanisms such as EBay and TradeMe. Both use intelligent agents to provide facility for users to make automated bids in auctions. To use the bidding agent, users only need to setup the maximum and minimum bid price for the item they are interested in(Bonabeau, 2002). Book.com uses continuous double auction that applies Markov model for agent behaviour to create bidding strategies. This auction supports trading process for users who can freely join and leave the trading market (Park, Durfee, & Birmingham, 2000). Sealed bid auction with econometric analysis was used in mussels' market in Netherlands. The purpose of this analysis was to identify factors that determine the mussels' price and to quantify the performance of individual purchase managers(Kleijnen & Van Schaik, 2011). It can be seen that the auction process is useful for trading goods and is also applicable to water allocation within a community irrigation scheme.

3 Multi-agent model for irrigation management

3.1 Conceptual design

This study focuses on using multi-agent approach to find an efficient mechanism for water allocation between farmers in a community irrigation scheme during water scarcity. As mentioned, each agent represents a farm that can calculate the total water requirement of the farm, prioritise crops to be irrigated, calculate water reduction for each crop in the farm, make decision whether to sell or buy water and negotiate with other agents. The multi-agent environment and the pseudo code for multi-agent water management system is shown in Fig.1. The system can be explained to two parts; 1) Total crop water need on single farm and 2) the negotiation process using first-price sealed bid auction. The crop water need is calculated using Equation (1) on each crop. The crop water need for a single farm is calculated using the single agent water management algorithm(Chiewchan, Anthony, & Samarasinghe, 2019). The agent is able to estimate the crop water need on a daily basis based on the farming information such as crop types, crop stage, and soil type (more details can be found in [3]).

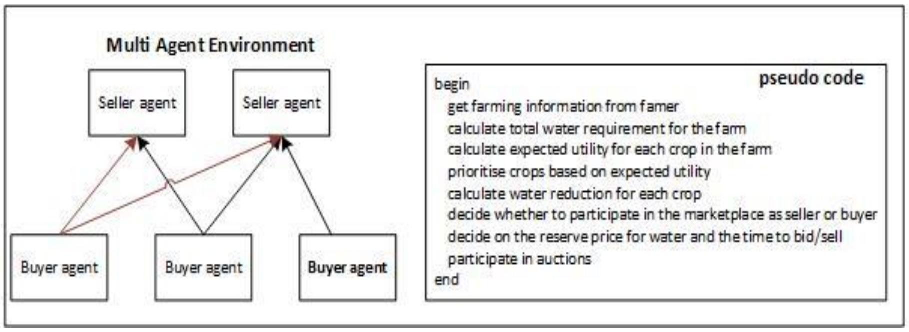


Fig. 1. Pseudo code for multi-agent irrigation management system

Agent creates a crops prioritized list which follows the decision rules based on productivity value, drought sensitivity and soil type respectively. The result of the calculation will show the total crop water need in the farm and whether the agent will be participating in the water marketplace as a bidder or a seller. The decision whether an agent should be a seller or a bidder is based on the farming profit calculation shown below:

$$P = \sum CV_i - \sum FC_j \quad (3)$$

Here, P is the total marginal profit in the farm, CV is the total crop value, FC is the total farming cost, i is the crops planted in the farm and j is the farming cost factors for each crop.

Based on the crop water requirement, the agent can decide to be a seller if it has excess water, or it can be a buyer (bidder) agent if it has water shortage. The seller agent will work out the reserve price (minimum price it is willing to sell the water) for its water based on price per cubic meter. On the other hand, a buyer agent sets a reserve price (maximum price it is willing to buy water) which is dependent on the expected profit in the farm. The water pricing equations are shown in (4, 5 and 6). The water price for agents varies by farming profit. We can assume that the profit will decrease during water scarcity but the total farm cost is the same. In this situation, the farming profit value will decrease if farmer does not have enough water for the farm as shown in Equation (4). On the other hand, if the farmer has more water than required, he can gain more profit by selling water to others as shown in Equation (5). The expected profit function is shown in Equation (6) where x is the profit changed value (in dollars), $f(y)$ is the total farm cost function and $f(z)$ is the utility function for water pricing. $f(z)$ is then used as a maximum price for the buyer agent and a minimum price for the seller agent.

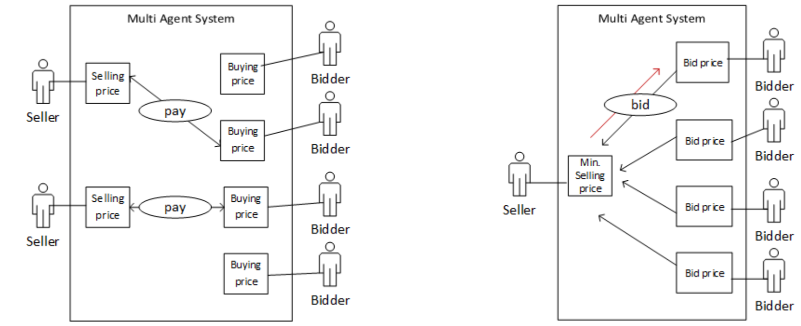
$$P - x = f(x)_{income} - f(y)_{farm\ cost} \quad (4)$$

$$P + x = f(x)_{income} - f(y)_{farm\ cost} \quad (7)$$

$$f(z) = \begin{cases} \sum CV_i - \sum FC_j - x & ; seller\ stage \\ \sum CV_i - \sum FC_j + x & ; buyer\ stage \end{cases} \quad (6)$$

3.2 Multi-agent irrigation management process

In this scenario, we used two negotiation mechanisms (direct negotiation with fixed price and first-price sealed bid auction). The direct negotiation with fixed price mechanism is where a seller wishes to sell his excess water with a fixed price. The seller will broadcast this sale to the all the agents in the marketplace. Any buyer agents who are willing to buy water at this price will respond with an offer to buy from the seller agent. If there are multiple buyers making the offers, the seller will sell the water at the price he set to the first buyer who offered to buy the water (see Fig.2 (a)). The second negotiation mechanism is using first-price sealed-bid auction. The seller broadcasts to all the agents in the marketplace with the auction deadline and each buyer agent will then make an offer to the seller agent. When time is up, the seller will select the highest bidder as the winner (see - (Fig.2 (b)) as long as the bid is equal to or higher than the seller's reserve price. In this case, the bidders have no knowledge of the reserve price set by the seller. They are also not privy to the bids of the other bidder agents.



(a) Direct negotiation with fixed price mechanism (b) First-price sealed-bid auction Mechanism

Fig. 2. Negotiation mechanisms

3.3 Experimental setup

The purpose of this experiment is to determine which negotiation mechanism is more efficient in water allocation within a community irrigation scheme. To test the performance of multi-agent irrigation management system, we conducted the two experiment using the two seller agents and twenty bidder agents using the two negotiation mechanisms. For each experiment, we randomly generated 20 farms with varying crop properties which are common in New Zealand's farm. Crop properties are randomized based on the growth stage and crop types. The farm size is fixed to 200 hectares and the water capacity to 15,000 m^3. The actual water need is calculated based on FAO's formula for calculating crop water requirement(Doorenbos & Pruitt, 1977). To simulate water scarcity situation, we run this experiment using three reduction schemes at 5%, 10% and 15% (these reduction schemes are set by the community irrigation scheme based on the water availability) and compared the total loss of all the farmers in the community. We also observe the additional profit earned by those sellers with excess water.

4 Results and Analysis

Table 1 shows the total loss for the all the farmers (sellers and bidders) in the irrigation scheme. If water is not traded among the agents, the total loss are 10.23% (5% reduction), 11.54% (10% reduction) and 13.11% (15% reduction). Using direct negotiation with fixed price mechanism to trade water, the total loss is reduced to 9.77%, 11.23% and 12.97% respectively. It can also be seen that, all the remaining water are distributed to the farms (shown as 0.00 in the table). This also shows that it is better to trade the excess water as the losses can be reduced. This would mean that the sellers gained additional profit by selling their water to the other farmers who need it which in turn allow the buyers to reduce their losses. Using first-price sealed bid auction mechanism, the loss is reduced further to 9.12%, 10.80 and 12.35% for the three reduction schemes. All excess water were also successfully traded. This indicates that water allocation using first-price sealed bid auction resulted in a lower loss compared to direct negotiation with fixed price mechanism. This also means that allocating water using auction mechanism is economically better than using fixed price mechanism.

Table 1. The average proposed water management for difference reduction schemes.

	Water reduction (m^3)					
	5% of reduction		10% of reduction		15% of reduction	
	Value	%	Value	%	Value	%
Total water left (m^3)	28,080	9.36	37,200.00	12.40	39,210.00	13.07
Total loss ($)	710,371	10.23	801,337.60	11.54	910,358.40	13.11
Fixed price mechanism						
Total water left (m^3)	0.00	0.00	0.00	0.00	0.00	0.00
Total loss ($)	678,428.80	9.77	779,811.20	11.23	900,636.80	12.97

Auction mechanism						
Total water left (m3)	0.00	0.00	0.00	0.00	0.00	0.00
Total loss ($)	633,292.80	9.12	749,952.00	10.80	857,584.00	12.35

Fig.3 shows the percentage of marginal profit based on trading mechanism. It can be seen from Fig.3 that farmers/agents with excess water cannot gain additional profit if water is not traded (shown as 0 in Fig.3). However, it can be seen that using direct negotiation, sellers gain additional profit. (1.97% with 5% reduction, 2.21% with 10% reduction and 3.57% with 15% reduction). This is as expected as trading excess water would lead to additional profit for the sellers. It can also be observed that using first-price sealed bid auction mechanism, the additional marginal profit is higher that the additional marginal profit gained from direct negotiation with fixed price. The additional marginal profit increases to 2.28%, 2.85% and 3.89% respectively. Both trading mechanisms yielded additional marginal profit, but first-price sealed bid auction would be the preferred mechanism as it generated higher additional profit margin.

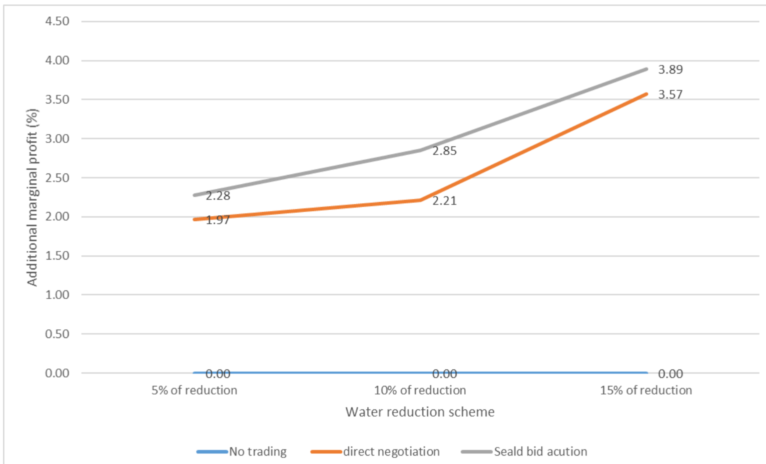


Fig. 3. The percentage of agent's marginal profit

5 Conclusion and discussion

In this paper, we describe a multi-agent irrigation management system that can be used to distribute water efficiently between farms in a community irrigation scheme. The advantage of this MAS system is in its ability to autonomously decide on behalf of the farmer whether to engage in a negotiation or not depending on the current water situation in the farm. This MAS is especially useful for farmer who needs to optimize marginal profit in the farm during water scarcity. Based on the preliminary experimental result, it can be seen that the total loss for each farm can be reduced using first-price sealed bid auction. This loss is much lower when compared to trading water using direct negotiation with fixed price. Moreover, seller agents with excess water were able to obtained additional profit when they traded their excess water. In this experiment, it can also be observed that using auction mechanism is better than direct negotiation as it resulted in higher (additional) marginal profit. For future work, we plan to extend this work by implementing combinatorial auction to trade water. In its current design, it is assumed that the farmers sell their excess water as a single unit. In reality, farmers might be more interested in buying parts of the water (purchase certain volume for a certain price) depending on their needs. This means, that if a farmer has a 1000m^3 in volume, he can choose to sell the water in units with different prices (200m^3 at $x, 500m^3 at $y and 300m^3 at $z). It is quite possible that farmers will be able to recover their losses further by using this mechanism and may result in a more efficient market. Other types of auction mechanisms will also be explored.

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