Irrigation, Water Market and Climate Change:
Three Essays

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Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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Abstract

Irrigation water is crucial for agricultural production and plays a vital role in ensuring food security, supporting economic development, and alleviating poverty, particularly in developing countries. However, climate change has brought numerous challenges in the use and management of irrigation water, such as reduced availability, changes in water regimes, and more frequent extreme weather conditions like droughts. These challenges have significantly altered the way water resources are managed and allocated, resulting in a paradigm shift in water governance since the 1990s. This shift emphasizes the economic value of water as a scarce resource, the need for integrated strategies to address water scarcity that involve all stakeholders, and the unpredictable nature of future climatic conditions and associated challenges that water governance must manage. Despite these changes, there is still an inadequate understanding of the challenges confronting irrigation water governance and the potential tools that can be used to address them. Economic instruments, such as market-based approaches, can be effective tools for managing water demand and allocating scarce water resources in the face of climate change. This thesis comprises three studies that examine the multidimensional challenges of irrigation water governance, the functionality of market-based instruments in water allocation, and their potential contribution to mitigating the impacts of climate change. The studies also investigate the effects of climatic conditions on the trading behaviour of water market participants.

The first study presents a comprehensive framework for assessing the ability of water governance, particularly in irrigation water management, to cope with climate change. The framework evaluates irrigation water governance based on five attributes: economic efficiency, equity, environmental sustainability, adaptability, and resilience. The study uses four case studies from various jurisdictions worldwide to demonstrate the application of the proposed framework. By mapping the characteristics of water governance in the studied regions and the scoring results based on expert opinions I collected, I identify strengths and weaknesses in each jurisdiction and overall patterns, which could inform future policymaking. My findings also indicate an improvement in the economic efficiency of irrigation water use over the past few decades and the contribution of market-based instruments in managing the impact of climate change.

The second study takes a closer look at market-based instruments in water management to examine their functionality and performance, using the Murray-Darling Basin (MDB) water market in Australia as a case study. The study investigates several key market attributes, including price and price volatility, traded volume, number and the average size of transactions, and net import across a number of trading zones in the sMDB, using a fixed-effect model. My analysis reveals that the price mechanism in the water market works efficiently, as the water prices signal the level of scarcity and reflect the value that can be derived from water resources through agricultural production. Other factors like crop structure and institutional settings also contribute to differences in market attributes across trading zones. Overall, the findings document that water markets serve well their fundamental purpose in water resource management, and that various products available in the market enhance market efficiency.

The third study uses a portfolio approach to analyze the impacts of climatic conditions, particularly water availability, on the optimal trading strategies of water market participants. This study utilizes transactional trading data from 2008 to 2019 in the southern Murray-Darling Basin (sMDB) water market to construct dynamically-adjusting optimal water portfolios for water market participants, including irrigators and non-landholders (i.e. pure investors) who have previously received little attention in related studies. The findings illustrate the benefits of portfolio management in improving returns, reducing risks and securing water supply, as opposed to the traditional ownership of a single type of water right. My findings also highlight the different roles that various water products play, based on the composition of optimal portfolios under different water availability conditions.

In summary, this thesis addresses the challenges that irrigation water governance confronts in the context of climate change and provides in-depth discussions about potential tools to deal with the challenges. My research highlights the crucial role of economic instruments, particularly water markets, in mitigating these challenges, based on empirical evidence and optimization results. The thesis points to the applicability and advantages of market-based approaches to natural resource management more broadly.

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Chapter 1 Introduction

This thesis consists of three independent yet interconnected studies. Each study is self-contained, with its own introduction, background and literature review. This introduction chapter aims to provide an overview of the scope of the three studies and the overarching research objectives. The last section of this chapter introduces each of the three studies and highlights their respective roles in addressing the research questions.

1.1 Background

Water is an indispensable resource for sustaining all forms of life on our planet, cultivating crops, supporting industrial production and economic growth, offering recreational opportunities, and inspiring admiration for its intrinsic and aesthetic value. Water scarcity is a key challenge to the continued development of human society and to the protection of the natural environment and ecological systems that envelop us. About 1.4 billion people live in areas with high and extremely-high water vulnerability (UNICEF, 2021) and about 4 billion people, nearly two-thirds of the world population, experience severe water scarcity during at least one month in a year (Mekonnen and Hoekstra, 2016). Among all uses of water, agriculture is the biggest water user, accounting for over 70% of total water abstractions worldwide (Grafton et al., 2016). Conflicts often arise between irrigation and other uses of water including environmental uses and among irrigators themselves (Molle and Berkoff, 2007). While meeting the irrigation demand has already been very challenging in many parts of the world, climate change exacerbates the stress through increased temperature and evapotranspiration rates, resulting in increased irrigation demand (IPCC, 2022). Reduced precipitation, increased climatic variability, along with more frequent, intense and prolonged drought events are also projected for many regions (IPCC, 2022), further challenging the ability of our water governance systems to manage this scarce resource efficiently while ensuring equitable opportunities exist for various groups of farmers to engage in irrigation and ensuring sustainable outcomes for the natural environment.

Much effort has been devoted to mitigating water scarcity. Traditionally, solutions to water scarcity rely on government-led centralised decision-making processes and technical solutions aiming at augmenting water supply to alleviate water stress (Pahl-Wostl, 2015). During the last century, massive construction of water storage and delivery infrastructure (e.g. dams, weirs, pumps and canals) have been carried out in response to the increased water demands resulting from intensified agricultural production and growing population (Wheeler and Garrick, 2020). The development of infrastructure has contributed to mitigating water scarcity by augmenting water supply, but the cost-effectiveness of doing so diminished with the rapid expansion and by the end of last century, it became very costly to further increase water supply, especially in developed countries (Chong and Sunding, 2006; Grafton et al., 2016). By the 1990s, there was a shift in the paradigm of water management away from solely relying on augmenting water supply toward combining with demand-side management measures, from focusing on technical solutions provided by the government towards recognizing the complexity in water management which requires the participation of various actors in society (Grafton et al., 2016; Molle and Berkoff, 2007; Pahl-Wostl, 2015). Demand-side management tools include educational approaches (e.g. campaigns), regulatory and planning processes (e.g. legislations and regulations) and economic-incentive-based instruments (e.g. water pricing, subsidies and water market) having been increasingly utilized (Wheeler and Xu, 2021). In the meantime, more emphasis has been placed on the economic value of water as a scarce resource and valuable input in production by the end of the last century. This turning point was marked by the Dublin International Conference on Water and the Environment in 1992 that stated 'managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources' (UN, 1992a).

The trend of devolution in the natural resource governance paradigm, along with the emphasis placed on the economic value of water, points to the use of the water market as a resource allocation mechanism. The water market is a mechanism through which water and water rights can be bought, sold, or leased, in part or in whole, from one to another (Griffin et al., 2012). This involves reforming water laws that transform a portion of public rights in water to rights that are divisible, transferable, privately managed and can be traded (Griffin et al., 2012). Water trading occurs in water markets in several forms, including temporary transfer of water use rights, permanent transfer of water use rights, medium-term leasing of water rights specified by contracts, and transfer of water delivery rights (Wheeler and Xu, 2021). Economic theory suggests that the market can serve as a powerful mechanism to efficiently and effectively reallocate water, maximizing the net benefit generated from water use by allowing water to be transferred from lower-valued uses to higher-valued uses (Dinar et al., 1997). In practice, however, successful operations of the water market require a range of legislative foundations, institutional settings and market regulations to be in place (Wheeler and Xu, 2021). The benefits of using the market as a tool to allocate water have been hotly debated in existing literature, with arguments for and against the water market being put forward. Criticism of the water market and concerns over market failures widely exist, including appropriate privatisation, negative externalities on the environment and inequitable allocation of benefits towards the wealthy and the powerful at the expense of the poor and vulnerable (Barlow, 2007; Hamilton and Kells, 2021; Harvey, 2003; Kiem, 2013). On the other hand, peer-reviewed economic studies find that many of these negative consequences represent failures of the surrounding institutional settings instead of inherent or inevitable outcomes of the water market *per se* (e.g. Grafton et al., 2016; Wheeler, 2022).

Despite the debates on the social impacts and net benefits of the water market, informal water trading and water markets historically existed in many regions (e.g. Italy, the United States, Spain and Mexico) (Wheeler and Xu, 2021). Since the 1970s, water markets have been formally established in several countries and regions (e.g. Australia, the United States, and Chile) with various levels of development and formality. A particularly notable example is the water market in the MDB, Australia, which is the biggest, most active, and most advanced water market in the world (Wheeler and Garrick, 2020). The MDB water market is equipped with well-defined water rights, relatively low transaction costs, and institutional arrangements that have evolved to facilitate the operation and management of water markets (Breviglieri et al., 2018; Grafton et al., 2011; Wheeler and Garrick, 2020). The participation rate is high, so that more than half of all irrigators in sMDB have traded entitlements (permanent water use rights) and more than three-quarters have traded allocations (temporary water use transfers) at least once (Seidl et al., 2020). There is also a range of security-differentiated water use rights and other products available in the market that have been utilized with increased sophistication by various participants, including non-land-holding investors (Seidl et al., 2020). The highly developed water market in the MDB with relatively abundant data provides us with an excellent example to investigate various attributes of the market and the investment behaviours of market participants. Such investigation may further shed light on understanding the role that market-based instruments can play in response to the challenges imposed by the changing climate. This thesis uses the MDB as a study region, combined with other case studies around the globe, to investigate various research topics around water governance and water markets as detailed in the next section.

1.2 Study objectives

Climate change has and will continue to impose unprecedented challenges on the governance of irrigation water. Although voluminous literature has been devoted to understanding how water governance can cope with the challenges brought by climate change and various management tools have been developed to facilitate the management of irrigation water, understanding of several key issues remains insufficient. Firstly, there is a lack of specific metrics or protocols that can be used to evaluate whether, and how well is the water governance system equipped to deal with climate change. Climate change does not simply aggravate water stress that already exists, but also imposes an unprecedented level of uncertainty in the supply of water that has important implications for the economically efficient, socially equitable and environmentally sustainable use of water, and for our ability to achieve such outcomes. While the problem is multi-dimensional, the articulation of such challenges and the ability of water governance to deal with them remain fragmented in the existing literature. Several lines of literature have discussed related topics from different aspects, including the use of economic and marketed-based instruments (e.g. Loch et al., 2013; Wheeler et al., 2014), adaptation behaviours (e.g. Adamson et al., 2017; Seidl et al., 2020), adaptive capacity building (e.g.Bettini et al., 2015; Pahl-Wostl and Knieper, 2014), institutional economic (e.g. Mariaet al., 2004), as well as environmental science and engineering aspects. There is, however, a lack of comprehensive study that pulls different aspects together and develop specific measures under one framework that provides a big picture of the challenges ahead and the ability to cope with such challenges.

Secondly, as a powerful reallocation tool, the water market may contribute to mitigating the challenges that climate change imposes on water governance. While many studies have been devoted to understanding the water market in economic literature (summarised in detail and examples of studies in Chapter 3), they have been largely focused on price movements. Other key market attributes that also have important implications for the functionality of water markets, such as trading volume and frequency, as well as price volatility, are under-studied. It is important to investigate these additional attributes to make an assessment of the functionality of water markets and to further understand the roles that water markets can play in mitigating the negative impacts of climate change.

Thirdly, an important way to understand the impacts of climate change is to investigate the trading and investment behaviour in water markets under different climatic conditions. Studies around the adaptation behaviour of irrigators mainly focus on farm management strategies instead of their trading behaviour in the water market. As the MDB water market becomes increasingly developed, the trading strategies employed by various participants become increasingly sophisticated. The understanding of trading and investment strategies employed by various groups of water market participants (e.g. perennial growers with inelastic demand and financial investors with no actual water demand) can shed light on the heterogeneous impacts of varying climatic conditions on different market participants.

The thesis contributes to knowledge on the above aspects by using three interconnected studies to explore the complex and dynamic relationships between climate change, water governance, water markets and individual behaviours. This thesis investigates these research topics on several scales (from the governance level to a market focus and to the individual level), using various methods including quantitative evaluation combined with qualitative case studies, empirical approaches and optimization methods. More detailed research objectives of each study and the methods used are provided in the next section.

1.3 Thesis structure

The rest of the thesis is structured as follows.

Chapter 2 presents the first analytical study that is built on a broad scope of water governance in an era of climate change. This chapter aims to evaluate the ability of water governance to cope with challenges imposed by climate change and map such abilities with the characteristics of water governance in the study regions based on the evaluation results. A comprehensive conceptual framework is proposed in this study to evaluate water governance based on five attributes: economic efficiency, equity, environmental sustainability, adaptability and resilience. Specific measures are developed for each attribute, which have been largely missing in previous literature. Four case studies of jurisdictions across the globe are presented to demonstrate the potentially wide application of the proposed framework, using scoring results based on expert opinions. The strengths and weaknesses of each water governance and overall patterns identified shed light on potential improvements in future policy making. This study also highlights the contribution of economic instruments, especially water markets, toward the mitigation of the negative impacts of climate change.

Chapter 3 narrows down the scope and focuses exclusively on the water market, using an empirical approach. While water markets have been widely adopted in many regions with various levels of development and market formality, there is a lack of comprehensive understanding of the functionality of water markets. This study examines the functionality and performance of the Murray-Darling Basin (MDB) water market in Australia by investigating fundamental drivers of key market attributes using transactional data. The study also explores differences between the ways the entitlement and allocation markets function, and the different roles that various products play in the market. While studies on the water market in the MDB have focused on the Goulburn-Murray Irrigation District (GMID), this study includes eight trading zones in the sMDB and utilized a fixed-effect model to control for fixed regional heterogeneities. This study also pulls water usage data by crop and transactional water trading data in these regions to build a unique dataset that has not been previously seen in the literature. Overall, the findings document that water markets serve well their fundamental purpose in water resource management, and that various products available in the market are enhancing market efficiency.

Chapter 4 takes one step further to investigate the trading behaviour and investment strategies of individual water market participants in their use of the water market as a risk management tool and water rights as valuable assets to invest in under different climatic conditions. This study employs a portfolio theory approach and transactional water trading data from 2008 to 2019 in major trading zones in the sMDB to build dynamically-adjusting optimal water portfolios for different groups of water market participants, i.e., irrigators and no-land-holding investors, the latter of whom have previously received little attention in related studies. The findings illustrate the advantages of portfolio management in improving expected returns, reducing risks, and securing water supply, in contrast to owning only a single type of water use rights. Our findings reveal that the composition of optimal portfolios varies under different water availability conditions, pointing to the different optimal strategies that may be employed by water market participants under different climatic scenarios and the different roles that various water products play in the market.

Chapter 5 summarizes the key findings of the three analytical studies and draws important conclusions. The chapter also discusses the limitations of this thesis and suggests directions for future research. Additionally, it explores the policy implications of the thesis.

The Appendices offer additional information and supporting materials to the three studies.

Chapter 2 Irrigation water governance in the face of climate change

2.1 Introduction

Climate change is expected to bring unprecedented challenges to the management of water resources. Changes in climate can alter the water cycle, and influence water availability both temporally and spatially. Projected changes in climate not only threaten arid and semi-arid regions where water uses are already under stress with decreased precipitation, but also impose new challenges through increased climatic variability in areas that typically enjoy sufficient water supply (OECD, 2015). Under a more variable climate, areas where water resources used to be sufficient may experience water scarcity during certain seasons, even with the average annual precipitation remaining similar to the historic levels. Increased climate variability also means increased intensity, length, and frequency of extreme conditions like floods and droughts, imposing an additional layer of difficulty in managing water (IPCC, 2022). In the face of intensified water scarcity and increased uncertainty in water supply, competition and conflicts around water use will arise among users from different sectors, like industrial, agricultural and urban water sectors, and between human society and the natural environment. These new challenges and complex interactions between various water users call on society to deal with water management problems with more integrative and comprehensive strategies (Hill, 2013; Pahl-Wostl, 2015).

Water management is traditionally characterized by top-down approaches and centralized decision-making processes that aim at providing technical solutions to well-defined and often segmented issues (Pahl-Wostl, 2015). While such an approach has contributed to the mitigation of water crises in the past century resulting from the rapid growth of population and intensified industrial and agricultural production, it has reached its limit and has proven to be inadequate in many cases (Wheeler and Garrick, 2020). It is getting increasingly costly and difficult to further augment the water supply, especially in developed countries (Chong and Sunding, 2006). A new paradigm of water governance, that started developing in the 1990s proposes that water be managed in a broader framework that recognizes the complexity in water management instead of simply relying on technical solutions to specific issues. UNDP (UNDP, 1997) defines water governance as "encompassing the political, economic and social processes and institutions by which governments, civil society, and the private sector make decisions about how best to use, develop and manage water resources". In contrast to the traditional top-down hierarchical system, the new paradigm of water governance features devolution and emphasizes the complex interactions between various interest-groups, institutions and organizations (Pahl-Wostl, 2015). It is important to have a range of public, economic, social and administrative systems in place and to form partnerships to encourage and ensure the participation of various stakeholders from different sectors, and resolve conflicts among different interest groups in the process of managing water resources (Tortajada 2010).

To develop adequate water governance that is resilient to climate change, it is important to first understand how water governance characteristics are associated with their ability to cope with climate change. There is however a lack of evidence for such linkages in the existing literature, especially in terms of economic and equity measures. In the context of climate change, it will be critical to have water governance geared up to mitigate the negative social-economic impacts of potential shortages and uncertainties in water supply, resolve conflicts and equity concerns that arise between competing users, and keep the balance between the economic development and the health of local environment and ecosystem. Therefore, this study proposes a multi-dimension framework that evaluates how water governance is prepared to deal with challenges imposed by climate change with a focus on irrigation water use from the perspectives of economic efficiency, equity and environmental sustainability. In addition, studies on water governance and climate change have focused on the adaptive capacity that indicates the innate ability of water governance to respond to uncertainties and new situations. Incorporating the findings of adaptive literature, I add two more attributes to the assessment framework: adaptability and resilience, and enforceability. This framework is the first that evaluates the ability of irrigation water governance on such a comprehensive scale and also the first to identify specific measures for these key attributes which allow for detailed diagnosis of a given water governance system and comparative studies across jurisdictions.

As this study focuses on irrigation water use, the economic aspect of water governance is of particular relevance. Among all uses of water, the agricultural sector stands out as the biggest water user, consuming approximately 70% freshwater globally (OECD, 2021). As water is a critical input—often the most important limiting factor in agricultural production—, shocks in the agricultural water supply can result in severe economic consequences and food security issues. Irrigation also plays an important role in poverty reduction, employment opportunity generation and regional development especially in developing countries (Tortajada, 2010). In addition, conflicts often arise between the agricultural use of water and the environmental and in-stream use of water, again due to the large volume of extraction of water for irrigation purposes (Molle and Beroff, 2007). It is thus crucial to understand how the ability of irrigation water governance to cope with climate change can be reflected in specific economic and economically-relevant equity and environmental terms. To further illustrate the use of our framework and demonstrate such linkage in specific water governance systems, I apply the developed framework to six jurisdictions, the MDB in Australia, Spain, Italy, Uruguay, Chile and California in the U.S., by quantitatively evaluating the ability of irrigation water governance in these regions to deal with climate change based on expert opinion (scoring) that I collected. Detailed discussions are provided for the first four jurisdictions as case studies based on the expert opinion to identify the strengths and weaknesses of water governance in the jurisdictions and their policy implications.

This chapter is organized as follows: the next section provides a review of related literature and discusses the gap in existing literature with regard to frameworks that assess the ability of water governance to cope with climate change. The third section introduces our evaluation framework and explains the measures I develop. The fourth section describes the methods I employed to conduct expert opinion surveys and case study analyses. In the fifth section, I present the survey results and four case studies where I analyse the scoring results in combination with the characteristics of water governance and projected changes in future climate in these regions. The sixth section provides discussions around the findings and a conclusion section is offered at the end.

2.2 Literature Review

The major trend in water policy and management in the past decade showed a shift from focusing on the role of government and centralized regulation to a more encompassing notion of water governance that emphasizes the roles that local communities and social networks play. Decentralization and privatization have gained popularity since the 1990s, fostering the shift of governance mode from bureaucratic hierarchies to market-based and network modes (Pahl-Wostl and Knieper, 2014). Together with the rise of 'demand-side management', more attention and emphasis have also been placed on the economic dimension of the use of water. The Dublin International Conference on Water and the Environment in 1992 proposed a set of principles that states 'managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources' (UN, 1992b). Today, water pricing is practised in most countries across all water use sectors, including agriculture. Water markets have also been operating in several countries with some successful examples including Australia, Chile and the USA. However, some studies, have also pointed out that privatization and market-based approaches have experienced failures, especially in some developing countries (Bakker, 2010). Pahl-Wostl and Knieper (2014) highlighted the importance of embracing the complexity of water governance instead of relying on a single instrument or governance mode to serve as a "panacea" for complicated water governance problems.

Much effort has been devoted to developing principles and frameworks to guide water governance and to assess their performance. The concept of "good governance" first proposed by the United Nations (UN) has become popular since the 1990s. It outlined a set of criteria from a normative perspective for attributes necessary to achieve effective governance and to overcome failures in the system (Rogers and Hall, 2003). Some core attributes/principles include inclusiveness, accountability and trustworthiness, effectiveness and transparency (Hill, 2013). The concept and principles of good governance have been used in analytical studies and empirical research to assess governance systems or public policies (Kooiman, 1993). It is found that in general, good governance is strongly correlated with desirable societal outcomes, such as higher per capita incomes, lower infant mortality and alleviated poverty issues (Rogers and Hall, 2003). Various organizations and studies have attempted to identify key components and developed indicators/assessment frameworks for achieving good governance in different fields. The International Union for Conservation of Nature (IUCN) proposed the Natural Resource Governance Framework (NRGF) which set the standards for desirable natural resource governance following the principles of good governance and provided practical guidelines for assessment (Campese et al., 2016). Examples of the NRGF principles include recognition and respect for legitimate tenure rights, devolution for community-based natural resource governance, sustainable resources and livelihoods, social and environmental accountability, and protection of the vulnerable members of society (Campese et al., 2016). Jiménez et al. (2020) took one step further to develop an operational framework that combines the desirable attributes under the concept of good governance with the notions of governance function (e.g. policy and strategy, planning preparedness, financing, regulation and monitoring, evaluation and learning etc) and governance outcomes (e.g. enabling conditions, behavioural change, change in social and environmental conditions etc) to assess and assist water governance. Integrated Water Resource Management (IWRM), another approach that became prominent in water management since the 1990s, also has framed the principles of good governance (Hill, 2013). IWRM promotes coordination in the development and management of water and other resources and aims to achieve socially equitable, economically sound and environmentally sustainable outcomes (Rogers and Hall, 2003). IWRM has been adopted by many countries, but its performance and outcomes achieved have been widely debated (Pahl-Wostl, 2015).

While frameworks and principles under the concepts like good governance and IWRM have provided guidelines for effective, sustainable and equitable water governance, they did not specifically address the challenges water governance is facing with climate change. Some studies have pointed out that it will become increasingly inadequate to merely apply past knowledge to current problems, especially in an era of climate change (Hill, 2013). The speed of change and the level of uncertainty that water governance faces in the context of climate change is unprecedented. Climatic change can cause both increased temporary variations and permanent shifts in climatological and hydrological patterns that may incur novel challenges beyond the realm of traditional and existing knowledge and experience (Smit and Wandel, 2006; Yohe and Tol, 2002). This stream of literature, therefore, focuses on understanding the adaptive capacity and resilience of water governance to deal with largely unpredictable challenges climate change may impose. Nelson et al. (2007) described adaptive capacity as the ability of the system to react to environmental and climatic change in order to facilitate and mobilise adaptation, both in anticipation of, and in response to future or existing pressures. More adaptative capacity is likely to lead to higher resilience of the system in the face of climate change (Engle et al., 2014). Some important topics in this stream of literature include the effects of formal institutional and legislative settings (Ebbesson, 2010), informal social networks (Nooteboom, 2006; Olsson et al., 2006), multi-level and polycentric governance (Ostrom, 2010; Pahl-Wostl et al., 2012) and social learning process (Butler et al., 2015; Pahl-Wostl, 2009; Pelling et al., 2008) on the ability of resource and environmental governance to adapt to climate change. While most literature in this field focuses on a small number of fragmented case studies, some large-scale comparative case studies have also been conducted to provide empirical evidence on key factors contributing to the adaptive capacity of resource governance. For example, Pahl-Wostl et al. (2012) took a contextual diagnostic approach based on water governance regime, regime performance and socio-economic context to comparatively assess the water governance in 29 national river basins across multiple countries. The study found that polycentric governance regimes together with effective coordination structures have an important influence on improving the adaptive capacity of water governance in coping with climate change.

Studies of the adaptive capacity have been focusing on the institutional and social components, including legislation, policies, formal and informal institutions, and the interplay between non-state and state actors as summarised above. However, the economic component, as one of the three pillars of the concept of sustainability, is largely missing from existing literature that deals with water governance evaluation in the context of dealing with climate change, i.e. the resilience and adaptive literature. In terms of relevant economic studies, Grafton et al. (2011) developed the first comprehensive and integrated framework to assess and compare water markets based on both qualitative and quantitative measures in three categories: institutional foundations, economic efficiency and environmental sustainability. Wheeler et al. (2021) developed a framework to assess the readiness of the water market using three steps: 1) background context which considers the hydrological information, and evaluates the existing institutional, legislative and regulative capacity to enable water trading; 2) market evaluation, development and implementation that considers the potential gains from trade, market scale, transaction cost, and market initiating policies; 3) monitoring and review that involves developing trade enabling mechanism which improves trade capacity and supports adaptation in the water market. While these two studies provided examples of key economic measures to consider for water markets and enabling institutional factors, they did not specifically address the challenges and uncertainties brought by climate change. The framework that is proposed in the present study also operates on a broader scope of water governance, instead of only focusing on the water market as an economic instrument. Drawing on both the adaptive capacity literature in the field of water governance and on economic literature, I propose a comprehensive framework that demonstrates how the ability to adapt to unforeseen situations and manage uncertainty can be reflected in economic measures/indicators and economically relevant social and environmental indicators. Such a framework can be used more generally to identify the strength and weaknesses in any water governance system and thus guide the development towards more resilient and adaptive governance of irrigation water.

2.3. Conceptual Framework

This section articulates each of the five attributes proposed in the evaluation framework in terms of their significance for the ability of water governance to cope with climate change and specific questions/elements one should focus on when evaluating such ability of water governance in a given jurisdiction. While the framework uses these five attributes as its foundational pillars for evaluation, it is essential to recognize the interconnectedness and potential conflicts among them. For instance, enforceability forms the bedrock of environmental sustainability. Disentangling these two components when addressing water governance issues can be challenging. Concurrently, the pursuit for economic efficiency often conflicts with environmental objectives or the principles of social equity. As such, even though all five attributes are aspirational, trade-offs are inevitable. Striving to attain the ideal in all attributes simultaneously in the real world may not be feasible. At the same time, water scarcity is a pressing global issue, but the governance of this essential resource is inherently local. Distinct geographical, socio-economic, and political contexts mean that the optimal water governance model may vary significantly across regions. Given the trade-offs often evident among the five attributes and the inherent challenges in realizing them all at once, it becomes crucial to assess the relevance of each attribute in relation to specific local conditions when addressing climate change challenges. In this section, I delve into the universal aspects of these five attributes. The subsequent section, which applies the framework to case studies, aims to integrate these principles with the unique characteristics inherent to each locale.

A summary of the key elements of each attribute and the overall structure of the evaluation framework is presented below in Figure 2.1.

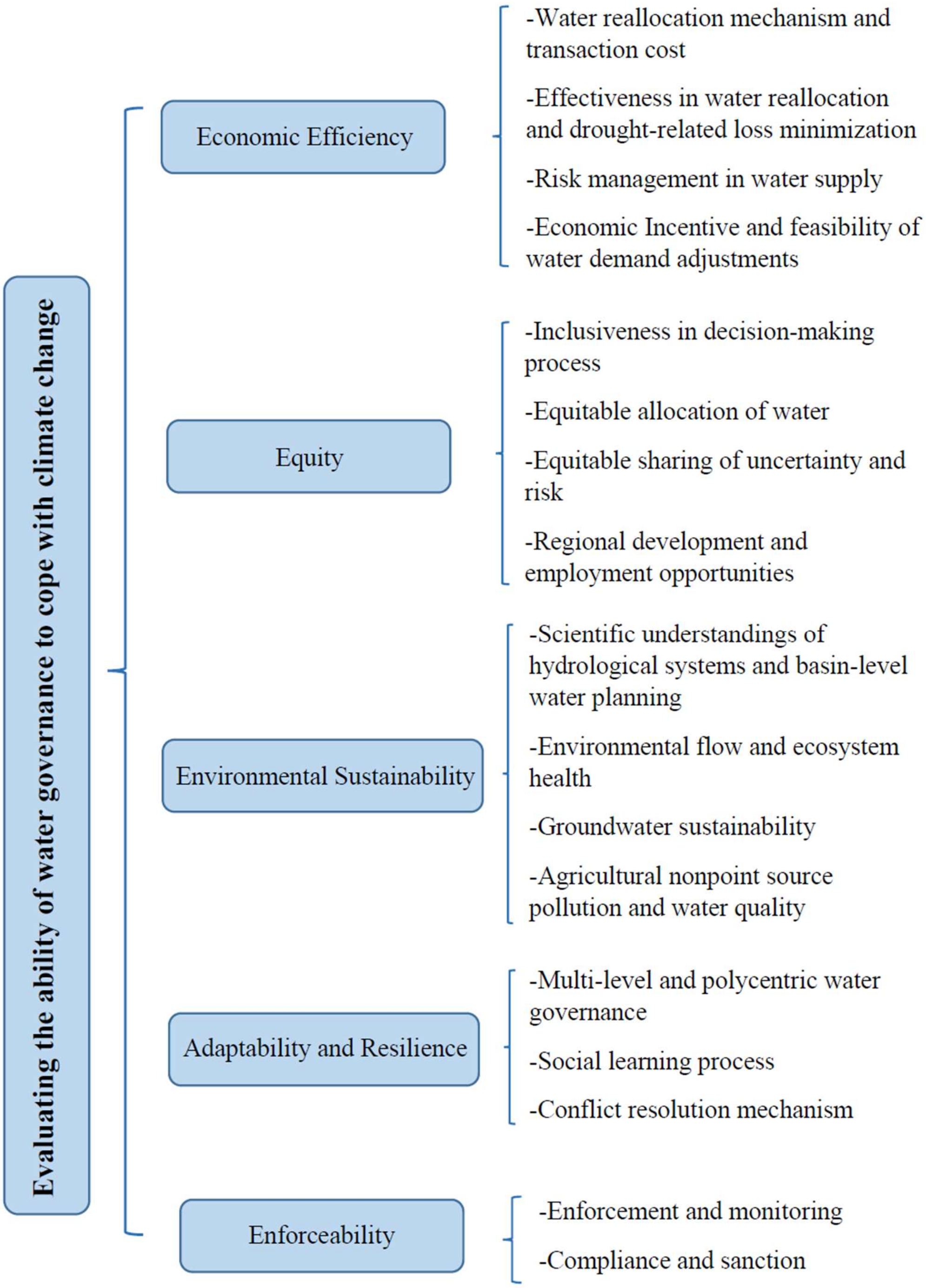

Figure 2. 1 An evaluation framework to assess how well water governance is prepared to cope with climate change.

2.3.1 Economic Efficiency

Economic efficiency in natural resource economics has been focusing on the welfare aspects of resource use (Wheeler and Xu, 2021). An allocation of natural resources, including water, is said to be economically efficient if it maximizes the net welfare generated from the use of the resource for society (Dinar et al., 1997). This can be achieved by allocating scarce water resources to their highest-valued uses until marginal benefits are equalized among competing users (Dinar et al., 1997). Market mechanism allocates water efficiently by creating price signals that reflect the scarcity value of water and value that can be derived from different water uses, potentially including environmental values if appropriate arrangements are in place, e.g. the Commonwealth Environmental Water Holder (CEWH) in Australia (Ancev, 2015). While the market-based approach theoretically offers a solution to efficient water allocation, the successful operation of a water market in reality requires a set of conditions to be met, including a variety of institutional and legislative arrangements (Wheeler and Xu, 2021). In regions or countries with limited institutional capacity, it may be more beneficial to rely on other mechanisms for water reallocation (Wheeler et al., 2021), such as water pricing, rotational delivery plans, voluntary agreements between user groups, or direct administrative orders. The emphasis, therefore, should be placed on the effectiveness of allocation (i.e. whether the marginal value of water use is equalized among all users) and the cost of allocation/reallocation, instead of the specific type of instrument used. When evaluating the economic efficiency of allocating water as a scarce resource, it is important to consider the potentially high administrative costs involved in decision-making and the deadweight loss incurred by inefficient water reallocation. In the face of increased variability of water availability, both temporally and spatially, flexible water reallocation among alternative users will be increasingly needed. The lack of instruments that support effective water reallocation at low costs in response to changing climatic conditions will greatly impede the economic efficiency of water use and result in significant losses, especially during unexpected drought events.

Since climate change is a continuous process, it is also important to consider economic efficiency in irrigation water use over multiple periods. This means that the expected total net benefit from water use over multiple periods should be maximized. It is therefore critical for water users to be able to respond to projected and perceived risks and benefits in the future. Climate change could result in both temporary and permanent shifts in water regimes (IPCC, 2022) that can potentially create large uncertainty in irrigated agricultural production planning. This could be a significant issue for irrigators who have inflexible water demand and relatively long production planning cycles, e.g. perennial crop growers. Effective water governance should be able to provide schemes or instruments to support irrigators to manage water supply risk inter-seasonally and for even longer periods based on expected risks and benefits. Possible tools include on-farm water collection systems, secure entitlements, long-term leasing of water, access to groundwater, availability of spot market water for purchase, etc.

To maximize the net benefit of irrigation water use, it is also important for water governance to facilitate and provide incentives for irrigators to adjust water demand based on climatic conditions in both the short and the long term. For this purpose, it is critical that water is managed volumetrically and is delivered on demand (by request). Volumetric management, where the volume of water supply and use is metered, is an important prerequisite for using economic incentive-based instruments like water pricing or tradable quotas (i.e. water markets). However, it is not implemented in most developing countries, as well as in many developed countries, and it is especially lacking for irrigation water use (Molle and Berkoff, 2007). In some regions, water is delivered and charged in bulk, for example, on the district or village level, which means that individual irrigators have no economic incentive to adjust their water uses (Molle and Berkoff, 2007). Delivery of water based on the demand of individual irrigators is therefore another important condition that enables irrigators to adjust water use, especially in times of water scarcity. Adjustment in water use can originate from switching between irrigated production and dryland farming, or between crops, e.g. perennial versus annual crops. Temporary (allocations) and permanent (entitlements) trading in water rights can serve as important tools to facilitate such adjustments. In the relatively short term, water reallocation can assist adjustment in demand by allowing annual crop growers to give up farming or irrigating in the current season and sell their water instead. In the long run, tradable water entitlements allow farmers to enter irrigation by purchasing entitlements and to exit by selling entitlements.

2.3.2 Equity

Equitable water governance should offer equal economic opportunities for all water users, i.e. should not be picking winners and creating distortions. As water is a critical input to agricultural production, this means equal access to irrigation water based on the marginal value of water use (i.e. productivity) and equal access to water services (e.g. delivery and drainage). In the context of climate change, this becomes more complex, as the meaning of equitable water governance refers to offering equal opportunities to all in the face of climate change, i.e. the water governance should not advantage or disadvantage certain groups in terms of their ability to deal with the negative impacts of climate change. Given the heterogenous demand elasticity for water among irrigators, their vulnerability to shocks in water supply can vary dramatically. For example, horticultural irrigators have much more inelastic demand than annual crop irrigators and will suffer high capital losses if there is an insufficient supply of water to maintain their perennial plantings. Access to risk management tools that help irrigators with inelastic water demand to mitigate the risks associated with water supply, and access to more secure water sources like groundwater can therefore contribute to the equity of water governance. This is of particular importance in the face of climate change given the increased variation in water availability and the higher possibility of lengthened drought events. The vulnerability of irrigators to droughts can vary depending on the water allocation and reallocation mechanisms. Under market-based mechanisms, irrigators with more flexible water demand can receive cash compensation by selling water during drought periods. Small irrigators with relatively inflexible water demand, e.g. horticultural irrigators, will be a lot more financially vulnerable to water supply shocks. In regions where the allocation of water in times of shortage depends on administrative orders from the authorities or local community agreements, interest groups with lower bargaining power may become more vulnerable during drought events. Some regions tend to secure water supply for perennial growers due to their high fixed costs, but without proper compensation, annual growers may then become financially vulnerable. This is not only an issue of distribution of wealth that could be generated from irrigation, but also an issue of sharing the burden of uncertainty and potential losses. With projected increases in the variability of water supply under future climate, it will become increasingly important to have mechanisms in place to support the vulnerable groups and reduce the uncertainty they bear, so no particular group is disadvantaged in their ability to deal with the impacts of climate change. For example, under market-based approaches, if there are mechanisms in place that enable small irrigators to securely lease water (potentially over a long period) from market participants that hold a large volume of water entitlements, the financial vulnerability of these small irrigators may be greatly reduced. Under non-market-based approaches, inclusiveness and representation of different interest groups in the decision-making process can make critical contribution in achieving economically and socially equitable allocation of water.

Spatial heterogeneity in water availability and water use can have impacts on regional developmental opportunities. Climate change may alter water regimes spatially which means that some regions may experience a larger reduction in water availability and higher variability in water supply than others. Changes in climatic conditions like temperature and evapotranspiration can also create a disadvantage for irrigated agriculture in certain regions or render them completely unsuitable for irrigation. Where water markets exist, trading patterns can change due to these factors too, so that large volumes of water may be traded out of regions that are not suitable for irrigated agriculture anymore. A large reduction in water use in a region due to these reasons, especially where irrigation used to be important, can cause a loss in job opportunities on farm and reduced economic activities, limiting the overall economic development of the region. Such reduction in irrigation water use can also cause irrigation infrastructure including weirs, channels and pipes to be underutilised and become stranded assets (Roper et al., 2006). When a large number of irrigators quit irrigation, the high costs of operating and maintaining the infrastructure will aggravate the financial burden of remaining water users and leave it financially not viable to provide water services at all (Roper et al., 2006). To achieve equitable outcomes in water allocation and use in the face of climate change, it is thus important for water policies to take into consideration the spatial heterogeneity in economic development and the vulnerability to changes in water regimes. In the meantime, other types of policies may need to be in place to support the economic development in the vulnerable regions rather than compelling irrigated agriculture to persist in these regions, e.g. through restrictions on water trading, which create distortions in the efficient allocation of scarce water resources.

2.3.3 Environmental Sustainability

Reduced average water availability and the increased frequency and severity of droughts in the projected future climate scenarios are likely to intensify the competition between agricultural and environmental water use, aggravating the vulnerability of aquatic and riparian ecosystems on top of the direct climatic impacts. Environmental flow, which is a water regime that reserves some water for the environment, has been utilized commonly to support river health and the functionality of ecosystems. Under the pressure of climate change, it will become increasingly important, and yet increasingly challenging for water governance to put effective policies and mechanisms in place to guarantee a minimum level of environmental flow, especially in times of drought, in order to avoid catastrophic ecological consequences and to maintain the benefits that freshwater ecosystems continuously provide to society. Market-based mechanisms have been used as a tool to provide environmental water for ecological outcomes by allowing environmental water holders to acquire entitlements through voluntary trades (e.g. the CWEH in the MDB, Australia). The CWEH is responsible for purchasing water entitlements and releasing acquired water to the environment when it is beneficial to do so (Connor et al., 2013, Ancev, 2015).

Groundwater is a relatively more secure source of water compared to surface water and thus can play an important role in the future security of agricultural production as a supplementary water source in the face of increased variability in climatic conditions (Castilla-Rho et al., 2017). The dependency of humankind on groundwater is high as groundwater represents 96% of unfrozen freshwater globally and accounts for 33% of total water withdrawal (Amanambu et al., 2020). In many parts of the world, however, the use of groundwater is not regulated or monitored. Excessive depletion and unsustainable use of groundwater without proper regulation may be further intensified with reduced surface water availability and increased variability. Effective regulations should be in place to cap and monitor the use of groundwater to guarantee the sustainability of groundwater use, which will be vital for the capability of water governance to cope with climate change in the long term.

Nonpoint pollution generated during agricultural production can have a large impact on water quality and the health of aquatic ecosystems (Badrzadeh et al., 2022). It is critical to understand the spatial distribution of pollution sources and the water regime to manage agricultural non-point pollutions (Badrzadeh et al., 2022). Alternation in the water cycle and resulting changes in land use, therefore, introduce additional uncertainties to the already challenging management of non-point pollutions.

Regulations and decision-making over environmental flow, water quality and groundwater should be based on a scientific understanding of the hydrological system and basin-level planning in a region. The cap on groundwater and implementation of environmental flow should be continuously monitored and revised if climatic conditions change.

2.3.4 Adaptability and Resilience

While past knowledge and experience may help with designing policies and building mechanisms that facilitate the adaptation to climate change, the high level of uncertainty projected in future climate and uncertainties within these projections themselves could impose unprecedented challenges for water governance. Solutions to these challenges may lie outside the boundaries of traditional knowledge, and it is therefore important to consider the innate ability of a governance system to adapt to changes originating from its structural features, the way it coordinates different actors in a society to cooperate in water management, and the pathways to learning from experience.

Studies focusing on the adaptive capacity of water governance have often placed emphasis on the structural features of governance. Polycentric structure and multi-level governance have been identified as being able to make important contributions to the ability of water governance to adapt to uncertainties and deal with unprecedented challenges (Folke et al., 2005; Ostrom, 2010; Pahl-Wostl et al., 2012). Polycentricity features multiple decision-making centres that are formally independent but coordinate under a set of accepted rules (Ostrom, 2010). For example, government departments, basin authorities and local administrators work together and coordinate on managing water resources under the same set of water laws. Polycentric governance enables flexible responses to unforeseen circumstances and experimentation through a certain level of autonomy of multiple decision-making centres and effective coordination between them both vertically (across administrative levels) and horizontally (across sectoral or jurisdictional borders) (Pahl-Wostl and Knieper, 2014). Polycentric governance overcomes the rigidity in policy response found in centralized regimes, and the low effectiveness and efficiency in fragmented regimes where there is a distribution of power but also a lack of coordination. Polycentric governance, therefore, is more adaptive to emerging challenges like climate change and more resilient to shocks and uncertainties (Pahl-Wostl and Knieper, 2014).

As past knowledge may be inadequate to deal with novel challenges, it will be increasingly important to have an effective learning process that enables the governance system to learn from the outcome of existing policy implementation and utilize the new knowledge to refine mechanisms, policies and regulations over time or potentially put in place new ones to cope with emerging challenges. Key questions to consider in order to gain a better understanding of the social learning process include whom to be engaged, at what scale and level the process of learning takes place, and the outcomes of learning. Learning can take place at different levels, from incremental changes in implementation strategies, revisiting underlying values and assumptions, to reflections on the processes by which learning takes place (Medema et al., 2014; Pahl-Wostl, 2009). The outcomes, therefore, may include changes in practice, in behaviours and values, and in institutions. The learning process thus is a process of managing change (Lebel et al., 2010). The understanding of, and facilitation for the social learning process contribute to the adaptive management of water in the face of climate change by enabling society to engage various actors, integrate knowledge from different sources and generate positive impacts towards more adaptive and sustainable policies (Medema et al., 2014).

In addition, it is vital to have effective conflict resolution mechanisms in place. Under increased water scarcity and unpredictability of water supply, potential conflicts related to irrigation water use may increase. Unresolved conflicts may hinder the implementation of water policies or harm the interest of water users, potentially resulting in negative social consequences. New types of conflict may also emerge that will need to be effectively solved.

2.3.5 Enforceability

Enforcement and monitoring are two critical factors/functions underlying all the above attributes. They are central to minimising water theft, securing environmental sustainability and acceptable water quality, and achieving equitable water allocation. There are challenges associated with the enforcement and monitoring of irrigation water use, often originating from the small sizes and large numbers of landholders, geographic dispersion and potentially high level of resistance to government intervention, especially those that are perceived as undermining farm profit and constraining agricultural production (Holley and Sinclair, 2012). Non-point pollution generated during agricultural production is also particularly difficult to regulate and monitor. Increased water scarcity and variation in water supply under future climate scenarios will further challenge the current ability of water governance to enforce and monitor irrigation water use. It is critical to have a set of effective enforcement mechanisms in place and to continuously monitor water use in order to achieve overall desirable outcomes. Effective enforcement mechanisms, such as rules and deterrence, advice and persuasion, criteria/principle-based regulation, facilitative regulation, risk-based regulation, and meta-regulation have been proposed and discussed in the literature (e.g. Holley and Sinclair, 2012) as potential solutions to address these challenges.

Recently, many studies have turned from investigating which regulation method will be the most effective to study the behaviour of regulated agents and the source of their motivation to comply. Pioneering this line of literature, Elinor Ostrom showed that inclusiveness in the decision-making process contributes to the compliance of regulated agents (Ostrom, 2000). Other factors identified to influence the compliance of regulated agents include legal punishment, economic costs, perceived social costs, shame, sanctions inflicted by local communities, issues of trust and/or individual or perceived societal norms, and the engagement of regulated communities' with the authorities (Ostrom, 2000). In the face of intensified water scarcity and an increased level of uncertainty in future climate scenarios, understanding of the source of effectiveness of enforcement and motivation for compliance from the perspective of regulated agents will become increasingly critical to ensure effective water governance and achieving desirable outcomes overall (i.e. in economic efficiency, equity, environmental sustainability and building of adaptive capacity).

2.4 Methods

In this study, I apply the framework discussed above to several case studies and evaluate each attribute of interest (i.e. economic efficiency, equity, environmental sustainability, adaptability and resilience, and enforceability) by asking experts in the related fields to score the attributes directly using online surveys[1]. For water governance related topics, due to its qualitative nature and the resulting difficulties to capture the characteristics and performances of water governance through quantitative methods, evaluations based on expert opinion on the same set of questions for multiple jurisdictions are commonly practised (Pahl-Wostl, 2015).

I identified and invited scholars who primarily focus on water governance/water economics, and preferably in relation to climate change, with multiple publications on the relevant topics for the jurisdictions included in this study to participate in our online survey. I mainly used keyword searching on Google Scholar combined with consultation with experts in the study jurisdictions who are familiar with the field and able to identify other relevant scholars. The keywords I used include “water economics” “water policy” “water governance” “climate change” and the names of the study jurisdictions. The invitations to participate were sent to identified experts through email. I collected their email addresses through public sources online, e.g. from publications or the contact information listed on their organizations’ websites. In total 123 invitation emails were sent to identified experts for the five study jurisdictions, including 19 for California in the U.S., 15 for Chile, 22 for Italy, 26 for Spain, 21 for the MDB in Australia and 19 for Uruguay. Given the region-specific nature of the case studies and therefore the small number of people working on this particular topic (i.e. water governance in the context of climate change with a focus on the economic factors), I consider that experts included in our invitation list is a reasonable approximation of the population of experts working in this field in those jurisdictions.

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[1] This survey of experts was approved by the human ethics committee, The University of Sydney [Project No: 2022/795].

I designed the questionnaire to be short in order to maximize the response rate and to obtain representative evaluation results for each jurisdiction. I eventually received 52 completed responses, with an overall response rate of 42%. Given that nearly half of the experts in the relevant fields completed the survey, the results are considered to be reasonably representative of the expert opinion for the study jurisdictions.

The survey was developed on Qualtrics.com platform. The survey was anonymous so that no personal information of respondents was collected during the survey and the results were non-identifiable. A sample of the questionnaire is provided in Appendix A. Scoring results from completed surveys were aggregated by jurisdiction for analysis as presented in the next section. A Likert scale with five levels is employed in the survey for the scoring of each attribute, where 1 represents the water governance that is poorly prepared to deal with challenges imposed by climate change in terms of the attribute in question, and 5 represents strongly prepared. While I tried to keep the survey short by asking the respondents to score on the five attributes directly, I provided supporting tables where specific sub-measures are identified for each attribute with detailed descriptions and example questions to consider. The supporting tables are provided in Appendix A. The survey instructions clearly stated that respondents should score each attribute based on the supporting tables provided to ensure a consistent understanding of the definition of the attributes among all respondents.

Subsequently, four case studies have been conducted for jurisdictions with the largest number of responses collected, i.e. Spain, the MDB Australia, Italy and Uruguay. California and Chile were excluded from the detailed analysis as case studies because the number of responses was relatively small, and therefore the confidence that those responses represent the overall view of the experts in these jurisdictions is lower. The scoring results were analysed in combination with water policies and climate scenarios for each case study jurisdiction to evaluate the ability of water governance to cope with climate change in these regions and identify strengths and weaknesses in irrigation water governance.

2.5 Results and case studies

2.5.1 Survey results summary statistics

The mean scorings from the expert survey for each jurisdiction are presented in Figure 2.2. The scorings results are also summarized below in Table 2.1, including the number of responses completed, mean scores, standard deviations (S.D.), minimum and maximum scores for each attribute and jurisdiction. Response rates are reported in parenthesis after the number of responses completed. The overall response rate is 42%, with variations between 37% to 48% for individual jurisdictions as shown in Table 2.1. The mean time respondents spent on completing the survey is 10 minutes.

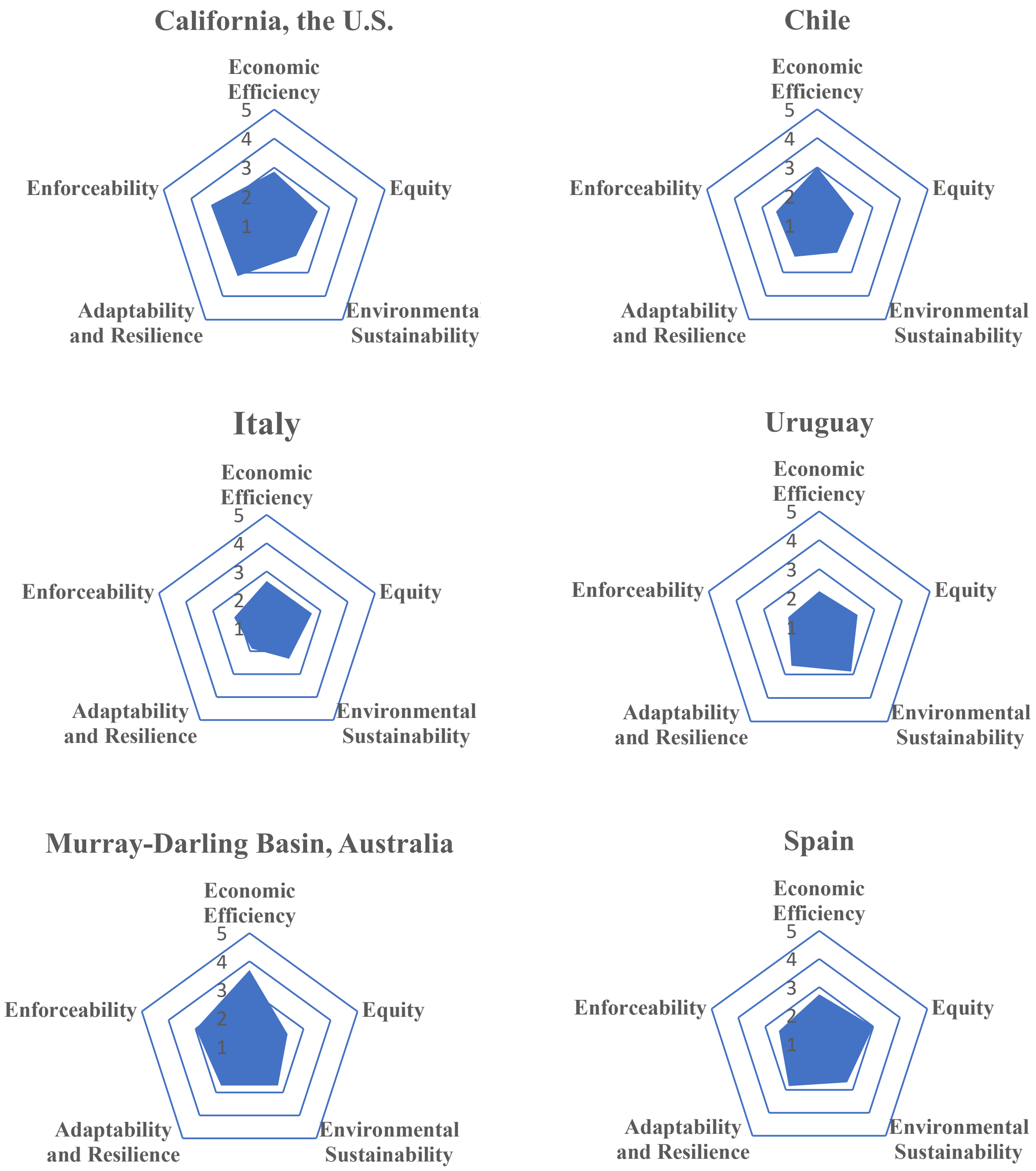

Figure 2. 2 Mean scores of key attributes of water governance in studied jurisdictions

Table 2. 1 Summary statistics of survey results

Region		Economic Efficiency	Equity	Environmental Sustainability	Adaptability and Resilience	Enforceability
California, the U.S.	N(resp rate)	7 (0.37)	7	7	7	7
	Mean	2.86	2.57	2.29	3.14	3.29
	S.D.	0.69	0.53	1.25	0.90	0.76
	Min	2	2	1	2	2
	Max	4	3	4	4	4
Chile	N(resp rate)	6 (0.43)	6	6	6	6
	Mean	3.00	2.33	2.17	2.33	2.50
	S.D.	0.89	1.03	0.98	1.03	0.84
	Min	2	1	1	1	2
	Max	4	4	3	4	4
Italy	N(resp rate)	9 (0.41)	9	9	9	9
	Mean	2.67	2.67	2.33	1.89	2.22
	S.D.	1.22	1.00	1.00	0.78	0.97
	Min	1	1	1	1	1
	Max	4	4	4	3	4
Murray-Darling Basin, Australia	N(resp rate)	10 (0.48)	10	10	10	10
	Mean	3.70	2.40	2.70	2.70	3.00
	S.D.	1.25	1.17	1.16	1.34	0.94
	Min	1	1	1	1	2
	Max	5	4	4	5	5
Spain	N(resp rate)	12 (0.46)	12	12	12	12
	Mean	2.75	3.00	2.67	2.83	2.50
	S.D.	0.75	1.04	0.49	0.94	1.00
	Min	2	2	2	1	1
	Max	4	5	3	4	4
Uruguay	N(resp rate)	8(0.38)	8	8	8	8
	Mean	2.25	2.38	2.88	2.63	2.13
	S.D.	0.89	0.74	0.83	0.92	0.83
	Min	1	1	2	2	1
	Max	4	3	4	4	3
Total	N(resp rate)	52 (0.42)	52	52	52	52
	Mean	2.88	2.60	2.54	2.60	2.60
	S.D.	1.04	0.96	0.94	1.03	0.96
	Min	1	1	1	1	1
	Max	5	5	4	5	5

2.5.2 Case Studies

2.5.2.1 Case study 1: MDB, Australia

The Murray-Darling Basin (MDB) is the most important agricultural production region in Australia (Wheeler and Garrick, 2020). The MDB covers an area of over 1 million square kilometers, spanning across four states (MDBA, 2021). The three longest rivers in Australia (the Darling River, the Murray River and the Murrumbidgee River) lie in the basin, together with over 1.9 million hectares of important wetlands (Quiggin et al., 2010; Wheeler and Garrick, 2020). Most of the basin is semi-arid, characterized by a high level of variability in water availability (Garrick et al., 2012). The average annual inflows of surface water into the basin are about 27,000 GL and around 50% are diverted for consumptive uses, mostly for agricultural production (Quiggin et al., 2010). The MDB produces $24 billion worth of agricultural products a year, with about one-third of the value coming from irrigated agriculture, consuming two-thirds of total irrigation water in Australia annually (MDBA, 2021). Tension and conflicts often arise among competing water users, especially between irrigation and environmental uses.

Water governance in MDB features a system of cooperative federalism (Alexandra, 2018) combined with a market-based approach to water management. The federal government is responsible for the enforcement and monitoring of the Basin Plan and water market rules, and determinations around environmental water allocation (Wheeler and Garrick, 2020). The independent authority, Murray-Darling Basin Authority (MDBA) is responsible for basin-wide planning and regulation, including determining environmental water allocation and catchment-level sustainable diversion limits (Wheeler, 2014). Individual states manage water use and make allocation decisions to entitlements within agreed limits (Wheeler and Garrick, 2020). The water market in the MDB was formally established in the 1990s and now often serves as an examplar worldwide for being one of the largest, most sophisticated and well-researched water markets in the world (Seidl et al., 2020). Well-defined water rights, supportive institutional setup and low transaction costs have contributed to the successful operation of this established water market (Breviglieri et al., 2018; Grafton et al., 2011; Wheeler and Garrick, 2020). The National Water Initiative in 2007 unbundled water from land, allowing water rights to be traded separately and held by non-land holders (Lee and Ancev, 2009). The unbundling of land and water has greatly incentivized various stakeholders to participate in the water market (Seidl et al., 2020), contributing to the trading volume in the market. The MDB water market has an annual turnover of about $6 billion (BoM, 2022) and most of the trading activities are concentrated in the southern part of the basin (sMDB) as the hydrological connectivity is much higher than in the northern part (nMDB), fostering relatively less constrained inter-valley trading (Wheeler et al., 2020). Water entitlements are defined as permanent use rights to a share of available water at a particular location, and the actual extraction is subject to various constraints including water availability in the current season (Wheeler et al., 2014). Entitlements are differentiated in reliability levels, reflecting different priorities in receiving seasonal water allocations, i.e. actual water available to extract. Both water allocations and entitlements are tradable, representing the two major types of water products in the MDB water market (Seidl et al., 2020). Other products and services like entitlement leasing and forward contracts on water allocations are also emerging in the market and are being increasingly utilized (Seidl, 2020).

In terms of climatic projection, the basin is expected to experience warming of 0.6-1.5°C compared to the baseline of 1995, with projected warming slightly stronger in the northern basin than in the southern regions (CSIRO, 2015). Evapotranspiration, which is heavily influenced by temperature, is also projected to increase by about 3%-12% in the MDB. Annual mean rainfall is projected to decrease for the southern basin, especially during the cool seasons (Timbal et al., 2015). The reductions in cool-season rainfall coupled with increased evapotranspiration are likely to have particularly significant impacts on soil moisture, runoff and stream flow in the southern regions where rainfall predominately occurs during the cool seasons (Whetton and Chiew, 2021). The intensity, duration and frequency of both flooding and drought events are projected to increase. Time spent in drought in the southern basin is expected to increase by about 25% by 2030 and by 30% by 2090 (Timbal et al., 2015). Overall, the MDB, especially the southern basin, is likely to experience an intensification of the water scarcity problem due to decreased water availability, coupled with increased irrigation demand and lengthened droughts.

2.5.2.2 Expert Scores of case study 1

Economic efficiency

Economic efficiency for the MDB was scored at 3.7, the highest among all case studies included in this study. The standard deviation was 1.25, with a minimum value of 1 and a maximum value of 5. Standard deviations for all scoring results for the MDB are generally higher than in other regions. A major reason is that two of the responses scored all attributes 1 or 2 for the MDB, while the majority of responses scored much higher. For the economic efficiency of the water governance in the MDB, eight out of ten responses scored either 4 or 5. This on average high score may be largely attributed to the highly developed and functioning water market, especially in the southern part of the basin. Existing literature demonstrated that water prices in the MDB are fundamentally driven by water scarcity (Bjornlund and Rossini, 2005; Zuo et al., 2019) and the value can be generated through water use in agricultural production, i.e. irrigation (Zhao et al., 2022; Grafton et al., 2016). This is an important indicator that scarce water resource is being efficiently allocated by the market based on the marginal value of use and therefore marginal willingness to pay from users. Such allocative efficiency is also reflected by reduced loss during drought events. For example, during the millennium drought, the worst drought on record in southeast Australia, the annual water use in irrigation during 2007-2009 decreased by 69%, while the gross value of irrigated agricultural production only reduced by 20% in real terms (Kirby et al., 2012). This shows the importance of water reallocation from lower-valued uses to higher-valued uses within the agricultural sector during droughts for minimising overall loss to society by improving water productivity. Water productivity, measured by adjusted gross value produced per unit of water used, more than doubled during this drought period (Kirby et al., 2012). There were notable signs of water reallocation and change of production plans: the water used by perennial plants like vineyards and orchards changed little, while water used by dairy and annual crops like rice, cotton, and pasture showed substantial declines (Kirby et al., 2012). Records of water trade transactions provide further evidence that water moved from annual crops like rice, and dairy to higher-valued horticulture (Kirby et al., 2012). It is evident that allocation trading enables irrigators to flexibly adjust water uses based on water availability and price, enabling benefits from water use to be maximized for society and losses to be reduced in case of droughts. While trading in water allocations enables demand adjustment and water reallocation in the short term, trading of permanent water rights (i.e. entitlements) allows for long-term water demand adjustment and production planning. For example, entitlement trading is used to exit farming/irrigation, restructure farm finance, and reduce debt (Seidl et al., 2020; Wheeler and Zuo, 2017; Zuo et al., 2015)

Low transaction cost can be another key factor for the high effectiveness and efficiency of the reallocation mechanism of the MDB water market, especially during dry periods when water trading becomes more active, i.e. the need for water reallocation increases (Zhao et al., 2022). Loch et al (2018) reported transaction costs of allocation trades in the MDB water market as a percentage of average trade prices ranging from 4% in 2012 to less than 0.5% in 2016. This range for entitlement trades was 0.1% in 2014 and 0.06% in 2016 for the Goulburn-Murray Water district, the most active water trading zone in the basin. Overall, the transaction costs, including time costs are relatively low in the MDB.

Other factors like well-defined water rights and institutional arrangements developed to assist water trading have all contributed to the flexible water reallocation mechanism based on a market approach. Various products available in the MDB water market have enabled irrigators to adjust water demand and manage water supply risks both in the short term and across multiple periods as discussed above. In the face of reduced water availability and increased variability as projected for the future climate scenarios in the MDB, there will be increasing needs for water reallocate as water availability fluctuates. These characteristics and functions of the water governance in the MDB will become increasingly important to allow water uses to be adjusted flexibly across jurisdiction, sectors and across time periods, improving the ability of the water governance to cope with the potential negative socio-economic impacts imposed by climate change.

Equity

The equity attribute of the MDB was scored at 2.4, with a standard deviation of 1.17. The minimum score was 1 and the maximum was 4. The equity aspect appears to be the biggest concern in terms of the ability of the water governance to cope with climate change in the MDB. Comments from the expert survey identified a significant lack of representativeness in the decision-making process as a primary concern. One respondent noted: “equity is very poor as irrigators are the single most powerful interest group in the basin, whereas environmental stakeholders, and especially indigenous stakeholders are largely shut out from decision making, and bear the brunt of losses from drought and reduced water supply.” The cap placed on the government water buyback program, as discussed earlier, may serve as an example of the overpowering political influence of irrigators over environmental water users. In addition, the development of tradable water entitlements and allocation regimes in Australia heavily depends on past access and usage while the indigenous communities have been historically disadvantaged in water access (Jackson et al., 2019). The colonial law excluded indigenous communities from exercising riparian rights and access to water licenses, rendering a high level of dispossession of land and water for indigenous communities in the basin (Macpherson, 2017). The current water laws and policies in Australia also provide no substantive reparation to redress the historical pattern of exclusion of indigenous communities from the water economy and related decision-making process (Jackson et al., 2019). The native titles, limited to “traditional and cultural” rights, which are the only that somewhat reflect precolonial water interests, are not tradable and are vulnerable to extinguishment (Macpherson, 2017). Irrigated agriculture makes a significant contribution to wealth generation and water entitlements as assets can yield significant financial returns (Wheeler et al., 2016). Exclusion of certain interest groups from the water economy, therefore, can greatly impede economic equality in water allocation. Some recent efforts have been made to support the participation of indigenous communities in the water market. For example, the federal government announced a $40 million programme in 2018 to purchase water entitlements for the cultural and economic needs of Aboriginal communities in the MDB (NIAA, 2022).

In conclusion, there is an inadequacy of inclusiveness in the policy-making process in the MDB and some interest groups like environmental users and indigenous communities are underrepresented. In addition, as discussed in the conceptual framework section, the water market can contribute towards equitable outcomes of water governance by enabling individual farmers to access additional water, manage water supply risk and plan for agricultural production according to their demand elasticity. Such contribution, however, seems to be under-recognized and is probably not reflected in the scorings. The benefits of the water market in mitigating the negative impacts and uncertainties imposed by climate change need to be based on an equitable market environment, i.e. a level playing field for all participants, without distortions and manipulations. There have been debates and concerns over market manipulation and speculative behaviours in the MDB, especially from the non-landholding and institutional investors. The Australian Competition and Consumer Commission (ACCC) has specifically investigated potential harmful conducts of institutional participants in the MDB water market and reported no significant evidence of such behaviour (ACCC, 2020).

Environmental sustainability

Environmental sustainability in the MDB was scored at 2.7, which was the second highest among the study regions. The standard deviation was 1.16. The minimum score was 1 and the maximum was 4. Water policies and water reforms in the MDB over the past two decades have been aiming to return the over-allocated basin to a sustainable level of extraction, and some progress has been achieved (Garrick et al., 2012). Government buy-backs of water entitlements have been used as a market-based approach to recover water for the environment through voluntary trades and with full compensation. The Commonwealth Environmental Water Holder (CWEH) was established by the Water Act in 2007 and made responsible for managing environmental water including purchasing entitlements from the water market and releasing water periodically to the environment when it maximizes the ecological benefits of doing so (Ancev, 2015). By mid-2019, the Commonwealth government has acquired 20% of total water entitlements on issue in the MDB as environmental water with a cost of about $2.5 billion (Grafton and Wheeler, 2018; Wheeler et al., 2021). This buy-back program was estimated to be much more cost-effective than other approaches, especially irrigation infrastructure subsidies, in terms of recovering water for the environment (Alexandra, 2018; Grafton and Wheeler, 2018, Lee and Ancev, 2009). The buy-back program serves as an example of integrating environmental goals into market-based water allocation approaches. However, political and public opposition, especially from irrigators for reduced water diversions, has resulted in a cap of 1500 GL being placed on the buy-back program in 2015, limiting its capacity to deliver water for the environment (Grafton and Wheeler, 2018). In the face of a drier climate and lengthened drought spells in the future, as projected, effective mechanisms to allocate water to the environment to meet ecological needs will be of great importance. To support the sustainable use of water in the context of changing climate and enabling the full value of water (including environmental value) to be reflected in market price, the cap on the water buy-back should be lifted and the CWEH to participate more actively in the water market. Sophisticated services and products available in the market, e.g. entitlement leasing (Wheeler et al., 2011), can also be utilized by the CWEH to further benefit both the environmental sustainability and economic efficiency of water use.

Groundwater is usually less monitored and less regulated than surface water, due to the inherent difficulty to measure underground water bodies and the complexity of the connectivity between surface and groundwater. The MDB case is no exception to the seemingly general rule that groundwater diversions remain weakly monitored (Wheeler et al., 2020). Barnett et al. (2020) reported that only 136 out of the total 288 (less than 50%) groundwater-management areas (GMAs) in Australia had volumetric limits for extraction as reported in 2016. Various policies and management tools have been developed to control and ensure a sustainable level of groundwater diversion (Nelson et al., 2020). For example, the 2007 Water Act placed a cap, "sustainable diversion limit" on both surface and groundwater resources in the basin. (Nelson et al., 2020) reported that 25% of the GMAs are classified as over-allocated and only 2% are over-used. While overuse does not seem to be a widespread issue today as concluded by Nelson et al. (2020), over-allocated areas represent a potentially serious problem when surface water availability is reduced in a drier future climate as projected.

Adaptability and resilience

The adaptability and resilience attribute was scored at 2.7 for the MDB which is among the middle rank in our case studies. The standard deviation was 1.34 with the minimum and maximum scores being 1 and 5, respectively. The scoring of this attribute appeared to have a larger discrepancy than other attributes, which may be ascribed to different opinions in terms of the most important factors contributing to the adaptability and resilience of water governance. While studies in adaptive capacity recognized the importance of multi-level governance, devolution of power and more inclusive governance processes that engage various stakeholders, water governance in the MDB has been dominated by top-down approaches and centralized control by federal or state governments (Dare and Daniell, 2017). Water governance in the MDB also features a high level of institutional complexity with a lack of coordination, resulting in a fragmented regulatory environment and ineffectiveness of water policies (Dare and Daniell, 2017). On the other hand, the highly-developed water market in the MDB enables efficient water reallocation with low costs and offers additional flexibility for water users to respond to water availability. Newly emerging products in the market, such as forward contracts and options, represent bottom-up strategies developed to cope with risks in water supply, which will add to the resilience of water management in the face of climatic variability. Various efforts have also been made by the government in recent decades towards a more adaptive and integrated water governance in the basin. For example, The MDB Plan, an inter-jurisdiction agreement passed in 2012 that provides guidance on water use across the basin, has made an important attempt to incorporate adaptive management. Notions on adaptive management set out in the MDB Plan emphasized using management as a tool to learn about and apply knowledge to relevant systems, linking knowledge, management, evaluation and feedback over a period of time and identifying and testing uncertainties (Crase, 2012). The Sustainable Diversion Limits (SDLs) that put a cap on the total volume of water that can be extracted in the basin, were also set to be variable in the MDB Plan, enabling new knowledge and changing context to be reflected in the limits over time (Allan et al., 2013). The operationalization of these concepts in adaptive management, however, remains challenging. The engagement of stakeholders has had limited impact on water policies and social learning has not yet been deeply integrated into decision-making in the MDB. Studies investigating water reforms in the MDB based on social-learning theories found that the learning process in water governance was largely confined to making incremental policy or behavioural changes, in contrast to fundamental revisits of the governance principles (McLoughlin et al., 2020). Overall, the importance of adaptive management, including features like devolution of power, multi-level coordination, “learning by doing” and inclusiveness have been recognized in water laws and policies in the MDB, but there is still large space for improvement for the implementation and operationalization of these concepts.

Enforceability

Enforceability was scored at 3 for the MDB, representing a relatively good level of enforcement especially compared to other countries and regions. The discrepancy in scoring for this attribute was also the smallest compared to the other attributes for the MDB, indicated by the standard deviation of 0.94. The minimum value was 2 and the maximum score was 5. This result is a bit surprising, considering the reported evidence of ‘water theft’ and other non-compliant in some areas (e.g. NSW), also as raised by some expert comments in the survey. The high score may be a result of recent improvements as the governments in the basin have endeavoured to make changes and improvements in water policy enforcement and extraction monitoring in recent years, in response to concerns previously raised. There are considerable differences between states in terms of enforcement and compliance (MDBA, 2017). VIC and SA are well metered with at least 80% of both groundwater and surface water takes being metered (Bretreger et al., 2021). VIC and SA also have a better compliance culture. NSW and especially QLD on the other hand, are poorly metered with under-resourced monitoring systems (MDBA, 2017). Various efforts have been made by the state governments to increase the effectiveness of sanctions and therefore improvement in compliance. VIC introduced tougher penalties in 2019, while NSW employed a more advanced penalty system that charges unlicensed take of water based on the spot market price at the time water was taken (Bretreger et al., 2021). Noncompliance thus will become more costly when scarcity is high, reflecting the resource cost of water theft to other users and the society under different water availability. Improved technologies like telemetering which allows reading remotely and in real-time, and remote sensing have also been suggested in various state documents to improve monitoring and compliance of water use, but have currently been used to a very limited extent in the basin (Bretreger et al., 2021). Overall, the enforceability in the MDB is considered relatively good based on the average score in the expert survey, which is consistent with the conclusions of other comparative studies (e.g. Palomo-Hierro et al., 2022). There is however, still an urgent need for further improvement as it will become increasingly critical to have effective enforcement and monitoring mechanisms in place to ensure economically efficient, socially equitable and environmentally sustainable water use in a basin like the MDB where water use is very competitive, especially in the face of projected reduced water availability and increased variability.

2.5.2.3 Case Study 2: Spain

Water availability in Spain is characterized by substantial spatial variation, with average annual precipitation ranging from 2,200 mm in the northern regions to only 120 mm in the south-eastern basins, where there are often episodes of water scarcity and lengthened droughts (Berbel and Esteban, 2019). Agriculture is the biggest water user that accounts for over 70% of total extraction. Water in Spain is regarded as a public asset and water access licenses are granted for a particular volume and for a fixed period (usually 75 years). The central government is responsible for managing inter-regional river basins, which are grouped into 'Hydrographical Confederations' (CHs) (Thiel, 2015). The CHs enjoy significant independence in terms of developing basin plans, managing water resources and public infrastructure, policy enforcement and applying sanctions (Thiel, 2015). Various stakeholders and actors including sectoral administrations (e.g. department of agriculture), regional governments, and water users are represented in the decision-making process of CHs (Thiel, 2015). The European Union's (EU) Water Framework Directive (WFD) has had a major impact on the paradigm of Spanish water governance, which has placed emphasis on several key focal points including water pricing, ecological protection, and public participation (Garrido and Llamas, 2009). In terms of economic instruments employed in water management, the water law reform in 1999 formally established spot water markets (water rights leasing) and water banks that serve as water exchange centres (Palomo-Hierro et al., 2015), while informal water trading has been existing in many water-scarce areas for a long time. Water markets and water banks, however, have played a limited role in reallocating water, as discussed below.

Future climate projections indicate stronger impacts in terms of temperature increase and precipitation reduction for Spain compared to the other EU countries (Escribano Francés et al., 2017). It is expected that precipitation and water availability will decrease by 9%-17% in the short to medium term (from 2041-2100) in Spain. Runoff and groundwater recharge are also projected to decrease, while temperature and evapotranspiration are expected to increase (Escribano Francés et al., 2017). This imposes additional difficulties on an already challenging situation and requires a careful rethink of the water governance.

2.5.2.4 Expert Scores of case study 2

Economic efficiency

The economic efficiency attribute is scored at 2.75 for Spain, which is among the middle rank of jurisdictions included in this study. The standard deviation was 0.75, indicating a relatively small discrepancy in scoring among the experts. The minimum score was 2 and the maximum was 5. It is however worth noticing that this average of 2.75 is lower than that of the other jurisdictions with established formal water markets (i.e. the MDB, Chile, and California). Indeed, despite the introduction of the spot water market and water banks in 1999, water trading has been playing an insignificant role so far (Garrido and Calatrava, 2009). Entitlements in Spain, usually granted for 75 years, are defined in *absolute volume* of extraction which can be reduced during dry periods (Palomo-Hierro et al., 2015). Entitlements are not differentiated in security levels and the reduction of allocations in times of drought follows the solidarity principle, which means that the same percentage of reduction is applied to all water users in the same catchment (Palomo-Hierro et al., 2022). Since irrigators with different crops often have very different marginal benefits of water uses, such an arrangement undermines the economic efficiency of water use. Entitlements are also generally not tradable, although a few exceptions exist (Palomo-Hierro et al., 2015). Water allocations can be traded through the spot market using formal lease contracts and water banks. Water banks generally only operate during dry periods and serve as an intermediary between potential buyers and sellers based on offers with fixed prices (Garrido and Calatrava, 2009). Palomo-Hierro et al. (2015) pointed out that water banks have made a limited contribution to reallocating water between consumptive users. Instead, they have been mostly used to allocate water to the environment. Water trading activities in Spanish water markets are concentrated in drought periods and are still very limited even in extremely dry years. For example, only 0.78% of total water use in Spain was transferred in 2007 which was a dry year (Palomo-Hierro et al., 2015). Water trading is more significant in the southeastern basins like the Jucar and Segura river basins, where about 4-5% of water can be transferred among users in a dry year (Palomo-Hierro et al., 2015). The Spanish water market overall is very thin with poor market information availability/transparency. Trading data (e.g. location, price and volume) are neither collected nor made publicly available (Palomo-Hierro et al., 2022). Trading activities could be impeded due to multiple reasons. Firstly, leasing contracts are confined to between water users only (Garrido and Calatrava, 2009), while non-water users in the MDB, Australia, for example, can also participate in the water market, contributing to the liquidity of the market. Secondly, transaction costs are likely prohibitive, as discussed in Palomo-Hierro et al. (2015). The authors highlight that the high fixed transaction costs imply that only lease contracts with very large volumes are economically feasible to carry out in the water markets in Spain, impeding mutually beneficial trades between individual farmers on a smaller scale.

Overall, there exist marked-based water reallocation mechanisms in Spain, but they have been playing limited roles so far. The efficiency and effectiveness of water reallocation especially during droughts are relatively low, resulting in the inability of the water governance system to minimize drought-related economic loss by enabling water to be transferred from lower-valued uses to higher-valued ones with minimum costs. There is also a lack of products or tools to facilitate irrigators to adjust water demand/use and manage water supply risk in the medium to long term. These characteristics of the water governance in Spain diminish its ability to cope with increased variability and decreased availability in water supply, where frequent reallocations of water and multi-period planning to manage temporal variability and risks in water supply will be absolutely essential.

Equity

The equity attribute was scored at 3 for Spain, which was the highest among all study cases. The standard deviation was 1.04 with a minimum score of 2 and a maximum of 5. There are several possible reasons for this high score. Firstly, the inclusiveness of various interest groups in water governance is considered to be good in Spain (Estrela and Sancho, 2016). Representatives are chosen from water users and social, economic and environmental organisations to form the Users Assembly using only hydraulic criteria, which gives a certain level of guarantee to their independence from political standpoints (Estrela and Sancho, 2016). In some regions, e.g. the Ebro River Basin, the representation of water users is proportional to water use. For example, irrigators in the Ebro River Basin have the most influence on the governing board as 90% of water concessions are granted to agricultural use in the region (Ballester and Lacroix, 2016). Such water user associations or governing boards play key roles in water administration, water governance and even in enforcement and budget management in Spain (Ballester and Lacroix, 2016). Estrela and Sancho (2016) provide more details on the decentralization and participation levels of different interested parties in water governance in Spain, highlighting the high level of participation of water users. This good level of inclusiveness in the decision-making process of water management contributes to the equitable governance of water. Inclusiveness in the decision-making process may become increasingly important in the face of climate change, as newly emerging challenges and conflicts will need to be solved by negotiation and bargaining between different interest groups including government agents, irrigation water users and environmental users. Communications engaging various interest groups and ensuring they are well-represented makes critical contributions to equitable solutions to conflicts in water use.

Secondly, as aforementioned, the reduction in water allocated to entitlements in times of water scarcity follows the solidarity principle in Spain. The equal proportional reduction applied to all water concession holders may be viewed as being “equitable”. However, this may be a misconception. Firstly, the solidarity principle is highly economically inefficient as the marginal value of water usage can vary dramatically among irrigators. A same percentage cut in water allocation, therefore, can lead to dead-weight loss that represents a loss for the society as a whole. In addition, such an arrangement does not necessarily lead to equitable outcomes, since the inelasticity of water demand and vulnerability of different irrigators can be very different as discussed in the conceptual framework section, so perennial irrigators will suffer from much higher loss due to shocks in water supply. One expert commented in the survey that there is “no risk sharing mechanisms” in Spain. There exist some mechanisms in place that can potentially mitigate such unequal impacts of water shortage on different irrigators in Spain, such as the entitlement leasing market and water banks, but their use has been limited. It is documented that publicly-owned water banks purchase and reallocate water at fixed-prices to other users, and sometimes for free to certain users, likely perennial growers (Palomo-Hierro et al., 2015). However, such policies largely remain exceptional and are not widely adopted. Meanwhile, the economic efficiency of this type of transfer is limited with fixed-price offers and centralized decision-making processes. The centralized and public nature of the water banks is also expected to be able to eliminate or at least reduce the chance of market manipulation and water banks are therefore perceived as being fairer (Palomo-Hierro et al., 2022). However, the MDB water market has demonstrated that privatization and marketisation do not necessarily lead to market abuse and manipulation (ACCC, 2020) but can enjoy a much higher economic efficiency gain. Overall, it is a bit surprising that Spain was scored the highest for the equity attribute among all case studies and it might be largely based on misconceptions of the fairness of water allocation mechanisms, especially in the context of climate change.

Environmental sustainability

Environmental sustainability was scored at 2.67 with a relatively low standard deviation of 0.49 for Spain. All scores are concentrated between 2 to 3 for this attribute. This score is among the middle rank compared to other case studies, but it probably represents a major concern for Spain as the second lowest score among all attributes. The environmental value of water and the importance to improve the ecological health of rivers are incorporated into the Spanish legislations in recent decades, especially following the relevant EU requirements (Zaragoza-Martí, 2019). In particular, environmental flow is considered to be a key measure to achieve the environmental objectives of the WFD (Mezger et al., 2019). The Spanish legislation has incorporated environmental flow and established relevant regulations with the main objective of achieving a good ecological status of surface water (Mezger et al., 2019). River Basin Authorities are responsible for quantifying water uses in the basin and regulating environmental flow through restrictions placed on consumptive water uses, under the supervision of the Minister of Environmental Affairs (MITECO). The actual implementation of environmental flow in Spain, however, experiences several shortcomings. For example, only minimum flow is defined in most water bodies, while other measures such as maximum flow and change rates also have important implications for river health (Mezger et al., 2019). These established minimum flows are often quite low in most water bodies (Mezger et al., 2019). Non-compliance with environmental flow requirements has also been identified in 40% of monitored water bodies (Mezger et al., 2019).

In terms of delivering water to the environment during drought periods, Spain has also employed market-based approaches, similar to the Australian case. River basin authorities may acquire water use rights temporally (or permanently in some exceptional cases) through voluntary trading with fixed price offers the so-called "Offers of Public Purchase of Water Rights" (Palomo-Hierro et al., 2015). This measure is usually implemented as an exceptional measure in emergency cases.

Overall, there are laws and policies in place to support the ecological protection of water in Spain, but the effectiveness of these regulations awaits further investigation and evaluation. The implementation of policies also experiences shortfalls and a lack of enforcement in many cases.

Adaptability and resilience

The adaptability and resilience of water governance in Spain was scored at 2.83, which was the second highest among surveyed jurisdictions. The standard deviation was 0.94. The minimum score was 1 and the maximum was 4. A possible reason for this comparatively high score relative to other jurisdictions may lie in the relatively high level of public participation in the Spanish water governance. Existing studies have often linked public participation with adaptive capacity building, potentially through improved social-learning and knowledge contribution, building social capital and trust, and improved capacity to achieve collaborative agreements (Ballester and Lacroix, 2016). Ballester and Lacroix (2016) used the case study of the Ebro River basin in Spain to demonstrate the contribution of public participation to adaptive capacity building. They reported that the participation of public groups in Ebro has led to increased knowledge of the local physical system, heightened public awareness of water management involvement, and improved social trust.

In the meantime, even the ‘in principle’ market mechanism and the definition of water rights have contributed to the building of adaptive capacity of Spanish water governance, despite their limited practice in reality (Palomo-Hierro et al., 2022). Although the trading mechanism is not yet as mature and flexible as the ones in Australia or Chile, for example, the use of market-based instruments may expand in the future in response to intensified water scarcity. The possibility of reducing water abstraction allowance during droughts based on the design of water rights also contributed to the adaptability of water governance in the face of increased variability in water availability (Palomo-Hierro et al., 2022). Nevertheless, changes in the specific rule of water rationing, i.e. the solidarity principle, are necessary to deliver economically efficient and equitable outcomes as discussed earlier.

Enforceability

Enforceability was scored at 2.5 for Spain, with a standard deviation of 1. The minimum score was 1 and the maximum was 4. The average of 2.5 was among the middle rank compared to other included case studies but it represents the biggest concern for the water governance in Spain. Enforcement and monitoring are generally considered to be poor in Spain (Palomo-Hierro et al., 2022). Metering is uncommon in agricultural water uses, so it is difficult to monitor actual water uses, and water right registers often cannot indicate real water withdraws (de Stefano et al., 2015). Water theft is widely documented especially in some hotspots like Donana and Mancha Occidental Aquifer and unauthorized takes tolerated by authorities are common (Palomo-Hierro et al., 2022). As mentioned above, episodes of non-compliance against established environmental flow have also been widely identified. Groundwater is also poorly monitored and regulated in Spain. A mixture of public and private groundwater rights exists according to the 1985 Water Act reform. The reform allows groundwater users abstracting water before 1986 to keep their private rights while any abstraction license issued later will be public rights (de Stefano et al., 2015). This created a high level of legal complexity and in practice, unlicensed and illegal take of groundwater have been common (de Stefano et al., 2015). Previous studies and reports have shown that about 60% to 90% of wells were illegal or in legal ‘limbo’ (de Stefano and Lopez-Gunn, 2012; WWF, 2006b). Overall, water laws are weakly enforced in many areas in Spain and non-compliance is common. Under a drier and more volatile future climate, it will be absolutely critical for Spain to improve the enforcement of water regulations to ensure the sustainable use and equitable allocation of scarce water resources.

2.5.2.5 Case study 3: Italy

Italy is relatively rich in water resources (Massarutto, 2015). However, there are notable spatial variations with the northern and central Italy enjoying better water availability than the southern regions (Benedini and Rossi, 2021). Water governance in Italy has traditionally treated water as an abundant and public resource (Benedini and Rossi, 2021). Similar to Spain, being an EU country, the EU’s relevant legislation and requirements have had an important impact on Italian water governance. The central government is responsible for implementing EU WFD and other EU legislation (European Committee of the Regions, n.d.). Specific water management responsibilities lie with regional authorities and governments. The country is structured into 20 regions and each region is responsible for managing water within its own jurisdiction with full control over water access licenses (Santato et al., 2016). There is a lack of a central water register, often resulting in incomplete and inconsistent water accounting information across regions and overallocation of water in some regions (Pérez-Blanco, 2021). Overall, water governance is fairly fragmented and lacks coordination between regions (Pérez-Blanco, 2021).

The climate change projections indicate a reduction in the average rainfall and up to a 40% reduction in runoff in Italy. The intensity of extreme climatic events, such as droughts is projected to increase. Agricultural water withdrawal is predicted to increase by up to 20% as a result of the combination of reduced rainfall and soil moisture and increased temperature (Pérez-Blanco, 2021). Changes in the timing of snowmelt from the Alps are also likely to have an important impact on the temporal distribution of water in Italy. The snowmelt discharge peak is projected to shift from May to April, leaving lower runoff from May to November when water demand is typically at its maximum (Pérez-Blanco, 2021). In other words, water scarcity will be intensified during the irrigation season.

2.5.2.6 Expert Scores of case study 3

Economic Efficiency

The economic efficiency attribute of water governance in Italy was scored at 2.67, which was among the lowest in our survey. The standard deviation was 1.22. The minimum score was 1 and the maximum was 4. Poorly designed water rights regimes may be a major reason for the low economic efficiency score. A large proportion of Water Abstraction Licenses (WALs), especially for irrigation purposes, do not have specified abstraction volume because metering of irrigation water use is not widespread (Berbel et al., 2019; Pérez-Blanco, 2021). Irrigation water is often charged at flat rates on a per-hectare basis, differentiated by crop type and irrigation technology (Garrido and Calatrava, 2010). For example, (Farrace, 2007) reported water charges between 160-500 euros/ha in Italy. Such a rate is much lower than what other water users pay and cannot even cover the financial costs (i.e. operation and maintenance costs) of water services. Garrido and Calatrava (2010) reported a financial cost-recovery rate of 70-80% in northern Italy and around 50% in central and southern Italy. Pérez-Blanco (2021) pointed out that such water pricing schemes coupled with the low percentage of cost recovery may allow irrigators to expand water use at relatively low private costs, but quite high social costs, especially in the face of reduced water availability and increased irrigation demand in the projected future climatic scenarios.

The Italian government made some efforts in the 2000s to introduce water trading and water markets to improve economic efficiency in water use following the calls of the EU WFD (Pérez-Blanco, 2021). These attempts, however, failed when the privatization and trading of water were repealed by the referendum in 2011, under suspicions that they will eventually lead to limited access to water as a fundamental right (Pérez-Blanco, 2021). Formal water trading and buybacks remain impossible in Italy ever since. As a result, the reallocation of water in Italy mainly relies on non-pecuniary mechanisms such as voluntary agreements between regions during severe droughts (Pérez-Blanco, 2021). These mechanisms, however, are not likely to facilitate flexible water reallocation and maximize economic efficiency in water use. Since the decisions are made on an aggregated level (between regions), it is hard, to reallocate water based on the marginal value of water use for individual users to achieve the efficient allocation of water. These mechanisms based on voluntary agreements can also involve high transaction costs, including the time costs and administrative costs of negotiation and implementation.

Equity

The equity attribute of water governance in Italy was scored at 2.67, the second highest among all study jurisdictions. The standard deviation was 1 with a minimum score of 1 and a maximum of 4. This result is again somewhat surprising. In Italy, environmental use and human consumption use of water enjoy priority over the agricultural and industrial water demand. Concessions that irrigators hold which allow them to withdraw water, either from surface or groundwater bodies, can be reduced in amount or revoked during droughts without any compensation (Boscolo, 2021). The reduction in water allocation in times of shortage is governed by the solidarity principle, similar as in Spain. This legislative framework, combined with the fact that irrigation water is non-tradable in Italy, means that irrigators have very limited opportunities to mitigate risks in water supply, leaving especially irrigators with inelastic water demand highly vulnerable to increased variability in water availability. As discussed earlier, just because there is 'equitable' i.e. proportional rollback for all irrigators in the face of water scarcity, does not mean that governance supports equity. This is especially the case in the face of climate change. The solidarity principle may lead to inequitable outcomes by disadvantaging some groups of irrigation water users in their ability to cope with climate change due to the heterogeneous elasticity of water demand. In addition, without clear water rationing rules and effective water reallocating mechanisms, water governance in Italy lacks a bottom-up mechanism for solving conflicts in times of water scarcity. As aforementioned, any conflict in water use will need to be solved at an aggregate level and often as exceptional cases, e.g. through voluntary agreement for water rationing made between regions, which may not lead to equitable outcomes for individual users. It seems that jurisdictions employing solidarity rule in water allocation and non-pecuniary mechanisms for water rationing, i.e. Italy and Spain, are rated higher for the equity attribute. This result points to a potential misconception of viewing market-based instruments and equity as conflicting in nature, whereas market-based instruments can actually contribute to equitable outcomes of water governance. Further discussion on this issue is provided in the discussion section.

Environmental sustainability

The environmental sustainability attribute was scored at 2.33 for Italy with a standard deviation of 1. The minimum score was 1 and the maximum was 5. As discussed earlier, the water pricing strategy combined with the lack of metering systems in irrigation water use enables irrigators to expand irrigation at relatively low costs (Pérez-Blanco, 2021). In the face of reduced water availability and increased frequency of drought events, this is likely to lead to unsustainable use of water (Barraqué, 2021). An “ecotax” has been incorporated in the water tariff for both publicly supplied and on-farm self-supplied water (typically groundwater) to reflect the impacts of water withdrawal on the environment and other users. This tax, however, is often very low, e.g. 0.0015 €/m^3 for self-supplied irrigators in the Puglia region, while the estimated pumping cost is 0.25-0.5 €/m^3 (Berbel et al., 2019). A flat rate also can hardly reflect the environmental impacts of water abstraction accurately as such impacts vary greatly based on water availability. For groundwater pumping, license fees are charged periodically, but they are mainly designed to cover the administrative cost and are not based on volumetric measures of actual water abstraction (Berbel et al., 2019). Similar to the problems with surface water pricing, this pricing and regulatory framework may encourage groundwater pumping at an unsustainable rate especially when surface water supply becomes more variable in future climatic scenarios. Lowering water tables have been already observed in many regions across Italy, and the increase in self-supplied irrigation water use is likely to be a major driver (Massarutto, 2015).

Similar to Spain, the environmental flow policy in Italy mainly focuses on the minimum flow, which may not be sufficient to achieve a good ecological status of rivers and riparian ecosystems (Santato et al., 2016)[2]. There is also no mechanism established to purchase and deliver water for the environment like the ones available in the MDB, Australia or in Spain. In a drier future climate as projected for Italy, it will be vital to design and put in place mechanisms to conserve and deliver water for the environment on a regular basis to avoid catastrophic ecological consequences.

Adaptability and resilience

This attribute was scored at 1.89 for Italy, the lowest among all case studies. The standard deviation of 0.78 was relatively small, indicating a consensus among experts in the scoring of this attribute. The minimum score was 1 and the maximum was 3. It seems that adaptability and resilience represent a major weakness for Italy, in terms of the ability of its water governance to cope with climate change. There are several possible reasons for this low score. Firstly, the water governance system in Italy is highly fragmented, with many legislations being in the same space and a lack of clear roles for various actors in administrating water policies (De Carli et al., 2021). There is also a lack of coordination between actors and among regions.

The referendum in 2011 as aforementioned, signaled strong opposition from the public against the use of market-based instruments in water management and privatization of water. Although the market itself is no panacea for all problems in water governance and can even create new problems, completely ruling out the use of market-based instruments may leave the governance system rigid and unable to deal with emerging challenges. Market-based instruments have been proven, e.g. in Australia, to be an effective risk management tool and can contribute to the adaptability of water governance in the face of climate change (Loch et al., 2013). Overall, it seems that water is still being treated as an abundant resource in Italy and droughts as exceptional cases, while the future climate projections signal substantial water stress in Italy. The unprecedented drought in the northern and central parts of Italy experienced in 2022 may be a harbinger of things to come. While few mechanisms and instruments have

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[2] The European Commission (2000) defined the good ecological status of surface water body as follows: “the values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.”

been in place in Italy to deal with potential new challenges, a transformational shift from reactive to proactive responses to water scarcity is urgently needed to increase the adaptability and resilience of the water governance in the face of climate change.

Enforceability

The enforceability was scored at 2.22 for Italy, the second lowest among all surveyed cases and only higher than Uruguay. The standard deviation was 0.97, with a minimum value of 1 and a maximum value of 4. Unauthorized water take is widely documented in Italy. It was estimated that about 1.5 million wells in Italy were unlicensed and about 50% of irrigated land was irrigated illegally in eight regions (Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria, Sicilia e Sardegna) (WWF, 2006a). The poor enforcement of water policies and regulations may be attributed to the tradition of viewing water as an abundant resource in Italy, while water is becoming scarcer in this region under the impacts of climate change. Without effective enforcement and monitoring systems being put in place, the widespread illegal abstractions of both surface and groundwater may lead to severe environmental consequences as well as social equity issues.

2.5.2.7 Case study 4: Uruguay

Uruguay overall enjoys abundant water resources with a rainy climate. The average annual rainfall is about 1300 mm and per-capita renewable water resource is estimated to be 17,514 cubic meters per year (Beekman et al., 2014). The rainfall, however, is characterized by extremely high irregularity and inter-annual variations, in terms of both frequency and intensity (FAO, 2015). As a result, rain-fed agriculture is practised but irrigation still plays a key role in agricultural production, supplementing water supply to high-value crops like rice (IICA, 2010). Irrigation demand reaches its peak during summer when evapotranspiration exceeds rainfall. Agricultural water withdrawals account for 87% of the total water withdrawal in the country. Rice is the major agricultural product irrigated in Uruguay, almost exclusively relying on the use of surface water (FAO, 2015). Perennial crops like fruit trees that account for a small proportion of agricultural products in Uruguay, on the other hand, utilize more groundwater for irrigation, likely because that groundwater supply is much more stable than surface water (FAO, 2015).

On the national level, the National Water Directorate (DINAGUA) which operates within the orbit of the Ministry of Housing, Territorial Planning and Environment (MVOTMA) is in charge of managing water resources. Its main responsibilities include granting, monitoring and regulating water concessions and permits, managing the national water registry and water inventory, and supervising and regulating public and private water delivery or storage works (CAS, 2013). The Ministry of Livestock, Agriculture and Fisheries (MGAP), through the General Directorate of Renewable Resources (RENARE) specifically manages water use for irrigation (FAO, 2015). On the regional level, regional irrigation boards that consist of both public and private members coordinate the use of water for irrigation, especially in times of water scarcity. Water concessions and permits are usually granted without a fixed term and can be revoked at any time for the public interest (CAS, 2013).

The climate projections for Uruguay show an increasing trend of temperature and precipitation. The intensity of extreme rainfall events is expected to increase, rendering flooding a major concern for Uruguay under future climatic scenarios (Castellanos et al., 2022). While Uruguay is expected to get wetter in terms of accumulative annual precipitation, the interannual variability of rainfall is projected to vary between -5% to 10% in the short term and between -7% to 35% in the long term (SNRCC, 2021). The frequency of drought events is also projected to increase under the accentuated influence of La-Niña (SNRCC, 2021). The high and growing interannual variability of precipitation and increased chance of droughts point to the need of having effective policies and regulations in place to cope with the high level of uncertainty in water supply.

2.5.2.8 Expert Scores of case study 4

Economic efficiency

The economic efficiency attribute was scored at 2.25 for Uruguay, the lowest among all study jurisdictions. The standard deviation was 0.89 with a minimum score of 1 and a maximum of 4. The constitution of Uruguay established that all water is in the public domain of the state and public water rights are usually granted as concessions for irrigation use (CAS, 2013). The 1978 Water Code of Uruguay stated that concessions can be revoked in case of drought for public interests (CAS, 2013). The Water Code also established that water charges should be put in place for abstractions of public water. The government in Uruguay, however, has not been able to develop a methodology to determine the charges for different groups of water users and the abstraction of water remains free of charge (FAO, 2015). The private sector is the major investor for irrigation infrastructure in Uruguay, while publicly funded infrastructure remains very limited and under-maintained (FAO, 2015). This may reflect the full recovery rate of operation and maintenance costs of irrigation infrastructure developed by the private sector and the potential mismatch between irrigation demand and public infrastructure constructions or their poor quality. Given the free-of-charge abstraction and the lack of formal water reallocation mechanisms, the economic efficiency of irrigation water use is likely to be very low and the ability to minimize economic loss by allowing water to be transferred to higher-valued uses in times of droughts is weak. Despite the projected increase in average annual precipitation in Uruguay, this inability of using and reallocating water efficiently renders the irrigation water governance in Uruguay vulnerable to drought events and shocks in the water supply.

Equity

The equity attribute was scored at 2.38, the second lowest among all study jurisdictions, with a relatively small standard deviation of 0.74, flagging the relatively high level of consensus. The minimum score was 1 and the maximum was 3. Since the 1970s, irrigation boards have been established in most jurisdictions in the country and were made official by the Irrigation Law in 1997 (FAO, 2015). The irrigation boards were created in response to the need of resolving conflicts among irrigation water users and coordinating water uses during the dry years (IICA, 2010). The irrigation boards that consist of representatives from local communities, academia, technicians and public agencies flag public participation in managing irrigation water. There is, however, a lack of evidence of how well different parties are represented on the boards and the actual influence of the boards in coordinating water use and resolving conflicts among water users. In a non-market setting, to ensure equitable allocation of water in times of shortage, it is vital to have clear water rationing rules and conflict resolution mechanisms, as well as a good level of inclusiveness in the decision-making processes.

Environmental sustainability

The environmental sustainability attribute was scored at 2.88, the highest among all study jurisdictions. The standard deviation was 0.83. The lowest score was 2 and the highest was 4. This relatively high score of environmental sustainability, however, may be attributed more to the rich natural endowment of water in the country and may not necessarily reflect the effectiveness of the mechanisms and regulations in place to ensure sustainability. There is currently a lack of knowledge on the state of groundwater at the national level and information on aquifers remains very scarce, partial and dispersed even for the most exploited ones (IICA, 2010). Given the projected increase in the variability of precipitation and surface water availability, there is a growing need to rely on groundwater as a more reliable source of water supply. This highlights the importance of understanding the groundwater systems and implementing regulations to ensure their sustainable use. Water quality has so far represented a minor concern in Uruguay (FAO, 2015). However, with the expected expansion of irrigated areas and intensification of irrigation under the influence of lengthened droughts, salinity and eutrophication problems may become more prominent.

Overall, although environmental issues are currently not prominent in Uruguay, there is a need for proactive measures to ensure groundwater sustainability, water quality and ecological health of rivers in the face of the expanded irrigation and increasingly variable climate in the future.

Adaptability and resilience

This attribute was scored at 2.63 for Uruguay, among the middle rank of all study cases. The standard deviation was 0.92, with a minimum score of 2 and a maximum of 4. The average score of this attribute is the highest for Uruguay, compared to other aspects. Uruguay has experienced a shift in the paradigm of water governance from a centralized and hierarchical model to a decentralized, participatory and integrated model over the past two decades (Trimble et al., 2021). The institutional structure of water governance in Uruguay consists of multiple levels of authorities that coordinate under the Water Code, including DINAGUA at the national level, regional councils of water resources, regional water offices, basin and aquifer commissions and irrigation boards as aforementioned (see CAS (2013) for their specific duties and functions). The multi-level structure and the regional focus of the multi-stakeholder irrigation board have facilitated polycentric governance and devolution of power, encouraged local participation and enabled more effective implementation of laws and regulations (IICA, 2010). However, barriers to intra-institutional and inter-institutional coordination also exist and fragmentation in water governance remains a challenge (Trimble et al., 2021). In sum, Uruguay has made various efforts towards more adaptive and inclusive water governance in the past two decades, which improved its ability to cope with challenges imposed by climate change. Many policies, however, are well-intended in design but poorly implemented, as discussed in the next section.

Enforceability

The enforceability was scored at 2.13 for Uruguay, the lowest among all study cases. The standard deviation was 0.83, with a minimum score of 1 and a maximum of 3. The water laws and regulations are poorly enforced. One striking example is that, as mentioned earlier, water abstraction charges have been included in the water law since 1978 to ensure sustainable use of water, but have never been actually implemented. The enforceability aspect was also identified as the biggest and the most critical weakness of water governance in Uruguay based on the comments received in the surveys. One expert noted: “The fragmentation is gradually overcome in the analysis and decision-making, but serious difficulties persist in the implementation of all the decisions adopted in the basin commissions." This lack of effective enforcement could be attributed to lower institutional capacity relative to other jurisdictions, as well as conflicting interests. Another respondent underscored this by stating, "many times they (water laws) cannot be applied for economic and/or social reasons." Water has been a relatively abundant resource in the country, but climate change now imposes new challenges for the water governance in Uruguay. Despite the increasing trend in the annual cumulative rainfall, an increase in the variability of water availability is projected and a higher probability of drought events is expected. The increased uncertainty in water availability necessitates the need of taking a proactive approach to water governance, including developing effective enforcement and monitoring mechanisms to ensure that water is managed in a way that is economically efficient, environmentally sustainable, and socially equitable, especially during the time of water scarcity.

2.6 Discussion

The scoring results from the case studies demonstrate the water governance in the MDB, Australia, is rated overall relatively high in terms of its ability to cope with climate change, reflecting the achievements of the series of water reforms since the 1990s. The equity aspect of the water governance in the MDB however, demands further improvement. Uruguay, on the other hand, is scored relatively low for all attributes, likely due to its overall-weak institutional capacity. For other jurisdictions, environmental sustainability represents a major concern for the water governance in California and in Chile. For Italy, adaptability and resilience appears to be a significant weakness of the water governance. The enforceability aspect represents the biggest problem for the water governance in Spain. Overall, our results show that experts do not believe that current water governance in study jurisdictions are adequately prepared to deal with climate change, as none of the attributes evaluated received an average score greater than 3. However, comparatively speaking, the ability of water governance to cope with climate change is rated higher in historically water-stressed regions, i.e. MDB, Spain, and California, compared to the traditionally water-abundant regions, i.e. Italy and Uruguay, with Chile somewhere in the middle. It seems that water scarcity has served as a catalyst for reforms and progress in water governance. Climate change, however, means that the historical pattern of climate and water availability is changing, and systems built to govern water as an abundant resource will likely be proven inadequate. For areas that used to enjoy sufficient water resources but are projected to experience (or are already experiencing) drier conditions, such as Italy and Chile, transformational changes in the local water governance are urgently needed in order to cope with the new challenges.

Water governance in the study regions tend to be most well-prepared for climate change in terms of economic efficiency. It is evident that the shift in water governance paradigm towards recognizing water resources as an economic good over the past decades (e.g. by the Dublin conference and the EU WFD) has achieved notable results. Various economic instruments, especially market-based approaches, have been put in place to improve the allocative, dynamic and productive efficiency in water use (Wheeler et al., 2021), which will assist in mitigating the increased uncertainty and intensified water scarcity due to climate change. In contrast, environmental sustainability appears to be the biggest weakness across studied water governance systems, warranting further improvements in the understanding of the ecological requirements of aquatic and riparian ecosystems and effective policies to ensure sustainable use of water.

Jurisdictions with developed water markets like the MDB, California and Chile, are scored high in terms of economic efficiency, which can be largely expected. There is, however, an interesting pattern that these jurisdictions are rated low in terms of equity. It is especially evident for the MDB and Chile, where the MDB has the highest score in economic efficiency and is the fourth place (out of six) for equity, while Chile is rated the second highest for economic efficiency and is the fifth place in terms of equity. On the other hand, Spain and Italy where the market mechanism is either not widely adopted (Spain) or not employed at all (Italy), have low economic efficiency but relatively high equity scores. It seems that economic efficiency and equity are perceived, even by experts, as potentially conflicting features. However, do market-based mechanisms necessarily lead to inequitable allocation of water while non-pecuniary instruments are somehow fairer? Our position is that this is not so. Market-based instruments provide individual farmers with access to additional irrigation water and serve as an effective tool to manage uncertainties in water supply and financial conditions on farm. A lack of such risk management tools, on the other hand, may leave some irrigators more vulnerable than others to uncertainties in the water supply that climate change imposes. Therefore, the misconception of viewing market-based instruments and equitable outcomes of water allocation as conflicting in nature may limit the ability of water markets to contribute to equitable sharing of both the benefit generated from water use and the risks in the supply of water. The MDB water governance has demonstrated that it is possible to combine environmental goals with market-based instruments, and it is definitely possible and important to integrate equity goals into the design of market-based instruments.

2.7 Conclusion

The unprecedented challenges that climate change is imposing necessitate fundamental transformations in the water governance paradigm. It calls for a shift from relying on simple technical solutions to utilizing various tools and coordination among various actors in the society, from focusing on a government-centred policy-making system to incorporating knowledge from different actors, and from reactive to proactive responses to extreme climatic conditions. While the dynamics of water governance to adapt to climate change is complex and the ability to cope with the emerging challenges is multi-dimensional, there is currently no framework that comprehensively evaluates how well a water governance system is prepared to deal with such challenges. The framework proposed in this study fills the research gap by evaluating the preparedness of irrigation water governance to cope with climate change based on five attributes: economic efficiency, equity, environmental sustainability, adaptability and resilience, and enforceability. Detailed discussions on four case studies map specific characteristics of water governance with its ability to cope with climate change. I demonstrated that the proposed framework can be widely adopted to evaluate water governance in any given jurisdiction around the globe in terms of its preparedness to deal with climate change. Strengths and weaknesses identified for particular jurisdictions and overarching patterns observed based on cross-regional comparisons point to important policy implications. Overall, water governance systems in the study jurisdictions are insufficiently equipped to cope with the unprecedented challenges brought by climate change, with environmental sustainability being the biggest concern.

Transformational changes are urgently needed to build more equitable, efficient, and resilient water governance that incorporates integrated management tools and inclusive decision-making processes, especially in regions that previously enjoyed relatively abundant water resources. Economic instruments, especially market-based instruments, can potentially make important contributions towards more resilient water governance in the face of climate change. Environmental goals and equity concerns can also be integrated into market-based instruments to achieve economically efficient, equitable, sustainable and adaptive water governance outcomes.

Chapter 3 Water market functionality: evidence from the Australian experience

3.1 Introduction

Market approaches to natural resource management in general and water markets in particular are gaining prominence globally (Wheeler et al., 2014). Water management traditionally focused on augmenting water supply through infrastructure development, such as building dams, reservoirs and pumps. These supply-side measures, however, soon reached their limits in many regions, and became increasingly costly (Breviglieri et al., 2018; Chong and Sunding, 2006; Grafton et al., 2016). In the face of intensified water scarcity as a result of the changing climate and increased water demand from population and economic growth (Breviglieri et al., 2018), the emphasis on treating water as a commodity (Hanemman, 2006) and the rise in popularity of market approaches to water management became more pronounced since the 1990s (Breviglieri et al., 2018; Molle and Berkoff, 2007). By establishing a price signal that reflects the scarcity value of water across competing uses—possibly including environmental uses—, water markets can efficiently allocate water to its highest economically valued uses, thus maximizing net benefits to society.

While formal water markets are now established worldwide, with notable examples in the United States, Australia, Chile, and Spain (Wheeler et al., 2020), questions about their functionality and performance persist. Evaluation of key market attributes, such as price and price volatility, traded volume, number and average size of transactions, and net imports across regions is fundamental to the assessment of market functionality. Equally, the assessment of regionally differentiated segments of a water market, and the evaluation of the disparate roles of various water products warrant close scrutiny. This study provides an encompassing assessment of the southern Murray Darling Basin (sMDB) water market in terms of these aspects. The comprehensiveness of this study lies in the investigation of: 1) multiple attributes of local water markets; 2) a set of trading zones in the sMDB; and 3) all major surface water use rights in the study regions. These investigations are conducted utilizing market transaction data over a fourteen-year period between 2007 to 2021. As one of the largest, most active and most advanced water markets in the world with abundant transaction data, the sMDB water market can serve as a template for understanding water markets more generally. Through this investigation, I aim to answer questions about the performance of the sMDB water market in terms of serving its fundamental purpose of directing water to its highest value uses; distinct roles that the permanent versus the temporary market and security-differentiated water use rights play; the level of heterogeneity/homogeneity of the set of highly connected yet segmented local water markets (trading zones) in the sMDB.

Despite the significance of the sMDB water market, existing literature has tended to focus on a single region (de Bonviller et al., 2020; Qureshi et al., 2010) or a few regions within the sMDB, especially the Goulburn-Murray Irrigation District (e.g.Bjornlund and Rossini, 2005; Wheeler et al., 2008; Wheeler et al., 2016). Studies across multiple regions (e.g. Haensch, 2022; Wheeler et al., 2014; Qureshi et al., 2009) rely on stated preference surveys on water trading, rather than market transactions data as this study does here. Existing literature also has been focused on prices and trading volumes of water, and their drivers (e.g. Bjornlund and Rossini, 2005; Brown, 2006; Colby et al., 1993; Connor et al., 2013; Jones and Colby, 2010; Michelsen et al., 2000; Wheeler et al., 2008), while the other attributes of the market, such as the frequency of trading and price volatility have been under-studied. The only study that statistically examined the price volatility of water products in the sMDB is Zuo et al., (2019), in their investigation of the impacts of government buybacks on the water market in VIC Goulburn.

The key market attributes studied exhibit temporal variation, necessitating an analysis over a relatively extended time series. This study therefore aims to understand the characteristics of the sMDB water market across different trading zones but also to trace the evolutionary path of these characteristics and identify factors influencing their changes over time. Overall, there is currently a deficit of cross-trading zone studies (especially those crossing state borders) in the sMDB, that delves into the characteristics of local water markets and their evolutionary trends based on historical transactions of both allocations and entitlements. The current study fills this gap in the literature. In addition, documenting market performance across a number of individual trading zones within sMDB brings a more general significance to this study. If water markets in individual trading zones of the sMDB are found to function similarly well, despite the notable differences between them characterized by trading constraints, differences in jurisdictional and geographic attributes, and heterogeneous crop structure, it will provide encouraging empirical indication that the water market could be an effective way to manage water resources in other regions of the world.

The benefit of implementing security-differentiated water rights has been hypothesized by previous studies (e.g. Lefebvre et al., 2012; Brent, 2017). Young and McColl (2003) hypothesized that two types of security are optimal since water users can then achieve different levels of reliability by mixing the two types of entitlements. Nevertheless, there remains an empirical research gap in documenting the distinctive roles these rights might play in the water markets, and their subsequent impact on market efficiency. Empirical studies focusing on the U.S. water markets have assessed the impact of the reliability, or seniority, of entitlements on water prices (Colby et al., 1993; Goodman and Howe, 1997; Payne et al., 2014), while such investigation in the MDB water market is missing. Moreover, the existing literature has primarily concentrated on the effects of reliability on water prices, neglecting other critical attributes such as the volume of trade and price volatility. This study fills these gaps by statistically comparing the price difference between the high and lower-security entitlements and then examining the response of the security-differentiated entitlements to important market fundamentals such as water availability through regression analysis. The findings contribute to a better understanding of the multifaceted roles these entitlements play in the market, particularly in satisfying heterogeneous demands for water usage and managing water supply. I also analyze the inherent distinctions between the entitlement market which is supposed to reflect long-term water demand, and the allocation market which is designed to reflect short-term demand, and the unique roles they each fulfil. Previous U.S. research, such as Brewer et al. (2008) and Brown (2006), has drawn comparisons between the leasing market—temporary transfer of water access rights, akin to the allocation market in the MDB—and the water rights market, which involves permanent transfer of water access rights, similar to the entitlement market in the MDB. While these studies provided insights into transaction characteristics that differ between temporary and permanent markets, thus hinting at their potentially diverse roles, they did not perform statistical tests to determine if these attributes respond differently to market fundamentals. This leaves the question of whether the markets for entitlements and allocations operate fundamentally differently unanswered. Furthermore, previous studies have only offered a static comparison between allocation and entitlement markets. In contrast, our research examines the temporal dynamics of these market types, thereby adding a valuable dimension of understanding to the field.

The paper proceeds as follows: in Section 2, I give a brief background and overview of the water market in the sMDB. Section 3 presents the data sources and summary statistics. Section 4 describes our empirical strategy and model specifications. Sections 5 and 6 present our findings and discussion of the findings. Section 7 offers conclusions.

3.2 Background and market overview in the MDB

The MDB water market was formally established in 1980s and water trading has since been growing. There are two types of markets in the MDB: permanent water rights (entitlements) market and temporary water allocation (the actual water) market (National Water Commission, 2011). The entitlements, which represent the permanent rights to certain shares of available water in a river or dam, vary in terms of security levels (Ancev, 2015). High-security entitlements (HSEs) have priority to receive water allocations before the lower-security entitlements when water supply is limited (Freebairn and Quiggin, 2006). The long-term average annual yield (LTAAY) of HSEs is 90-95%, which means that holders of HSEs can expect to receive an average of 90-95% allocation of actual water (Wheeler et al., 2016). In contrast, the LTAAY of general-security entitlements (GSEs, applicable only to NSW) is approximately 70%, and it is only 30% for the low-reliability entitlements (LREs, applicable only to VIC) (Wheeler et al., 2016). The seasonal allocations of water to entitlements are announced progressively during a water year (which starts in July) by local authorities based on water availability. The allocated water stays accessible to be withdrawn or traded by the entitlement holders throughout the water year, and unused water would be lost at the end of the water year unless it is “carried-over” (Loch et al., 2012). Carryover can be used or traded in the next season but it is not identifiable in the transaction records, so it is not directly analyzed in this study using water trading data. On the other hand, carrying-over unused allocation requires carryover capacities under a license, sometimes referred to as “empty parking space” for water. Entitlements of lower securities such as GSEs and LREs are often entitled for more carryover capacity than HSEs and are therefore used and traded as carryover products (Seidl, 2020). This is especially the case for LREs in the study regions that historically receive no water allocation and are exclusively traded for their carryover capacity. Because of this, transactions of LREs can reflect the demand of carryover capacity, even though carryover trades are not directly identifiable in trading records.

During the early stages of the market, water entitlements were tied to agricultural land, which meant that only agricultural landholders were allowed to own water entitlements. Water trading therefore was limited to only between irrigators, which impeded the efficiency of the market (Wheeler et al., 2013). Aimed at facilitating efficient water allocation towards its highest-valued uses and reducing the barriers to trade, a series of water reforms took place since the 1990s (Lee and Ancev, 2009). The unbundling of land and water, and other policy reforms created preconditions for the rapid development of the water market (Hanemann and Young, 2020). This resulted in non-land-holding investors participating in the market, which has greatly intensified water trading in the MDB (Wheeler and Garrick, 2020). With the increased level of market participation, some derivative products such as forward contracts, entitlement leasing, and carryover capacity leasing have been developed (Seidl, 2020). Various stakeholders view the water market like any other financial market, applying sophisticated investment management (Seidl, 2020). There have also been debates over the impacts of non-land holders, especially large institutional investors, on the market. Some suspect that the speculative activities by financial investors drive up the entitlement and allocation prices (see Wheeler, 2022). However, previous literature found that water scarcity is the fundamental driver of water prices (Seidl et al., 2020; Zuo et al., 2019). The Australian Competition and Consumer Commission (ACCC) conducted an inquiry into MDB water market and reported no evidence of market power or market manipulation by financial investors (ACCC, 2020).

3.3 Data

3.3.1 Study area

This study focuses on the surface water markets in the southern MDB (sMDB) where water trading is the most active. The sMDB covers parts of New South Wales (NSW), Victoria (VIC), South Australia (SA) and the Australian Capital Territory (ACT). While the trading zones in the sMDB are mostly hydrologically connected and enjoy a similar climate, there are some important differences, such as trading restrictions, crop structure and institutional differences across jurisdictions. These differences could lead to development of diverging water market outcomes across trading zones. It is therefore important to consider and control for the trading zone heterogeneities when analyzing the characteristics of the water market. Here, in total eight major trading zones from both NSW and VIC are included in this tsudy, covering some 80% of all water market transactions in the sMDB.

Five major trading zones are analyzed for both the entitlement and allocation market: NSW Murray and NSW Murrumbidgee, VIC Murray 6 above Barmah Choke, VIC Murray 7 Barmah Choke to SA, and VIC 1A Greater Goulburn. These five trading zones are the largest ones in the sMDB for both entitlement and allocation trading, constituting over 70% of transactions. They are also important regions for irrigated agriculture, including high-value crops like cotton and almonds, as discussed below in Section 3.3. The locations of these trading zones are shown in Figure 1. NSW Murray actually consists of two trading zones, NSW 10 Murray above Barmah Choke and NSW 11 Murray below Barmah Choke. The entitlement transaction data obtained from NSW water register does not distinguish between these two trading zones—transactions from both zones are listed under the NSW Murray Regulated River. Given that these two trading zones are geographically close to each other, and they share the same water source and thus the same water allocation announcements, I combine NSW 10 and NSW 11 in our analysis, referring to them together as NSW Murray.

I include additional three trading zones for the allocation markets: VIC 1B Boort, VIC 3 Lower Goulburn and VIC 6B Lower Broken Creek with locations also shown in Figure 3.1. These trading zones are among largest trading zones in terms of trading frequency and were investigated in ACCC (2020). However, the frequencies of trading are in general too low to generate reliable estimates of the key attributes for the entitlement market in these zones. Specifically, these three trading zones on average have less than 10 entitlement transactions per quarter with non-zero prices, or even no transaction at all in some quarters. The frequencies of allocation trading in these three trading zones, on the other hand, are sufficient for our analysis. Additionally, SA Murray, which is a relatively large and active trading zone, is not included in this study due to transactional trading data not being accessible.

Benefiting from the highly interconnected hydrological systems in the sMDB, water trading across jurisdictions is relatively unhampered. This contributes to the market efficiency in allocating scarce water resources (Young and Macdonald, 2001). Nevertheless, there are existing limitations on interregional water trading, such as the predetermined limits applied between specific trading zones (Hughes et al., 2023). Water entitlements, on the other hand, are inherently linked to their source and cannot be traded across regions. The mechanism of "tagged trading" allows a change in the point of use of an entitlement to a different region while the entitlement is still subject to the allocation conditions of the source zone (Victorian Water Register, 2023a). Consequently, tagged trading of entitlements essentially mirrors interregional allocation trading. In cases of binding restrictions on interregional trading, price differentials emerge between regions (Hughes et al., 2023). Here, I am interested in analyzing factors influencing the direction of price gaps between zones in both the allocation and entitlement markets.

Figure 3. 1 sMDB trading zones studied: 1A Greater Goulburn, 1B Boort, 3 Lower Goulburn, 6 VIC-Murray above Barmah Choke, 6B Lower Broken Creek, 7 VIC-Murray Barmah Choke to SA, 10 NSW-Murray above Barmah Choke, 11 NSW Murray below Barmah Choke and 13 Murrumbidgee (source: Murray-Darling Basin Authority).

3.3.2 Data sources

This study uses data on historical allocation announcements, transactions in allocations and entitlements, and water usage by certain crops. The data spans the period from 2007 to 2021 water year, in an attempt to utilize all available transactional market data. All transaction data on prices and volumes, and water allocation announcement records were sourced from NSW and VIC state water registers. The dataset on irrigated crop water use was obtained from the Australian Bureau of Statistics (ABS), which reports the application of irrigation water by crop in each natural resource management (NRM) region on an annual basis. As far as I am aware, this is the first time that crop water usage data is compiled with water trading data for the MDB. The cumulative rainfall data was based on monthly rainfall provided by the Bureau of Metrology (BoM) and subsequently processed by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) to suit catchment-level analysis.

3.3.3 Quarterly rainfall

I use cumulative rainfall as an indicator of water availability. It is expected that at times of higher rainfall the irrigation water demand and allocation purchases will be lower. Limited by the level of disaggregation of the rainfall data, trading zone VIC 1B and 3 are assumed to receive the same rainfall as VIC 1A, and VIC 6B the same rainfall as VIC 6. These regions are geographically close and follow the same allocation schemes (see Section 3.3.4). As shown in Figure 3.2, the rainfall in the study regions exhibited highly aligned movements but differed in absolute values. Overall, VIC 6 received the highest rainfall while VIC 7 received the lowest rainfall during the study period.

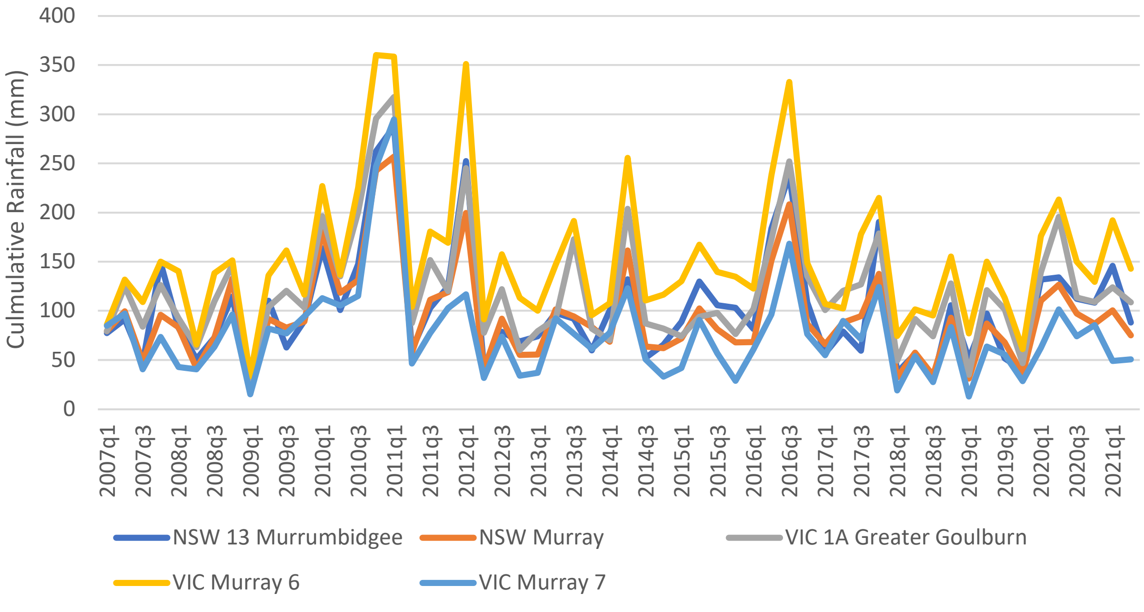

Figure 3. 2 Historical quarterly rainfall (in mm) in study regions

3.3.4 Historical allocation announcement

Historical allocation announcements by trading zone are shown in Figure 3.3. VIC 1B and VIC 3 share the same allocation determinations with VIC 1A as they belong to the same water source(Victorian Water Register, 2023b). Similarly, VIC 6B share the same allocation determinations with VIC 6 (Victorian Water Register, 2023b). Historical allocations for LREs in the studied VIC trading zones are not presented in Figure 3.2, because they have historically received zero allocation.

HSEs, especially those in NSW, received a full allocation (or at least 95%) even during the driest years (Figure 3.3). In contrast, GSEs did not receive a full allocation almost half the time. This is because HSEs have priority to receive a full allocation when the water supply is insufficient (Freebairn and Quiggin, 2006). GSEs only receive allocation after all water demand from HSEs has been met. Therefore, the allocation made available to GSEs in NSW trading zones is much more sensitive to water availability than the allocation given to HSEs.

Figure 3. 3 Historical allocation for high-security and GSEs in the studied trading zones.

3.3.5 Summary statistics for the transaction and key crop data

Tables 3.1-3.3 show the quarterly summary statistics for HSEs, GSEs and LREs, respectively. The transaction prices are expressed in real terms using 2020 as the base year. There are 13 missing observations for the VWAP and average transaction size of HSEs in Murrumbidgee because no transactions were recorded during those quarters. On the other hand, the traded volume and number of transactions are simply 0 during those quarters, so the number of observations for these two variables is also 56. Quarterly data is employed for three reasons: 1) the frequencies of entitlement trading are in general relatively low, so the values for the attributes averaged weekly or even monthly would often be based on too few observations to be reliable; 2) agricultural production plans, which drive the water demand of irrigators, usually do not vary at time intervals shorter than a quarter; 3) the crop water use data are only available on annual basis.

Table 3. 1 Quarterly summary statistics of key variables by trading zone for HSEs

Trading Zone		VWAP (2020 AUD)	Traded volume (ML)	Number of transac per quarter	Average transac size (ML/transac)	Total volume on issue (ML)
NSW 13	Obs	43	56	56	43	56
Murrumbidgee	Mean	3750.84	845.38	3.25	292.74	351139.10
	S.D	2022.39	1397.65	3.06	465.71	9053.26
	Min	1265.75	0.00	0.00	15.33	340587.00
	Max	8122.62	7073.00	17.00	2000.00	364284.20
NSW Murray	Obs	56	56	56	56	56
	Mean	3699.85	1285.42	11.39	114.82	187895.80
	S.D	2179.21	1180.08	5.51	90.43	2143.20
	Min	1599.07	25.00	1.00	7.38	183340.60
	Max	9289.90	5717.35	26.00	480.71	189704.10
VIC 1A	Obs	56	56	56	56	56
Goulburn	Mean	2681.70	9381.42	158.20	55.03	983458.50
	S.D	810.17	7427.07	52.87	27.18	0.00
	Min	1466.39	1687.70	26.00	19.86	983458.50
	Max	4680.06	32354.90	317.00	126.88	983458.50
VIC Muray 6	Obs	56	56	56	56	56
	Mean	2659.51	4190.27	45.43	88.41	320450.10
	S.D	1039.40	2599.00	16.35	33.69	0.00
	Min	1272.82	365.00	3.00	33.44	320450.10
	Max	5209.56	15248.20	87.00	182.80	320450.10
VIC Murray 7	Obs	56	56	56	56	56
	Mean	3036.17	13488.25	166.27	73.45	937737.30
	S.D	1429.85	15454.90	50.37	63.79	0.00
	Min	1445.81	216.90	16.00	13.56	937737.30
	Max	6720.77	85372.20	300.00	347.04	937737.30

Table 3. 2 Quarterly summary statistics of key variables by trading zone for GSEs

Trading Zone		VWAP (2020 AUD)	Traded volume (ML)	Number of transac	Average transac size (ML/transac)	Total volume on issue (ML)
NSW 13 Murrumbidgee	Obs	56	56	56	56	56
	Mean	1423.15	8007.10	10.30	778.46	1904430.00
	S.D	441.89	8135.31	4.87	865.92	32810.71
	Min	723.25	337.00	2.00	105.75	1885405.00
	Max	2253.14	36936.00	20.00	5276.57	2019804.00
NSW Murray	Obs	56	56	56	56	56
	Mean	1325.53	5088.94	15.21	302.30	1671974.00
	S.D	359.29	7289.21	7.67	377.13	2431.79
	Min	715.55	155.00	2.00	36.09	1668265.00
	Max	2061.23	40112.00	36.00	2242.50	1674485.00

Table 3. 3 Quarterly summary statistics of key variables by trading zone for LREs

Trading Zone		VWAP (2020 AUD)	Traded volume (ML)	Number of transac	Average transac size (ML/transac)	Total volume on issue (ML)
VIC 1A Goulburn	Obs	56	56	56	56	56
	Mean	288.71	3526.54	57.20	60.26	427266.80
	S.D	109.42	2159.16	21.42	21.12	0.00
	Min	149.69	442.40	13.00	32.93	427266.80
	Max	541.37	12770.40	106.00	120.48	427266.80
VIC Muray 6	Obs	56	56	56	56	56
	Mean	302.07	1674.56	19.27	87.64	130679.40
	S.D	143.57	935.47	8.32	35.34	0.00
	Min	126.32	170.40	3.00	34.50	130679.40
	Max	601.34	4173.70	40.00	202.90	130679.40
VIC Murray 7	Obs	55	55	56	55	56
	Mean	350.61	1725.50	22.86	72.80	179515.20
	S.D	220.23	1131.15	11.31	41.44	0.00
	Min	143.50	154.60	0.00	29.24	179515.20
	Max	1247.27	4746.40	54.00	301.13	179515.20

For the crop water use data, I match the NRM regions with water trading zones based on their geographic location with correspondences shown in Table 4 below. The NRM region "Murrumbidgee" in the dataset during 2010-2015 has been replaced by "Riverina" since 2016. The trading zone VIC Murray 7 geographically extends across two NRM regions "Mallee" and "North Central". To better reflect the crop structure in VIC Murray 7, I use the weighted sum of the key crop water usage data of the two NRM regions, weighted by the total volume applied.

This study focuses on cotton and fruit & nut trees as key crops due to their high economic value and quick expansion in the study regions over the studied period. For instance, cotton cultivation, which was historically absent in the sMDB, has experienced rapid expansion in the Murrumbidgee region over the past two decades. By 2016, Riverina (which aligns with the Murrumbidgee water trading zone) emerged as the third largest cotton-growing region in Australia in terms of gross value produced (GVP), contributing 20% of the cotton GVP in NSW (NSW DPI, 2016). As shown in Figure 3.4, the percentage of total irrigation water applied to cotton in Murrumbidgee has increased significantly since 2010. At the same time, the percentage of irrigation applied to fruit and nut trees has grown over 10% in NSW Murray, NSW Murrumbidgee and in VIC Murray 7. The significant increases can be attributed to the expansion of the almond industry in these regions (Murray-Darling Basin Authority (MDBA), n.d.-a). As shown in Figure 3.5, large acreage of almond trees has been newly planted in Australia during the past five years, indicated by the "non-fruit-bearing" trees as they are young and not yet productive. These new trees are predominately planted in southern NSW and northern VIC (Almond Board of Australia, 2021). ABARES predicts that the maturing of these new almond trees will have further effects on the water market in sMDB and will intensify the impacts of inter-regional trade restrictions (Gupta et al., 2020). This study is interested in investigating if the quick expansion of these high-value crop industries is correlated with the divergence in entitlement and allocation prices across trading zones, as described and presented in Section 3.3.6. Other high-value crops such as grapevines are not included because there have not been significant changes in the acreage of these crops in the studied trading zones over the study period. Meanwhile, it is important to recognize a key difference between cotton and fruit & nut tree in terms of their asset values. Cotton, being an annual crop, has a substantially lower asset value and more flexible water requirements compared to perennial fruit & nut trees. Thus, these two categories serve as distinct representations of annual and perennial crops, while both maintaining high economic value.

Table 3. 4 Crop water usage summary statistics by trading zone

Trading Zone (NRM in parenthesis)		Volume applied to cotton (ML)	Volume applied to fruit and nut trees (ML)
NSW Murray (Murray)	Obs	56	56
	Mean	10109.6	13329.2
	S.D	7117.21	7246.37
	Min	0	5135.3
	Max	22259	24828
VIC Murray 6 (North East)	Obs	56	56
	Mean	0	1374.88
	S.D	0	963.677
	Min	0	394
	Max	0	4384
VIC Murray 7 (North Central, Mallee)	Obs	56	56
	Mean	0	126085
	S.D	0	53596.1
	Min	0	43229
	Max	0	207929
NSW 13 Murrumbidgee (Murrumbidgee 2010-2015; Riverina 2016-2019)	Obs	56	56
	Mean	198932	70307.7
	S.D	148170	20688.1
	Min	11933	41816
	Max	536107	107448
VIC 1A Greater Goulburn (Goulburn Broken)	Obs	56	56
	Mean	54.7143	48230
	S.D	199.061	6119.84
	Min	0	36406
	Max	766	60024

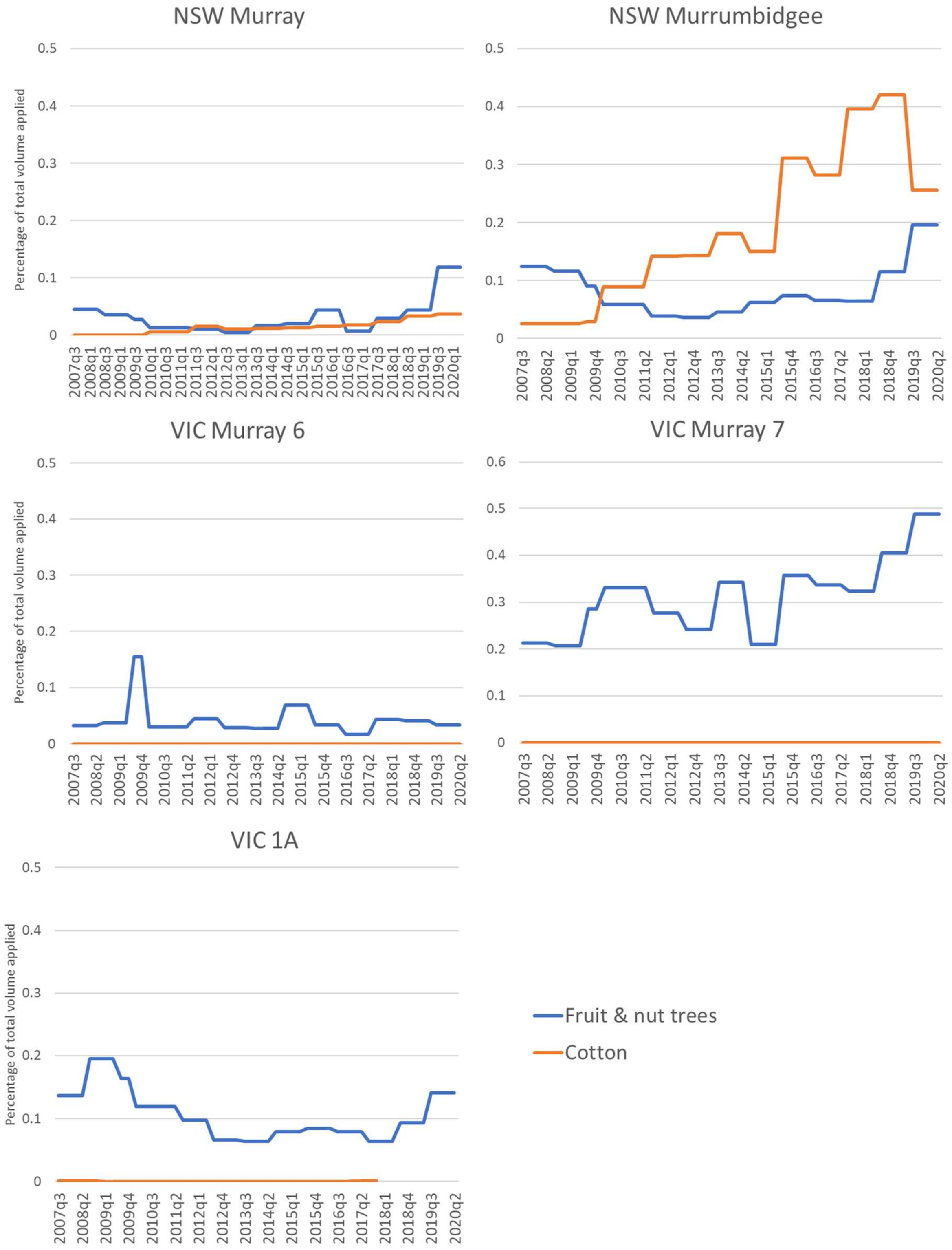

Figure 3. 4 Percentage of the total volume of water applied to cotton and fruit & nut trees in major sMDB trading zones.

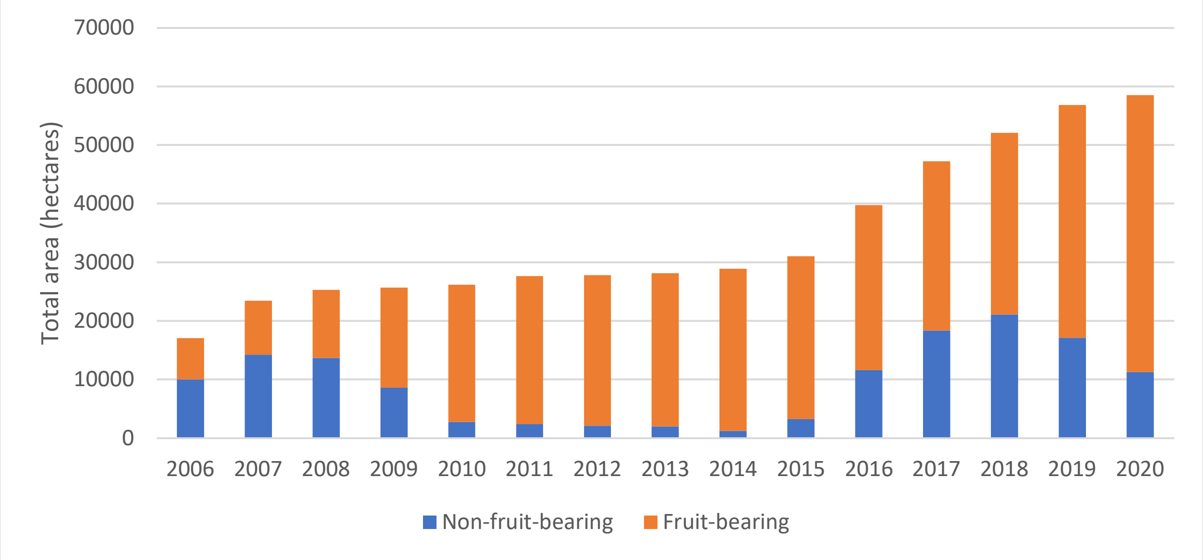

Figure 3. 5 The total area (hectares) of almond trees planted in Australia (data source: Almond Board of Australia (2021))

Table 3.5 shows summary statistics for the allocation market. Price averages (VWAP) for water allocation are similar across studied trading zones. The water markets in VIC 1B, 3 and 6B are significantly smaller than the others, in terms of traded volume and number of transactions per quarter.

Table 3. 5 Quarterly summary statistics of key variables by trading zone for allocation

Trading Zone		VWAP	Traded volume (ML)	Number of transactions	Avg transac size (ML/transaction)
NSW 13	Obs	55	55	55	55
Murrumbidgee	Mean	234.74	65635.68	319.18	297.76
	S.D	261.90	37267.63	302.33	204.45
	Min	9.05	3031.60	5.00	51.56
	Max	1300.12	151454.10	1833.00	909.17
NSW	Obs	56	56	56	56
Murray	Mean	255.84	43144.53	288.66	190.15
	S.D	272.24	25411.05	171.61	157.42
	Min	6.30	2762.10	19.00	42.49
	Max	1278.15	125469.30	747.00	996.26
VIC 1A	Obs	56	56	56	56
Goulburn	Mean	230.08	65629.89	943.71	84.05
	S.D	222.44	31226.64	593.95	38.49
	Min	11.61	5052.20	134.00	23.81
	Max	985.52	137266.80	3162.00	182.95
VIC 1B	Obs	56	56	56	56
	Mean	211.10	4536.67	43.00	148.72
	S.D	198.25	3223.04	45.80	118.80
	Min	7.99	164.00	6.00	20.50
	Max	1040.79	15355.00	244.00	662.14
VIC 3	Obs	56	56	56	56
	Mean	207.27	2382.41	28.20	121.16
	S.D	185.78	1481.51	19.93	123.66
	Min	7.88	34.00	2.00	17.00
	Max	691.69	6807.10	99.00	750.00
VIC 6B	Obs	56	56	56	56
	Mean	246.94	1748.28	29.50	67.68
	S.D	226.48	1655.65	19.37	49.23
	Min	9.51	54.10	1.00	13.53
	Max	945.59	8832.50	95.00	291.55
VIC Muray 6	Obs	56	56	56	56
	Mean	228.98	18705.14	240.07	83.90
	S.D	196.60	12476.87	132.89	36.96
	Min	14.27	717.20	26.00	15.16
	Max	737.27	58750.30	630.00	163.18
VIC Murray 7	Obs	56	56	56	56
	Mean	236.40	73900.48	855.88	105.84
	S.D	210.17	41985.15	558.49	57.44
	Min	14.03	3719.60	72.00	19.37
	Max	795.08	161127.60	2466.00	270.48

3.3.6 Volume-weighted-average prices

Entitlement prices have long been a focus of the literature on water markets. As summarized in Section 1, numerous studies in the U.S. have investigated the influence of seniority/priority on entitlement prices (Colby et al., 1993; Goodman and Howe, 1997; Payne et al., 2014). A t-test is provided in Appendix B.1 for the price difference between HSEs and lower-security entitlements in the same state. The t-statistics suggest that HSEs have significantly higher prices than lower-security entitlements.

I am also interested in price movements of entitlements of the same reliability category over time and across trading zones. As shown in Figure 3.5, the movements of HSEs prices across five major trading zones were highly aligned over the period 2010 to 2016. More recently (since 2016), however, the prices started to diverge across trading zones. The differences across zones kept increasing between 2016 to 2020. At the end of the 2020 water year, the quarterly VWAP for HSEs in NSW Murray was about $8000/ML, about twice the price of HSEs in VIC Goulburn at that time. Divergences also occurred in the prices of GSEs and LREs across trading zones, though to a less notable extent than for the HSEs (Figure 3.6). Similar observations can be made for allocation trading (Figure 3.6). The allocation prices across eight trading zones from both NSW and VIC were mostly aligned during 2010 to 2019. The prices diverged during 2019 and then quickly converged back together at the beginning of 2020. The allocation prices exhibited again minor divergences during 2020 and then converged in early 2021.

Overall, entitlement and allocation prices across different trading zones appear to be following each other closely during the first part of the study period (2010 to 2015), and then show various levels of divergence during the second half, from 2015 to 2021. Given the highly connected river system, similar climate and water availability conditions that these trading zones share, it is worth investigating the drivers behind the price divergence across trading zones.

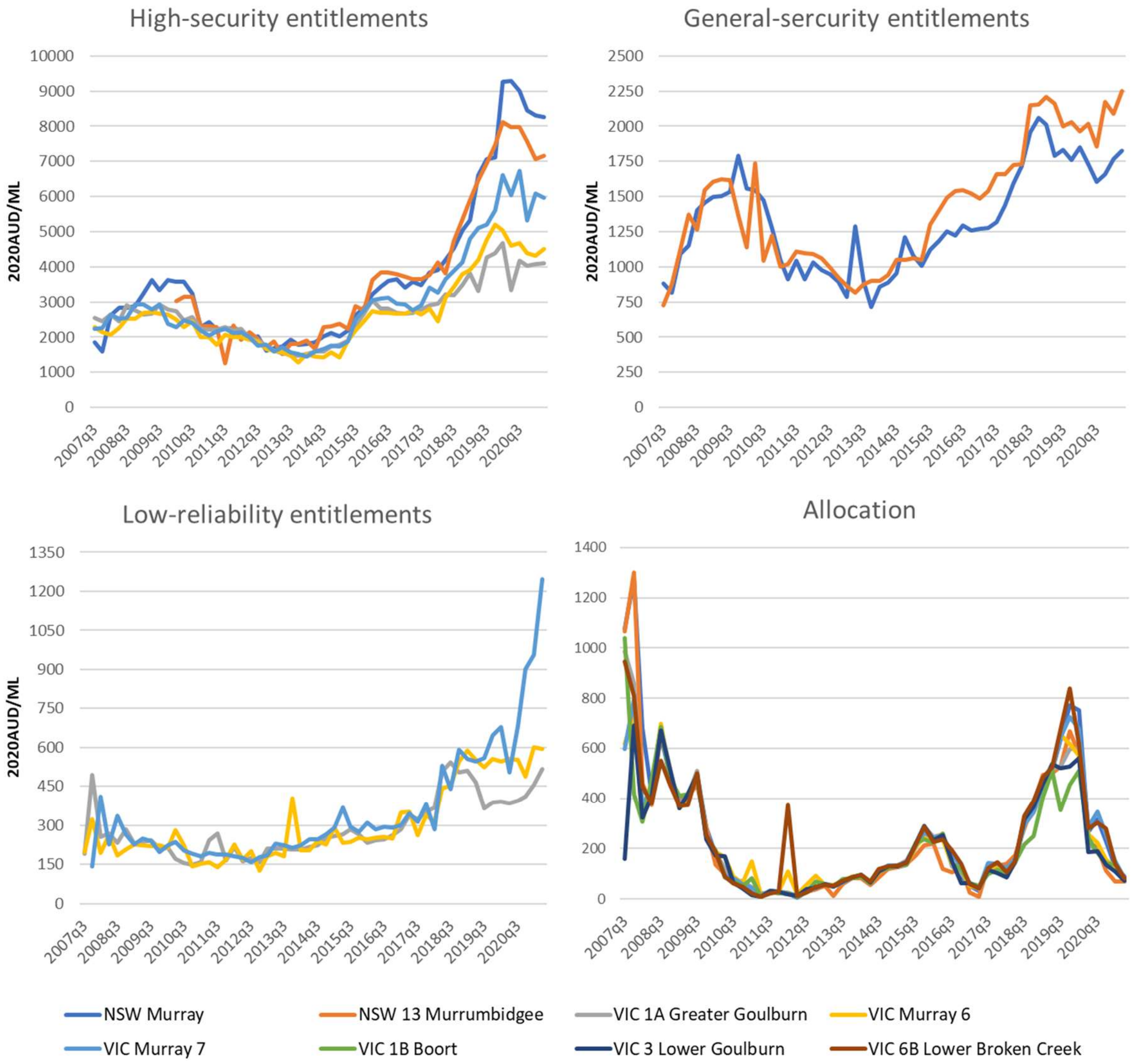

Figure 3. 6 Quarterly volume-weighted average prices of entitlements by reliability level and water allocation in major sMDB trading zones.

3.3.7 Price volatility

Price volatility is measured in the standard deviation of the prices of water products. As shown in Figure 3.7, HSEs on average exhibited higher price volatilities during the later period (2018 to 2021), while this was not the case for the lower-security entitlements. The allocation price volatilities in all trading zones exhibited some large spikes caused by a small number of transactions with prices significantly higher or lower than the prevailing spot price. The allocation price volatilities showed smaller differences across trading zones during the latter half of the studied period, especially from 2018 to 2021.

Figure 3. 7 Within-quarter price volatilities (measured by standard deviations) of entitlements by reliability level and water allocation in major sMDB trading zones.

3.3.8 Traded Volume

Traded volumes of entitlements and allocations are shown in Figure 3.8. On average all trading zones traded a larger volume of HSEs during the early years, from 2010 to around 2016, despite one large spike in VIC 7 in 2019. In general, traded volumes of entitlements did not exhibit seasonality. This is expected since entitlements are regarded as long-term investments, in contrast to allocations which are mostly used to meet seasonal water demand that displayed some level of seasonality (Figure 3.8), with peaks usually occurring during the first quarter. The traded volume in NSW Murrumbidgee shows a somewhat different pattern, which might be attributed to the Murrumbidgee inter-valley trade (IVT) restrictions that limit trade between the Murrumbidgee and the other major trading zones (Sarah Wheeler et al., 2020). The IVT restrictions were likely to have an important influence on the water trading for irrigators in Murrumbidgee, resulting in a different pattern of traded allocation volume. The IVT restrictions were binding during 2015-2016, restricting water trading out of Murrumbidgee while the water trading into Murrumbidgee was restricted for long periods during 2017-2019, due to strong demand from cotton growers in Murrumbidgee (BoM, 2021; BoM, 2020)

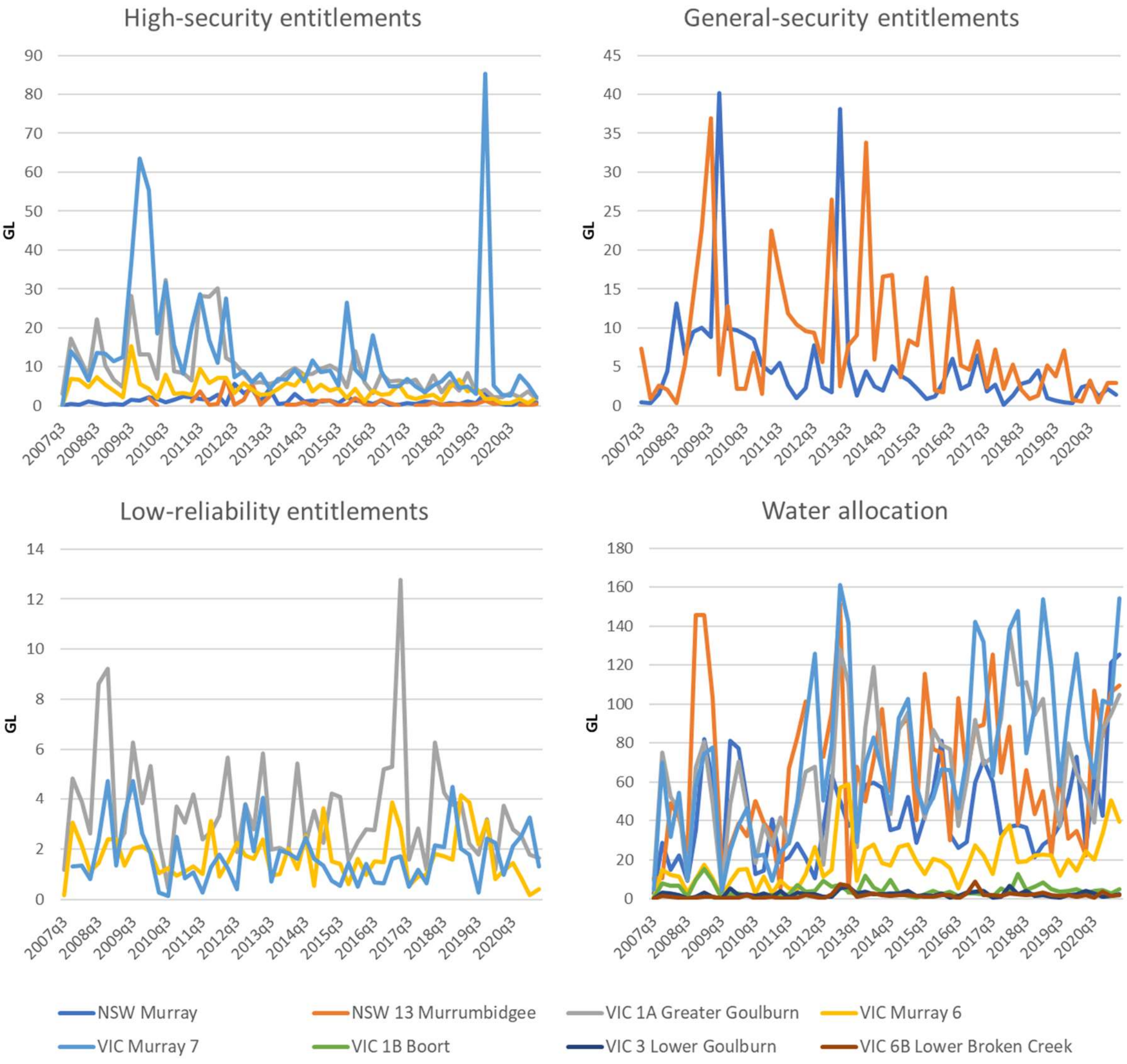

Figure 3. 8 Quarterly traded volume (GL) of entitlements by reliability level and water allocation in major sMDB trading zones.

3.3.9 Number of transactions and average transaction size

Figure 3.9 shows the number of transactions for entitlements and water allocation and Figure 3.10 shows the average transaction sizes. The number of transactions of entitlements did not show clear seasonality, consistent with the pattern for traded volumes. The number of transactions in the allocation market showed clear seasonality, peaking around the first or second quarter and plunging during the third quarter (Figure 3.9). Allocation trading took place in VIC 1A and VIC 7 in the form of more frequent and, on average, smaller transactions, while Murrumbidgee tended to have on average significantly larger transaction sizes, again similar to the pattern for entitlement trading. This is possibly a result of the IVT restrictions that traders rush to trade on a limited quota by placing large orders once the trading restriction opened up temporarily.

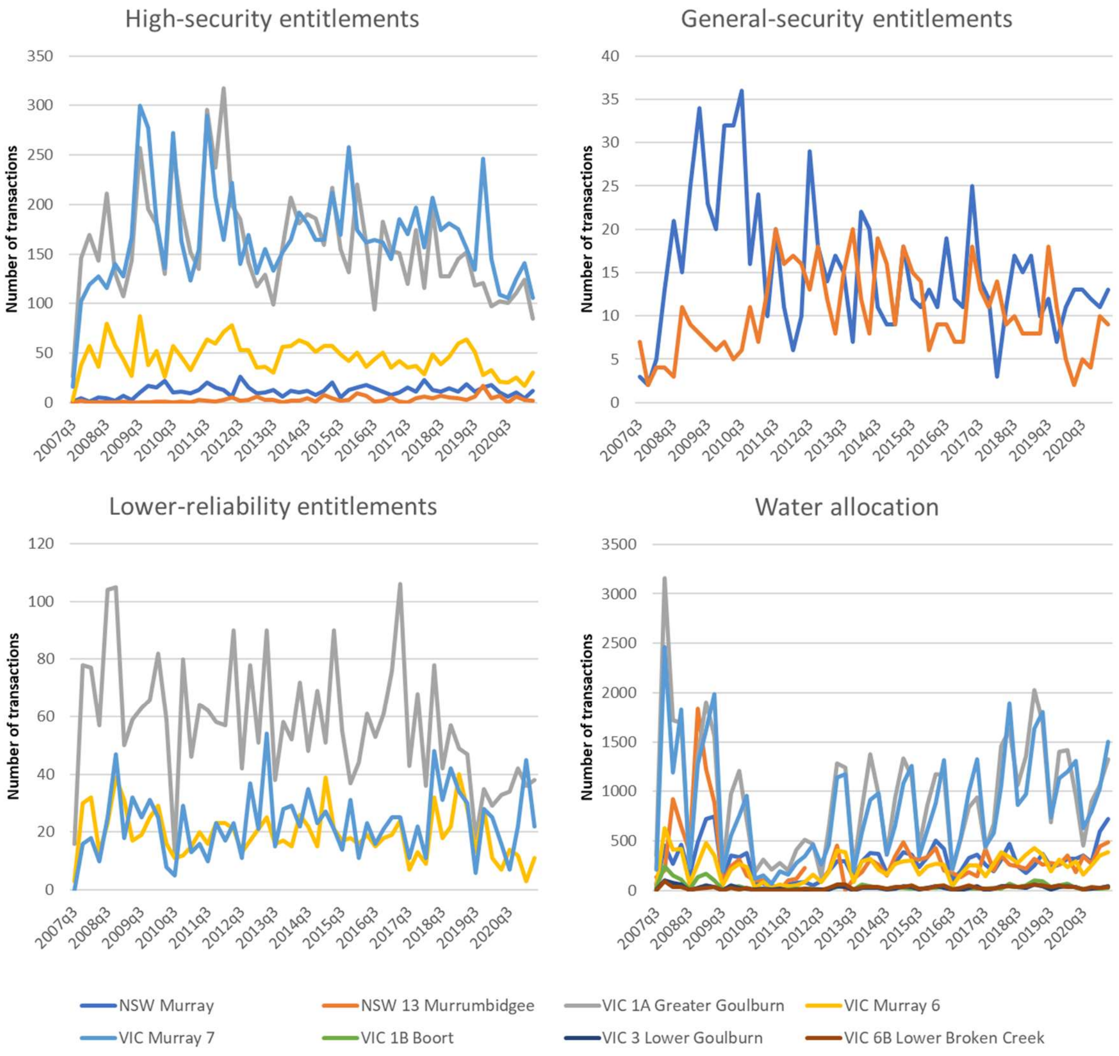

Figure 3. 9 Quarterly number of transactions for entitlements by reliability level and water allocation in major sMDB trading zones.

Figure 3. 10 Quarterly average size of transations for entitlements by reliability level and water allocation in major sMDB trading zones.

3.4. Methods

3.4.1 Empirical design—fixed-effects model

The empirical analysis in this chapter aims to investigate differences in key market attributes across trading zones and factors that influence changes in these key attributes over time. While the trading zones in sMDB are in general similar and hydrologically connected to each other, there are some important differences that can lead to heterogeneity in the local market characteristics. This includes differences in time-invariant zone-specific characteristics such as climate, size of the market, geographic characteristics, historical crop type and irrigation infrastructure that may influence key market attributes. While ignoring these time-invariant zone-specific characteristics may lead to omitted variable bias in estimation, the effects of these characteristics are fixed over time and are not useful for understanding the observed changes in key market attributes over the sample period. I therefore use fixed-effects to control for the effects of these time-invariant zone-specific factors on the set of market attributes I study. On the other hand, time-varying zone-specific characteristics such as the composition of market participants (e.g. proportion of financial investors versus traditional water users), market liquidity, and the level of market maturity have important effects on the key attributes of the water market. However, it is not possible to directly estimate and separate the effects of these time-varying characteristics at this stage due to lack of data (e.g. identification of trader types in the transaction data is not currently possible) or due to difficulties in measuring and quantifying the stages of market development. A time trend is estimated for each zone, in an attempt to capture the joint effects of these time-varying characteristics.

I present the models for each attribute in the following subsections. Each model is estimated separately for allocations, and for entitlements of three reliabilities: high-security, general-security (NSW trading zones only) and low-reliability (VIC trading zones only). All models use the Newey-West estimator to produce estimates of standard errors robust to heteroskedasticity and serial correlation. The maximum lag order of autocorrelation specified for the Newey-West estimator is two, based on the approach proposed by Greene (2018) who suggested a rule of thumb for the estimation of maximum lag order of autocorrelation for Newey-West standard error: *m=int(T^(1/4))*, where *m* is the optimal lag order and *T* is the number of periods in the dataset.

3.4.2 Volume-weighted-average prices

To understand the major drivers of entitlement prices and to formally test if the observed price divergences across trading zones are statistically significant, I focus on the fixed-effect model with trading-zone-time interaction terms. The model is specified as follows:

$$VWAP_{it} = \beta_0 + \beta_1 Allo_{it} + \beta_2 Rainfall_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Fruit\_nut_{it} + \beta_5 Cotton_{it} + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.1]$$

where the outcome variable $VWAP_{it}$ is the volume-weighted-average price of the studied water product (allocation or entitlement) in the i^{th} trading zone in quarter *t*. The explanatory variable $Allo_{it}$ records the cumulative allocation of the studied entitlement in the i^{th} trading zone in period *t* (only used in the model for entitlements). Variable $Rainfall_t$ measures the cumulative rainfall in millimeters during the t^{th} quarter in the i^{th} trading zone, while $Rainfall_{t-1}$ represents rainfall in the previous quarter.

The key crop water usage variables, $Fruit\_nut_{it}$ and $Cotton_{it}$, measure the percentage of total volume of water applied to fruit & nut trees and cotton, respectively, in the i^{th} trading zone. Note that the crop water usage data are only available on an annual level while quarterly data are used for the other variables. The percentage of water applied to fruit &nut trees and cotton reflects the crop structure in each trading zone as well as the demand for irrigation water. A higher proportion of irrigation water devoted to these high-value crops indicates a more inelastic water demand in a given zone, and may affect water prices of both permanent water rights and water allocations in that zone. Potential endogeneity between price and quantity (i.e. water use in this case) is a common concern. However, percentage of water applied to high-value crops is not used in this model to identify a causal relationship between crop water use and entitlement prices, but to control for the changing cropping pattern in studied trading zones. The almond and cotton industries have been growing very fast in some of the sMDB trading zones (e.g. VIC Murray 7 and NSW 13 Murrumbidgee) and have been identified as factors contributing to the price gaps between regions (e.g. see ACCC, 2020 and Hughes, 2023), which is why I include the water use of these high-value crops as control variables in the VWAP model.

The fixed effects, $\sum_{i=2}^{n} \alpha_i D_i$, capture the impacts of trading-zone-specific time-invariant factors. This specification allows the intercept α_i of each trading zone, indicated by the dummy variable D_i, to be explicitly estimated in the model (except for one baseline zone, Goulburn in this case, that is dropped to avoid multicollinearity). The term $\sum_{i=2}^{n} \gamma_i D_i t$ measures the impacts of the zone-time interaction terms on the outcome variable, where the time trend variable t is measured in quarters and is estimated as a continuous variable. The interaction terms enable us to estimate a different time trend for each trading zone to evaluate the effects of some time-varying, zone-specific factors.

Price series can exhibit a high degree of autocorrelation as the current prices may be highly correlated with prices observed in immediately preceding time periods. To assess the possible bias and to incorporate the dynamic aspect of the data, I use an alternative model with lagged dependent variable for robustness check. The procedures and results of this alternative model based on the Arellano-Bond estimator are presented in the Appendix B.2.

3.4.3 Price divergence

To further investigate the drivers behind the divergence in prices of water products, I employ the following model:

$$DF\_VWAP_{it} = \beta_0 + \beta_1 DF\_Allo_{it} + \beta_2 Rainfall_{it} + \beta_3 DF\_Volume\_onissue_{it} + \beta_4 DF\_Fruit\_nut_{it} + \beta_5 DF_{Cotton_{it}} + \delta t + u_{it} \tag{3.2}$$

While the variables are defined similarly as in Eq.[3.1], the prefix *DF_* means the variable measures the difference between the values of that variable in the i^{th} trading zone and that in VIC 1A Greater Goulburn during the same period. VIC 1A Goulburn is used as the baseline trading zone here for two reasons: 1) it is the largest trading zone in terms of entitlement volume on issue and one of the most active trading zones in terms of traded volume in sMDB; 2) the entitlement prices are consistently the lowest in Goulburn compared to other trading zones, making it easier to compare the price divergences between zones. Since the dependent variable already measures the differences in VWAP between zones, it is no longer appropriate to include trading-zone-fixed effects. I thus estimate this model using OLS.

The additional variable $Volume\_onissue_{it}$ represents the total volume on issue of the studied entitlement in i^{th} trading zone in period *t*. This variable is used as a proxy for the size of the water market in a trading zone. This variable is not included in the FE models because it is time invariant for the VIC trading zones and slowly varying for the NSW trading zones. It therefore cannot be estimated under the *within* transformation in FE models.

I use the difference between the percentage of volume applied to fruit and nut trees (the same for cotton) in the i^{th} trading zone and that in VIC Goulburn, denoted by $DF\_Fruit\_nut_{it}$ (DF_Cotton_{it} for cotton), to reflect the differences in the relative importance of these high value crops in irrigation between different zones. The hypothesis is that water prices are likely to increase more dramatically in those trading zones where there have been notable increases of the acreage under these crops during the study period. The model given in

Eq. [3.2] formally tests the significance and magnitude of the effects of these high-value crops in driving water price differences among trading zones.

The fundamental value of an entitlement lies in its ability to generate water allocation. The differences in allocation received by entitlements of the same reliability between trading zones, denoted by DF_Allo_{it}, is therefore expected to influence price differences. I also include the water availability variable $Rainfall_{it}$ in this model to test if the price divergences among zones are enlarged during relatively dry periods. Increases in the water use by high-value and perennial crops like fruit and nut trees are likely to drive up water prices, which could be further intensified during drought period as the perennial irrigators have high willingness to pay for water to keep the plants alive.

3.4.4 Price volatility

Price volatility often receives great attention from both researchers and market participants, because it reflects the riskiness of a market. In the water market, price volatility may reflect the fluctuations in the cost of water allocation purchases in meeting irrigation needs and in the return on investment in permeant water rights (entitlements). I measure volatility in this model by the standard deviations of prices. The model of price volatility that I estimate is as follows:

$$Price\_sd_{it} = \beta_0 + \beta_1 Allo_{it} + \beta_2 Rainfall_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Fruit\_nut_{it} + \beta_5 Cotton_{it} + \beta_6 VWAP_{it} + \beta_7 Trans\_size_{it} + \beta_8 Volume\_traded_{it} + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.3]$$

where $Price\_sd_{it}$ is the standard deviation of the price of water products in the i^{th} trading zone during the t^{th} quarter, so it reflects price dispersion within a quarter for each trading zone. I keep entitlement allocation $Allo_{it}$ and $Rainfall_{it}$ in the model to study the impact of water supply on the volatility of water prices.

Two additional variables are included in the price volatility model: the total traded volume of the studied water product, $Volume\_traded_{it}$, and the average transaction size (in terms of volume), $Trans\_size_{it}$. The volume-volatility relation has long been debated in the finance literature, with most studies finding a positive correlation between traded volume and stock return volatility (Kyröläinen, 2008). The average size of transactions is calculated by dividing the total traded volume by the number of transactions in a quarter. By including this variable, I can adequately study the impacts of large-volume transactions, the so-called bulk trading, on the volatility of prices.

3.4.5 Total traded volume and number of transactions

Traded volume is an important indicator of how active the water market is in a trading zone. The number of transactions is used as an alternative measure of how frequently transactions happen in the market and thus how active the water market is in a trading zone. The models are specified as follows:

$$Volume\_traded_{it} = \beta_0 + \beta_1 Allo_{it} + \beta_2 Rainfall_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Volume\_onissue_{it} + \beta_5 Fruit\_nut_{it} + \beta_6 Cotton_{it} + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.4]$$

$$Num\_transactions_{it} = \beta_0 + \beta_1 Allo_{it} + \beta_2 Rainfall_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Volume\_onissue_{it} + \beta_5 Fruit\_nut_{it} + \beta_6 Cotton_{it} + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.5]$$

where total traded volume $Volume\_traded_{it}$ and the total number of transactions $Num\_transactions_{it}$ are the outcome variables and the explanatory variables are defined similarly as in the previous models.

3.4.6 Models of Water Allocations

All models of the allocation market are constructed very similarly to those for the entitlement market, except for two differences: 1) two variables, total volume on issue and cumulative allocation for each entitlement, are excluded from the allocation models because they are only relevant for the entitlements. I keep the allocation to GSEs in NSW Murray as a proxy for general water availability. 2) I include additional quarter dummies in the allocation models to control for the seasonality exhibited in the allocation market but not in the entitlement market. The models are specified as follows:

Volume-weighted price model:

$$VWAP_{it} = \beta_0 + \beta_1 Rainfall_{it} + \beta_2 Fruit\_nut_{it} + \beta_3 Cotton_{it} + \beta_4 Rainfall_{it-1} + \beta_5 Quarter_t + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.6]$$

All the variables are defined similarly as in the entitlement price model, i.e. Eq. [3.1]. The additional quarter dummies, $Quarter_t$, indicate if the t^{th} quarter in the dataset is the first, second, third or fourth quarter in the calendar year. The first quarter is used as the base category here. Allocation prices are expected to show seasonality, which should be reflected by the estimated coefficient on $Quarter_t$.

Price volatility model:

$$Price\_sd_{it} = \beta_0 + \beta_1 Rainfall_{it} + \beta_2 Fruit\_nut_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Cotton_{it} + \beta_5 VWAP_{it} + \beta_6 Trans\_size_{it} + \beta_7 Volume\_traded_{it} + \beta_8 Quarter_t + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.7]$$

All variables are defined similarly as in the entitlement price volatility model, i.e. Eq. [3.3].

Total traded volume model:

$$Volume\_traded_{it} = \beta_0 + \beta_1 Rainfall_{it} + \beta_2 L\_Rainfall_{it} + \beta_3 Fruit\_nut_{it} + \beta_4 Cotton_{it} + \beta_5 Quarter_t + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.8]$$

The number of transactions model:

$$Num\_transactions_{it} = \beta_0 + \beta_1 Rainfall_{it} + \beta_2 Fruit\_nut_{it} + \beta_3 Rainfall_{it-1} + \beta_4 Cotton_{it} + \beta_5 Quarter_t + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \quad [3.9]$$

All variables are defined similarly as in Eq. [3.4] and Eq. [3.5]. Both total traded volume and number of transactions of water allocations reflect how active the allocation market is. The market is expected to be more active during the irrigation season which extends from November to mid-May (Australian Bureau of Statistics, 2007).

An additional model for the net import of allocations in a trading zone is presented in Appendix B.3.

3.5 Results

3.5.1 Entitlement market

3.5.1.1 Volume-weighted-average prices

The regression results for entitlement prices are shown in Table 3.6. There is strong evidence that allocation made available to HSEs is negatively associated with their VWAPs, while there is only weak evidence showing a positive relationship between rainfall in the current quarter and HSE prices. These results indicate that HSE prices are more responsive to water supply specifically made available for HSE holders to withdraw rather than to rainfall as such. The percentage of water applied to fruit & nut trees is positively associated with VWAPs in the HSE model. The estimated coefficient indicates that if the percentage of water applied to fruit & nut trees increases by 1%, the price of HSEs will increase by AUD94.7 in that trading zone, corresponding to a 2.9% increase based on the overall average HSE price. The estimated slopes of the zone-specific time trends indicate an overall increasing trend in HSE prices and possible explanations are discussed in Section 3.6.

The regression results for the GSE model are similar to those for HSEs. Percentages of the allocation made available to GSEs are negatively associated with their prices ($p<0.05$). The percentages of water applied to fruit & nut trees positively contribute to GSE prices. A 1% increase in the percentage of water applied to fruit & nut trees in a trading zone increases GSE price in that zone by AUD 32.2, corresponding to 2.3% increase based on the average price in Table 3.5. For the LRE, allocation level and percentage of water applied to cotton in a trading zone are dropped out of the model, because all the studied LREs in Victoria receive zero allocation and grow no cotton, as discussed in Section 3.3. The prices of LREs are negatively associated with the contemporaneous and lagged rainfall. There is also evidence ($p<0.05$) indicating that water applied to fruit & nut trees positively affect the prices of LREs.

Estimation results from the alternative Arellano-Bond model (shown in Appendix B.2) are consistent with the FE models, confirming the robustness of the FE models and that the inclusion of lagged dependent variable does not change our major findings.

Table 3. 6 Fixed-effects estimation results on entitlement VWAP by reliability level

	High Security	General Security	Low Reliability
Rainfall	1.42*	0.22	-0.25**
	-1.89	-0.63	(-2.79)
Lagged Rainfall	0.91	0.54*	-0.33***
	-1.29	-1.69	(-3.66)
Allocation	-2148.24***	-335.37**	
	(-6.33)	(-2.67)	
Fruit&Nut Water Applied pct	9474.55***	3221.38**	491.89**
	-4.72	-2.12	-2.48
Cotton Water Applied pct	-4397.03*	418.78	
	(-1.95)	-0.48	
VIC Murray 7	2932.43		-742.2
	-0.95		(-1.07)
NSW 13 Murrumbidgee	-11334.90**	-1155.03	
	(-2.58)	(-0.74)	
NSW Murray	-10549.33**		
	(-2.32)		
VIC Murray 6	748.77		-437.32
	-0.35		(-1.36)
Qrt	63.78***	8.74**	4.82***
	-7.88	-2.55	-4.67
VIC Murray 7 # Qrt	-19.95		3.08
	(-1.32)		-0.91
NSW 13 Murrumbidgee # Qrt	62.45**	4.63	
	-2.95	-0.58	
NSW Murray # Qrt	57.88**		
	-2.73		
VIC Murray 6 # Qrt	-0.82		2.29
	(-0.09)		-1.55
Constant	-10863.75***	-597.1	-740.74**
	(-5.91)	(-0.81)	(-3.15)
Observations	263	110	165
R-squared	0.7635	0.6446	0.5935

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

3.5.1.2 Price divergence

The results of the price divergence model (Eq. [3.2]) by entitlement reliability are shown in Table 3.7. The negative coefficient on rainfall indicates that the price gaps of HSEs among trading zones are enlarged during relatively dry periods. The results also show that HSE price differences (between each trading zone and the baseline VIC Goulburn) are positively correlated with allocation differences. The differences between the proportion of irrigation water devoted to cotton ($p<0.05$) and fruit & nut trees ($p<0.1$), among trading zones are also positively correlated with the price differences. The implication is that entitlement prices diverge based on the ability to yield water allocation and the value that can be derived from the usage of the water. The differences in total volume on issue are negatively associated with price differences. The baseline trading zone, VIC Goulburn, is the largest zone in our dataset for HSEs in terms of total volume on issue and also the zone with the lowest entitlement prices. So, the negative coefficient sign here suggests that the larger the trading zone is (closer in size to the Goulburn), the smaller the price difference will be. This result reflects that HSE prices tend to be lower in larger trading zones. The estimated coefficient on the time trend suggests that the differences between prices in different trading zones are increasing over time.

The results of the GSE models are similar. The allocation differences ($p<0.1$) and the differences in the proportion of irrigation water applied to cotton ($p<0.001$) are positively associated with entitlement price differences. This result is not surprising since cotton has recently become a major high-value crop in the two NSW trading zones, especially in Murrumbidgee. The time trend variable also has a significant and positive coefficient, indicating increased divergence in VWAPs over time. For the model of LREs, the differences in percentage of water applied to fruit & nut trees are positively correlated with the price differences of entitlements ($p<0.05$). Similar to the HSE model, the negative coefficient on the difference in total volume on issue indicates that the prices of LREs are lower in larger trading zones. The significant and positive coefficient of the time trend also indicates increasing differences between the LRE prices over time.

Table 3. 7 Estimation results on entitlement VWAP differences (price divergence across trading zone) by reliability level

	High Security	General Security	Low Reliability
Rainfall	-1.59**	-0.09	0.01
	(-2.95)	(-0.59)	(0.12)
DF_Allocation	890.29***	168.16*	
	(3.49)	(1.94)	
DF_Fruit&Nut Water Applied	957.32*	1597.68	180.31**
	(1.92)	(1.48)	(2.62)
DF_Cotton Water Applied	2153.64**	694.91***	
	(3.25)	(4.39)	
DF_Volume on Issue	-0.00***	-0.00	-0.00**
	(-4.58)	(-1.51)	(-2.34)
Qrt	30.66***	0.92*	2.30***
	(6.77)	(1.98)	(4.04)
Constant	-6510.48***	-207.96**	-500.18***
	(-6.67)	(-2.07)	(-4.03)
Observations	267	112	167
R-squared	0.434	0.421	0.231

t statistics in parentheses
* p<0.1 ** p<0.05 *** p<0.001

3.5.1.3 Price Volatility

The results on price volatility of entitlements, measured by the standard deviation of the prices, are shown in Table 3.8. Total traded volume is negatively correlated with the price volatility in both HSE and LRE models, which suggests that entitlement prices are relatively less volatile in more active trading zones. Allocation is negatively associated with price volatility in the HSE model, indicating higher price volatility for HSEs during relatively dry periods when allocations are lower. The result also suggests that HSE prices are more volatile in regions with a higher proportion of water devoted to high-value crops, i.e. fruit & nut trees and cotton. The percentage of water applied to fruit & nut trees is also positively associated with price volatility of LREs.

3.5.1.4 Total traded volume

The estimation results for total traded volume of entitlements are shown in Table 3.9. The trading zones, NSW Murray, Murrumbidgee, and VIC Murray 6 which are smaller then the baseline zone VIC Goulburn, have lower estimated intercepts. The estimated coefficients of the zone-specific time trends indicate a decline of traded volume over time in all trading zones. For example, the slope of the time trend for the baseline zone is estimated to be -233.93, indicating a decreasing trend in traded volume over time and the slope of the time trend for NSW Murray can be calculated as -233.93+174.71= -59.22, which also indicates a decline in traded volume over time but at a slower rate. The flatter time trends combined with the lower intercepts mean that differences in traded volume caused by zone-specific characteristics are diminishing over time among these trading zones. The percentage of water devoted to fruit & nut trees in an area is positively associated with the traded volume of HSEs, while both percentages of water applied to cotton and fruit & nut trees are negatively associated the total traded volume of GSEs ($p<0.05$).

3.5.1.5 Number of transactions

The estimated results for the number of transactions in the entitlement market are shown in Table 3.10. In the model for HSEs, allocation is positively associated with the number of transactions, indicating HSEs with higher allocation are traded more frequently. Like in the model for traded volume, the number of transactions shows a decreasing trend over time for HSEs but not for the lower-security entitlements.

For GSEs, the percentage of water applied to fruit & nut trees is negatively associated with the number of transactions in a quarter, suggesting that a higher proportion of high-value crops irrigated in a trading zone has a depressing effect on the trading activities of GSEs.

Table 3. 8 Fixed-effects estimation results on price volatility by reliability level

	High Security	General Security	Low Reliability
Rainfall	0.3	0.11	0.08
	(-1.49)	(-0.66)	(-0.28)
Lagged Rainfall	-0.28	0.29	-0.42**
	(-1.14)	(-1.47)	(-2.37)
Allocation	-289.55***	-22.75	
	(-4.14)	(-0.54)	
Total Volume Traded	-0.00**	0	-0.02*
	(-2.56)	(-0.1)	(-1.69)
Average transaction size	0.19	-0.01	-0.27
	(-1.28)	(-0.41)	(-0.94)
Fruit&Nut Water Applied pct	2067.99***	-256.88	966.56**
	(-3.93)	(-0.71)	(-2.12)
Cotton Water Applied pct	932.31**	26.1	
	(-2.15)	(-0.1)	
VIC Murray 7	1148.22		-311.68
	(-1.49)		(-0.40)
NSW 13 Murrumbidgee	5574.83***	229.17	
	(-3.75)	(-0.84)	
NSW Murray	84.43		
	(-0.1)		
VIC Murray 6	409.92		-673.55
	(-0.68)		(-1.28)
Qrt	10.02***	-0.27	-3.11*
	(-4.59)	(-0.25)	(-1.70)
VIC Murray 7 # Qrt	-6.64*		0.39
	(-1.77)		(-0.11)
NSW 13 Murrumbidgee # Qrt	-26.55***	-1.2	
	(-4.03)	(-0.87)	
NSW Murray # Qrt	-0.31		
	(-0.08)		
VIC Murray 6 # Qrt	-1.53		3
	(-0.57)		(-1.33)
Constant	-1705.00***	198.51	871.07*
	(-3.44)	(-228.128)	(-1.89)
Observations	254	110	165
R-squared	0.441	0.1244	0.1272

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

Table 3. 9 Fixed-effects estimation results on entitlement traded volume by reliability level

	High Security	General Security	Low Reliability
Rainfall	0.4	-8.24	-1.91
	-0.07	(-0.80)	(-1.54)
Lagged Rainfall	-3.47	-9.83	-2.55
	(-0.71)	(-0.82)	(-1.61)
Allocation	1394.44	-2983.63	
	-0.64	(-1.04)	
Fruit&Nut Water Applied pct	40947.32**	-78666.15**	633.64
	-2	(-2.85)	-0.24
Cotton Water Applied pct	6258.86	-28144.83**	
	-1.17	(-2.17)	
VIC Murray 7	37955.3		-6565.69
	-0.94		(-1.57)
NSW 13 Murrumbidgee	-31398.1	-34834.04	
	(-1.29)	(-1.22)	
NSW Murray	-43482.19**		
	(-2.70)		
VIC Murray 6	-37057.16**	-6857.40*	
	(-2.45)		(-1.77)
Qrt	-233.93***	-120.49*	-28.50*
	(-3.49)	(-1.95)	(-1.85)
VIC Murray 7 # Qrt	-195.13		20.12
	(-1.05)		-1.01
NSW 13 Murrumbidgee # Qrt	103.13	216.79	
	-0.94	-1.54	
NSW Murray # Qrt	174.71**		
	-2.59		
VIC Murray 6 # Qrt	157.26**		23.73
	-2.45		-1.29
Constant	55455.42***	37382.38**	10258.92**
	-3.59	-2.5	-3.16
Observations	268	110	165
R-squared	0.3979	0.2109	0.2933

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

Table 3. 10 Fixed-effects estimation results on entitlement number of transactions by reliability level

	High Security	General Security	Low Reliability
Rainfall	0.01	0	-0.02
	(-0.3)	-0.43	(-1.15)
Lagged Rainfall	-0.06*	-0.01	-0.03*
	(-1.79)	(-0.64)	(-1.87)
Allocation	28.38**	-2.46	
	(-2.33)	(-0.90)	
Fruit&Nut Water Applied pct	41.33	-75.41**	-38.06
	(-0.82)	(-3.15)	(-1.62)
Cotton Water Applied pct	6.42	-9.16	
	-0.47	(-0.81)	
VIC Murray 7	-204.62		-214.05***
	(-1.26)		(-5.55)
NSW 13 Murrumbidgee	-492.99***	-57.38*	
	(-4.73)	(-1.85)	
NSW Murray	-431.42***		
	(-4.57)		
VIC Murray 6	-336.28***	-142.54***	
	(-3.36)		(-4.26)
Qrt	-1.60***	-0.12	-0.66***
	(-3.64)	(-1.40)	(-4.72)
VIC Murray 7 # Qrt	0.92		0.85***
	-1.26		-4.5
NSW 13 Murrumbidgee # Qrt	1.51**	0.27*	
	-3.32	-1.8	
NSW Murray # Qrt	1.29**		
	-3.17		
VIC Murray 6 # Qrt	1.03**		0.47**
	-2.36		-3.05
Constant	488.52***	46.14**	210.61***
	-4.93	-2.23	-6.98
Observations	270	110	165
R-squared	0.8639	0.3029	0.6744

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

3.5.2 Allocation Market

3.5.2.1. Volume-weighted-average prices

Table 3.11 presents the regression results for key attributes of the allocation market. There is strong evidence that the allocation prices are negatively associated with both contemporaneous rainfall and rainfall from the previous period. The proportion of irrigation water applied to fruit and nut trees exhibits a positive association with the allocation price, which is consistency observed within the HSE and GSE price models. Additionally, there is a weak evidence suggesting a positive association between the percentage of water dedicated to cotton and the allocation price. The findings also indicate a clear seasonality in allocation prices, with peaks during the first and fourth quarters—these correspond to the summer growing season in the sMDB, when irrigation demand also reaches its peak. Estimation results from the alternative model using Arellano-Bond estimator (presented in Appendix B.2) are again similar to those from the FE models, confirming the robustness of the FE models.

3.5.2.2 Price Volatility

The volatility of water allocation prices is negatively associated with traded volume (Table 3.11), similar to the results for entitlements. This result reflects the importance of more active trading in terms of reducing price volatility and uncertainty in the market. The percentage of water applied to fruit & nut trees is positively associated with price volatility. The estimated coefficients of the quarter dummies indicate that price volatility is higher during the first and fourth quarters.

3.5.2.3 Traded volume

There is strong evidence that rainfall is negatively associated with the traded volume of allocation (Table 3.11), which can be expected since rainfall is a substitute for irrigation water. The traded volume of water allocation also exhibits clear seasonality that it peaks during the first quarter, again the growing season in the sMDB. Traded allocation volume is negatively associated with the percentage of volume applied to fruit & nut trees, and the magnitude of the coefficient is large. A possible explanation is that irrigators growing these high-value perennial crops tend to rely on their own entitlements for water supply instead of relying on the allocation market.

3.5.2.4 Number of transactions

Consistent with the regression results for total traded volume, the number of transactions per quarter for allocation trading is negatively correlated with the percentage of water applied to fruit &nut trees (Table 3.11). While the total traded volume during the first quarter is significantly higher than all the other quarters, the number of transactions in the first quarter is not statistically higher than in the second quarter. This result suggests that allocation transactions during the second quarter are still frequent but with smaller trade size on average.

Table 3. 11 Fixed-effects estimation results for allocation market

	VWAP	Price Volatility	Volume Traded	Number of Transactions
Rainfall	-0.52***	0.31**	-52.95***	-0.88***
	(-4.66)	(2.75)	(-4.01)	(-4.05)
Lagged Rainfall	-1.14***	0.04	-34.92**	-1.22***
	(-8.92)	(0.34)	(-2.17)	(-5.06)
Total_volume_traded	-0.00**			
	(-2.19)			
Average_trade_size		-0.11*		
		(-1.80)		
Fruit&Nut Trees Water Applied pct	2603.12***	438.82**	-131229.67***	405.00
	(7.89)	(2.54)	(-3.78)	(0.99)
Cotton Water Applied pct	477.64**	31.98	-33023.13	-349.04
	(1.98)	(0.35)	(-0.42)	(-0.81)
Quarter Dummy=2	-35.79**	-53.36***	-9112.81***	-0.07
	(-2.73)	(-3.71)	(-3.66)	(-0.00)
Quarter Dummy=3	20.56	-58.86***	-19043.73***	-270.43***
	(1.10)	(-3.56)	(-6.25)	(-7.52)
Quarter Dummy=4	48.60**	-13.73	-9076.77***	-82.30**
	(2.66)	(-0.84)	(-4.23)	(-2.62)
NSW 13 Murrumbidgee	1807.95**	-344.88	14699.91	259.37
	(2.37)	(-1.20)	(0.11)	(0.14)
NSW Murray	1202.96	-403.26	-16051.51	-602.37
	(1.53)	(-1.17)	(-0.20)	(-0.37)
VIC 1B Boort	-52.62	-249.67	124166.11**	-463.08
	(-0.10)	(-0.58)	(2.59)	(-0.30)
VIC 3 Lower Goulburn	-87.15	-338.35	116566.68**	-649.87
	(-0.15)	(-0.87)	(2.43)	(-0.41)
VIC 6B Lower Broken Creek	173.59	3.26	85804.84*	-620.51
	(0.21)	(0.01)	(1.71)	(-0.39)
VIC Murray 6	411.01	-58.53	33501.29	-559.06
	(0.53)	(-0.13)	(0.63)	(-0.36)
VIC Murray 7	1865.68**	313.68	-240889.91***	-461.10
	(2.38)	(0.76)	(-3.36)	(-0.22)
Qrt	1.04	-1.48	652.04**	0.69
	(0.51)	(-1.38)	(3.05)	(0.10)
NSW 13 Murrumbidgee # Qrt	-8.62**	1.24	-57.65	-3.91
	(-2.43)	(0.96)	(-0.09)	(-0.47)
NSW Murray # Qrt	-4.74	1.59	-84.67	-0.37
	(-1.35)	(1.02)	(-0.23)	(-0.05)
VIC 1B Boort # Qrt	0.15	0.71	-854.22***	-2.05

Table 11(continued)

	(0.06)	(0.37)	(-3.81)	(-0.30)
VIC 3 Lower Goulburn # Qrt	0.36	0.92	-829.38***	-1.27
	(0.14)	(0.53)	(-3.71)	(-0.18)
VIC 6B Lower Broken Creek # Qrt	0.24	-0.42	-713.74**	-0.97
	(0.06)	(-0.23)	(-3.09)	(-0.14)
VIC Murray 6 # Qrt	-0.90	0.10	-394.68	-0.27
	(-0.26)	(0.05)	(-1.61)	(-0.04)
VIC Murray 7 # Qrt	-11.35**	-1.80	1252.14***	0.89
	(-3.12)	(-0.96)	(3.58)	(0.10)
Constant	-93.55	473.07**	-41689.57	1103.17
	(-0.20)	(1.98)	(-0.89)	(0.71)
Observations	439	438	439	439
R-squared	0.4	0.26	0.73	0.65

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

3.6. Discussion

3.6.1. Water availability and water prices

Water availability is a central determinant of pricing within water markets (Bjornlund and Rossini, 2005; Wheeler et al., 2008), yet its relationship has not been thoroughly investigated across the sMDB and existing evidence remains fragmented. Bjornlund and Rossini (2005) identified a significant negative correlation between allocation levels and allocation prices, exploring the link between rainfall and allocation price in the Goulburn-Murray Irrigation District (GMID). However, their regression analysis did not factor in rainfall. Wheeler et al. (2008)incorporated a monthly water deficit variable (NDKyab) and allocation level into their examination of allocation and entitlement prices in the GMID. However, they discovered no statistically significant connection between entitlement price, water deficit, or allocation level. Zuo et al. (2019) considered only allocation level, omitting rainfall in their scrutiny of allocation and entitlement price within VIC Goulburn.

In this comprehensive analysis spanning multiple trading zones in the sMDB, both rainfall and allocation percentages serve as water availability indicators. The FE price models reveal compelling evidence that HSEs and GSEs are more strongly influenced by the allocation level than by rainfall. This outcome, although intriguing, is to be expected since entitlements' inherent value is linked to the rights of water allocation, while rainfall does not necessarily (or at least not in a linear fashion) contribute to streamflow or available water in dams (Vervoort et al., 2021). Achieving water allocation from rainfall necessitates a specific intensity to form runoff, influencing dam storage or river flow (Fowler et al., 2022; Vervoort et al., 2021). Conversely, LREs prices appear to be inversely related to rainfall. This variation reflects the distinct nature of the three entitlement types: HSEs and GSEs are valued for their capacity to supply water via actual water allocations, while LREs function primarily as carryover products tied to seasonal irrigation needs. Interestingly, the results of the LRE model closely resemble the findings of the allocation market, which is primarily steered by seasonal irrigation demands. Our study further substantiates that allocation prices are inversely tied to both current and prior quarter rainfall. An increase in rainfall increases irrigation water supply and curtails irrigation demand, leading to a negative effect on allocation prices. Overall, the findings of this study provide robust evidence that the price mechanism in the sMDB water market functions well in terms of signaling the level of water scarcity/supply in the region across multiple important trading zones.

3.6.2 Effects of high-value crops on the local water markets

The burgeoning industries of almond and cotton within the study regions have come into focus due to their prospective influence on entitlement and allocation prices. Government report, such as Westwood et al. (2019) has linked the sharp rise in water prices in recent years with the rapid expansion of the almond industry but did not empirically examine this relationship. The FE price models in this study show that the proportional significance of fruit and nut trees in irrigation within a trading zone has a substantial and positive effect on allocation prices and on all three types of entitlements. This positive correlation can be expected, as growers of perennial crops such as almonds, which necessitate significant initial capital investment, are apt to show higher willingness to pay for water and water rights to maintain their vitality and productivity during dry periods. In contrast, when examining cotton, the percentage of water allocated to this crop within a region does not exhibit a strong correlation with entitlement prices but does influence allocation prices. This finding underscores that the demand for entitlements, notably HSEs and GSEs, aligns more with the need to secure long-term water supplies for perennial crops with extended production plans and inelastic water demand, rather than merely satisfying short-term, seasonal irrigation needs. Crops like cotton, which possess high economic value but display flexibility in water demand between seasons (allowing for suspension during dry years), exert a positive effect on allocation prices but a limited impact on entitlement prices.

In addition to the influence of high-value crops on water prices, they also exert impacts on price volatility and trade volume. A positive correlation is identified between the percentages of irrigation water devoted to fruit and nut trees in a trading zone and the price volatility of HSEs, LREs, and water allocation. Simultaneously, evidence suggests that a higher proportion of water consumption by high-value crops, particularly fruit and nut trees, has a suppressive effect on the traded volume of GSEs and water allocations, although findings for the HSE model are contradictory. While the transfer of water to uses with high economic value may indicate efficiency gains through trading, it is worth noting that a water market within a region containing a higher concentration of high-value, and particularly perennial crops, may exhibit characteristics of being both thinner and more volatile. This complex interplay offers essential insights into water market dynamics and the multifaceted effects of specific crop industries.

3.6.3 Uncertainty in the market

Price volatility in the water market presents an important source of uncertainty for irrigators in terms of access to water, management of production costs, or assessing investment risks, especially for those who regard entitlements as assets. (Zuo et al., 2014) investigated price clustering and bidding behaviour within the Murray-Darling Basin (MDB) allocation market and identified two primary drivers: uncertainty for buyers and strategic behaviour for sellers. The research emphasized that buyer clustering behaviour is often propelled by heightened market uncertainty, especially during hotter and drier conditions. This insight illuminates buyers' primary focus on risk management and securing access to water resources during difficult periods. Regression results in this study dovetail on the findings of Zuo et al. (2014), showing that the prices of HSEs and LREs tend to become more volatile during drier spells. The factors behind this observation differ, as the volatility correlates with allocation level for HSEs and lagged rainfall for LREs. Such effects can be further amplified by the positive correlation between the presence of fruit & nut trees in irrigation within a region and water price volatilities. These results highlight the potential risk of escalated uncertainty in the entitlement market during extreme drought, particularly in areas with a high concentration of perennial crops.

This study also unveils that the price volatilities of HSEs, LREs (though the evidence for LREs is weak) and allocations are inversely related to traded volume. This finding stands in contrast to findings of financial literature, where a positive correlation between volume and volatility has generally been observed (Kyröläinen, 2008). However, it is worth noting that the water market exhibits unique characteristics compared to financial markets. The water market, particularly the entitlement market, tends to be quite thin, featuring sometimes only a handful of transactions within a month or even a quarter. With infrequent transactions, the prices can be highly scattered. As such, an increase in trading volume may actually contribute to decreased volatility. This insight underscores the critical importance of fostering and enabling more active entitlement trading and the potential benefit of trading activities performed by non-land-holding investors in terms of reducing uncertainty in the market, and the investment and management risk that irrigators bear.

3.6.4 Distinct nature of the allocation versus entitlement market in the sMDB

The allocation market generally demonstrates a higher level of homogeneity across trading zones compared to the entitlement market, as can be expected. Water allocations are largely homogenous products and can be traded relatively freely across trading zones while entitlements are tied to their water sources. Our models incorporate zone-specific time trends to assess the influence of potentially significant, yet unobserved, time-variant factors on key market attributes. These estimates illuminate the evolutionary paths of the examined market attributes in each trading zone, going beyond the impacts of control variables. The zone-specific factors, particularly the time-variant ones, appear to exert minimal influence on allocation price volatility and the number of transactions. However, there are notable differences across trading zones within the entitlement market as indicated by the significance of the zone-specific terms. The estimation results reveal an increasing trend in entitlement prices over time across all trading zones, but especially significant in the two NSW trading zones. Notably, the price disparities among trading zones are also widening over time, particularly for HSEs, as suggested by the price difference model. A plausible explanation for this trend, and one that has been widely debated, is the potential influence of large institutional investors driving up entitlement prices for speculative gains (as summarized by Wheeler, 2022).If this were true, prices in zones with a larger share of entitlements held or traded by financial investors would be higher. However, since the data required to directly test this hypothesis is not publicly available, it is not possible to control for them directly in our models. Nevertheless, the unobserved impacts of financial investors on water prices may still be reflected in our zone-time interaction terms (or the time trend variable in the price divergence model), given that investor activities are likely time-varying. The ACCC water market inquiry report (2021) suggests that the largest four institutional investors predominantly hold entitlements in VIC rather than NSW. Our empirical findings therefore conflict with the notion that large financial investors are driving up entitlement prices, a conclusion that is in line with the ACCC's assessment, which found no evidence of market power (ACCC, 2021).

An alternative explanation for the overall upward trend in entitlement prices across all trading zones may be rooted in the expectations of market participants concerning future water supply and demand. If there is a prevailing belief that future climate conditions will be drier or that future water demand will escalate (as being projected and reported by BoM and CSIRO, 2022), entitlement prices will likely follow an upward trajectory. This consideration is particularly pertinent with the rapid growth of the almond industry in southern NSW and VIC over the last five years. The expanses of newly planted, yet unproductive, almond trees foreshadow a substantial increase in future water demand in these regions (Gupta et al., 2020). As the trees reach maturity, this anticipation may evolve, contributing to widening price disparities across trading zones. Such dynamics may interplay with existing differences in crop structure, adding complexity to our understanding of market behaviour.

Another finding in the entitlement market pertains to the indication of decreasing trends in traded volume and the number of transactions for all three types of entitlements (with the exception of the number of transactions model for GREs) beyond the impact of factors controlled for in the models (Tables 3.9 and 3.10). This trend is particularly pronounced for HSEs. There are at least two potential explanations for these decreasing trends: 1) the presence of factors that inhibit entitlement trading, with their negative impacts intensifying over time; 2) a shift towards long-term ownership of entitlements, especially HSEs, as opposed to short-term trading. It is worth noting that there is only weak evidence for these trends in the GSE and LRE models, making it unlikely that any factor would discriminatorily impede HSE trading. Furthermore, prior literature has documented a rise in market participation and enhancements in institutional and governance structures, promoting active trading in the southern Murray-Darling Basin (sMDB) water market over the last decade (Loch et al., 2018; Seidl, 2020; Wheeler and Garrick, 2020; Zuo et al., 2019). Therefore, these declining trends in trading volume and frequency may signify a shift in HSE ownership towards long-term holders, possibly high-value users such as horticultural irrigators. Seidl et al. (2020) reported that owning excessive water entitlements (especially HSEs) as a buffer is a dominant strategy for many irrigators. Although their study did not analyze such behaviour of irrigators by industry (e.g. broadacre, dairy vs horticulture), it can expected that such strategy is especially important for irrigators with perennial horticulture crops since their water demand is generally more inelastic. In addition, Seidl et al. (2021) pointed out based on a survey with 1000 irrigators in the sMDB that more irrigators prefer expansive adaptation strategies in response to climate change, which include increasing entitlement holdings. The decreasing trend estimated in entitlement volume traded in our analysis also run counter to recent suggestions that investors have been manipulating the market through abusive behaviours such as high-frequency trading (see Wheeler, 2022). The results also imply a maturation of the entitlement market, reflecting progress toward the fundamental goal of channeling water resources to their most valuable uses.

In summary, this study found that the allocation markets in the set of eight trading zones in sMDB exhibit a relatively high level of homogeneity while the characteristics of the entitlement markets are complicated by various zone-specific factors. Our findings also indicate that the trading activities in the entitlement market are more profoundly shaped by long-term factors and production planning, whereas the allocation market responds mainly to seasonal irrigation needs. The allocation models reveal robust seasonal patterns, with the first quarter of the year marked by more frequent transactions, greater trading volumes, higher prices, and increased volatility. Given that irrigation activities in the sMDB are typically concentrated in the summer months, it is logical to observe more intense allocation trading, with corresponding higher prices during this period.

3.7 Conclusion

Market approaches have become increasingly used for efficient allocation of scarce resources in natural resource management, including fisheries, forestry and water (Wheeler and Xu, 2021; Young and McCay, 1995). Highly developed natural resource markets can be similar to other asset markets in terms of their sophistication, but may also exhibit distinct characteristics, for example that they are often much thinner than financial markets and trading activities are usually subject to more restrictions. Our study contributes to the exiting literature on natural resource markets by providing a comprehensive examination of a set of key attributes for the water market in Australia. The findings from this study document the overall functionality of the water market, and provide additional evidence of the use of market mechanisms to manage natural resources.

I conclude that the price mechanism in sMDB water market is functioning well as the prices are highly responsive to the level of scarcity of water resources and reflect the value that can be derived from the use of the water. In addition, the decreasing trends in price volatilities found in our models may be a sign of maturing of the sMDB water market. My findings stress the importance of encouraging more active water trading that could contribute to reducing uncertainty in the water market. I also conclude that the water market is functioning well in the sense that water rights suitable for long-term investment purposes like HSEs have been increasingly owned by long-term users while products designed to meet temporary and seasonal demand like allocations have been traded increasingly actively, indicating increased adoption of water market by irrigators.

Overall, I find that the allocation market is relatively more homogenous across different trading zones than the entitlement market. The dynamics in the various market attributes of allocation market mostly reflect seasonal demand for irrigation water and the variations in most of the market attributes are largely explained by the explanatory variables included in our models. The entitlement market, on the other hand, exhibits no seasonality and a higher level of heterogeneity across trading zones, which adds additional complexity to understanding the operation and functionality of the entitlement market. Our results indicate that there are still unobserved factors influencing the entitlement markets. While data necessary to directly test and separate the impacts of various unobserved factors are not currently available (e.g. data on financial investor activities), the zone-specific time trends estimated in our models could be largely explained by theoretical expectations, as discussed in Section 6.

Market-based approaches to natural resource management should not be regarded as a panacea since markets have their limitations and successful operation of the markets requires a set of enabling conditions. Numerous studies discussed market failure or third-party impacts associated with water markets (e.g. Bourgeon et al., 2008; Hanak, 2003; Wheeler et al., 2020) and failures in the institutional arrangements of water rights and markets in Australia (Young and McColl, 2003). Young and McColl (2005) defined the robustness of a system for tradable entitlements and allocations based on reforms and institutional arrangements. Wheeler (2021) proposed a framework to assess the prerequisite conditions for establishing water markets. Nevertheless, the findings of our study point to the more general benefits of water markets, as they seem to perform well in serving its fundamental purpose of directing scarce water resource towards its highest valued uses and facilitating irrigators to effectively manage water supply risks in agricultural production. These findings are encouraging in terms of the applicability of market mechanisms for natural resource management more broadly.

Chapter 4 Optimal Water Portfolio in Southern Murray-Darling Basin

4.1 Introduction

Water scarcity has been a significant global problem and threatens the livelihood, economy and environment in many parts of the world (Grafton et al., 2011). There is also growing evidence that water scarcity will be aggravated in the future, as a result of the increasing water demand, population growth and climate change (Breviglieri et al., 2018; Donohew, 2009; Grafton et al., 2011). The traditional practices to manage water scarcity have been focusing on increasing water supply through engineering approaches, such as building dams, pumps, reservoirs and other infrastructure (Breviglieri et al., 2018; Chong and Sunding, 2006; Grafton et al., 2016). Such supply-side measures, however, have been increasingly challenging and costly to support (Chong and Sunding, 2006; Grafton et al., 2016), while water markets have risen as an important demand-side management tool to allocate water resources and mitigate water crises in the past decades. Despite the debates over market efficiency and potential negative impacts of water market on third parties, water markets have been developed in many regions globally and this has assisted in mitigating water scarcity, including in Chile, the western U.S, Spain, South Africa, and most notably, Australia (Regnacq et al., 2016). The water market within the Murray Darling Basin (MDB), Australia serves as a particularly prominent example of the most advanced and most active water market in the world, with well-defined water rights, relatively low transaction costs, and institutional arrangements that have evolved to facilitate the operation and management of the water market (Breviglieri et al., 2018; Grafton et al., 2011; Wheeler and Garrick, 2020). The highly developed MDB water market trades a wide range of water use rights (referred to as ‘products’ in this chapter) that vary in availability and reliability. These products not only provide competitive returns for investment (Bjornlund and Rossini, 2007; Wheeler et al., 2016), but also provide irrigators with diversified tools in managing water supply risk in agricultural production (Seidl et al., 2020).

While the literature has covered many aspects of the water market in the MDB, as summarized in the literature review section, there remains a lack of understanding of the dynamic strategies and combination of products that water market participants, especially irrigators, should employ under varying water availability conditions. Seidl et al. (2020) reported that although institutional investors and agri-corporates frequently employ diversified water portfolios and sophisticated management strategies, small-scale irrigators often rely on a singular type of water entitlement. This traditional approach to water asset management impedes these their potential to maximize the net benefits derived from their investments and limits the risk-mitigating advantages of owning diverse entitlements. Therefore, the findings of this study can motivate small irrigators to adopt more sophisticated water management strategies, by demonstrating the potentially high returns achievable through diversified portfolios and by providing insights into optimal portfolio compositions under varying water availability scenarios.

The objectives of this paper are three-fold. Firstly, this study aims to develop a framework for dynamic optimal water portfolios for both financial investors and irrigators, covering the period 2008 to 2019. Our optimization model differs from traditional portfolio optimization by allowing some participants, i.e. the irrigators, to have a minimum water yield constraint in addition to the usual expected return/variance constraints to satisfy their water demand. As far as I am aware, this study is the first, both in sMDB and in the world, to develop such a framework. The analysis of optimal portfolios helps us understand how optimal strategies of water market participants should vary given their water demand (for irrigators), and current and expected future water availability. Secondly, I compare the optimization results with and without controlling for the downside risk, by employing both the Mean-Variance (MV) and the Mean-Semivariance (MSV) models. This chapter investigates the heterogeneity across different water rights in terms of the characteristics of their return, i.e. expected return, variance and downside variance of returns. Thirdly, by analysing the optimal composition of water portfolios generated for investors and irrigators at a given point in time, this study intends to understand the link between the weights of the various water rights in the optimal portfolios and the water availability at that time. Such understanding sheds light on the different roles that security-differentiated water entitlements play. For example, some entitlements serve as means to guarantee water supply in dry periods and thus are preferred by irrigators, while some provide relatively stable returns under different rainfall conditions that are preferred by investors. Our analysis that links optimal portfolio compositions to water availability also allows for heterogeneous patterns of returns for different water rights. For example, some entitlements have higher expected returns and take greater weight in optimal portfolios during dry periods while some entitlements perform better during wet periods. This is important for estimating the impacts of the change in future water availability on the market and the behaviour of market participants.

While the optimization framework in this chapter was developed for the water market in sMDB, its application is not limited solely to this context. It can also be generalized to gain insights into trading behaviour in water markets in other countries, as well as in other natural resource markets, such as fisheries or carbon markets. One of the main features of this framework is the incorporation of constraints on the physical quantity of the natural resource (e.g. the water constraint in this study), which allows market participants to allocate capital investments in a way that maximizes financial gains while also ensuring a certain level of output of the natural resources. This approach may be particularly relevant for management of natural resources in industries such as fisheries and forestry.

The remainder of this chapter is organized as follows. The second section offers background information on the MDB water market. The third section provides a review of relevant literature on water markets in sMDB and the application of portfolio management in natural resource economics is provided in the next section. The fourth section presents our choices of the MV and MSV models as our optimization models and the framework of our investor and irrigator models, which distinguish between participants with and without a water demand constraint. Then the following two sections outline our methods and provide the summary statistics of the trading data and allocation data. Optimal results from investor/irrigator models using both MV and MSV frameworks are presented and compared in the results section. The eighth section provides discussions on the findings of the study. Concluding remarks are provided in the final section of this chapter.

4.2 Background

The MDB water market was initiated in the 1980s and is now one of the largest in the world. The total volume of water entitlements on issue was about 20,000 GL in 2020-21 accounting for half of the total volume in Australia, which translates into about \$6 billion AUD at the yearly average price (BoM, 2021). The trading activities are mainly concentrated in the southern Murray Darling Basin (sMDB), which covers parts of New South Wales (NSW), Victoria (VIC) and South Australia (SA). The high degree of hydrological connectivity of the river systems in the sMDB allows for relatively unrestricted inter-state and inter-system trading (Wheeler et al., 2020). As a result, the sMDB water market is highly active, accounting for about 80-90% of all the transactions in the MDB water market (BoM, 2019b). Over half of all irrigators in sMDB have traded entitlements (permanent water rights) and more than three-quarters of irrigators have traded allocations (temporary water transfers) at least once (Seidl et al., 2020). The high participation rate indicates that the water market has become an important tool for irrigators to manage water supply (Seidl et al., 2020).

Water entitlements and water allocations are the major products available in the MDB water market (Wheeler et al., 2013). An entitlement represents a permanent use right to a share of available water supplies in a river or dam. Each entitlement receives seasonal allocations of water that can be withdrawn based on water availability and the security level of the entitlement. The security level of the entitlement indicates an entitlement's priority of receiving water (Freebairn and Quiggin, 2006). The allocation of water volume to high-security entitlements (HSEs) will always be fulfilled first, before any remaining water can be made available to entitlements with lower security levels, such as general-security entitlements (GSEs) or low-reliability entitlements (LREs). The allocation announcements are made by local authorities progressively during a water year that starts in July, and the allocated water stays accessible throughout the water year (Loch et al., 2012). The unused allocation will be lost at the end of the water year unless the entitlement holder chooses to carry over the allocation into the next season (Loch et al., 2012). In the sMDB, a long-term average yield of 95% can be expected by HSEs, 70% for GSEs (available only in NSW) and 30% for LREs (only in VIC) (Wheeler et al., 2016). Entitlements associated with different water sources can vary in supply reliability as well. The groundwater entitlements in NSW for example, have been receiving 100% allocation in recent decades, even during the millennium drought from 2001 to 2009 (NSW State Water Register, 2019). The extraction of groundwater, however, can be subject to local restrictions (Wheeler et al., 2021). Extraction limits apply when the groundwater level falls below a trigger level (Wheeler et al., 2021).

The tradable entitlements were tied to agricultural land during the early stages of the water market in the MDB, i.e. one could not own water rights without owning agricultural land. As a result, water trade was limited between irrigators and the efficiency of the water market was impeded (Wheeler et al., 2013). A series of water reforms that started in the 1990s, especially the unbundling of land and water in 2007 has greatly boosted water trading in MDB (Wheeler and Garrick, 2020). The unbundling of land and water has allowed investors that do not own land or operate irrigation enterprises to participate in the market (Wheeler and Garrick, 2020). These financial investors and some large irrigation corporations have been actively utilizing and developing sophisticated products such as forward contracts, entitlement leasing, and carryover capacity leasing (Seidl, 2020). In recent years, concerns have been raised about nonirrigator market participants engaging in speculative activities that may drive up water prices. However, existing literature suggests that water scarcity is the primary factor affecting water prices (Seidl et al., 2020; Zuo et al., 2019). In addition, previous research acknowledges that the separation of water and land ownership has increased participation in water trading, enhanced water market efficiency, and led to the development of various derivatives, such as forwards and options (Wheeler et al., 2013; Seidl et al., 2020; Wheeler and Garrick, 2020).

4.3 Literature Review

As one of the most well-studied water markets in the world, a series of previous works have been devoted to understanding irrigators' trading behaviour in the MDB water market, including their motivation and trading strategies (Wheeler and Garrick 2020; Seidl et al., 2020; Loch et al. 2012;Haensch et al. 2016; Haensch et al., 2019a), the effects of water trading and water prices on farms (Wheeler et al., 2014;Zuo et al., 2015;Wheeler et al., 2014), the price elasticity of demand and supply of entitlements (Zuo et al., 2016), and irrigator's risk preferences in water trading (Nauges et al., 2016; Zuo et al., 2015). Previous studies have shown that irrigators have been utilizing different water products available in the MDB water market for various purposes (Seidl et al., 2020). Trading of permanent products like entitlements is often used by irrigators to restructure water portfolios and farm finance, adjust supply security, relocate farm enterprises, adjust production scale or exit farming (Zuo et al. 2015; Wheeler and Zuo 2017; Haensch et al. 2016; Haensch et al., 2019b). However, permanent water right trades also have some downsides, as pointed out by Wheeler, Zuo, and Hughes (2014), in the sense that entitlement purchases are sometimes associated with reduced farm profit and increased debt, while entitlement sales are associated with higher anxiety level due to decreased supply security (Wheeler et al., 2018). On the other hand, trading of temporary products like water allocations or forward allocations is usually used to mitigate temporary water scarcity, increase water supply flexibility and increase profitability (Loch et al., 2012). The types of irrigated crops have important effects on the trading strategies and the portfolio of water rights held by irrigators. For example, broadacre and pasture irrigators usually are the first ones to switch from buying to selling allocation in times of drought while horticultural irrigators are found doing the opposite (Adamson et al., 2017; Wheeler et al., 2013; Zuo et al., 2015). Meanwhile, horticultural irrigators pay greater attention to entitlement ownerships since water supply reliability is crucial for perennial crop production (Wheeler et al. 2014). In summary, a range of tradable water products in the MDB have brought important benefits, including improving the economic efficiency of water use by transferring water from lower-valued to higher-valued users (Wheeler et al., 2014;Qureshi et al., 2009), assisting irrigators in managing supply risks facing droughts, salinity problems and climate change (Bjornlund, 2006; Grafton et al., 2016; Haensch et al., 2016b), and allowing irrigators to adjust production plans with greater flexibility and achieve better economic profits (Loch et al., 2012; Wheeler et al., 2014).

While a considerable amount of effort has gone into understanding the various aspects of the water market in sMDB and their effects on farm businesses as aforementioned, most of the existing literature does not include or compare various types of water products, such as entitlement across different security levels, regions and water sources (e.g. surface vs groundwater). There is only a limited number of studies that have qualitatively analyzed the heterogenous impacts of different water rights on farm production and on irrigators' preference for entitlements (Freebairn and Quiggin, 2006; Wheeler et al., 2014; Zuo et al., 2016). In general, these studies found that horticultural irrigators whose crops have high capital value tend to have more inelastic demand for water (Zuo et al. 2016) and prefer to hold HSEs to ensure water supply (Freebairn and Quiggin 2006; Wheeler, Zuo, and Hughes 2014). In contrast, broadacre growers have more elastic demand and tend to hold entitlements with lower security levels and lower prices, such as GSEs (Freebairn and Quiggin 2006; Wheeler et al. 2014). LREs, on the other hand, often serve as carry-over products (a more detailed discussion is given in the data section) (Seidl, 2020).

The trading behaviour of non-irrigating (non-landowners) participants in the water market, has received little attention in related academic research so far. This situation is partly due to the lack of information on the type of counterparty in the water trading data (Seidl et al., 2020). The unbundling of land and water rights in 2007 has enabled non-landowners to participate in the water market and it was estimated that about 12% of sMDB water entitlements were owned by non-landholders by 2018 (DELWP, 2019)[3]. Studies on investment returns on water entitlements in the MDB have shown that water entitlements can outperform traditional share markets, especially in times of droughts with spiking water prices (Bjornlund and Rossini, 2007; Wheeler et al., 2016). High returns from water entitlements are likely to continue to attract non-landholding investors to participate in the water market and understanding their

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[3] For more discussion and information about this number please refer to (Seidl et al., 2020).

trading behaviour is therefore of great importance for the overall water market. There is already evidence that market participants in general have become more sophisticated in trading and more willing to speculate over the past decade (Seidl et al., 2020). The qualitative survey conducted by Seidl, Wheeler, and Zuo (2020) has demonstrated that the majority of the MDB irrigators still manage water supply in a conservative way, that they own water rights mainly for historic reasons and do not trade them frequently. On the other hand, some "savvy" irrigators, especially big agri-corporations have started to view water rights primarily as investment assets and own diverse water portfolios to achieve better returns (Seidl et al., 2020). Additionally, a small group of more sophisticated traders, mostly financial investors and some of the above-mentioned agri-corporates not only diversify their water rights portfolio but also trade temporary products like water forwards, water options and parking leasing (carry-over capacity leasing) (Seidl et al., 2020). It seems that with the maturing of the water market in the MDB and improvements in water policies and institutions, it is now possible to treat water assets as being comparable to other financial assets and benefit from investing in them (Wheeler et al. 2016). There is, however, a clear gap in the literature when it comes to the knowledge of returns on investments for different types of water rights and optimal combinations of these rights. Only two studies, namely Bjornlund and Rossini (2007) and Wheeler et al. (2016), have investigated the returns on entitlement holding. They estimated the return on entitlements by using a 5-year internal rate of return (IRR) methodology, which assumes an entitlement is purchased at the beginning of the investment period and sold after 5 years with allocation sales occurring intermittently. Both studies found that water entitlements can outperform the S&P/ASX cumulative index, which was especially the case in the early 2000s when the rainfall was continuously low. While these two studies provide valuable insights into the performance of water entitlements as an investment asset, there are some remaining limitations that need to be addressed. Firstly, the studies were limited to Goulburn-Murray Irrigation District (GMID) only and did not take into account other regions where water markets are active. Secondly, they treated different types of entitlements (e.g. HSEs and LREs) as the same product, while the return on different entitlements can vary significantly. Thirdly, the studies did not consider a diversified holding (a portfolio) of water rights and more frequent rebalancing of the holdings to maximize the returns.

To fill these gaps in the literature, the present study investigates the return on investment in water rights through a portfolio approach, which allows the investors/irrigators to hold water rights with diversified sources and security levels. The dynamically-adjusting portfolios constructed in this study also allow for frequent rebalance of the portfolios on a weekly or monthly basis. Portfolio management initially gained popularity in financial markets, but nowadays is also widely used in areas such as natural resource management (Alvarez et al., 2017; Knoke et al., 2005; Koellner and Schmitz, 2006) or agricultural production (Power and Cacho, 2014), where scarce resources, such as land, have to be allocated optimally to maximize the return. So far, only a few studies have applied portfolio theory to water management issues, involving investment in permanent water rights. Gaydon et al. (2012) compared farm-level irrigation strategies using an approach of portfolio optimization. Several on-farm and off-farm strategies were considered, such as deficit irrigation and changing crop mix. However, in terms of water supply options, they only considered allocation purchases and sales through government buyback schemes, without considering entitlement trades. Paydar and Qureshi (2012) conducted a similar study, applying portfolio optimization to farm water management options, including the option of conjunctive use of surface water and groundwater and entitlements sales. This study, however, did not explicitly consider entitlements as an investment asset.

This study advances the application of portfolio management in water markets, as well as in other natural resource markets more generally in several ways. Firstly, water rights with different security levels and water sources are treated as separate products in portfolio selection. This allows for a better understanding of the heterogeneity across the returns on different water rights in the current literature. Secondly, this study is one of the very few studies in natural resource economics that uses semi-variance as the risk measure in addition to the traditional use of variance. The use of semi-variance enables risk-averse agents to control specifically for risks of below-average performance of the portfolios. Thirdly, our irrigator model allows users to treat water as both production input and investment asset so that irrigators have control over the risks in input supply and risks in investment return at the same time.

4.4 Theory

4.4.1 Modern portfolio theory and the efficient frontiers

Markowitz introduced the celebrated Modern Portfolio Theory (MPT) in 1952 which considers two criteria in optimal portfolio selection: the expected return of the portfolio and the variance of the portfolio return. The theory points out that agents face trade-offs between gains from investment and the volatility of the gains. Specifically, the mean-variance (MV) framework is based on the notion that investors would prefer portfolios that have high expected returns and low variance of returns. In other words, a portfolio would dominate another if it has a higher expected return and the same variance of returns, or if it has the same expected return but a lower variance. The MV analysis is intuitive and computationally tractable as it formulates the decision-making process in portfolio selection as an optimization problem: the agents hope to maximize the expected return of a portfolio subject to a given variance, or the agents hope to minimize the risk (variance) of the portfolio contingent on a given level of expected return (Kolm et al., 2014).

The optimization conducted under the MV model produces an “efficient frontier”, which represents a collection of portfolios that are not dominated by any other portfolio (Rachev et al., 2008). Figure 4.1 gives a visual illustration of the MV model, where the blue dots represent portfolios with random weights and the red line represents the efficient frontier that consists of portfolios with minimized volatility at each level of return. Portfolios on the efficient frontier are traditionally called “efficient portfolios” because they are Pareto efficient in the sense that further increase in the expected return will necessarily increase the portfolio variance, or a further decrease in the portfolio variance will necessarily decrease the expected return (Shah and Ando, 2015). The efficient frontier provides a geometric interpretation of the trade-off between the expected portfolio return and the risk, as measured by the variance of return in the MV model.

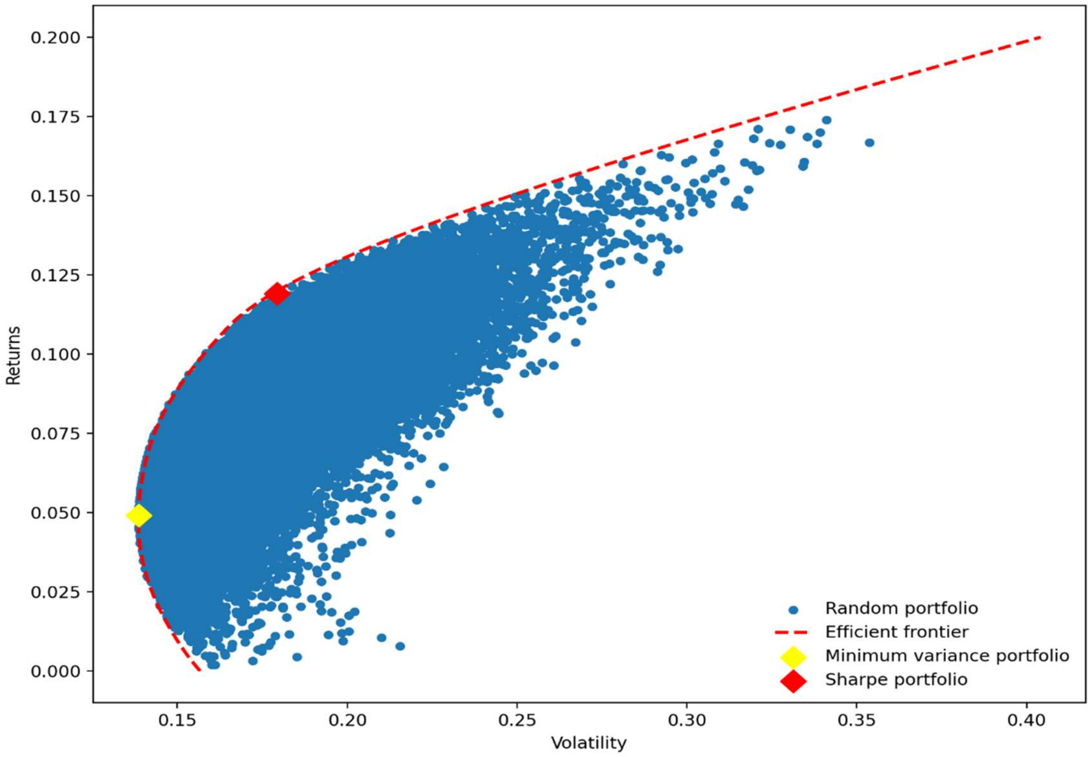

Figure 4. 1 A visual example of the MPT, illustrating the efficient frontier, minimum variance portfolio and Sharpe portfolio.

Markowitz's MV framework has had important impacts on studying investment choices under uncertainty and has been widely employed, especially in financial practice (Kolm et al., 2014). Several major drawbacks of the MV model, however, have been identified in the related literature. The first major drawback is that optimal results generated by the MV model are in general inconsistent with the expected utility theory (Rachev et al., 2008). The expected utility (EU) theory was first introduced by von Neumann and Morgenstern in 1944 and has since dominated the field of decision-making under uncertainty (Quiggin, 1993). The EU theory states that expected utility characterizes agents' preferences when uncertainty is present and that agents tend to choose ventures that maximize their expected utility (Quiggin, 1993). Due to inconsistency with the EU theory, the MV analysis cannot guarantee that the optimal portfolio generated is the same as the portfolio that is the most preferred by all utility-maximizing agents with non-satiable and risk-averse preferences (Boasson et al., 2011). The consistency between the MV and the EU analysis can be achieved under certain assumptions, for example, if the returns of the assets have a normal distribution. The consistency will also hold if the investors have quadratic utility functions (Markowitz, 2014). Rachev et al. (2008)

showed that MPT can be greatly expanded and can even become consistent with expected utility theory by replacing the variance with some other measure of risk, such as Average Value at Risk (AVaR). This measure is frequently used in the financial market, but it requires a large number of observations below target returns or an explicit assumption about the distribution of returns (Boasson et al., 2011). In addition, AVaR requires the investor to specify a probability level of cumulative losses (Wiener, 1998). Therefore, AVaR is not very practical in many fields outside finance where transaction data and other related required information are limited.

Another important drawback of the MV analysis is that it approximates the risk carried by a portfolio through the variance of returns. As widely acknowledged, variance is a symmetric measure of dispersion that accounts for both upward and downward variations in data. On the other hand, the risk is asymmetric in nature, reflecting the uncertainty associated with a loss or underperformance of a portfolio (Francis and Kim 2013). By pursuing the minimization of the variance at each given level of expected returns, the MV optimization model effectively penalizes both over-performing and under-performing assets in a portfolio (Francis and Kim, 2013). In addition, the MV model cannot distinguish among portfolios with different distributions of returns, as long as they have the same mean and variance. For example, two portfolios B1 and B2 with probability density functions of returns P_{B1} and P_{B2} in Figure 2 have the same mean and variance, but the downside risk associated with the portfolio of B1 is lower than B2 since the distribution of B1 is positively skewed. Despite this fundamental difference, the MV model will identify portfolios B1 and B2 as being equally desirable, since they have the same mean and variance of returns. The MV model, therefore, fails to control for the downside uncertainty in this type of situation.

In response to these shortcomings, an alternative proxy for risk suggested initially by Markowitz, and subsequently used by many other researchers is the semivariance (Harlow, 1991; Markowitz, 1959; Roy, 1952). Unlike the variance, the semivariance only accounts for the dispersion that is below the mean returns, or another reference point. Therefore, using the semivariance may be more appropriate for portfolio optimization. Most studies employing MPT in natural resource or environmental economics are based on MV models, and only a few of those have employed semivariance (e.g. Shah and Ando 2015), as summarized in (Alvarez et al., 2017)). In this study, optimal portfolios for water rights in selected trading zones in sMDB are estimated using both MV and MSV models to compare the optimal portfolios without and with control over the downside risks.

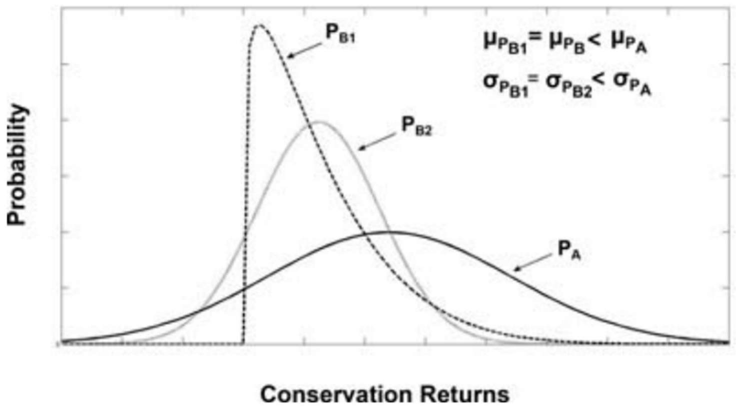

Figure 4. 2 Conceptual figure of portfolios with different distributions of returns (Shah and Ando 2015).

4.4.2 Final optimal portfolio selection

The efficient frontier produced by MV or MSV models can consist of an infinite number of portfolios. Therefore, studies employing MV or MSV usually focus on some critical points on the efficient frontiers. Critical points on efficient frontier widely used include the minimum variance portfolio which has the lowest variance among all portfolios, and portfolios that maximize certain performance measures (Rachev et al, 2008). In this study, the "final optimal portfolio" on each efficient frontier is chosen by maximizing the Sharpe ratio in MV models and the Sortino ratio in MSV models. Figure 4.1 provides examples of the minimum variance portfolio and the Sharpe portfolio that maximizes the Sharpe ratio.

The Sharpe ratio is one of the most important and widely used portfolio performance measures in portfolio management (Zakamouline and Koekebakker, 2009). The ratio is defined by: $\frac{E(Rp)-E(Rf)}{\sigma}$, where $E(Rp)$ is the expected return of the portfolio, $E(Rf)$ is the expected return of risk-free investment and σ is the standard deviation of portfolio returns. The portfolio with a maximized Shape ratio has the highest risk-adjusted expected return, which means the portfolio has the highest expected return for each unit of variability in its future performance (Rachev et al 2008). The performance measure I use for the MSV model, the Sortino ratio $\frac{E(Rp)-E(Rf)}{SSD}$, is very similar to the Sharpe ratio, with S.D. in the denominator substituted by the semi-standard deviation (SSD), which is the square root of the semi-variance. The portfolio with the greatest value of the Sortino ratio has the highest downside-risk-adjusted expected return among all the efficient portfolios on the efficient frontier. The long-term bond rate could be used as a proxy for the expected rate of return for risk-free investment $E(Rf)$, but since a constant in the formula of both Sharpe ratio and Sortino ratio will not affect the optimization results and since the bond rates in Australia have been close to zero in recent times, models in this chapter assume $E(Rf) = 0$ for simplicity[4].

In addition, a diversification constraint $\bar{x}$, i.e. setting the maximum portfolio weight that can be allocated to a single asset in the portfolio, is employed in the estimation of the final optimal portfolios. Such constraint is frequently employed in portfolio management (Rachev et al. 2008).

4.4.3 Recursive estimation

A static optimal water portfolio using all available historical data may not be very helpful to understand the optimal trading strategies for agents in the water market, because the optimal portfolios should vary with price changes in water rights, which are often driven by water scarcity as aforementioned. To show how the optimal portfolios vary with water prices and water availability, I recursively estimate the optimal portfolios based on historical price data, using a sliding estimation window. The length of the estimation window, T, represents the time period which an agent would consider relevant to their decisions. So, the expected returns of the water portfolio and the variance/semivariance of the returns are calculated using the historical price data over the period T. This estimation window "slides down" in time to allow agents in the model to update their knowledge of water prices in the market over time. Each time the estimation window "slides down" with increment *t*, it indicates that the optimal portfolio is rebalanced. Financial investors are considered to be more sophisticated at managing water rights portfolios in this study, so I allow the investor model to be re-estimated (rebalanced) on a weekly basis to utilize new information in the market frequently and achieve better returns on investment. In contrast, the rebalance decisions for irrigators are likely to be made based on production plans and irrigation demands, which would be adjusted on a less frequent basis. So, the model allows the irrigator model to be re-estimated on a monthly basis.

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[4] This study refers to period from 2008 to 2021, during which cash rates in Australia stayed consistently low (e.g. below 3% except in years 2009 to 2012).

The recursive estimation produces one optimal portfolio per week/month, for investors/irrigators respectively, throughout the study period from 2008 to 2019. The following sections specify the MV and MSV optimization models separately for investors and irrigators.

4.4.4 The Investor Model

There has been a growing number of financial investors who participate in the Murray-Darling water market. Since these investors do not engage in agricultural production, the investor model in this study assumes that they are only interested in optimizing the returns from investments in the water market, without having consumptive water demand. In other words, this model assumes investors only invest in water entitlements and sell all allocations whenever it becomes available to gain revenue.[5] It is similar to an investor holding a stock in the stock market, where the investor can obtain capital gain/loss from changes in the stock prices and get dividends at the same time. According to Markowitz's portfolio theory, the MV model for investors is defined as:

$$\text{Min } Var_p \tag{4.1}$$

$$\text{subject to } E(R_p) = \sum_{i=1}^{n} x_i E(R_{wpi}) \geq \overline{R_p}$$

$$\sum_{i=1}^{n} x_i = 1, \bar{x} \geq x_i \geq 0$$

where the weights of individual products in the portfolio, x_i, sum up to 1. The portfolio variance, Var_p, is calculated as:

$$Var_p = \sum_{i=1}^{N} \sum_{j=1}^{N} x_i x_j Cov_{i,j} = \boldsymbol{x}^T \Sigma \boldsymbol{x} \tag{4.2}$$

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[5] Financial investors in the water market can engage in more complicated trading activities, for example, entering forward contracts assuming short positions (the sell side), which creates water demand for investors because they have to deliver the agreed amount of water at the maturity of the contract (Seidl et al., 2020). However, due to the lack of public trading data on derivative products including forward contracts (Seidl et al., 2020), it is not possible to model forward products in this study. Additionally, a very small number of investors would speculate and arbitrage on water allocations. Given that speculation on water allocation is not wide-spread (Seidl et al., 2020), such behaviour is not modeled in this chapter as well.

where $\boldsymbol{x}$ is a vector of portfolio weights for the water entitlements and $\sum$ is the variance-covariance matrix of the entitlement returns.

In the constraint of optimization problem [4.1], $E(R_p)$ is the expected return of the portfolio, constrained to be equal to or greater than a given level of return $\overline{R_p}$. The expected portfolio return $E(R_p)$ is defined as a weighted sum of expected returns of individual water products, $E(R_{wpi})$, which is calculated as the average of historical returns r_{wpi}^t of that entitlement over each period *t* in the estimation window with length *T*:

$$E(R_{wpi}) = \frac{1}{T}\sum_{t=1}^{T} r_{wpi}^t \qquad [4.3]$$

where r_{wpi}^t consists of two parts: capital gain (or loss) from holding the entitlement over period *t* (a week or a month as aforementioned), and the revenue from allocation sales. Mathematically, r_{wpi}^t is defined as:

$$r_{wpi}^t = \frac{P_{ENi}(t) - P_{ENi}(t-1) + P_{Ai}(t) \cdot Q_{ENi}(t)}{P_{ENi}(t-1)} \qquad [4.4]$$

where $P_{ENi}(t)$ is the average price of the *ith* entitlement per ML over period *t* and $P_{Ai}(t)$ is the average spot market price for water allocation per ML over period *t* in region *i*. Water allocations attributable to the i^{th} entitlement during period *t* are represented by $Q_{ENi}(t)$.

The MSV model is defined similarly as the MV model with portfolio variance substituted by portfolio semivariance as shown below:

$$\text{Min } SV_p \qquad [4.5]$$

$$\text{subject to } E(R_p) = \sum_{i=1}^{n} x_i E(R_{wpi}) \geq \overline{R_p}$$

$$\sum_{i=1}^{n} x_i = 1, \bar{x} \geq x_i \geq 0$$

where $\bar{x}$ is the diversification constraint and SV_p is the portfolio semivariance. The semivariance of the returns of i^{th} entitlement is defined as below following Nawrocki (1991):

$$SV_i = \frac{1}{T}\sum_{t=1}^{T}[max\ (0, (E(R_{wpi}) - r_{wpi}^{t})^2] \qquad [4.6]$$

The above definition ensures that the semivariance of the *i^th^* entitlement only takes the dispersion into account when the return of the *i^th^* entitlement during period *t* is below the average return within the estimation window *T*.

The co-semivariance matrix, which is an analog of the variance-covariance in Eq. [4.2], captures the co-movement of semivariance between the returns of water rights. Nawrocki (1991) provided an algorithm to arrive at a symmetric version of such a matrix and defined it as:

$$CSM_{ij} = SV_i^{1/2} \cdot SV_j^{1/2} \cdot \rho_{ij} \qquad [4.7]$$

where CSM_{ij} represents the co-semivariance matrix between entitlement i and entitlement *j*, and ρ_{ij} is the correlation coefficient between the two entitlements.

The semivariance of a portfolio therefore is:

$$SV_p = \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j CSM_{i,j} = \boldsymbol{x}^T \boldsymbol{S} \boldsymbol{x} \qquad [4.8]$$

where $\boldsymbol{x}$ is a vector of portfolio weights for the water entitlements and $\boldsymbol{S}$ is the co-semivariance matrix of the entitlement returns.

Again, the optimization problems in Eqs. [4.1] and [4.5] are used to produce efficient frontiers, which consist of all efficient portfolios that minimize portfolio variance/semivariance at each level of expected return. The final optimal portfolio I estimate and analyze is obtained by maximizing the Sharpe ratio (Eq. [4.9]) and Sortino ratio (Eq. [4.10]) respectively, assuming a zero risk-free return as discussed earlier.

$$Max\ \frac{E(Rp)}{\sigma} \qquad [4.9]$$

$$Max\ \frac{E(Rp)}{SSD} \qquad [4.10]$$

4.4.5 Irrigator Model

The irrigator model is fundamentally similar to the investor model but is more complex in three ways: a) irrigators in our model have a water demand constraint and a resulting budget constraint; b) irrigators can purchase water allocations on the spot market to satisfy their minimum water demand, and can sell unused allocation at the end of the water year (I assume that irrigators do not speculate on water allocation); c) irrigators portfolios will be rebalanced on a monthly instead of a weekly basis as aforementioned.

The minimum water demand constraint $\bar{w}$ in the irrigator represents the physical volume of water (in ML) an irrigator demands in each period t. By adjusting this water constraint, the model can reflect the flexibility in water demand for irrigators in different industries. As pointed out by multiple studies, irrigators in dairy or broadacre crops in general have higher flexibility in production planning and irrigation demand, and they are often the first ones to switch from purchasing allocation to selling allocation facing increasing water prices (Wheeler et al., 2014; Zuo et al., 2015). In contrast, irrigators in horticulture industries have low flexibility in irrigation demand, since they need to irrigate at least a minimum amount to keep their perennial crops alive and avoid large capital losses (Wheeler et al., 2014).

The water constraint specifies that the total amount of water available to use during period *t* for an irrigator needs to be equal to or greater than the minimum water demand $\bar{w}$ and is therefore defined as:

$$W_{total}(t) = W_{unused}(t-1) + W_{received}(t) \geq \bar{w} \qquad [4.11]$$

where $W_{unused}(t-1)$ is the unused allocation left from the last period *t*-1 and $W_{received}(t)$ is the additional volume of water (in ML) that becomes available during the current period *t*.

The volume of water received $W_{received}(t)$ from a portfolio during period *t* consists of two components: water allocation received by entitlements in the portfolio and additional purchased allocation. In the below equation, $S_{ENi}(t)$ represents the shares (in ML) of the i^{th} entitlement held in the portfolio over period *t* and use $S_a(t)$ to denote the volume of water allocation (in ML) purchased during period *t*. So, the volume of water received, $W_{received}(t)$, can be expressed as:

$$W_{received}(t) = \sum_{i=1}^{n} S_{ENi}(t) Q_{ENi}(t) + S_a(t) \qquad [4.12]$$

where $Q_{ENi}(t)$, as defined earlier, is water allocation received by the *i^th^* entitlement during period *t*. The shares of an entitlement held in the portfolio, $S_{ENi}(t)$, is calculated from the total value of the portfolio, the weight of that entitlement in the portfolio and its price per share. Let *V (t)* represent the size (in terms of total value) of the portfolio at time *t*, so the share of the i^{th} entitlement with weight x_i in the portfolio is:

$$S_{ENi}(t) = \frac{V(t) \cdot x_i}{P_{ENi}(t)} \qquad [4.13]$$

Similarly, let x_a denote the proportion of portfolio value devoted to purchasing water allocation and $P_{Ai}(t)$ denote the average price of temporary water allocation during period *t,* the shares of water allocation purchased from the spot market during period *t* is:

$$S_a(t) = \frac{V(t) \cdot x_a}{P_A(t)} \qquad [4.14]$$

where $\sum_{i=1}^{n} x_i + x_a = 1;\ x_i, x_a \geq 0.$

In the above, the water constraint is derived for an irrigator. Now I modify the MV model with this additional water constraint, defining it as:

$$\text{Min } Var_p \qquad [4.15]$$

$$\text{subject to } \mathrm{E}(R_p) \geq \overline{R_p}$$

$$W_{total}(t) \geq \overline{w}$$

where $\sum_{i=1}^{n} x_i + x_a = 1, \bar{x} \geq x_i, x_a \geq 0$

The framework is similar to the investor model in that it is assumed that an irrigator aims to minimize the portfolio variance subject to a given level of expected portfolio return and the water constraint. The portfolio variance, Var_p, is calculated using Eq. [4.2]. Since the purchased allocation is consumptive which means it does not have a return, one cannot calculate the variance of the return for an allocation purchase. Therefore, the allocation purchase is not included in the calculation of the portfolio variance. The portfolio variance in the irrigator model is still calculated from a weighted variance-covariance matrix of the returns of entitlements, the same as in the investor model.

The calculation of the expected portfolio return, $E(R_p)$ in the irrigator model is different from that of the investor model, as the allocations in the irrigator model are consumptive and make no contribution to the portfolio return. To show how the portfolio value changes, let us assume at the beginning of period *t*, a portfolio has a total value *V(t)* with portfolio weights x_i and x_a:

$$\mathrm{V(t)} = \sum_{i=1}^{n} \frac{V(t) \cdot x_i}{P_{ENi}(t)} \cdot P_{ENi}(t) + \frac{V(t) \cdot x_a}{P_A(t)} \cdot P_A(t) \qquad [4.16]$$

Then, at the beginning of period *t*+1, due to price changes of water entitlements, the portfolio value *V(t+1)* is:

$$\mathrm{V(t+1)} = \sum_{i=1}^{n} \frac{V(t) \cdot x_i}{P_{ENi}(t)} \cdot P_{ENi}(t+1) \qquad [4.17]$$

The expected return of the portfolio over period t is:

$$\mathrm{E}(R_p) = \mathrm{E}\left[\frac{\mathrm{V(t+1)} - V(t)}{V(t)}\right] \qquad [4.18]$$

which can be simplified to:

$$\mathrm{E}(R_p) = \sum_{i=1}^{n} x_i \, r_i - x_a \qquad [4.19]$$

where r_i is the expected return to the capital for the i^{th} entitlement during period *t* to *t*+1, i.e. $r_i = E(\frac{P_{ENi}(t+1) - P_{ENi}(t)}{P_{ENi}(t)})$.

Combined with the recursive estimation explained above, Eq. [4.15] produces one MV efficient frontier per month for an irrigator. As in the investor model, the irrigator model under the MSV framework simply substitutes the portfolio variance with portfolio semivariance in the objective function, using Eq. [4.6]. The final monthly optimal portfolios selected among all the efficient portfolios on the efficient frontiers are again obtained by maximizing the Sharpe ratio and Sortino ratio in Eq. [4.9] and [4.10].

4.5 Data

4.5.1 Data sources and study regions

I use data on transactions in the water market of key trading zones within the southern MDB for the water years 2008 to 2019. Data on entitlements and allocation transactions including the date, water source, price and trading volume were obtained from NSW and VIC state water registers. Trading zones included in this study are NSW Murray, NSW 13 Murrumbidgee, VIC 1A Greater Goulburn (VIC 1A), VIC Murray Dart to Barmah (VIC 6), VIC Murray Barmah to SA (VIC7), Lower Murray groundwater and Lower Murrumbidgee deep groundwater, with the first five for surface water and later two for groundwater. NSW Murray consists of two trading zones, NSW 10 Murray above Barmah Choke and NSW 11 Murray below Barmah Choke. The entitlement transaction data do not make the distinction between these two trading zones. Since these two trading zones are geographically close to each other, and they share the same water source and therefore the same water allocation announcements, NSW 10 and NSW 11 are combined in this study, referred to together as NSW Murray.

These five surface trading zones are selected because they are the most important areas for irrigated agriculture in the Southern MDB (Wheeler and Garrick, 2020; Qureshi et al., 2012), and are the areas where the water market is most active. The two groundwater trading zones, Lower Murray groundwater and Lower Murrumbidgee deep groundwater, included in this study are among the most active areas for groundwater trading. They also geographically correspond to the included surface water trading zones in NSW, namely Murray and Murrumbidgee. As for VIC, trading data for groundwater entitlements and allocation products are not available, so it is not possible to include any groundwater products for VIC.

In total, 12 water entitlements from the seven trading zones are studied in this chapter as introduced above. These include HSEs, GSEs and AEs for NSW, and HSEs and LREs from VIC. In our model, investors and irrigators can hold any type of water entitlements in any included trading zones, but the models assume only intra-valley entitlement and allocation trades to avoid further complications of inter-valley trading restrictions.

4.5.2 Data summary statistics

4.5.2.1 Summary statistics of the water rights prices and temporary allocation prices

Tables 4.1 and 4.2 show the summary statistics of the entitlements and their allocations, where all prices are inflation-adjusted and are expressed in 2018 AUD. Entitlements with the same security level tend to have similar means and standard deviations. The HSEs in general have the highest average price, but their prices are more volatile than the other products. The HSEs in VIC have a lower average price than those in NSW likely due to the lower annual allocation:

on average 90% for VIC compared to 97% for NSW (Figure 4.3). In addition, the strategy employed by NSW authorities is much more aggressive than in VIC (Seidl, 2020) in the sense that NSW authorities tend to announce all possible allocation to entitlements at the beginning of a water year while VIC authorities tend to announce progressively over the year. For example, in VIC Goulburn, entitlement holders have seen 0% opening allocation for 14 years in succession from 1998 to 2012 and allocations are only made available incrementally later over the year (Wheeler et al., 2016). In contrast, HSEs often receive 95% opening allocation. This means that entitlement holders in VIC often bear a higher level of uncertainty in receiving allocations during the early periods in a season compared to those in NSW. The prices of GSEs are less than half of the HSEs prices in the same trading zones, due to lower allocation received: on average 60% annually. Aquifer entitlements in Murrumbidgee on average have higher prices than those in Murray. In both Murray and Murrumbidgee, aquifer entitlements receive 100% allocation every year, but the extractions of groundwater are subject to more restrictions than the use of surface water (Wheeler et al., 2021) so entitlement holders may not always be able to extract the full allocation. LREs in VIC have the lowest average prices. They historically receive 0% allocation in the three zones studied in VIC and effectively serve as carry-over products (Seidl et al., 2021). Table 4.2 shows the price statistics for temporary allocation trades. The allocation prices have similar means and standard deviations across trading zones. In the study areas, the price of surface water allocations is on average about three times higher than that of groundwater allocations.

Table 4. 1 Summary statistics of weekly entitlement prices during 2008-2019 water year ($/ML in 2018 AUD)

		Mean	Median	S.D.	Minimum	Maximum
NSW Murray	HSE	2,921.3	2,840.5	1,097.7	1,282.3	6,907.9
	GSE	1,205.7	1,220.8	324.4	640.6	2,238.6
	AE	868.7	779.3	317.4	427.2	1,869.6
NSW 13 Murrumbidgee	HSE	3,054.5	3,065.4	1,133.3	1,044.0	6,888.0
	GSE	1,315.2	1,235.0	386.1	711.8	2,240.1
	AE	1,591.7	1,558.5	602.3	602.3	3,444.0
VIC 1A Goulburn	HSE	2,370.9	2,408.7	645.7	1,274.5	4,161.8
	LSE	236.2	215.4	95.9	106.8	586.1
VIC Murray 6	HSE	2,277.9	2,239.0	723.6	1,130.8	4,920.0
	LSE	235.9	214.9	107.8	95.5	622.2
VIC Murray 7	HSE	2,528.6	2,448.4	888.1	1,172.3	5,711.9
	LSE	257.8	232.1	120.6	97.6	705.2

Table 4. 2 Summary statistics of weekly water allocation prices during 2008-2019 water year ($/ML in 2018 AUD)

		Mean	Median	S.D.	Minimum	Maximum
NSW Murray	Surface water	170.8	111.5	158.9	10.2	679.3
	Groundwater	56.6	34.4	56.2	2.0	257.3
NSW 13 Murrumbidgee	Surface water	154.2	93.7	160.3	10.7	703.2
	Groundwater	50.1	31.2	54.6	2.3	270.6
VIC 1A Goulburn	Surface water	171.4	102.6	162.5	12.0	757.9
VIC Murray 6	Surface water	170.0	111.8	165.8	8.0	838.8
VIC Murray 7	Surface water	173.8	118.8	161.4	9.6	753.5

4.5.2.2 Historical allocation determinations for studied entitlements

The historical allocation determinations for all entitlements were obtained from NSW and VIC state water registers. The allocation determinations are announced progressively by the local authority in each zone throughout a water year, which starts in July every year. Entitlement holders have access to the announced allocation during the current water year and to carried-over allocations from previous year, if any.

Figures 4.3 and 4.4 show the cumulative allocations to HSEs and GSEs in study areas during water year 2008 to 2019. Consistent with the design of the different security levels, HSEs typically receive more stable water allocation than GSEs. Even in dry years, the total annual allocation for HSEs rarely goes below 95%. In contrast, GSEs receive 100% allocation in wet years, but in dry years they could receive zero allocation due to their lower priority. Allocations to GSEs, therefore, are obviously a lot more sensitive to variations in water availability. Given that the trading zones in the sMDB included in this study draw from the same water source (i.e. River Murray) and the high degree of hydrological connectivity in this area, I consider the allocation determination made for GSEs in NSW Murray as a proxy of water availability. Consequently, the periods where GSEs in NSW Murray receive full allocation are considered as relatively wet periods and periods where GSEs in NSW Murray receive low allocations as considered relatively dry periods.

LREs in the study areas in VIC (VIC1A, VIC6 and VIC7) are not shown in the graph because they historically receive 0% allocation (VIC State Water Register, 2020). These LREs, however, still have been frequently traded with average prices of around 200-300 AUD (Table 4.1). This is because the LREs are useful as carry-over products as mentioned above (Seidl et al., 2020). According to the regulations on entitlements in NSW and VIC, an entitlement cannot hold an allocation of more than 100%, and any extra water (over and above 100%) under the entitlement is subject to spilling (VIC DSE, 2012). HSEs and GSEs, especially the former, thus are not good choices for carrying-over, because they often receive new allocations at the beginning of a water season, resulting in carry-over spill. The LREs historically receiving 0% allocation therefore can serve as "empty parking spaces" for water holders that they can transfer unused allocation to LREs and carry them over into the next season with a high degree of certainty (Seidl 2020). The historical allocation determinations to aquifer entitlements in the two trading zones in NSW are also not shown because they historically receive 100% allocation every season. However, it is worth noting that groundwater extractions are subject to additional restrictions. So, even though aquifer entitlements usually receive 100% allocation, the account holders may not always be able to extract all the allocated water.

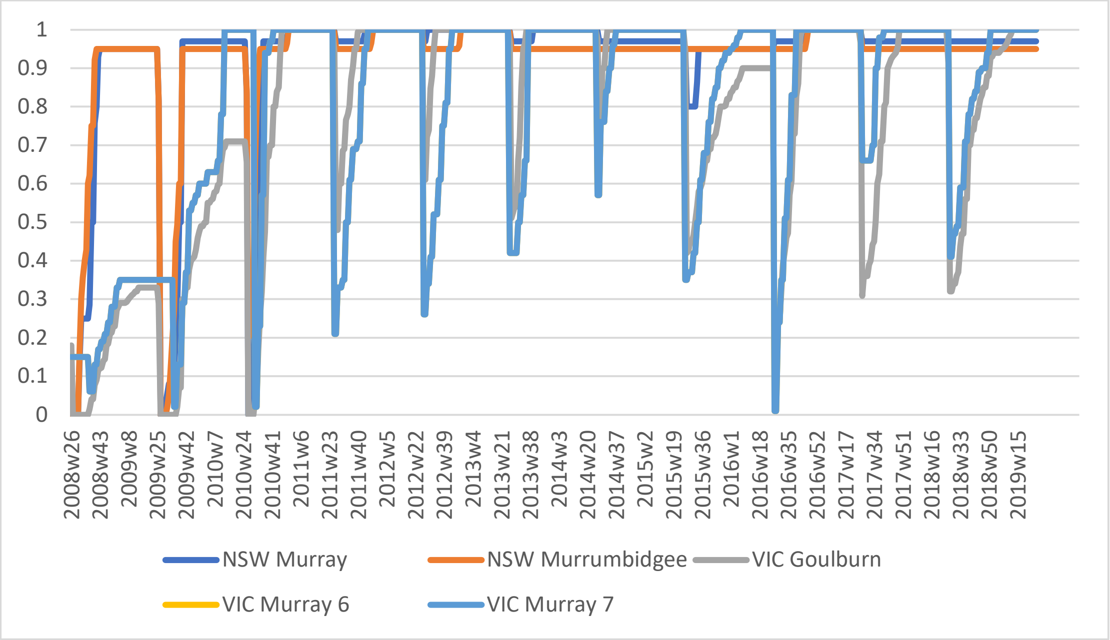

Figure 4. 3 Historical allocation determinations for HSEs in study regions in NSW and VIC

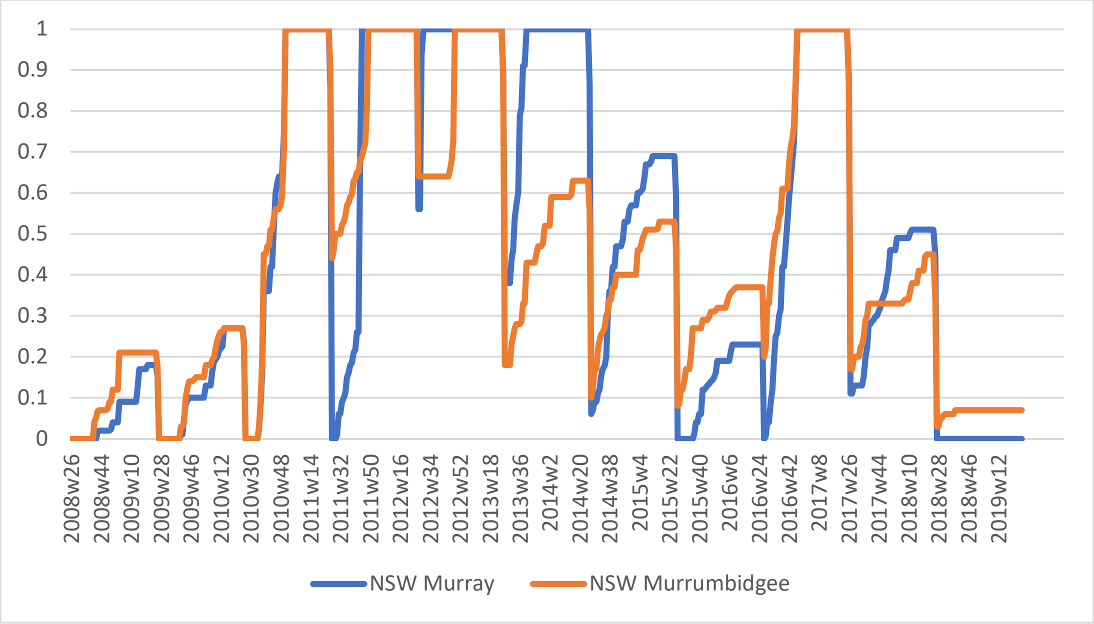

Figure 4. 4 Historical allocation determinations for GSEs in studied regions in NSW

4.5.2.3 Weekly entitlement prices: the trends and the drivers

Figures 4.5 – 4.8 show the weekly average prices for all entitlements and allocation products. The prices of HSEs appear most notably related to water availability (Figure 4.5). The high-security entitlement prices especially showed a significant increase in response to the poor water availability since 2017. General security and aquifer entitlements showed similar trends in prices but were less responsive than the HSEs (Figures 4.6 and 4.7). GSEs reached as high as $2,000 in dry periods and as low as $500-1,000 / ML in wet periods. The average prices of LREs showed a slight upward trend over time. It is worth noticing that a series of LRE transactions with prices significantly lower than prevailing market rates repeatedly occurred during the study period. These transactions are most likely some long-term leasing agreements for carry-over capacity instead of permanent transfers of LREs. However, due to the absence of information differentiating between leasing agreements and permanent transfers in the water trading data, it is not possible to identify and exclude transactions for entitlement leasing. The occurrence of these repeated low-priced transactions has resulted in lower average prices during some weeks, leading to high volatility in weekly average prices, particularly towards the end of the study period, as shown in Figure 4.7. Figure 4.8 shows the weekly average prices of temporary water allocation products. The average prices of surface water allocation were similar across the five trading zones included and again showed a negative trend with water availability. Groundwater allocations were much cheaper than surface water allocation in dry years, but in wet years the surface water prices dropped dramatically, and the price gap became very small. The prices of groundwater were relatively more stable except for the notable increase between 2017 to 2019 due to the extended droughts.

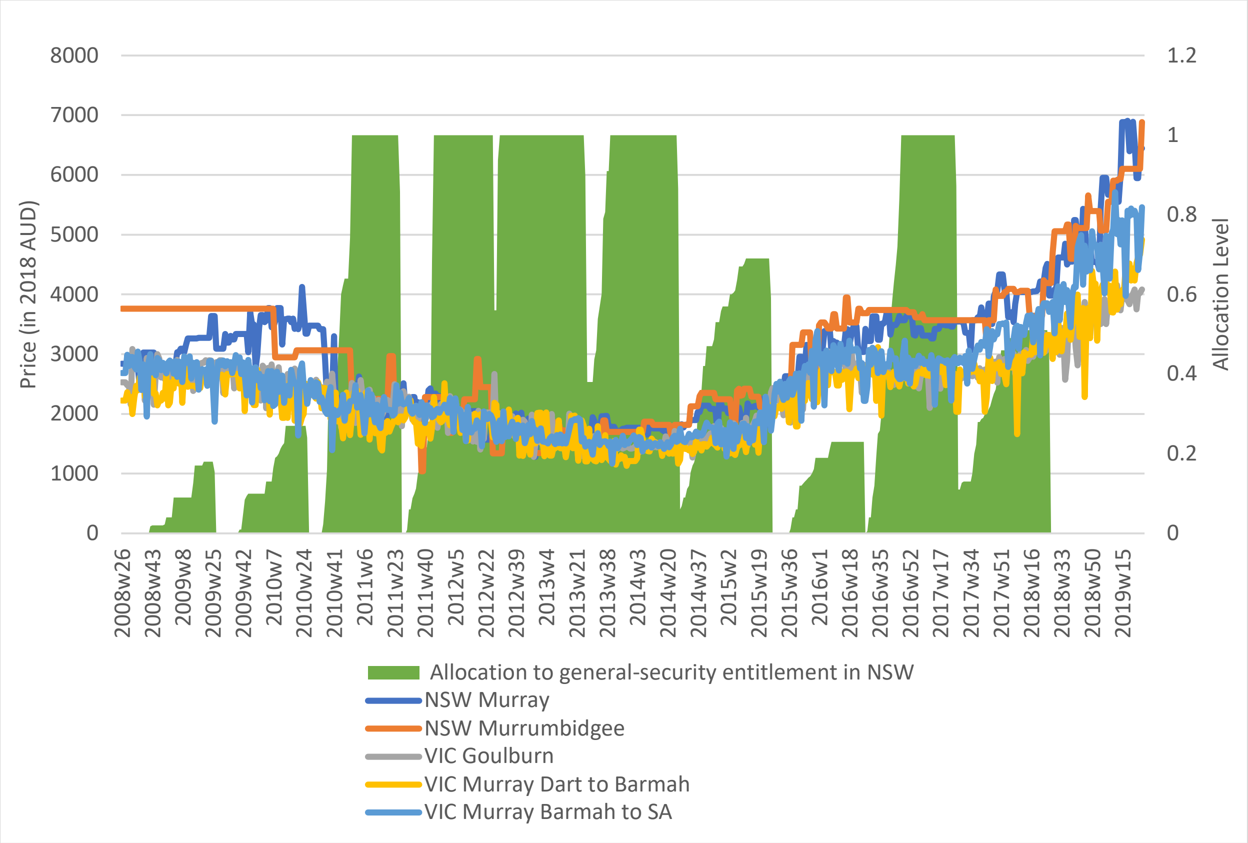

Figure 4. 5 High-security entitlement weekly average prices ($/ML in 2018AUD)

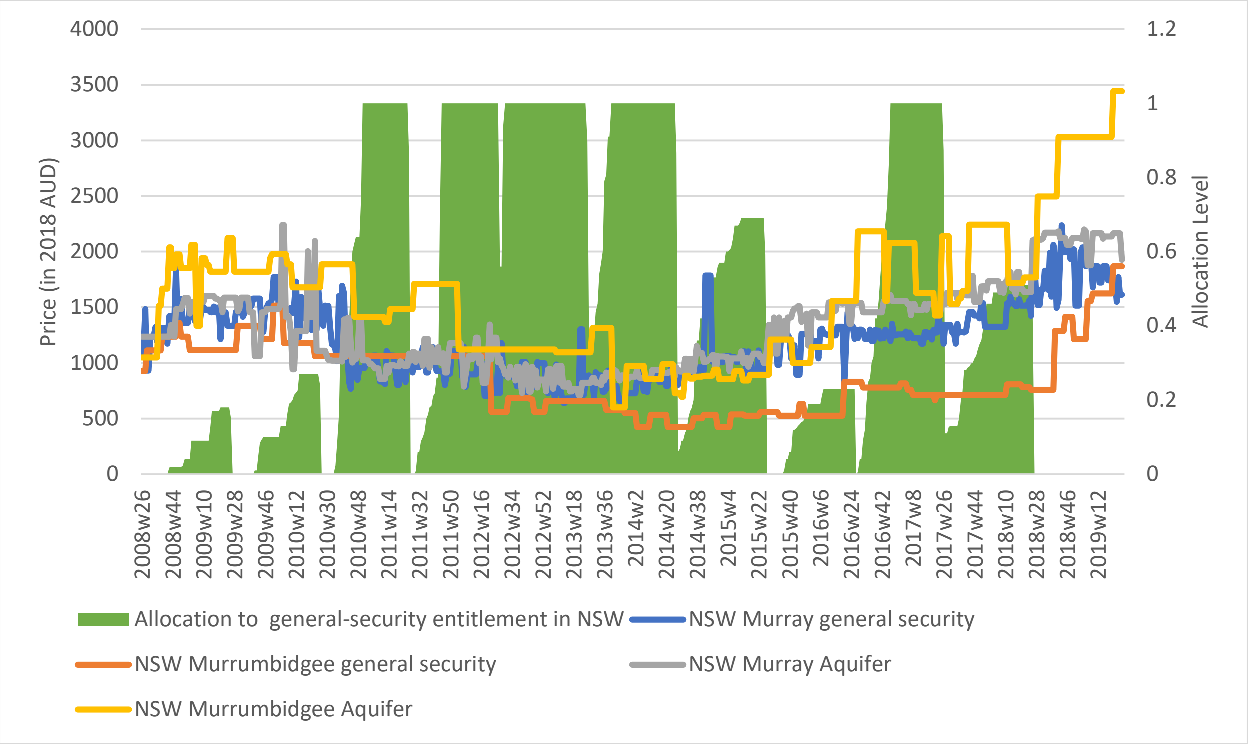

Figure 4. 6 GSEs and aquifer entitlements weekly average prices ($/ML in 2018 AUD)

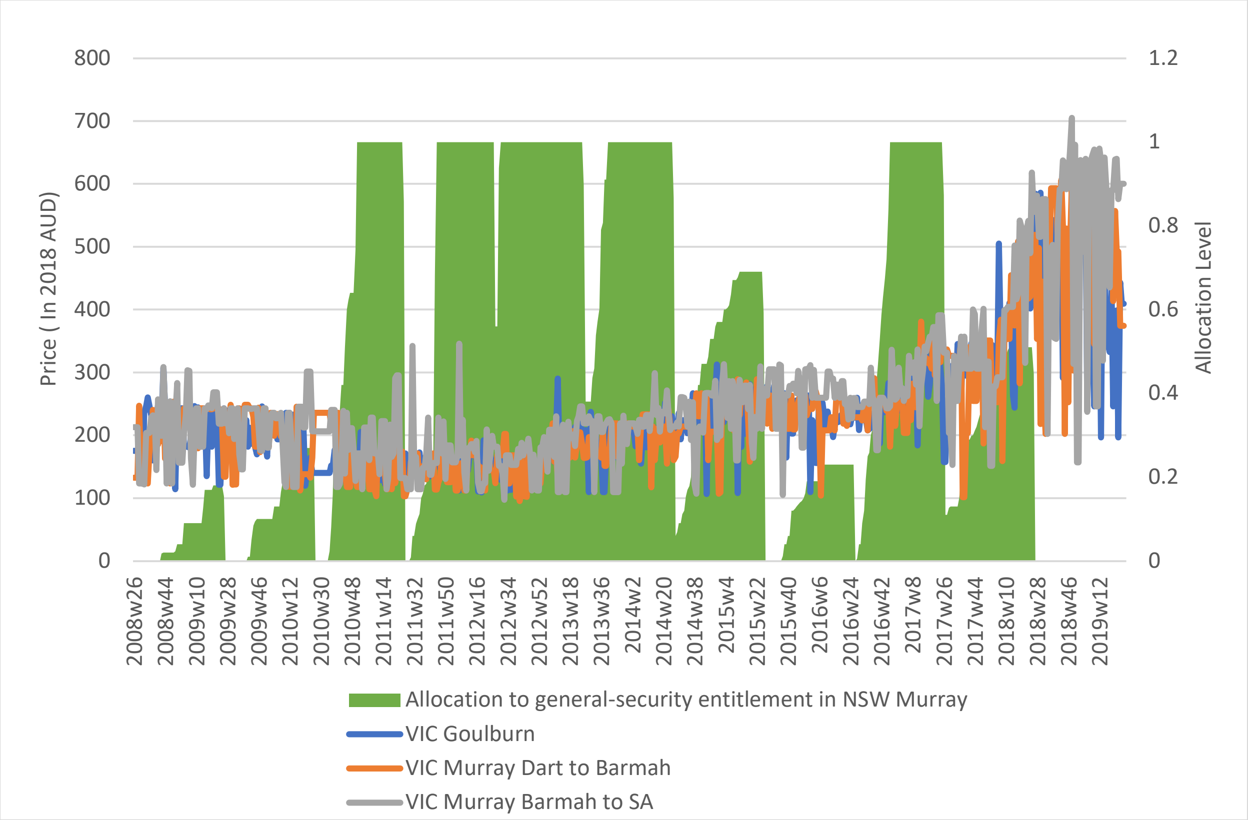

Figure 4. 7 Low-reliability entitlement weekly average prices ($/ML in 2018 AUD)

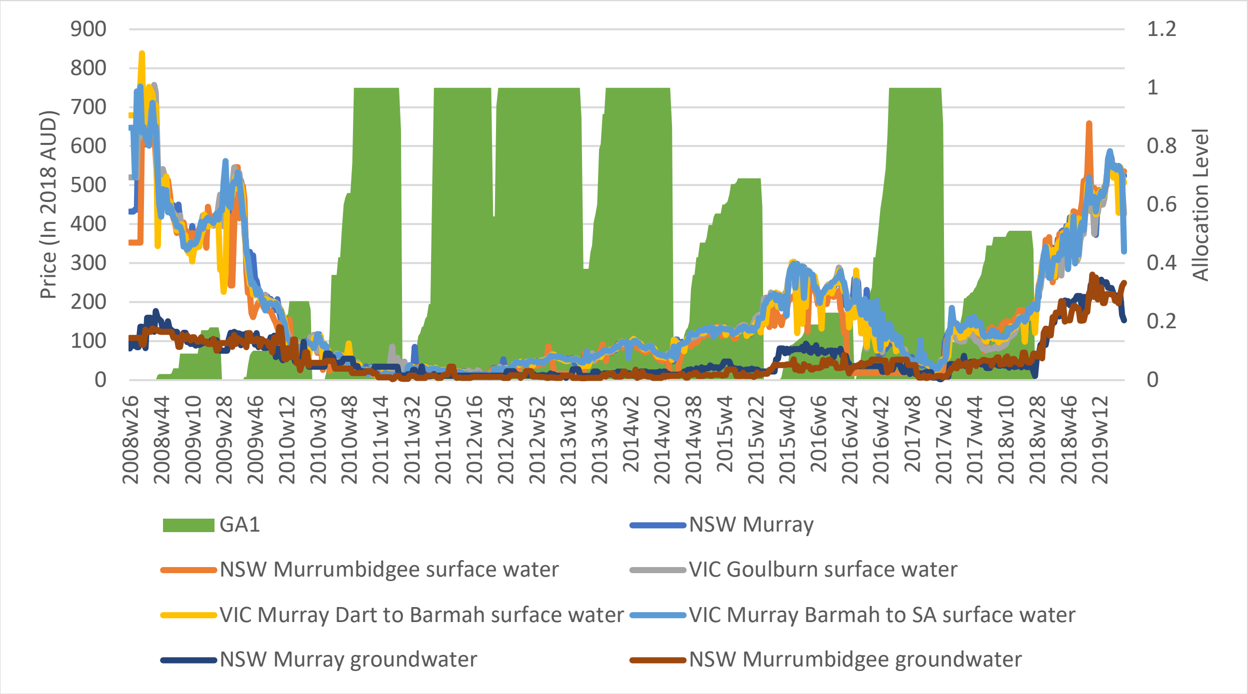

Figure 4. 8 Water allocation weekly average prices ($/ML in 2018AUD)

4.6 Method

4.6.1 Investor Model

The optimization models were programmed consistent with Eq. [4.1] to Eq. [4.4] for the MV model and Eq. [4.5] to Eq. [4.8] for MSV using Python. The matrix of returns containing the return of each type of water right at each period within the estimation window is constructed based on Eq. [4.3]. To calculate the revenue from allocation sales, I use the average weekly allocation for $Q_{ENi}(t)$ in Eq. [4.4] which is calculated by dividing the total annual allocation announced for the i^{th} entitlement by the number of weeks in a year i.e., 52. In other words, the model assumes that when an investor holds an entitlement for a year, he/she sells the available allocation evenly throughout the year at the average allocation price for each week. Based on the return matrix of entitlements obtained, the portfolio return and variance are calculated using Eqs. [4.1] and [4.2].

For the recursive estimation, I consider an estimation window *T* with three different lengths: 1, 3, and 5 years (i.e. 52, 156 and 260 weeks), during which investors in the model make portfolio management decisions on a weekly basis by maximizing the Sharpe ratio. The length of the estimation window reflects different levels of reliance on historical information. For example, if an investor believes that only the price information in the past 1 year would be relevant to decision-making at the current time, then the optimization model would use an estimation window of 52 weeks. The initial estimation uses price data of the first 52 weeks in the dataset, which are from week 26 in 2008 to week 25 in 2009 (as a water year starts on July 1st, which is usually the 26th week in a year) to build the matrix of returns as described above. Then, based on the expected portfolio return and portfolio variance calculated from the matrix of returns, the optimization problem in Eq. [4.9] produces a final optimal portfolio under the MV framework. This final optimal portfolio represents the best choice of water rights for this investor at the end of week 25 in 2009. After one period, i.e. a week in the investor model, the investor would update the knowledge of the prices and re-estimate the optimal portfolio at the end of week 26 in 2009 using price data from week 27 in 2008 to week 26 in 2009. This procedure will produce a series of weekly optimal portfolios for an investor throughout the water year 2008 to the water year 2019. In the final optimal portfolio selection, I use $0 \leq x_i \leq \bar{x} = 0.5$ as the diversification constraint in all models. In other words, the optimal portfolio weight for any individual entitlement is capped at 0.5. This constraint is employed to avoid the portfolio assigning all weights to a single type of entitlement. However, since it is a major interest of this study to analyse the optimal composition of water portfolios under different water availability conditions, this cap is set relatively high at 0.5 to reduce its impact on the optimization results. The constraint of 0.5 is not binding most of the time in the recursive estimation of the optimal portfolios.

The weekly MSV optimal portfolios are generated using similar procedures as the MV model described above, substituting the portfolio variance with portfolio semivariance and using the Sortino ratio instead of the Sharpe ratio as illustrated in the previous section.

4.6.2 Irrigator Model

The expected portfolio return in the irrigator model is calculated using Eq. [4.13]. Note that in an irrigator model, the expected return of the portfolio does not include revenue from allocation sales, because the model assumes irrigators use all allocation received and only sell unused allocation at the end of the water year when the account balance is about to be reset. The portfolio variance/semivariance is calculated similarly to the investor model. The upper bound of optimal portfolio weight for individual entitlements, $\bar{x} = 0.5$, is employed in the irrigator models as well.

4.6.2.1 The choice of initial portfolio value

As discussed in section 4.4.5, an initial portfolio value, *V(t)*, is required to calculate the actual water yield of the portfolio that satisfies the minimum water constraint in ML. Due to a lack of available data on the size (value) of water assets held by irrigators in sMDB, a hypothetical value of 1 million AUD is used as the initial portfolio value *V(t)*, which would roughly correspond to an average irrigator's water usage in our study regions, estimated as follows. The majority of irrigators in NSW hold GSEs (Seidl et al., 2020), which are expected to receive 70% allocation in the long term (Wheeler et al., 2016). Therefore, based on the average prices of GSEs in NSW Murray and Murrumbidgee (Table 4.1), a hypothetical portfolio of 1 million AUD can purchase about 793ML GSEs, with an expected water yield of 556ML annually. According to the water use dataset from the Australian Bureau of Statistics (ABS, 2009-2019), irrigating agricultural businesses in the study areas in NSW and VIC apply on average about

510ML water annually during the period 2009 to 2019 as shown in Table 4.3.[6] The annual average volumes of water applied are weighted by the number of irrigating businesses in each region. The average volume of water applied, 510 ML, is slightly lower than the expected annual allocation of 556ML of our hypothetical 1M AUD portfolio. However, the survey scope of the ABS water use dataset was all agricultural businesses with an estimated value of agricultural operation above AUD 40,000, which would include a large number of small businesses that are likely to be irrelevant to the water market. Therefore, the hypothetical value of 1M AUD is considered to be a reasonable representation of the size (total value) of the water portfolio that a typical agricultural business would hold in the study region in sMDB. So, I use $1 million as the initial portfolio value in the irrigator model and reset it every water year, at the beginning of July. Annual profit/loss before resetting the portfolio value will be presented in the result section.

Table 4. 3 Area weighted average volume of water applied by irrigating businesses from 2009 to 2019 in studied regions in NSW and VIC (Source: ABS (2009-2019))

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Avg.
Annual Demand	222.3	309.4	527.0	642.6	533.5	492.2	538.7	643.0	702.1	481.6	510.0

4.6.2.2 Monthly minimum water demand

In the irrigator model, since the optimal portfolios are rebalanced on a monthly basis with a water constraint, the minimum monthly water demand is needed. There is however no available water demand for irrigators on a monthly basis that I am aware of. So, I derive monthly water demand based on typical crop mix and crop factors, using the annual demand (Table 4.3). The crop factor indicates the proportion of evaporation that must be replaced by irrigation, which changes with crop type and crop stage (WA DPIRD, 2017). In this study I use the crop factor provided in the PRIDE user manual (PRIDE, 2007). The crop factors in each month are first normalized by the total (summation of) crop factors in a year to calculate the monthly water demand as a proportion of the annual water demand for each type of crop. Secondly, the crop

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[6] The price data used in this paper covers the period of water years 2008 to 2019. The smallest estimation window used in this study is the 1-year window, which means the first optimal portfolio can be produced for an irrigator will be the first week in water year 2009. Therefore, water use data is collected from 2009 to 2019.

mix is considered in study regions. Based on the ABS water use dataset (ABS, 2009-2019), major irrigated crops include pastures, cereals (wheat and barley), rice, cotton, fruit and nut trees, and vegetables. Combining the crop factor and the crop mix, I produce the monthly water demand in table below (Table 4.4), which highlights the highest irrigation demand during summer and allows some irrigation in autumn and at the end of winter to support winter crops.

Table 4. 4 Monthly water demand splits as proportions of annual demand

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Demand Split	0.2	0.15	0.1	0.05	0	0	0	0.05	0.05	0.1	0.1	0.2

The minimum water requirement in the irrigator model, $\bar{w}$, in a given month of a year, therefore, is calculated as the product of the annual demand in that year from Table 4.4 and the monthly demand split from Table 4.5. As defined by the water constraint in Eq [4.10], the total available water for each month including allocation generated by entitlements, allocation purchased and unused allocation from previous month must meet the minimum water demand $\bar{w}$. Any additional water left will automatically carry over into the next month and unused allocation will be sold at the end of the water year (in June).

4.7 Results

As discussed in section 4.4, the optimal portfolios are estimated using estimation windows with three different lengths: 1 year, 3 years and 5 years. The longer the estimation window is, the shorter the period I can estimate for the weekly/monthly optimal portfolios. For example, the dataset starts in July 2008 (week 27), so the first weekly optimal portfolio I can obtain using a 5-year estimation window would be for week 27 in 2013, while using a 3-year estimation window this would correspond to week 27 in 2011. The average values of the expected portfolio returns, portfolio volatilities and realized returns for models using different lengths of estimation windows are summarized in Tables 4.5 and 4.6 for investors and irrigators, respectively. The expected return and portfolio volatility (measured in standard deviation for the MV model and semi-deviation for the SMV model) of the optimal portfolios were based on price data during the period [*t-T, t*]. The realized portfolio returns, which measure the out-of-sample performance of the selected optimal portfolios, were calculated using the optimized portfolio weights by the end of time *t* and the real return of each asset in the portfolio during the next period *t*+1. As shown in Table 4.5, the expected portfolio returns in the investor setting estimated using different estimation windows are similar, but the realized returns increase significantly with the length of the estimation window for both MV and MSV models. This result suggests that utilizing more historical information leads to a better out-of-sample performance by the models. The MSV model performed slightly better on average than the MV model in terms of realized returns. This is expected since the MV model penalizes upward variations (above target performance) which is actually desirable. It is also expected that the volatility of expected returns in MSV models, which is measured by semi-standard deviation is about half of the volatility (i.e. the standard deviation) of portfolios in MV models. As shown in Table 4.6, the model performance in the irrigator setting exhibited a similar pattern that portfolios estimated with a longer estimation window had higher realized returns on average.

Table 4. 5 The expected return, expected portfolio volatility and realized portfolio return of the weekly optimal portfolios for **investors** estimated using 1-year, 3-year and 5-year estimation window in both MV and MSV models.

	MV			MSV		
Average value	1yr weekly	3yr weekly	5yr weekly	1yr weekly	3yr weekly	5yr weekly
Expected Portfolio Return	0.0105	0.0116	0.0115	0.0109	0.0123	0.0123
Realized Portfolio Return	-0.0019	0.0079	0.0111	-0.0026	0.0083	0.0120
Expected Portfolio Volatility	0.0329	0.0440	0.0444	0.0190	0.0268	0.0275

Table 4. 6 The expected return, expected portfolio volatility and realized portfolio return of the weekly optimal portfolios for **irrigators** estimated using 1-year, 3-year and 5-year estimation windows in both MV and MSV models.

	MV			MSV		
Average value	1yr monthly	3yr monthly	5yr monthly	1yr monthly	3yr monthly	5yr monthly
Expected Portfolio Return	0.0183	0.0165	0.0140	0.0192	0.0173	0.0149
Realized Portfolio Return	-0.0122	0.0158	0.0215	-0.0080	0.0175	0.0236
Expected Portfolio Volatility	0.0409	0.0626	0.0603	0.0255	0.0385	0.0381

The following sub-sections present the composition of the dynamically-adjusting optimal portfolios estimated using the MV and the SMV models for both investors and irrigators. I will focus on the results obtained using a medium length estimation window of 3 years due to limited space. The optimization results for 1-year and 5-year estimation windows are provided in Appendix C. The major patterns and conclusions drawn from the models using 1-year and 5-year estimation windows are similar to those obtained using the 3-year estimation window.

4.7.1 Optimal portfolios in the investor model estimated with the MV framework

Figure 4.9 presents the composition of the weekly-rebalanced optimal portfolios for investors, estimated under the MV framework with a 3-year estimation window[7]. Since the initial estimate used three years of water market transaction data, the estimate started in week 27 of the 2011 water year (July 2011). The optimal portfolio weights for the twelve types of water rights across different trading zones are grouped into four categories based on their reliabilities, i.e. HSEs, GSEs, LREs and AEs. The portfolio weights, therefore, sum up to 1 across four series for each week in Figure 4.9. Again, note that the years referred to in this study correspond to water years that start in July.

As shown in Figure 4.9, the portfolio weights of HSEs and AEs showed similar trends over time as they both had relatively low portfolio weights during 2012-2015 and relatively high

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[7] The weight of each type of entitlements by reliability and by trading zone is capped at 0.5, but Figures 4.9, 4.12, 4.16 and 4.19 show optimal entitlement weights aggregated by reliability only for clarity. Therefore, the weights of each type of entitlement (i.e. HSEs, GREs, LREs and AEs) can exceed 0.5 in these figures.

portfolio weights during 2011-2012 and 2016-2019, which were especially notable for AEs. LREs on the other hand showed an opposite trend as their aggregate portfolio weight reached a peak during 2012-2015 and decreased afterwards. GSEs were estimated to have relatively stable portfolio weights over the study period, with the weights during 2012-2015 being slightly higher. As discussed above, allocations made available for GSEs can serve as a reasonable indicator of water availability in the sMDB. Based on the allocations for GSEs in Figure 4.4, 2010-2014 were relatively wet, so that GSEs received full allocations, while 2015-2019 were relatively dry except for 2016. It is evident that the optimal portfolio weights of different types of entitlements varied with changes in water availability, besides a notable lag in such variations—as can be expected since the optimal portfolios were estimated using 3 years of historical information. Specifically, the aggregate portfolio weights of HSEs and AEs, particularly for the latter, tended to be higher during periods of poor water availability. In contrast, the aggregate portfolio weights of GSEs and LREs, especially the latter, tended to be higher during periods of good water availability.

The expected portfolio returns and volatilities (shown on the secondary axis) of the same model are presented in Figure 4.10. The portfolio returns and volatilities exhibited similar trends, with an increase observed during 2011-2013, followed by a decrease after 2013. The portfolio volatilities were estimated to be decreasing faster than the expected portfolio returns since 2015. In other words, the optimal portfolios estimated using historical transaction information were expected to have on average decreasing but increasingly stable returns in more recent years of the study period. This trend corresponded to the realized portfolio returns, as presented in Figure 4.11. The realized returns clearly showed smaller fluctuations during the later years of the study period, especially after 2016.

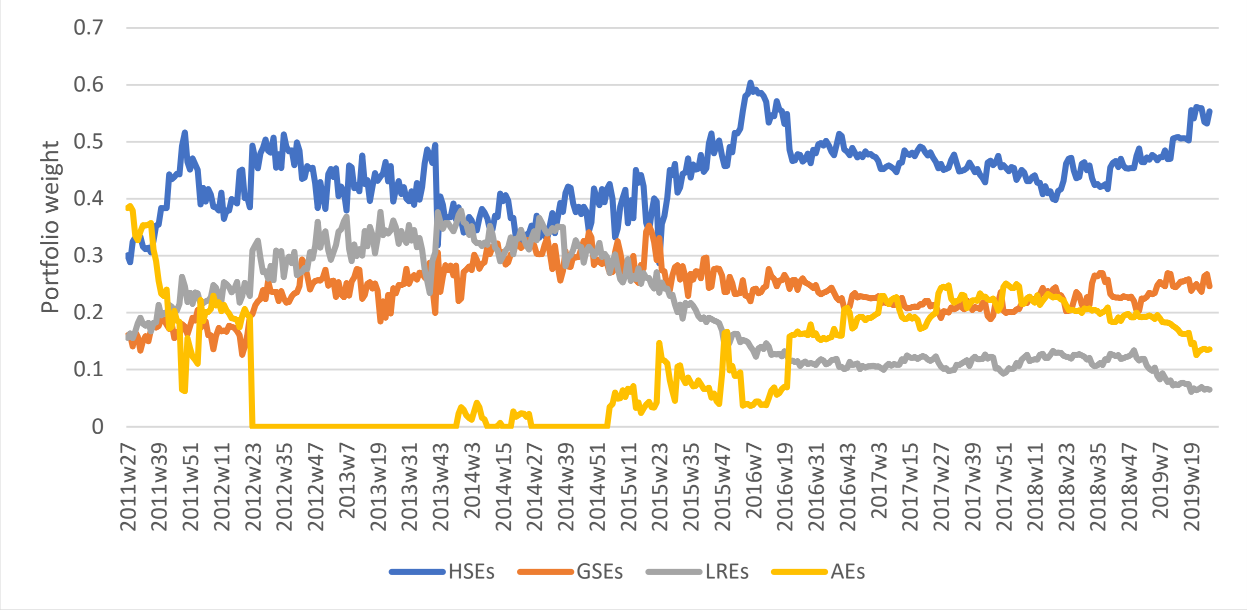

Figure 4. 9 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Variance** optimization framework and 3-year estimation window.

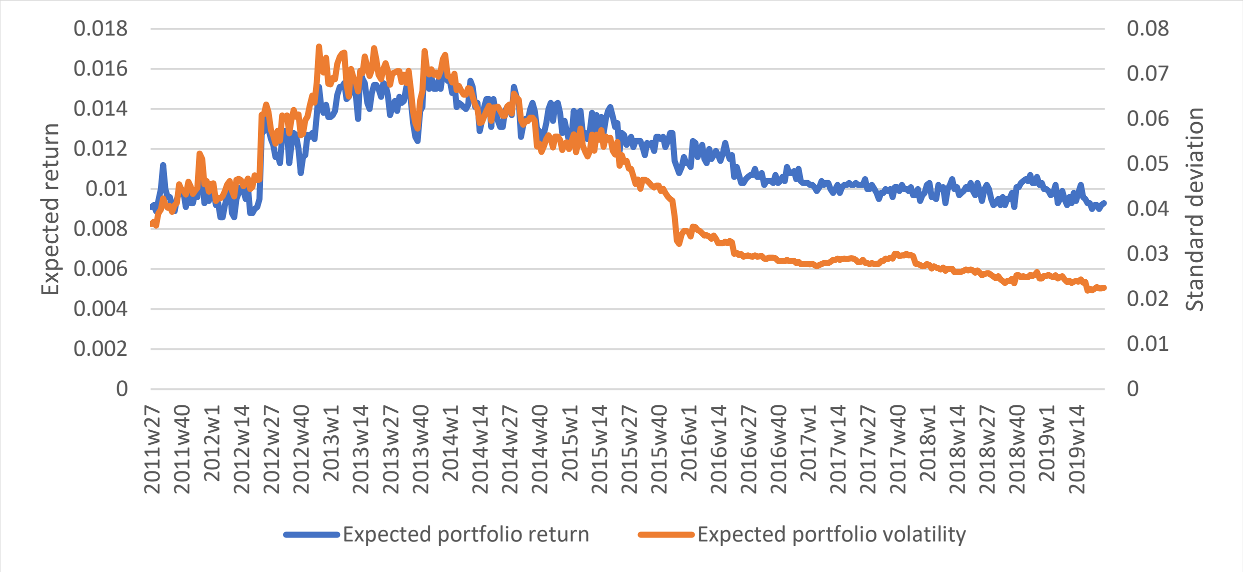

Figure 4. 10 Expected return and expected volatility of the weekly-rebalanced optimal portfolios in the **investor model**, estimated with the **Mean-Variance** optimization framework and 3-year estimation window. Expected portfolio volatility is measured in the standard deviations of the expected portfolio returns.

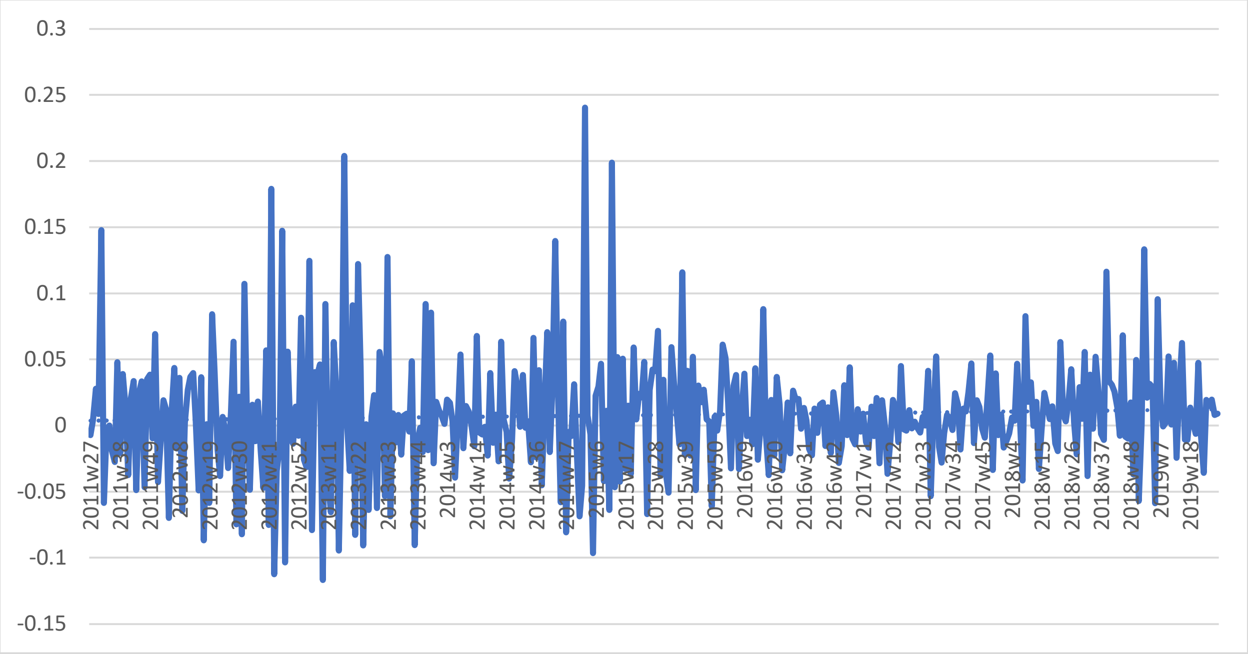

Figure 4. 11 Realized returns of the weekly-rebalanced optimal portfolios in the investor model, estimated with the **Mean-Variance** optimization framework and **3-yea**r estimation window.

4.7.2 Optimal portfolios in the irrigator model estimated with the MV framework

The composition of the monthly-rebalanced optimal portfolios of the irrigator model, estimated under the MV framework with a three-year estimation window is presented in Figure 4.12. Overall, the optimal portfolio weights had greater fluctuations across time in the irrigator model than in the investor model, primarily due to the different aggregations of the data. The prices (and therefore returns) vary more dramatically on a monthly basis than they do on a weekly basis. Optimal portfolio weights, therefore, would also change more significantly on the monthly basis. The trends in optimal portfolio weights of each type of entitlement are similar to those in the investor model, but the relative weights in the portfolios are different. For example, LREs were estimated to have higher weights before 2015 and lower afterwards similar to the investor model. The portfolio weights of LREs however, were much higher in the irrigator model than in the investor model during 2011-2015. This is most likely due to the different aggregations of the trading data. The monthly aggregation of LREs likely smoothed out the fluctuations in the weekly prices of LREs due to the existence of leasing agreements (as discussed in section 4.5.2.3), rendering the LREs to be picked up by the MV model. In contrast, HSEs were allocated very low portfolio weights during 2011-2015, and high portfolio weights during 2015-2019. In the case of AEs, the portfolio weights for AEs were on average higher during the second half of the study period with two particularly notable spikes during the dry periods in 2015-2016 and 2018-2019. The portfolio weights of GSEs showed a less clear trend, with the average weight during the earlier half of the study period being slightly higher than during the latter half. Overall, the optimization results of the irrigator model are similar to the investor model in that LREs and to a lesser extent GSEs were preferred during relatively wet periods while HSEs and AEs were preferred during relatively dry periods.

Portfolio weights assigned to allocation purchases were very low compared to the weights of entitlements. This can be expected as allocation purchases did not offer returns to the portfolio, so the model in effect minimizes the weights assigned for allocation purchases. Figure 4.13 presents the weights for allocation purchases to show the patterns. Allocation purchases were clearly concentrated between January and April, corresponding to the peak of the irrigation demand estimated in Table 4.4. Larger weights were also given to allocation purchases during years of low allocation to entitlements, e.g. 2015-2016 and 2018-2019.

Figure 4.14 presents the expected portfolio returns and volatilities. Compared to the investor model, the expected portfolio for the irrigator model showed a less clear trend and greater fluctuations. The portfolio volatilities on the other hand, exhibited a clear decreasing trend. In Figure 4.14, the large spikes in portfolio volatility and dips in returns during early 2016 and 2018-2019 corresponded to the spikes of weights allocated to AEs as shown in Figure 4.12. These unfavourable changes in portfolio performance (i.e. lower returns and higher risks) reflect the tradeoffs between the financial returns of the portfolios and the minimum water demand from irrigators during times of poor water availability. The realized returns of the monthly portfolios for irrigators also corresponded to such a pattern that realized returns dropped significantly during times of poor water availability, as shown in Figure 4.15.

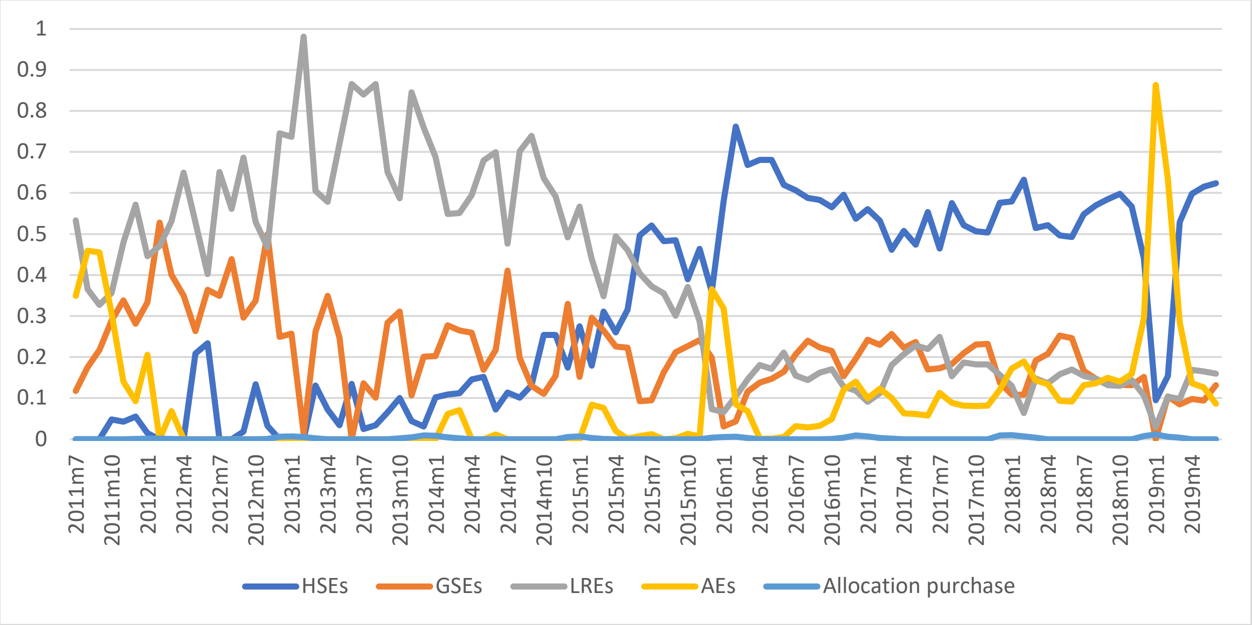

Figure 4. 12 Optimal weights of entitlements and allocation purchases in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and the 3-year estimation window.

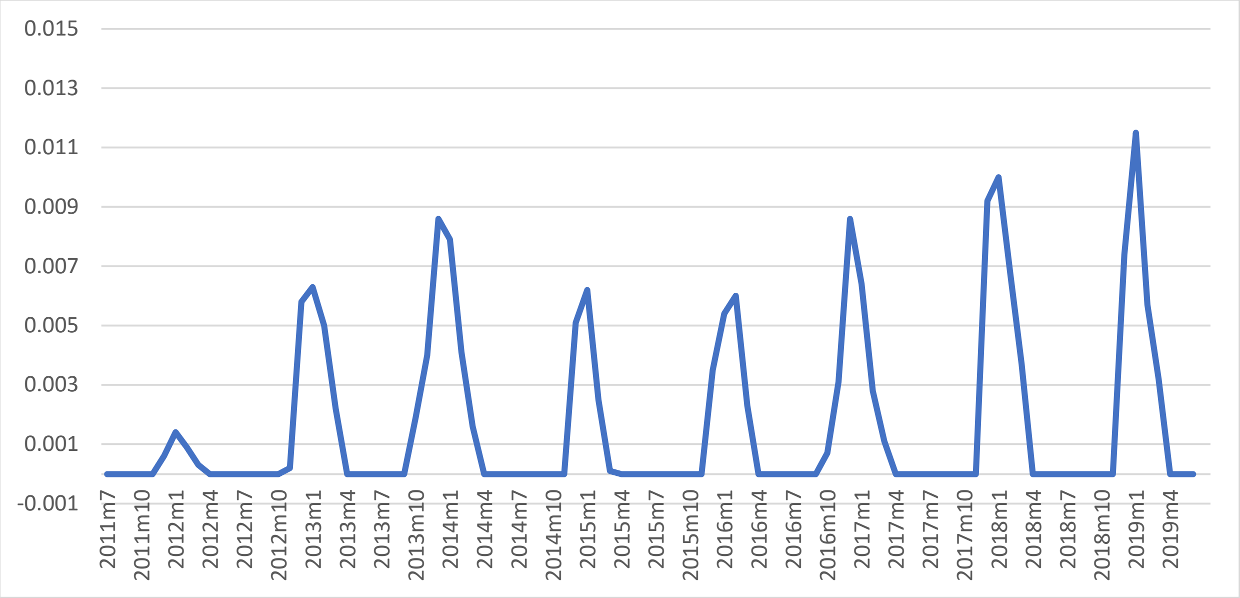

Figure 4. 13 Optimal weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and the 3-year estimation window.

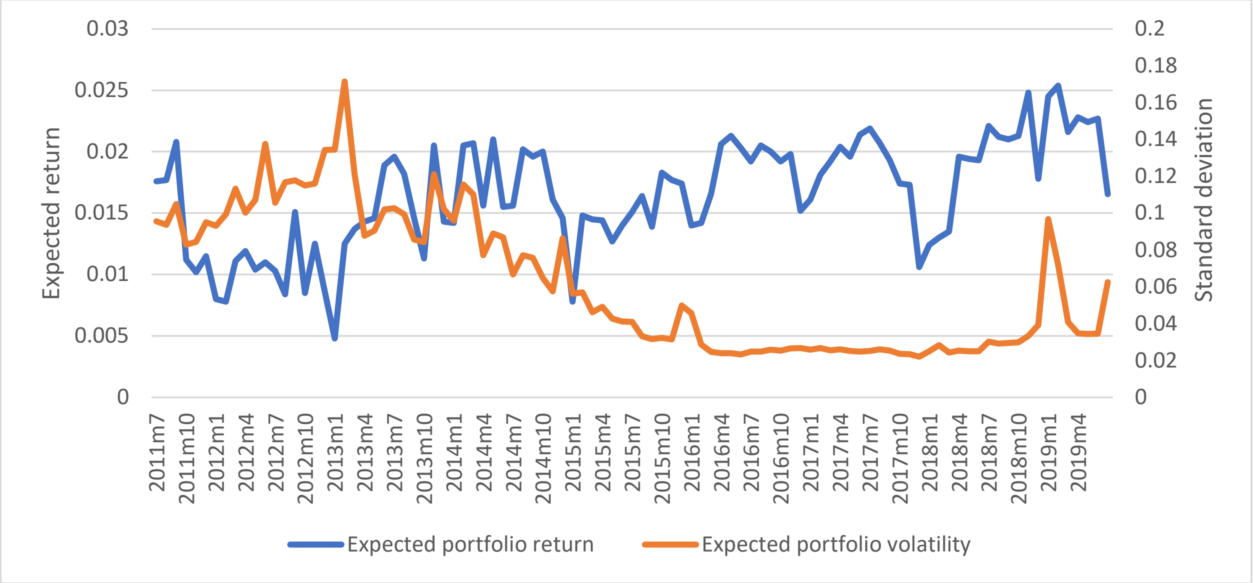

Figure 4. 14 Expected return and expected volatility of the estimated weekly optimal portfolios in the **irrigator model**, estimated with the **Mean-Variance** optimization framework and the 3-year estimation window. Expected portfolio volatility is measured by the standard deviation of the expected portfolio returns.

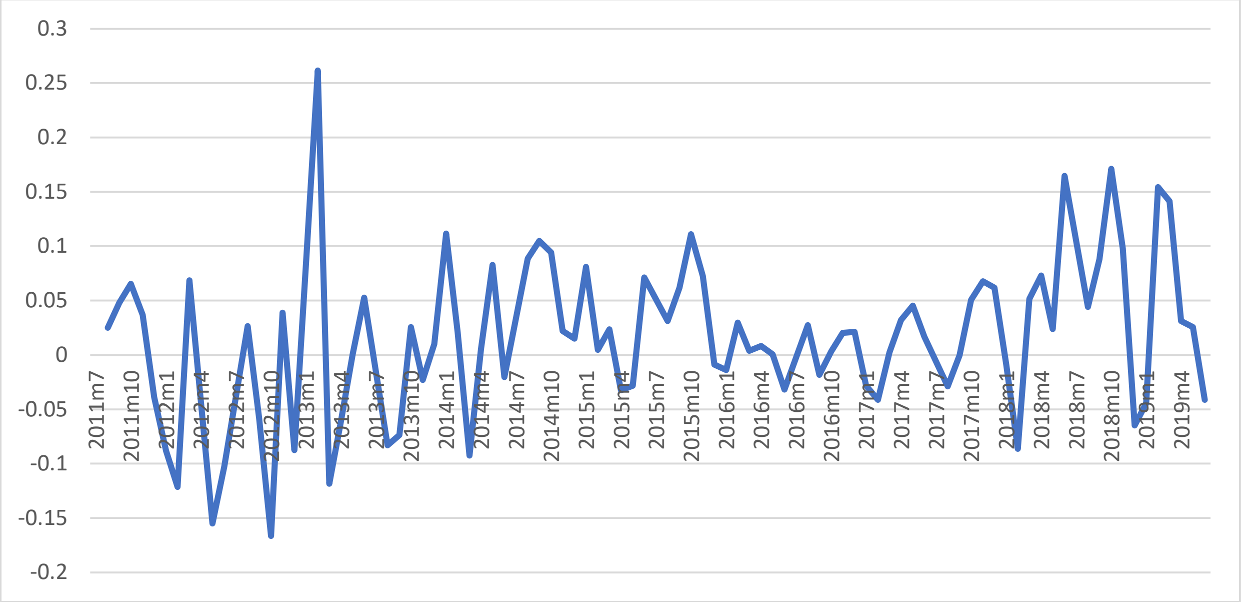

Figure 4. 15 Realized return of the estimated monthly optimal portfolios in the **irrigator model**, estimated with **Mean-Variance** optimization framework and the 3-year estimation window.

4.7.3 Optimal Portfolios in the investor model estimated with the MSV framework

The composition of the weekly-rebalanced optimal portfolios for the investor model is presented in Figure 4.16. Overall, the optimal portfolios estimated under the MSV framework are similar to those estimated under the MV framework. A major difference is that the AEs were notably more favoured in the MSV model, due to their lower downside variance.

Figure 4.17 presents the expected portfolio returns and volatilities, and Figure 4.18 shows the realized portfolio returns for the investor model estimated with the MSV framework. The expected returns of optimal portfolios in Figure 4.17 also exhibited a similar pattern as in the MV model. The MSV model performed slightly better in terms of realized returns (on average less than 0.01% higher weekly) than the MV model using both the 3-year and 5-year estimation windows (Table 4.6). The similarity and consistency of the optimization results between the MV and MSV models provide evidence for the robustness of our optimization framework.

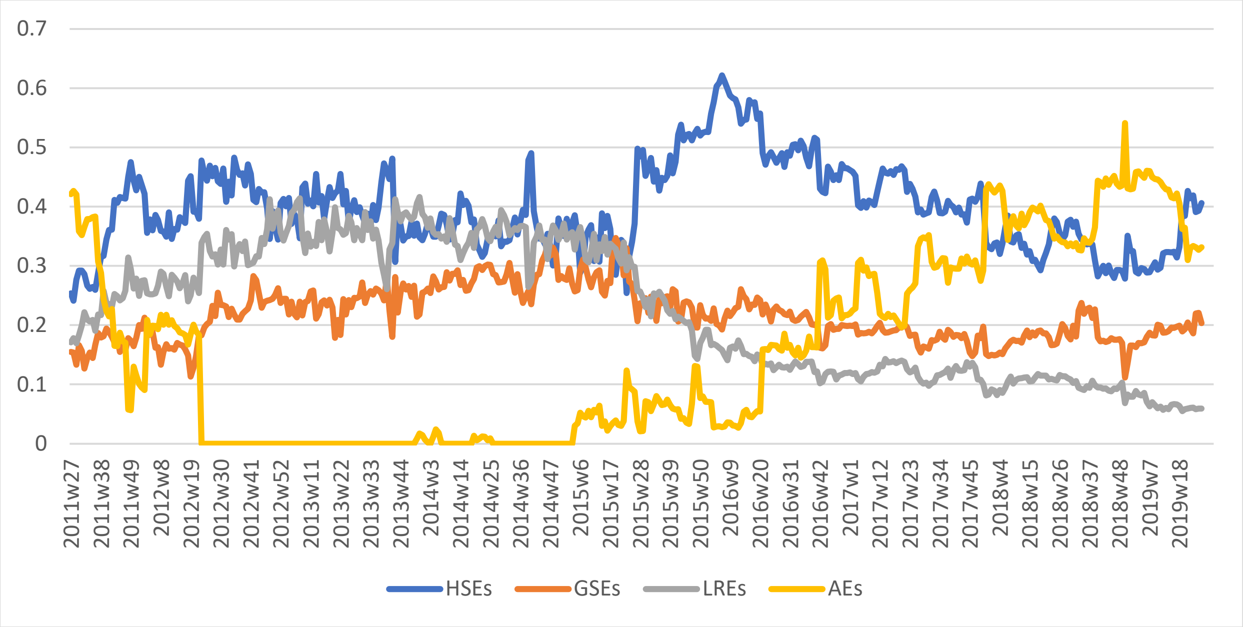

Figure 4. 16 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Semivariance** optimization framework and the 3-year estimation window.

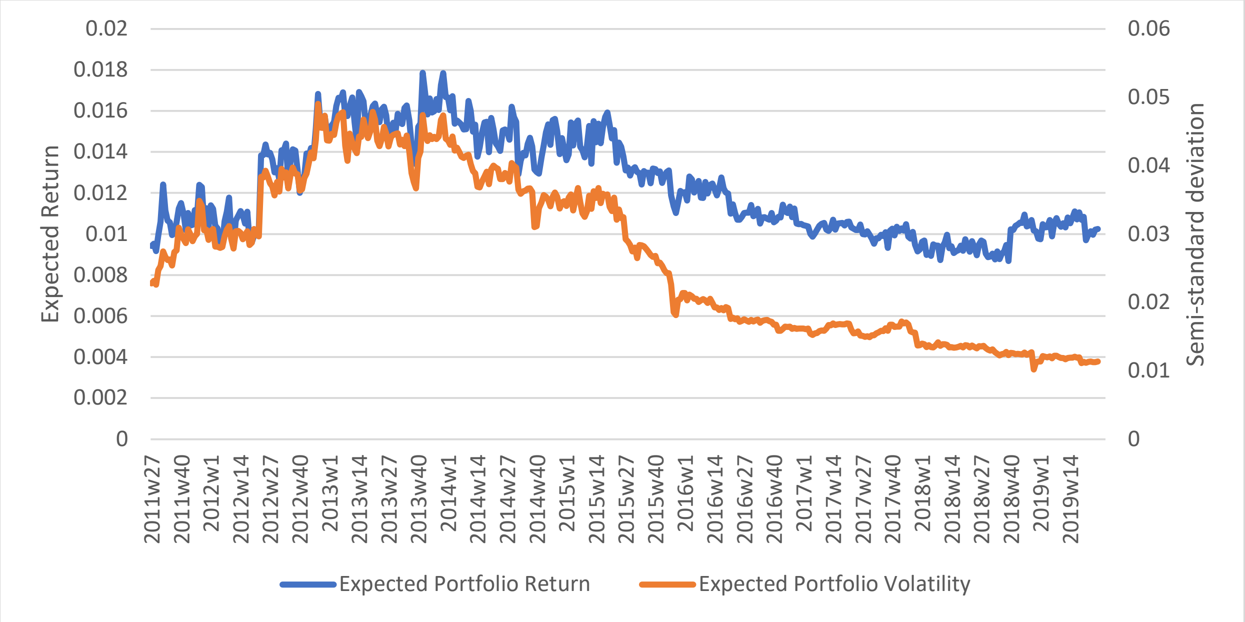

Figure 4. 17 Expected return and expected volatility of the estimated weekly optimal portfolios in the investor model, estimated with **Mean-Semivariance** optimization framework and 3-year estimation window. Expected portfolio volatility is measured by the semi-standard deviation of the expected portfolio returns.

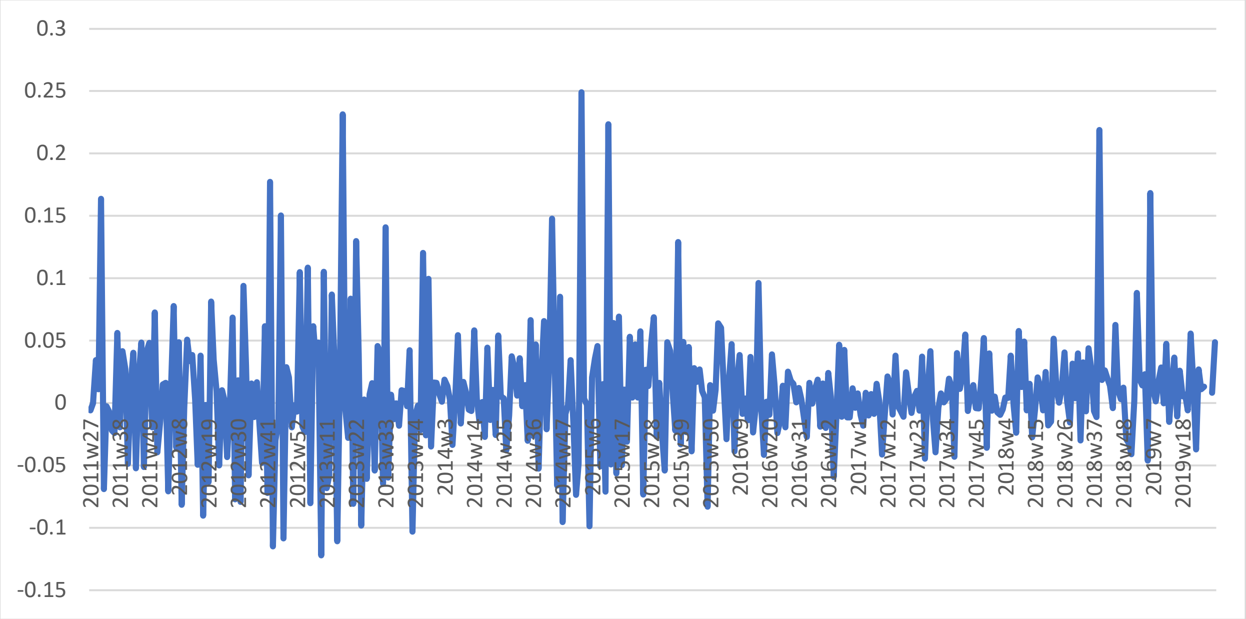

Figure 4. 18 Realized return of the estimated monthly optimal portfolios in the **investor model**, estimated with the **Mean-Semivariance** optimization framework and the 3-year estimation window.

4.7.4 Optimal Portfolios in the irrigator model estimated with the MSV framework

For the irrigator model, the optimization results estimated with the MSV framework are again similar to the MV framework, as shown in Figure 4.19. The weights allocated to LREs during the first half of the study period were higher than those estimated under the MV framework, as was the case with the investor model, as well. The weights of AEs during the second half of the study period (a relatively drier period) were slightly higher on average, though with less prominent spikes compared to the MV model for the irrigators. HSEs were also preferred during this relatively drier period for their higher yields of water allocations. Allocation purchases were again concentrated between January to April (Figure 4.20).

As shown in Figure 4.21, the expected portfolio returns showed a slight upward trend, while the expected portfolio volatility exhibited decreasing trend. The realized returns of the monthly-rebalanced portfolios showed a slight upward trend (Figure 4.22), but did not show an obvious reduction in the variation of the realized returns over time as the investor models did (Figure 4.11 and 4.18).

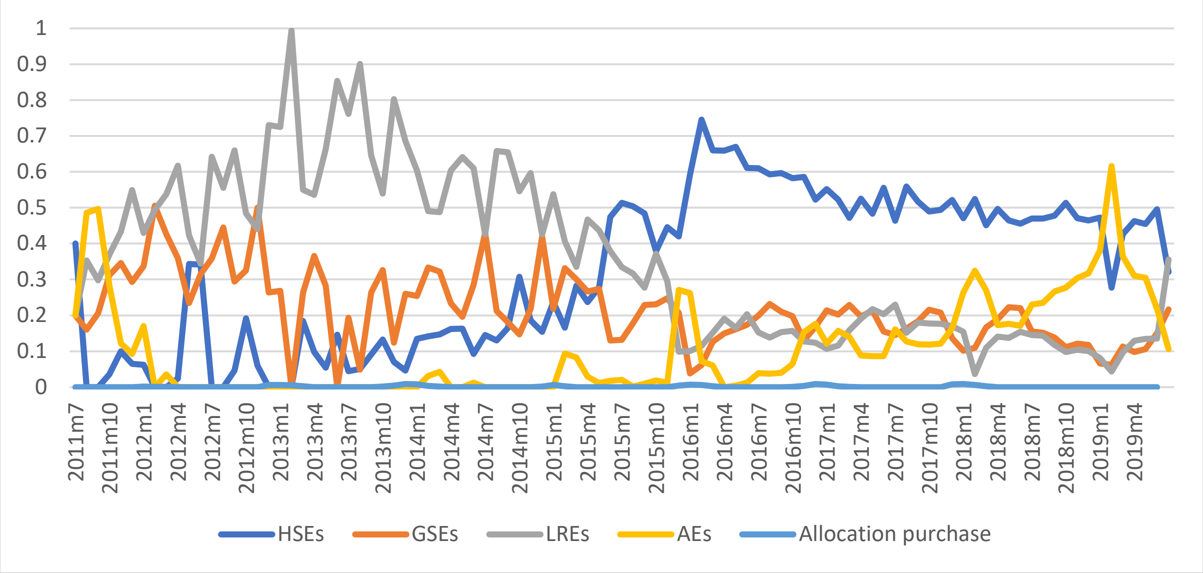

Figure 4. 19 Optimal weights of entitlements and allocation purchases in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and the 3-year estimation window.

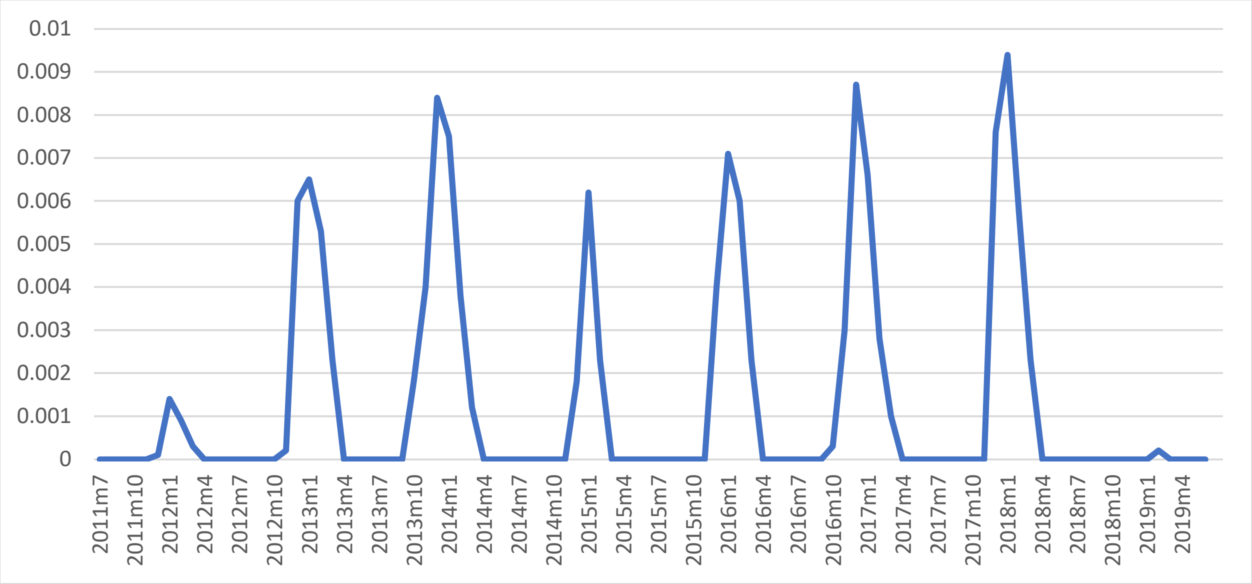

Figure 4. 20 Optimal weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and 3-year estimation window.

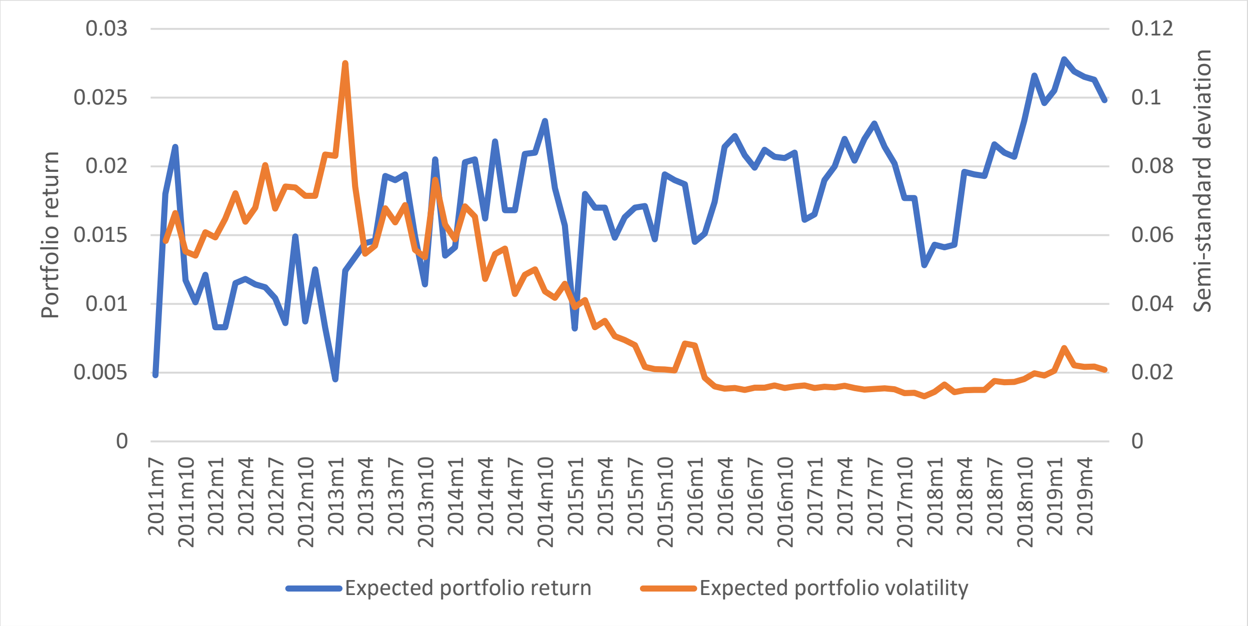

Figure 4. 21 Expected return and expected volatility of the estimated weekly optimal portfolios in the **irrigator model**, estimated with **Mean-Semivariance** optimization framework and 3-year estimation window. Expected portfolio volatility is measured by the semi-standard deviation of the expected portfolio returns.

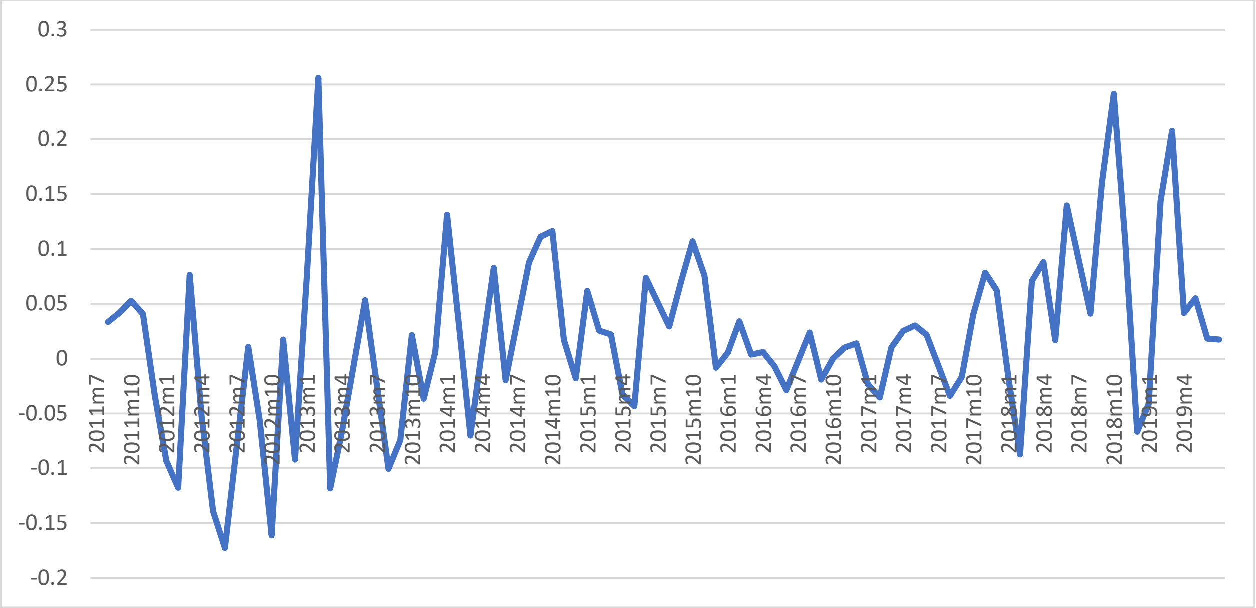

Figure 4. 22 Realized return of the estimated monthly optimal portfolios in the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and the 3-year estimation window.

4.8 Discussion

4.8.1 Model performance and benefit of portfolio diversification

The performance of the optimization models in terms of realized returns seems to be influenced by several factors: the length of the estimation window, the rebalancing frequency (weekly vs monthly), the optimization framework (the MV vs the MSV) and allocation purchases in the irrigator model. For both the MV and the MSV models, optimal portfolios estimated using longer estimation windows tend to perform better in terms of realized returns. In other words, a larger amount of historical information used allows the models to better predict future returns to different products and therefore build better portfolios. This can also partially explain the significantly better performance of the weekly-rebalanced optimal portfolios over the monthly-rebalanced ones in terms of realized returns (Table 6). The monthly models are built on much fewer observations since there are only 12 monthly average prices but 52 weekly average prices for each water entitlement in a year. Another major reason for the higher returns to weekly portfolios is that they allow the holder to utilize the variations in market prices more frequently by adjusting the portfolios on a weekly basis. The positive relationship between the length of the estimation window and the model performance highlights the importance of transparency and accessibility of water trading data for water market participants to make better investment decisions. Currently, it is impossible to distinguish transactions of derivatives like entitlement leasing, forward contracts, options and carry-over parking from spot market transactions. Such limitations in data records will limit market participants' ability to make trading decisions that maximize their gains and contribute to the overall efficiency of the market. In addition, the lack of transparency in the publicly accessible trading data may lead to asymmetric information and advantage those market participants with better information (e.g. institutional participants and water brokers), leaving the market outcomes inequitable.

In the irrigator model, allocation purchases can affect model performance. Unlike the investor model where portfolio returns are independent of the portfolio's total value, allocation purchases in the irrigator model do not generate any return but only decrease the portfolio value. Theoretically, when alternative investment options other than water entitlements are considered, allocation purchases would be desired if they cost less than the opportunity cost of investing in water entitlements, such as forgone interests. In this study, the opportunity costs of holding entitlements are assumed to be zero since interest rates were close to zero during the last decade and no other investment options are considered. However, if the opportunity costs of holding entitlements are high, as seen with the high interest rates recently in late 2022 to 2023, it is important to consider this factor when deciding between investing in entitlements or purchasing allocation.

The weekly realized return of 0.0079 on average for the investor's MV model with a 3-year estimation window (Table 6) translates into an annualized return of 42.2%. When transaction costs are considered, the annualized return should be lower than estimated in this chapter, but it should still be significantly higher than the returns of single-type entitlement holding estimated by Wheeler (2016). For the corresponding irrigator model, monthly rebalanced portfolios had a realized return of 0.0158, which translates to an annualized return of 22%, on top of satisfying the minimum water use estimated based on historical use. The returns on water portfolios can outperform many financial products, given that the annualized return of S&P/ASX is only about 5% (MarketIndex, 2023). These results highlight the benefits of diversified portfolios in terms of generating desirable returns and encourage irrigators to manage their water portfolios more sophisticatedly to achieve better returns while satisfying irrigation needs.

4.8.2 Optimal portfolio weights under varying water availability

The composition of optimal portfolios, in terms of weights assigned to different products, varies with water availability. In both investor and irrigator models, HSEs and AEs tended to be more preferred during dry periods while LREs had a significant advantage during relatively wet periods. The portfolio weights placed on GSEs had a relatively stable trend across periods with different water availability but were slightly more preferred during wet periods. These results seem intuitive based on price changes that can be expected. For example, prices of HSEs should increase during dry periods, followed by higher returns. However, it is important to note that the MV and MSV models not only consider the returns on products, but also take into account the volatilities of the returns and the relative movements (covariances) between the returns of different types of entitlements in an attempt to minimize the portfolio volatility. It means that the preferred products, e.g. HSEs during dry periods, do not only have higher returns but also have lower risk associated with the returns. These results highlight the distinct roles that security-differentiated entitlements play in the market. Entitlements with a reliable supply of water, i.e. HSEs and AEs, perform better under poor water availability whereas entitlements with less reliable allocation, such as GSEs, or those with no allocation, i.e. LREs that typically serve as carry-over products tend to gain an advantage during relatively wet periods. Such trends hold true for both irrigator and investor models, despite differences in the specific weights assigned to various types of entitlements in the optimal portfolios. For example, LREs had higher weights during the first half of the study period in the irrigator model compared to the investor model, which is likely due to differences in data aggregation (i.e. weekly vs monthly).

It is notable that the irrigator model placed higher weights on AEs to meet minimum water constraints during dry periods (e.g. 2015-16, 2018-19) with low allocation made available to surface water entitlements, especially GSEs. Although HSEs, especially those from NSW received full allocations even during dry periods, they were much more expensive than AEs, making them less cost-effective in terms of generating water allocation, given the budget constraint of the irrigator portfolios. It is important to note that groundwater extractions and transfers are subject to constraints associated with local groundwater levels as mentioned earlier (Wheeler et al., 2021). The intervalley trading and delivery of surface water are also subject to various constraints (e.g. IVTs). Therefore, it is impractical for irrigators to hold (and use the water generated from) the optimal portfolios estimated in this study, which consist of 12 types of entitlements including both surface water and groundwater entitlements across different trading zones and states. There are also pumping costs associated with extracting groundwater that may render the costs of using AEs to meet irrigation demand higher than estimated in the models here. However, the main purpose of this study was not to build practical trading strategies for irrigators, but to understand the optimal behaviours of different water market participants given various water availability conditions. The results of the irrigator model point to the benefit of groundwater substitution in times of droughts, although various restrictions may limit such practices. As a more reliable water source, groundwater can play a crucial role in future climate scenarios with a projected higher level of variability in water supply as well as more frequent and intense droughts. Access to groundwater is vital for risk management in agricultural production. In addition, a better understanding of groundwater recharge pathways, and more effective regulations and monitoring of groundwater extractions will be of increasing importance to ensure the sustainable use of water resources.

4.9 Conclusion

Facing increasing water scarcity globally, the optimal strategy for irrigators to manage water supply and invest in water resources has become an important topic to investigate. Markowitz's Modern Portfolio Theory (MPT) has been widely employed in natural resource management to improve efficiency in allocating scarce resources among different uses. This study is the first to apply MPT in water rights (entitlements) holdings toward irrigation needs. This study has estimated dynamically rebalanced optimal portfolios consisting of a range of security-differentiated tradable water entitlements across different regions in the sMDB, Australia. Weekly and monthly rebalanced optimal portfolios are estimated separately for pure investors and irrigators based on whether they have water demand constraints. Both Mean-Variance (MV) and Mean-Semivariance (MSV) frameworks are employed in this study, with the latter one being often acknowledged to be superior to the MV model but has been rarely applied in the field of natural resource economics.

The optimal portfolios estimated in this study have demonstrated the benefit of holding a diversified water portfolio in terms of higher returns and lower risks compared to owning only a single type of entitlement. The results have also shown that weights assigned to security-differentiated entitlements vary with water availability conditions and exhibited heterogeneous trends. Overall, entitlements with reliable water supplies such as HSEs and AEs are preferred in the optimal portfolios during dry periods. In contrast, entitlements with less reliable allocations but are cheaper, such as GSEs or LREs which serve as carry-over products have higher weights in optimal portfolios during relatively wet periods. These results emphasize the diverse functions of different entitlements in the market and their capacity to satisfy varied demands for managing water as both a production input and an investment asset. In the face of a drier future climate with higher variability in water availability and intensified drought events in the MDB, it becomes increasingly important for water market participants, especially small irrigators, to diversify their water portfolio and employ more sophisticated management strategies to reduce risks associated with water supply and improve farm profitability.

Chapter 5 Conclusions

5.1 Summary of the thesis

This thesis is dedicated to understanding the impacts of climate change and water availability on the governance of irrigation water, the characteristics of water markets, and the behaviour of market participants, while seeking to shed light on the means to cope with the challenges. The thesis consists of three independent studies presented in Chapters 2 to 4, which explore these topics through various scopes and methods. Chapter 2 proposes a comprehensive framework to evaluate the preparedness of water governance to deal with unprecedented challenges imposed by climate change. Expert opinions were collected using online surveys to quantitatively evaluate water governance based on the proposed framework in six jurisdictions worldwide. Four case studies (i.e., the MDB in Australia, Spain, Italy, and Uruguay) combined quantitative evaluation results of water governance in the study regions with their characteristics and climate projections to provide targeted assessments of water governance and suggest policy implications for these jurisdictions. Chapter 3 provides an assessment of the functionality of the MDB water market by investigating a set of key market attributes, including prices, price volatility, frequency and volume of trading, and net imports. The study covers entitlement markets in five trading zones and allocation markets in eight trading zones in the sMDB over a fourteen-year period (from July 2007 to June 2021). This study is the first to investigate the MDB water market on such broad spatial and temporal scales. The study used fixed-effects models with trading-zone-specific time trends to control for both time-varying and time-invariant heterogeneities of the trading zones. Chapter 4 models the trading and investment behaviours of different types of water market participants under different water availability conditions, using a portfolio optimization approach. In the chapter I describe how I built dynamically-adjusting optimal portfolios for irrigators and non-land-holding investors based on Markowitz's Portfolio Theory. The optimization model differed from traditional portfolio optimization by allowing some participants, i.e. the irrigators to have a minimum water supply constraint in addition to the classical expected return/variance constraints. The study employed both the mean-variance (MV) models and the mean-semi-deviation (MSD) models, with the latter dedicated to controlling for downside risks that represent a major concern in agricultural productions.

5.2 Summary of key findings

Chapter 2 found that water governance in the surveyed jurisdictions have varying levels of preparedness to cope with climate change. Overall, water governance in the study regions have the highest level of preparedness in terms of economic efficiency and the lowest level of preparedness in terms of environmental sustainability. The current water governance in these regions are insufficiently prepared to cope with challenges brought by climate change, even though some of them (e.g. the MDB and California) are supposed to be the most advanced water governance systems with sound legal framework, supportive institutional settings and functioning market mechanisms. I found that water governance in traditionally water-stressed regions, such as the MDB, Spain, and California, are better equipped to deal with climate change than in traditionally water-abundant (or at least less-stressed) regions, such as Uruguay and Italy. The adoption of water markets was found to contribute to the ability of water governance to cope with climate change by improving the economic efficiency of irrigation water use and serving as a risk management tool for water supply. However, a seemingly negative relation was observed between the use of water markets and equity scores, indicating the potential misconception (even among experts) of viewing market-based instruments and equitable allocation outcomes as conflicting in nature. Misconceptions like this may become a critical obstacle for water governance to be fully equipped to cope with the unprecedented challenges brought by climate change.

Chapter 3 arrived at generally positive findings on the functionality of the water market in the MDB. Water availability was negatively associated with prices of entitlements and allocations, while the concentration of high-value crops (such as fruit/nut trees and cotton) in a catchment was positively associated with the price. Such results indicate that the price mechanism in MDB water market is functioning well in the sense that prices are highly responsive to the level of scarcity of water and reflect the value that can be derived from the use of the water. The price volatilities of HSEs and allocations were negatively correlated with trading volumes, indicating the importance of encouraging active water trading. This result sheds light on the potential contribution from participation of non-land-holding investors in terms of reducing price volatility and uncertainty in the water market. The study also found that security-differentiated entitlements play different roles in meeting the water demand of various crops. Horticulture was more reliant on the HSEs than lower-security entitlement and it was likely that HSEs have been increasingly transferred to, and held by perennial growers in response to increasing variability in water supply. The demand for the LREs in VIC that do not supply water but usually serve as carry-over 'parking' products showed an opposite pattern than the demand for HSEs that yield stable water allocation. These results indicate that irrigators in different industries in the MDB have been utilizing the range of products and services provided in meeting heterogeneous demands of water supply and for various purposes, including short-term water supplementation, long-term production planning, and risk management over multiple periods.

Chapter 4 showed that water rights can be managed sophisticatedly and generate returns that are comparable to financial assets. Diversification in water portfolios can assist irrigators in managing risks in water supply while obtaining capital gains from their holdings of entitlement that may contribute to the financial viability of the farm. Seidl et al., (2020) documented that irrigators in the MDB tend to rely on only a single type of entitlements in their region for water supply while larger agri-corporates and financial investors own diverse portfolios and utilize more sophisticated management strategies. Our findings should encourage irrigators to adopt more sophisticated strategies and offer guidance on developing approaches to diversify their water portfolios, while meeting certain water supply constraints. The optimization results in Chapter 4 showed that optimal weights of different entitlements vary under different climatic conditions. High-security and aquifer entitlements tend to be preferred under poor water availability conditions, while low-reliability entitlements are preferred under abundant water availability, as can be expected. Aquifer entitlements are strongly preferred by the MSD model for its stability in prices.

5.3 Key conclusions

Key conclusions that can be drawn from the findings of this thesis are summarized below:

- Water governance around the world is currently insufficiently prepared to cope with the challenges imposed by climate change. Environmental sustainability represents a major weakness in the ability of water governance to deal with climate change, while economic efficiency represents a relative strength.
- There is a particularly pressing need for transformational changes and improvements in water governance in historically less water-stressed areas as they are generally less

prepared for the challenges of intensified water scarcity and increased variability of water availability.

- The water market in the MDB is functioning reasonably well in terms of serving its fundamental purpose of directing water to its highest-valued uses. Price signals in the market reflect the level of water scarcity and the value that can be generated from water uses.
- A wide range of products available in the MDB water market serve heterogeneous demands of irrigators to supply and manage water on various time scales (e.g. short vs medium vs long term).
- The water market can make significant contributions to mitigating the negative impacts of climate change by improving economic efficiency in water use, providing irrigators with various risk management tools, and assisting in adjusting water demand over the long term.
- Besides economic efficiency, diverse goals such as environmental and equity goals can be incorporated into the design of the water market to facilitate the delivery of desirable water governance outcomes.
- Misconceptions exist about the water market that view market-based instruments and equitable water allocation as conflicting. These misconceptions may limit the water market's ability to serve as a powerful risk management tool for dealing with the high level of uncertainty in future climate and water availability scenarios.

5.4 Limitations and future research opportunities

There are several limitations in this thesis in terms of methodology and data. While they did not critically impact the findings of this thesis, there are benefits in addressing these limitations in future research. The limitations and potential extensions or improvements in the future are summarized below.

In Chapter 2, the experts scored the five attributes of water governance in the nominated regions directly. While detailed sub-measures for each attribute were provided, scoring and weighting of these sub-measures were not required or reported. This design was employed to maximize the response rate by minimizing the complexity and time requirement of completing the survey. Given our limited resources (e.g. only email communications were possible and no financial compensation was offered to the participants), the small population of scholars working on relevant topics (I identified only about 20 scholars per jurisdiction) and the final response rate of 42%, I consider the benefit of this approach justified. However, this approach raises several limitations. Firstly, although the instructions clearly stated scoring should be based on the supporting tables provided and the benchmark for the scoring should be considered as “an ideal or a textbook case preparedness”, it was impossible to assess how much time participants spent on reading through the supporting tables carefully and to what degree they based their scorings on the supporting tables. It was also difficult to guarantee a common understanding of the benchmark as scholars working with water governance in different jurisdictions/countries are likely to have different expectations of “a textbook case preparedness”. Secondly, because no scoring was made for sub-measures, it was difficult to disentangle the impacts of individual sub-measures on the final score of each attribute, which could have important policy implications. The discussions around the scoring results of the attributes would be more reliable and accurate if scoring and weighting of sub-measures are available. Nevertheless, many participants left optional comments in the survey to illustrate the rationale of their scorings, which assisted the discussions around the scoring results. It will be greatly beneficial to the understanding of the ability of water governance to deal with climate change if future research with more resources can allow for more detailed scoring using the same framework. Additionally, conducting surveys through workshops can provide detailed instructions and discussions, which can ensure a common benchmark in scoring.

In Chapter 3, the trading-zone-specific time trends captured the aggregate influence of all unobserved time-varying zone-specific characteristics, including the structure of water market participants (e.g. the proportions of financial investors, large agri-corporates and small farms), on the outcome variables. These zone-specific characteristics may have opposite impacts on the outcome variables and offset each other’s effect in the estimation of the coefficients of the zone-specific time trends, leaving it impossible to draw conclusions about the impacts of individual factors. It was within the research scope to test for the impacts of the structure of the water market participants on key market attributes, as it may have important implications of the functionality and the “fairness” of the market in response to the hot debates over the existence of market manipulation and distortion from financial investors. The data necessary to explicitly control for the structure of the market participants, however, were not available. The ACCC has gathered relevant information on the type of entitlement holders in the market, but it has not made this information publicly available. Our direct request to the ACCC to share the data was also not successful. Although the ACCC’s report (2020) stated that no sign of significant market distortion was found, it will be desirable and beneficial for future research to test for it formally and empirically in order to draw more credible conclusions on the functionality of the water market. The ACCC should make this data available to the public. In addition, the research period of this study did not cover periods of extreme droughts during 1996-2010 or periods of intense flooding during 2022-2023. As these extreme events are expected to be more frequent and intense, it is necessary for future research to test whether the water market can perform similarly well under such extreme climatic conditions.

In Chapter 4, a key limitation of the portfolio optimization approach is that transaction costs of rebalancing the portfolio were not considered. The major research interest was to understand the composition of optimal portfolios for different water market participants under various water availability conditions, instead of generating a practical trading strategy. Given the complexity in estimating the transaction costs associated with entitlement trading (including processing time) and its relatively minor importance in terms of answering the research question, the optimization models in Chapter 4 did not incorporate transaction costs. However, such an approach will lead to an over-estimation of the net portfolio returns. In addition, there are several possible extensions for this optimization framework, such as a management tool for irrigators to diversify their portfolios and manage water on farm more sophisticatedly. It is also possible to develop a management tool for environmental water based on the irrigator model, where the water constraint accounts for a minimum environmental demand for water. Additional risk constraints to control for the ecological cost of not delivering sufficient water quantity can also be incorporated. To develop these extensions it will be critical to incorporate transaction costs into the framework in order to build practical trading strategies that maximize the net return.

5.5 Policy Implications

5.5.1 The use of market-based instruments in achieving environmental goals

Chapter 2 has shown that environmental sustainability is the biggest weakness of water governance in the face of climate change based on the study of multiple jurisdictions around the globe. Although various instruments have been put in place to ensure the sustainable use of water, such as water pricing, their effectiveness remains limited. The pricing of irrigation water in many parts of the world today is too low to generate substantial impacts on water conservation and often does not explicitly take into account the environmental costs of water abstraction (Molle and Berkoff, 2007). In the face of increased variability in water supply and intensified extreme climatic events, especially droughts, it is critical for water pricing schemes to reflect not only the maintenance and operation costs of water services but also the resource costs[8] and environmental costs of water abstraction to guarantee sustainable use of water (i.e. to achieve full cost recovery) (Garrido and Calatrava, 2010). Environmental costs of water abstraction vary spatially and temporally and under different climatic conditions making it difficult, if not impossible, to incorporate them into water pricing schemes based on fixed prices. On the other hand, it is possible to incorporate the environmental costs of water abstraction into market mechanisms to reflect the dynamic nature of these costs through market prices. The water buyback program in the MDB, as discussed in Chapter 2, and the management of the acquired environmental water provide an example of incorporating environmental goals into the design of market-based instruments. While the acquisition of entitlements contributed to alleviating the over-allocation issue in the basin and reserved a significant proportion of water for the environment (Connor et al., 2013), the current management and delivery of environmental water are not likely to maximize the environmental benefit.

Firstly, the CEWHs have not been actively participating in the temporary allocation market or entitlement leasing market. By participating in the allocation and leasing market, the CEWHs can return water to agricultural production through allocation sale or leasing out entitlements when the environmental demand is low and the ecological benefit is outweighed by the irrigation benefit (e.g. after flooding events) and generate additional operating budgets that can be used to purchase allocation or lease in entitlement to supplement environmental flow when the ecological benefit is high (Connor et al., 2013; Wheeler et al., 2013). By doing so, the spot market prices of water will not only signal the scarcity level of water resources but also the environmental value of water varying under different climatic conditions. In addition, the utilization of different products in the market and portfolio management can further benefit the management of environmental water (Wheeler et al., 2013). The dynamically-adjusting optimal water portfolios built for irrigators in Chapter 4 demonstrated the benefit of diversified entitlement portfolios combined with allocation purchase in obtaining capital returns while

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[8] Resource cost of water abstraction is usually defined as the opportunity costs of a given use of water, i.e. the forgone economic value of water allocated to a given user (Garrido and Calatrava, 2010). In a water market, the resource cost of water is the market price of water netted of the costs associated with the abstraction and delivery (Garrido and Calatrava, 2010).

securing water supply from various sources. This conceptual framework can be adopted to reflect the environmental demand for water and ecological risks of not delivering, and build trading schemes for environmental water. Such schemes can maximize the ecological benefits and generate budgets for future operation while controlling for the risks involved in water availability.

Secondly, the basin-scale evaluation of environmental water delivery has mostly relied on hydrological indicators, such as baseflow and freshes[9], while the evaluation based on ecological responses is limited to fragmented site monitoring (Stewardson and Guarino, 2018). To design a water delivery scheme that maximizes the ecological benefits under varying climatic conditions, it is crucial to establish ecological indicators for basin-scale evaluation and link the ecological responses with the delivery of environmental water and climatic characteristics. While the water buyback program in the MDB sheds light on the potential of combining environmental goals into the design and operation of market-based instruments, which will demonstrate increasing importance in the face of climate change, there is currently a pressing need for more active management of the environmental water and better evaluation framework for its delivery.

5.5.2 The use of market-based instruments in achieving social and equity goals

Concerns over the equity impacts of water trading and water markets have long existed and have been hotly debated in the literature. However, these discussions have rarely been put into the context of climate change. Climate change not only exacerbates water scarcity but also challenges the management of water in an unprecedented way through increased uncertainty in future climatic conditions and intensified extreme climatic conditions that will stress-test the existing governance system. Therefore, the discussion of the social and equity impacts of water markets in the context of climate change should focus on mitigating uncertainty in future water availability and dealing with extreme weather conditions. In this sense, equitable outcomes of water governance should concern equal opportunities to cope with the increased level of uncertainty, possibly through access to risk management tools and information on climatic projections. As discussed in Chapter 2, irrigators in different industries have different levels of

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[9] Freshes are short-duration flow events, also known as flow pulses that submerge the lower parts of the channel (VEWH, 2023).

vulnerability to water supply shocks. Horticultural growers with relatively inelastic water demand and high capital investment can be a lot more vulnerable to climate change than annual crop growers, and they are also found to experience the highest level of psychological distress associated with financial difficulties and water shortage (Wheeler et al., 2018). Water markets can contribute to the equitable sharing of both water resources and uncertainties in their supply by enabling more vulnerable irrigators to access additional water supply through allocation purchases and supporting long-term production planning through entitlement purchases. Allocation and entitlement sales, on the other hand, can be used as means to improve the financial conditions of farms and to restructure the farms (Wheeler et al., 2014). Chapter 3 has demonstrated that water market participants are utilizing the wide range of products available in the MDB water market for various purposes and meeting heterogeneous irrigation demands. A well-defined entitlement framework that outlines how risks in water supply will be shared among water entitlement holders and the government also provides a base and a level of certainty for irrigators to plan for production (Loch et al., 2013). These benefits, however, do not suggest that water markets can work as a panacea for all water governance problems or should be established in all regions because the implementation of water markets should be based on a careful estimation of the potential gains from water trading, and its successful operation requires a range of conditions to be met (e.g., as summarised in Wheeler et al., 2021). Water policies and water markets also should not be made responsible for all distributional and equity issues, as they require other policies to be in place. However, it is important to recognize the potential of water markets to contribute to mitigating the negative impacts of climate change and to seek ways to improve their ability to deliver economically efficient, socially equitable, and environmentally sustainable outcomes.

Concerns over water markets, including 'appropriation through accumulation' and exploitation, have long existed (Grafton et al., 2016), and the implementation of water markets is often linked with socially inequitable outcomes (as also shown in Chapter 2). While examples of these negative impacts associated with the marketization and privatization of water can be found, there are studies arguing that these are not inherent outcomes of water markets but are often failures of the surrounding institutional and social settings (e.g. Grafton et al., 2016; Wheeler, 2022). Our results in Chapter 3 also substantiate the point that water markets can function well under appropriate institutional settings, and that key attributes in the market, such as prices, price volatilities and volumes, should reflect the market fundamentals. Simply ruling out the use of water markets based on misconceptions of water markets (as seems to be the case in Italy) without a careful estimation of the potential benefits and discussions around the enabling factors represents a net loss to society, especially in terms of its ability to deal with challenges imposed by climate change. Therefore, instead of ruling out the use of water markets, it is more beneficial to investigate ways to improve the functionality of water markets and reduce the chance of market abuse, e.g. through exercising market power and utilizing asymmetric information. This can be done through enhanced regulation and information transparency. For example, compulsory price reporting (which has already been implemented in the MDB), clearly distinguishing between spot market trades and derivatives (leasing, forward, option, etc.) in transaction records, and better public information on the type of entitlement holders and traders (e.g. land-holding vs non-land holding, individual vs institutional traders) are all important for ensuring equity in water market participation and creating a level playground for all participants.

5.6 Final remarks

Water scarcity is a significant issue for human society, particularly in the context of climate change, which presents unique challenges due to the high level of uncertainty involved. Traditional knowledge and experience may not provide adequate guidance for addressing the novel and complex issues that arise in the face of climate change. As the largest consumer of water worldwide, the agricultural sector is particularly vulnerable to the impact of water scarcity and increased uncertainty in future water availability. Therefore, the governance of irrigation water is of utmost importance. This thesis is devoted to exploring the challenges that irrigation water governance may face in the future and how market-based instruments can assist in mitigating those challenges, particularly in the face of high uncertainty surrounding future water availability. The thesis contributes to our understanding and knowledge of irrigation water governance, water markets, and individual behaviours in a context of varying climatic conditions, using a range of approaches and methods.

Overall, climate change has and will continue to impose unprecedented challenges to the governance of irrigation water, while the current water governance is insufficiently prepared to deal with these challenges. To better address the challenges, it is critical to employ adaptive management strategies that are resilient to uncertainties in future climatic conditions and to utilize innovative tools that facilitate the delivery of economically efficient, environmentally sustainable, and socially equitable outcomes. Water markets, as powerful reallocation and risk management tools can play a critical role in mitigating the negative impacts of climate change and contribute to the delivery of desirable outcomes. The thesis shows that water markets can function well under appropriate institutional and social settings. However, misconceptions of water markets are impeding their utilization in response to a drier and more variable climate in the future. Changes in perceptions of market-based instruments are needed and should be based on sound empirical evidence of the functionality and fairness of the water markets. Policy reforms and improvements in regulations are also necessary to further enhance the functionality of water markets as reallocation and risk management tools and ensure an equitable environment for all water market participants.

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Appendix A Supplementary materials for Chapter 2

A.1 Initial recruitment email to experts for evaluating water governance in study jurisdictions

Dear colleague,
Together with a PhD student, Maruge Zhao, we are developing a framework to evaluate how water governance systems, especially in relation to irrigation water use, are prepared to deal with challenges imposed by climate change. The framework is used to evaluate a water governance system based on five attributes we consider: economic efficiency, equity, environmental sustainability, adaptability and resilience.

We are writing to invite you, as a prominent expert in the field, to provide your expert opinion on the water governance system in your nominated jurisdiction on these five attributes by scoring each attribute on a 1-5 scale.

The link below takes you to the web-form on the University of Sydney platform. Filling the web-form should only take you about 5 minutes to complete.
Web-form link: https://sydney.au1.qualtrics.com/jfe/form/SV_6gx4TnzkkTayWvs
We highly appreciate your input into our study!

Please note that your response is completely voluntary. No personal information will be collected, and your response will be non-identifiable in our study.

Thank you very much for taking the time to provide us with your expert opinion!

Best regards,
Tiho Ancev

A2. A sample of the questionnaire developed using Qualtrics.com

Introduction and participant information

Water governance in a context of climate change

You are invited to participate in a research study that develops a framework to evaluate how well are irrigation water governance systems prepared to deal with challenges imposed by climate change. The study is being carried out by Associate Professor Tiho Ancev and PhD candidate Maruge Zhao at the School of Economics, the USYD. You are invited to participate in this study because you have published academic work on water governance related topics for jurisdictions nominated in our study, which include California, Australia, Chile, Italy, Spain and Uruguay. You will be asked to provide your expert opinion on the water governance system in your nominated jurisdiction by scoring five attributes. The questions will only take you about 5 minutes to complete. **Please click on the arrow at the bottom of the page to proceed to the questionnaire.**

The questionnaire is anonymous and will not collect any of your personal information. Your participation is completely voluntary. By submitting your responses, you consent to take part in the study. You can withdraw any time before you submit however once your responses are submitted, they cannot be withdrawn. Any information you provide will be stored securely. We are planning for the study findings to be published. The scoring results will be aggregated in our study to draw conclusions and you will not be individually identifiable in these publications. We do not expect that there will be any risks or costs associated with taking part in this study. You will not receive any direct benefits from being in the study. No individual feedback will be possible since the survey is anonymous, and any feedback of results will be general group responses. If you are interested in receiving feedback about the overall results of this study or if you require any further information, you can contact us at maruge.zhao@sydney.edu.au.

The ethical aspects of this study have been approved by the Human Research Ethics Committee (HREC) of The University of Sydney [2022/795] according to the National Statement on Ethical Conduct in Human Research (2007). If you are concerned about the way this study is being conducted or you wish to make a complaint to someone independent from the study, please contact the University: Human Ethics Manager human.ethics@sydney.edu.au +61 2 8627 8176.

Questions

Please provide your expert opinion on how well the water governance in your nominated jurisdiction is prepared to deal with challenges imposed by climate change using the five attributes as described below. Please select the jurisdiction where your expertise lies first and then rate each attribute on a **1- 5 scale**. For the purpose of reference, please consider the scaling relative to what you would regard as an ideal or textbook case preparedness. The scale is defined as follows:

1 represents that water governance is **poorly prepared** to deal with challenges imposed by climate change in terms of this attribute.

2 represents that water governance is **somewhat prepared** to deal with challenges imposed by climate change in terms of this attribute.

3 represents that water governance is **reasonably prepared** to deal with challenges imposed by climate change in terms of this attribute.

4 represents that water governance is **well prepared** to deal with challenges imposed by climate change in terms of this attribute.

5 represents that water governance is **strongly prepared** to deal with challenges imposed by climate change in terms of this attribute.

1. Please read the detailed definitions and key elements for each attribute [through this link](). It is important that you understand clearly the scope of this research and our description of the attributes so that you can provide your scores with this in mind.

Please choose the jurisdiction for which you are assessing the water governance: (We understand that there are differences in water governance across regions within the below jurisdictions, but please focus on the common patterns/overarching governance framework for irrigation in the jurisdiction. If you wish, you can indicate in the comment box to which specific subregion(s) within your jurisdiction your scores are most pertinent.)

○ The Murray-Darling Basin, Australia
○ California, the U.S.
○ Chile
○ Italy
○ Spain
○ Uruguay

2. Economic efficiency: assess [on a 1-5 scale] whether current water governance enables the society to use scarce water resources economically efficiently, to adequately manage risk, to support long-run adjustment in irrigation demand, especially in the face of reduced availability and increased uncertainty in irrigation water supply (please refer to the definitions and key elements for this attribute through this link).

○ 1 ○2 ○ 3 ○ 4 ○ 5

3. Equity: assess [on a 1-5 scale] the equity consequences of the current water governance in terms of the distribution of welfare related to water use, the sharing of losses related to unfavorable climatic conditions (e.g. droughts), developmental equity (e.g. job opportunities) and inclusiveness in the decision-making process (please refer to the definitions and key elements for this attribute through this link).

○ 1 ○2 ○ 3 ○ 4 ○ 5

4. Environmental sustainability: assess [on a 1-5 scale] the ability of the current water governance to avoid over-depletion and degradation of water as a natural resource and to avoid catastrophic ecological consequences, and the ability to sustain long-term environmental quality (please refer to the definitions and key elements for this attribute through this link).

○ 1 ○2 ○ 3 ○ 4 ○ 5

5. Adaptability and resilience: assess [on a 1-5 scale] the ability of the current water governance to operate under extreme situations and unforeseen circumstances and the ability to evolve and refine over time, incorporating and utilizing new climatic information, community experiences and shifts in governance paradigms (please refer to the definitions and key elements for this attribute through this link).

○ 1 ○2 ○ 3 ○ 4 ○ 5

6. Enforceability: assess [on a 1-5 scale] how well the current water governance policies and rules are enforced and continuously monitored (please refer to the definitions and key elements for this attribute through this link).

○ 1 ○2 ○ 3 ○ 4 ○ 5

7. Please leave any comments that will further illuminate your scoring (optional):

A.3 Supporting tables for evaluating water governance in the context of climate change

Table A.3. 1 Sub-measures, example questions and potential challenges for the economic efficiency attribute

	Measures	Example questions to consider	Potential challenges imposed by climate change
Economic Efficiency	Allocative efficiency and drought-related loss minimization	Is the level of water scarcity reflected in the cost of irrigation water? To what degree is water allocated to the most productive users? To what degree is the economic loss minimized for the society when water availability is reduced during droughts?	Climate change can result in both increased water scarcity and increased variation of water availability. Efficient use of water (i.e., optimal allocation of water) is especially important to maximize net benefit from water use or minimize loss during droughts.
	Water resource reallocation	How does the current governance system reallocate water in times of shortage? What is the cost of reallocation (including the transaction cost and cost in the decision-making process)?	Increased variation in water availability may require scarce water resources to be frequently reallocated. Climate change therefore may exacerbate the economic inefficiency resulting from the inflexibility or high transaction cost of water reallocation.
	Risk management	Are there instruments or policies in place to help irrigators to manage risk in water supply and thus minimize the expected loss in case of droughts over multiple periods?	Increased variation in water availability implies increased uncertainty in water supply and agricultural production. Instruments in place that can serve as tools for irrigators to manage such risk could improve overall economic efficiency by minimizing expected loss in agricultural production.
	Economic incentive and demand adjustment	Is water managed volumetrically? Is water delivered on irrigators' demand (request) or based on pre-arranged quotas/rotation? Does the current water governance system allow and provide economic incentives for irrigators to adjust water demand in both the short and the long run?	Climate change can result in both temporary and permanent shifts in water regimes. If the system lacks the ability to facilitate long-term adjustment in irrigation demand (e.g. change in long-term production plan or crop pattern; entering or existing irrigated agriculture), it may become increasingly difficult to cope with the changing water availability and exacerbate economic inefficiency in irrigation water use over time.

Table A.3. 2 Sub-measures, example questions and potential challenges for the equity attribute

	Measures	Example questions to consider	Potential challenges imposed by climate change
Equity	Inclusiveness in decision making	Are different interest groups included and well-represented in the decision-making process, especially regarding the allocation of water resources? Are the decisions made exclusively by the authorities, or the market or they are collective choices?	Increased competition for water and uncertainty in the water regime can lead to increased complexity in understanding the impacts of water regulations on different interest groups. Inclusiveness in the decision-making process may be the key to socially equitable outcomes in the context of climate change.
	Allocation of water resource	How are the water resources initially allocated? Who eventually uses the irrigation water? Are these allocations equitable?	Reduced water availability or altered stream flows may intensify conflicts in water use and water use priorities, such as conflicts between upstream vs downstream water uses.
	Regional development and employment opportunity	Are there any changes in regional economic development and employment opportunities as a result of water reallocation or as a result of changes in water regime and climatic conditions for irrigated agriculture due to climate change? Are regions experiencing negative impacts being compensated?	Projected changes in climate could potentially make some areas unsuitable for agricultural production and result in a loss of employment opportunities. Water reallocation may also (on top of the climate impacts) result in a loss of job opportunities in irrigated agriculture and issues like stranded assets.
	Sharing of losses and uncertainty (distributional equity)	Who bears the losses when there is water scarcity and loss in agricultural production becomes inevitable? Is the loss compensated? Who bears the uncertainty in the irrigation water supply?	Communities may increasingly frequently confront inevitable loss in agricultural production due to changes in future climate (e.g. reduction in water availability, increased variability in water availability and increased drought spells). The share of loss and the burden of uncertainty will play an important role in achieving economic equity.

Table A.3. 3 Sub-measures, example questions and potential challenges for the environmental sustainability attribute

	Measures	Example questions to consider	Potential challenges imposed by climate change
Environmental Sustainability	Water Quality	Non-point pollution from agriculture	Increased temperature and intensified rainfall may aggravate the negative impacts of pollution from agricultural production.
	Groundwater sustainability	Is groundwater regulated and monitored? Is there a cap on the total amount of groundwater that can be extracted to guarantee sustainable use of groundwater?	Reduced availability and increased variability of availability for surface water may lead to increases in demand for groundwater as a reliable water source. The sustainability of groundwater is therefore vital for coping with climate change.
	Environmental flows & ecological health	Are there effective instruments or policies in place to guarantee minimum environmental flow during droughts? How is the "minimum flow" decided?	Reduced availability and increased variability of availability for surface water may increase the vulnerability of riparian ecosystems. It may become more difficult to guarantee minimum environmental flow as the competition between irrigation use and environmental use of water gets escalated.
	Basin and catchment level water planning	Is there basin-level planning in place based on a scientific understanding of the local hydrology?	Intensified water scarcity may increase conflict between agricultural and environmental uses. Basin-level planning is needed to support long-term sustainable water use.

Table A.3. 4 Sub-measures, example questions and potential challenges for the adaptability and resilience attribute

	Measures	Example questions to consider	Potential challenges imposed by climate change
Adaptability and resilience	Learning process	Are there mechanisms and platforms to facilitate collective learning, knowledge exchange and innovative approaches for the implementation of governance functions (e.g. capacity development mechanisms that promote public awareness raising and support the community or stakeholder networks)?	Continuously changing water regimes (both spatially and temporally) imposes higher requirements for the ability of the water governance system to self-organize in a situation of uncertainty, to learn from past experiences and to adapt to new situations.
	Multi-level water governance	What is the structural feature of the governance system (e.g. centralized vs decentralized, hierarchical vs polycentric or market-based)? Is there a set of overarching rules in place? Is there effective coordination between power centres?	Polycentric governance features multiple decision-making coordinate effective under a set of accepted rules and self-organised networks in water governance. Natural resource and environmental governance literature, especially the ones focusing on the adaptive capacity of water governance have found that polycentricity can make an important contribution to the ability of governments to adapt to the unprecedented situation and manage uncertainties under the influence of climate change.
	Conflict resolution mechanism	Are there effective mechanisms in place to resolve conflicts among water users or between water management agencies and users?	Under increased water scarcity and unpredictability of water supply, potential conflicts related to irrigation water use may increase. Unresolved conflicts may hinder the implementation of water policies or harm the interest of water users, potentially resulting in negative social consequences.
	Financial sustainability	Can the costs involved in the maintenance and operation of the water management infrastructure be recovered, e.g. through water pricing?	Water management is likely to be more resilient if the system is financially self-sustained (i.e. does not depend heavily on external/government funding)

Table A.3. 5 Sub-measures, example questions and potential challenges for the enforceability attribute

	Measures	Description	Potential challenges imposed by climate change
Enforceability	Enforcement and monitoring	To what degree are water policies and regulations enforced and monitored?	Reduced water availability and escalated competition in water use among users may make it increasingly important and challenging to enforce and monitor existing water regulations.
	Compliance and sanction	Are irrigators compliant with the rules? Are the sanctions for non-compliance high?	Inclusiveness in the initial decision-making process is important for compliance (e.g. collective choices are likely to have better compliance than top-down commands). Effective sanctions also need to be in place to discourage non-compliance. In the face of increased complexity in water management and increased uncertainty in the water regime, it will become increasingly important to consider the design of sanctions and the decision-making process involved to encourage better compliance.

Appendix B Supplementary Materials for Chapter 3

B.1 T-test of security-differentiated entitlement prices

In this Appendix, a t-test is provided for the price difference between HSEs and lower-security entitlements in the two states studied. To the best of my knowledge, no study has statistically compared the price difference between security-differentiated entitlements in the sMDB. Table B.1.1 below reports t-test results, which suggest that HSEs have significantly higher prices than lower-security entitlements in the same jurisdiction.

Table B.1. 1 T-tests for the difference in VWAP between the HSEs and the lower-security entitlements in the studied states. *Ho:* there is no significant price difference. *Ha:* The VWAPs of HSEs are significantly higher than that of the lower-security entitlements.

	Entitlement	VWAP	Number of Observation	Std.Err	p value
NSW	HSE	3722.34	99	211.27	0.00
	GSE	1374	112	38.16	
VIC	HSE	2792.46	168	87.12	0.00
	LRE	313.57	167	12.78	

B.2 Arellano-Bond model as a robustness check

We present an alternative model using the Arellano-Bond estimator to assess the possible omitted variable bias associated with the exclusion of lagged dependent variable and as a robustness check of the FE models. The inclusion of both fixed-effect terms and lagged dependent variable in the same model may give raise to endogeneity problem, resulting in estimation bias known as the Nickell's bias (Nickell, 1981). The Arellano-Bond (1991) estimator, one of the commonly used GMM estimators, is often employed to solve such endogeneity issue. The Arellano-Bond (1991) estimator utilizes the orthogonality conditions between lagged dependent variables and the disturbance term, producing consistent and efficient estimation for dynamic panel data. There are however, two major shortcomings in the use of the Arellano-Bond estimator: 1). this GMM estimator eliminates all fixed-effect and zone-time interaction terms that we are interested in by first differencing the equation; 2). the inclusion of lagged dependent variable takes over a large part of the explanatory power given the autoregressive nature of prices, while the lagged dependent variable does not provide helpful information in terms of the drivers of the prices. Therefore, we believe that the FE model provides better insight into the fundamental drivers of water prices, but we present this alternative model to test if the inclusion of lagged dependent variable will change our main conclusions. The following model is estimated using the Arellano-Bond estimator:

$$VWAP_{it} = \rho_0 + \rho_1 VWAP_{i,t-1} + \rho_2 Rainfall_{it} + \rho_3 Rainfall_{it-1} + \rho_4 Allo_{it} + \rho_5 Fruit\_nut_{it} + \rho_6 Cotton_{it} + \tau t + u_{it} \quad \text{[B.2.1]}$$

All the variables are defined similarly as in Eq. [3.1]. Without the fixed-effect and zone-time interaction terms, we now include a constant term ρ_0 and a single time trend t in the model. Note that with the lagged dependent variable $VWAP_{i,t-1}$ in Eq.[B.2.1], the coefficients now estimate the short-run impacts of corresponding explanatory variables on the dependent variable instead of the long-run impacts as estimated in Eq.[3.1]. The long-run impact of one variable in this case can be recovered by dividing its estimated coefficient by one minus the estimated coefficient of the autoregressive term. For example, the long-run impact of $Allo_{it}$ is $\frac{\rho_2}{1-\rho_1}$.

Arellano-Bond model estimation results

Table B.2.1 shows estimation result for the Arellano-Bond model on entitlement prices by reliability level. There is a positive and significant correlation between the lagged prices and current prices in all three models, as expected. The significance of allocation percentage and the percentage of water applied to fruit and nut trees are in general weaker in the Arellano-Bond models compared to the FE models. The percentage of water applied to fruit and nut trees becomes insignificant for GSEs and LREs in the AB model. The allocation level is negatively correlated with entitlement prices in the HSE and GRE models, but with a slightly weaker significance in the former ($p<0.05$). The in-general weaker significance of explanatory variables in the Arellano-Bond model compared to the FE model is to be expected since the high correlation between the dependent variable and lagged dependent variable has taken over most of the explanatory power (one of the shortcomings in the use of Arellano-Bond estimator as discussed). The results of the Arellano-Bond model confirm that the inclusion of lagged dependent variable does not change our major conclusions, albeit the weaker statistical significance.

Table B.2. 1 Arellano-Bond estimation results on entitlement VWAP by reliability level

	High Security	General Security	Low Reliability
Lagged VWAP	0.90***	0.74***	0.86***
	(34.67)	(11.81)	-12.71
Rainfall	-0.62	-0.35	-0.03
	(-1.47)	(-1.12)	(-0.28)
Lagged Rainfall	-0.47	0.12	-0.11
	(-1.12)	(0.36)	(-1.08)
Allocation	-337.38**	-128.60**	
	(-2.87)	(-2.08)	
Fruit&Nut Water Applied pct	1346.78**	831.65	70.2
	(2.40)	(1.24)	-0.55
Cotton Water Applied pct	1539.20	324.82	
	(1.53)	(1.29)	
Qrt	10.60***	1.94	1.51**
	(3.93)	(1.20)	-2.69
Constant	-1752.96***	-50.73	-268.63**
	(-3.54)	(-0.17)	(-2.38)
Observations	246	108	161

t statistics in parentheses

* p<0.1 ** p<0.05 *** p<0.001

Table B.2.2 presents the results of the model using the Arellano-Bond estimator for allocation prices. The estimation results are similar to the FE model that allocation prices are negatively associated with rainfall and positively with water applied to fruit & nut trees ($p<0.05$) and cotton ($p<0.1$). These results again confirm the robustness of the FE models we focus on.

Table B.2. 2 Arellano-Bond estimation results on allocation VWAP

	Allocation VWAP	t-statistics
L.VWAP	0.70***	(26.14)
Rainfall	-0.22**	(-2.57)
Lagged Rainfall	-0.60***	(-6.80)
Fruit&Nut Trees Water Applied pct	299.90**	(2.18)
Cotton Water Applied pct	328.37*	(1.80)
Qrt	-0.06	(-0.17)
Constant	128.00	(1.62)
Observations	429	

* $p<0.1$ ** $p<0.05$ *** $p<0.001$

B.3 Net import model for the allocation market

I present an additional model for the net import of allocation in a trading zone. Figure B.3.1 below shows the net import of water allocation by trading zone. We are interested in the direction in which water allocations flow, and the factors behind these movements. Crop type could potentially be a factor influencing the net import of different trading zones. Trading zones with more crops that are relatively flexible in water demand, such as broadacre crops or pastures, are more likely to become net exporters of water allocations, especially during dry periods. Trading zones with more horticultural crops and other permanent crops are more likely to become net importers of allocation because irrigators in these regions need to meet minimum water demand to keep the valuable permanent crops alive.

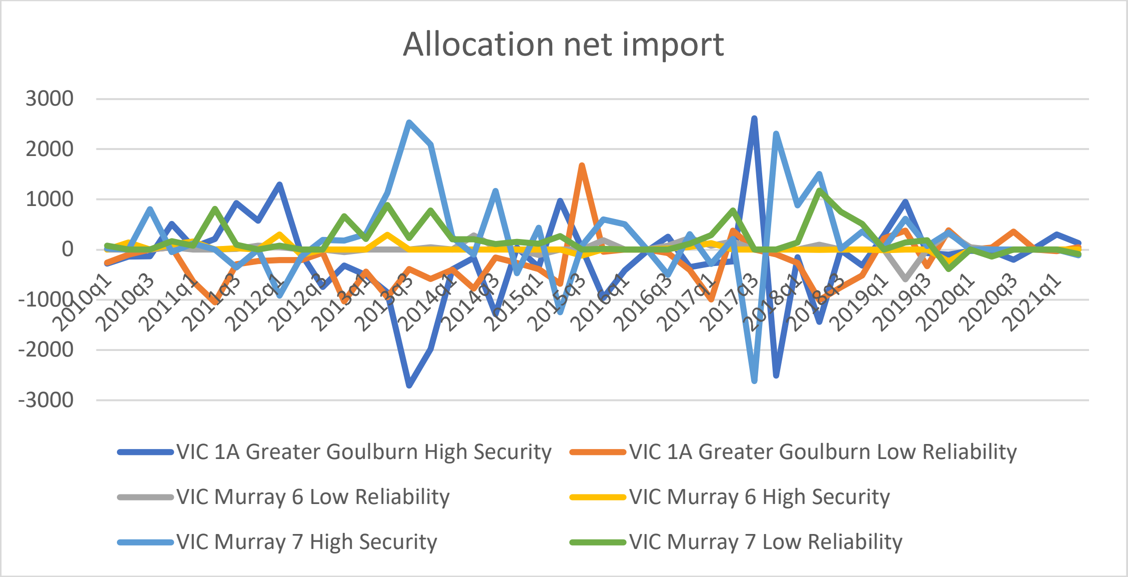

Figure B.3. 1 Quarterly net import of allocation in major sMDB trading zones

Net import model

$$Net\_import_{it} = \beta_0 + \beta_1 Rainfall_{it} + \beta_2 Rainfall_{it-1} + \beta_3 Fruit\_nut_{it} + \beta_4 Cotton_{it} + \beta_5 VWAP_{it} + \beta_6 Quarter_t + \delta t + \sum_{i=2}^{n} \alpha_i D_i + \sum_{i=2}^{n} \gamma_i D_i t + u_{it} \qquad [B.3.1]$$

Eq. [B.3.1] defines the econometric model for net import. The dependent variable Net_import_{it} represents the net volume of water imported (import volume net export volume) into the i^{th} trading zone during the t^{th} quarter. The other variables are defined similarly as in the above models. We expect that trading zones with higher allocation prices and higher proportion of water devoted to high value crops (cotton and fruit & nut trees) to import more allocation from other zones.

Estimation results

The estimated model fits poorly, and it is difficult to see any patterns for the volume of net import (Table B.3.1). It is possible that net import is more heavily influenced by trading restrictions between zones rather than these included factors in the model.

Table B.3. 1 Fixed-effects estimation results on allocation net import

	Allocation Net Import	t-statistics
VWAP	-4.58	(-0.43)
Murray General Allo	2811.36	(0.67)
Fruit&Nut Trees Water Applied pct	54819.53	(1.40)
Cotton Water Applied pct	44557.14	(0.85)
Quarter Dummy=2	-776.12	(-0.29)
Quarter Dummy=3	-1070.65	(-0.40)
Quarter Dummy=4	-1865.06	(-0.88)
NSW 13 Murrumbidgee	39277.95	(0.43)
NSW Murray	20551.89	(0.22)
VIC 1B Boort	-48265.21	(-1.11)
VIC 3 Lower Goulburn	-54632.36	(-1.37)
VIC 6B Lower Broken Creek	-51068.38	(-1.26)
VIC Murray 6	-41107.69	(-0.74)
VIC Murray 7	-36829.08	(-0.41)
Qrt	-126.72	(-0.58)
NSW 13 Murrumbidgee # Qrt	-248.07	(-0.55)
NSW Murray # Qrt	-107.63	(-0.25)
VIC 1B Boort # Qrt	217.24	(1.08)
VIC 3 Lower Goulburn # Qrt	223.83	(1.20)
VIC 6B Lower Broken Creek # Qrt	222.96	(1.18)
VIC Murray 6 # Qrt	173.29	(0.68)
VIC Murray 7 # Qrt	156.52	(0.37)
Constant	26727.94	(0.55)
Observations	319	
R-squared	0.134	

* $p<0.1$ ** $p<0.05$ *** $p<0.001$

Appendix C Supplementary materials for Chapter 4

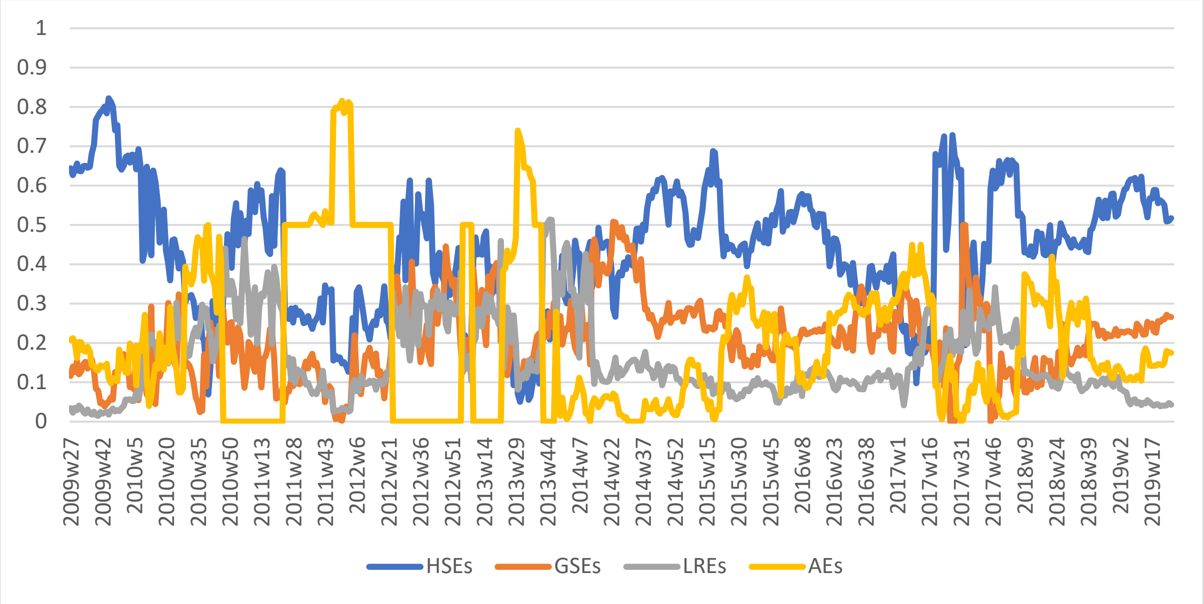

Figure C. 1 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Variance** optimization framework and **1-year** estimation window.

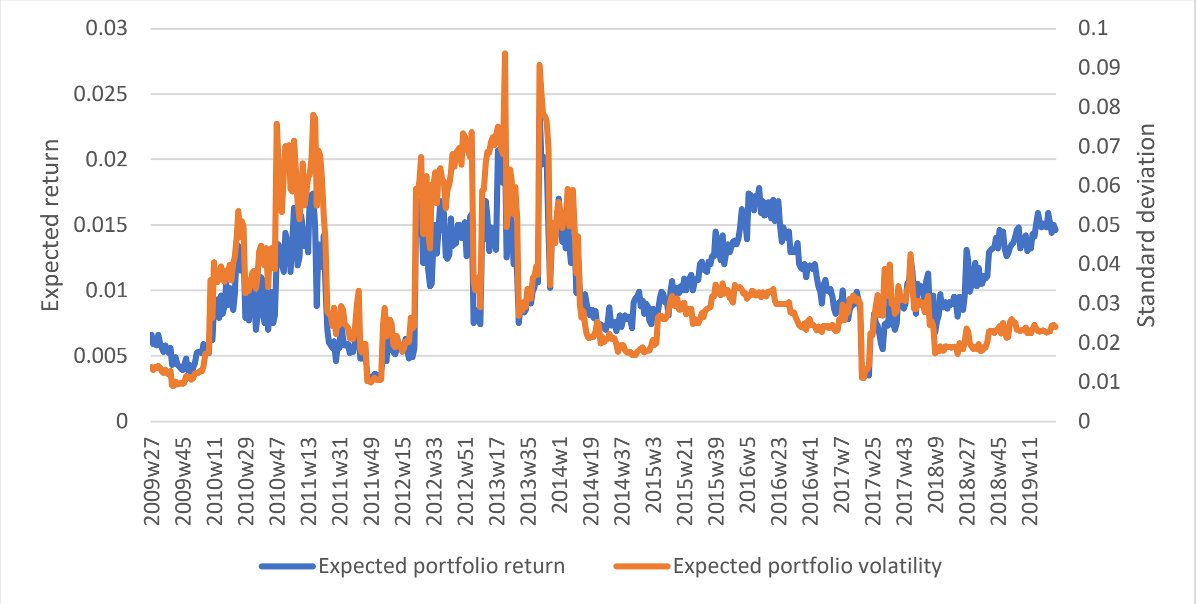

Figure C. 2 Expected return and expected volatility of the weekly-rebalanced optimal portfolios in the **investor model**, estimated with the **Mean-Variance** optimization framework and **1-year** estimation window. Expected portfolio volatility is measured in the standard deviations of the expected portfolio returns.

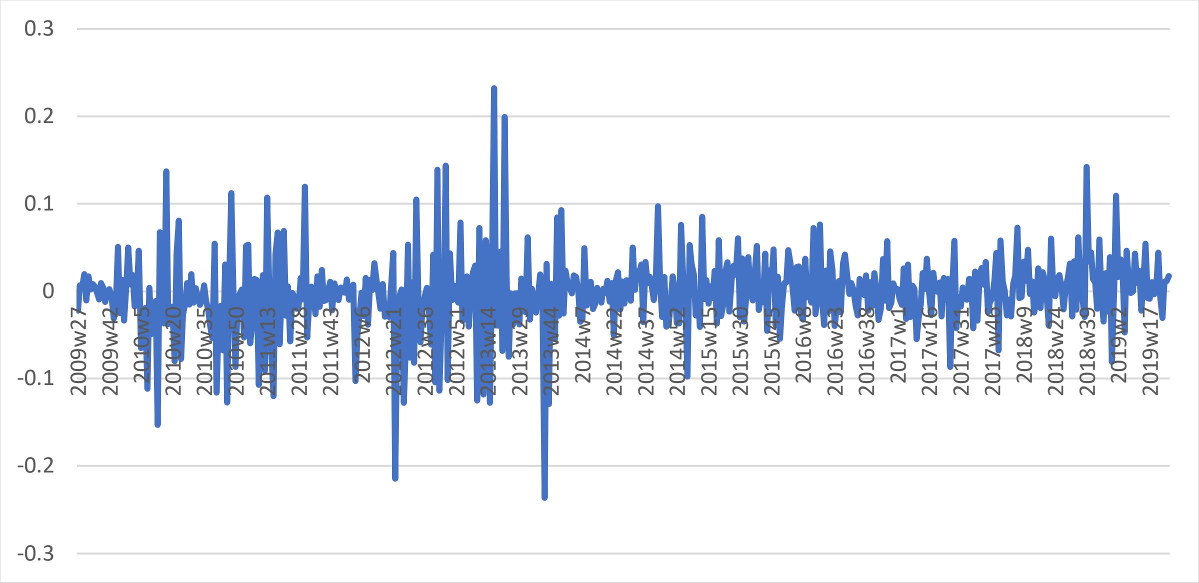

Figure C. 3 Realized returns of the weekly-rebalanced optimal portfolios in the investor model, estimated with **Mean-Variance** optimization framework and **1-year** estimation window.

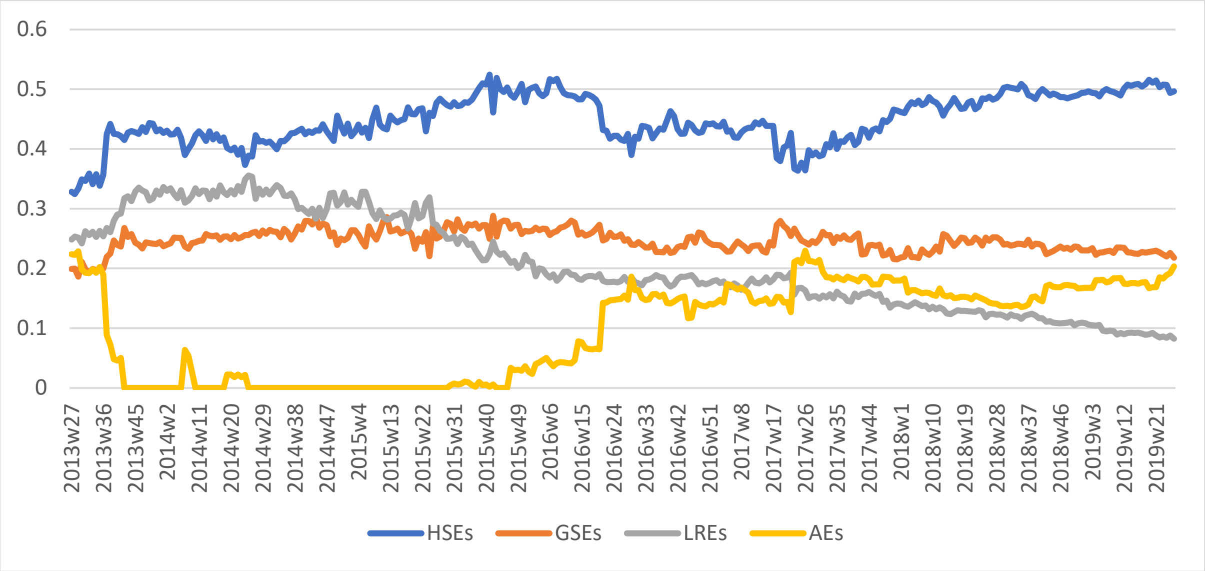

Figure C. 4 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window.

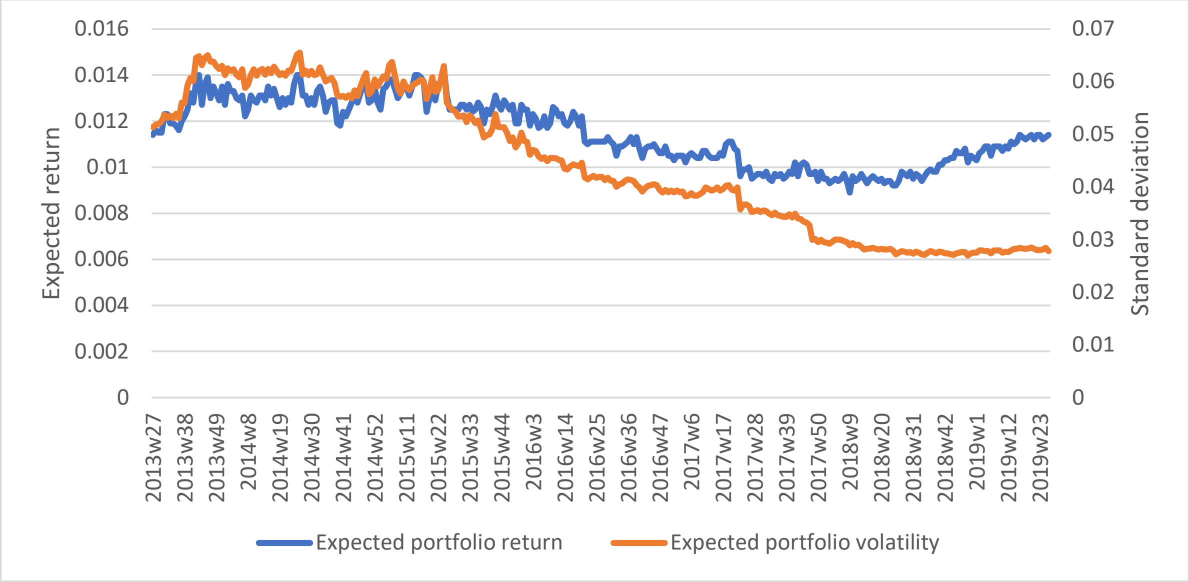

Figure C. 5 Expected return and expected volatility of the weekly-rebalanced optimal portfolios in the **investor model**, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window. Expected portfolio volatility is measured in the standard deviations of the expected portfolio returns.

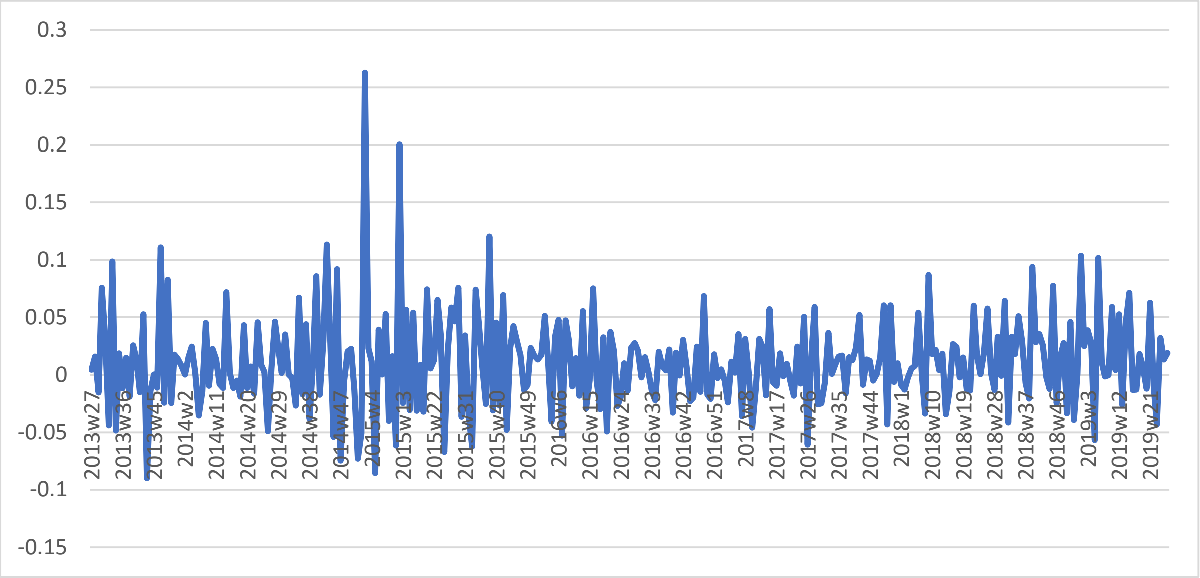

Figure C. 6 Realized returns of the weekly-rebalanced optimal portfolios in the investor model, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window.

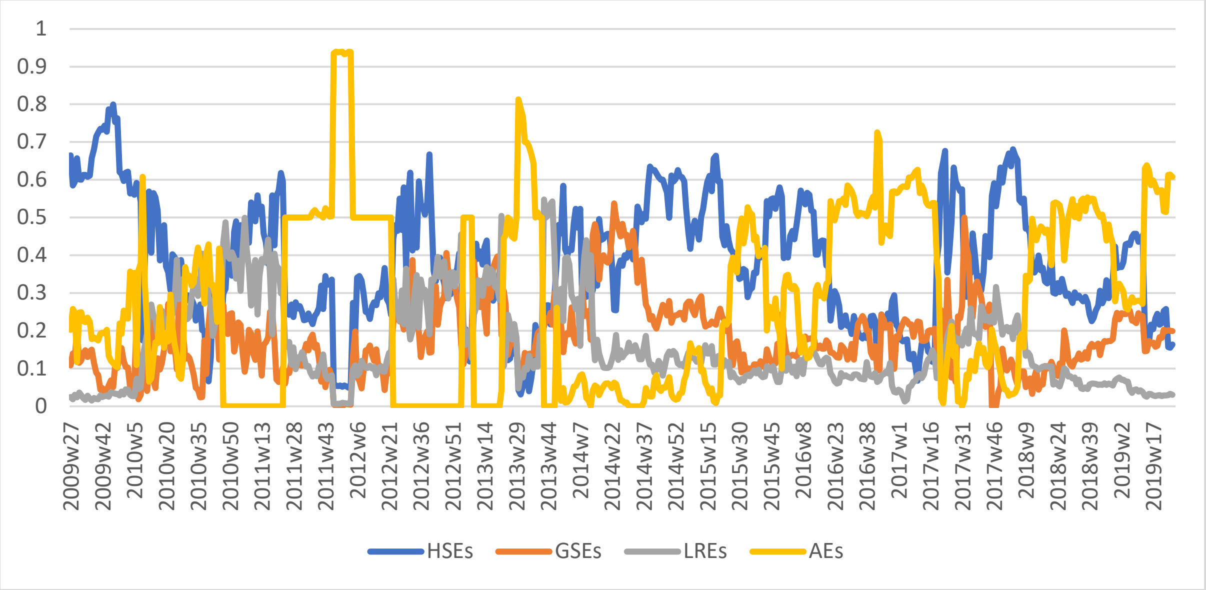

Figure C. 7 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Semivariance** optimization framework and **1-year** estimation window.

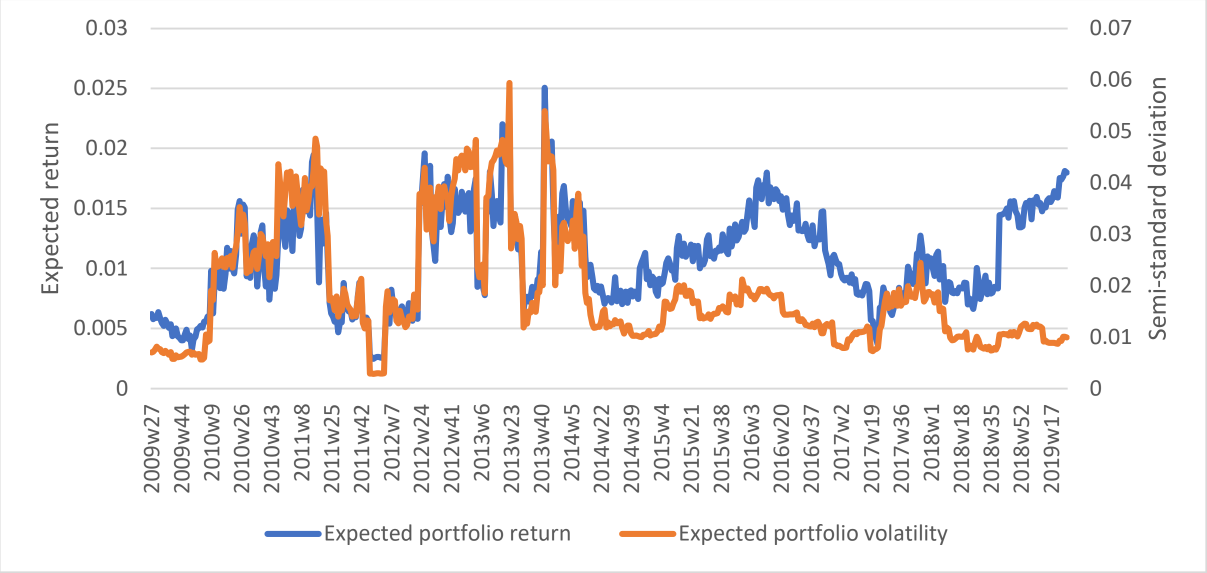

Figure C. 8 Expected return and expected volatility of the weekly-rebalanced optimal portfolios in the **investor model**, estimated with the **Mean-Semivariance** optimization framework and **1-year** estimation window. Expected portfolio volatility is measured in the semi-standard deviations of the expected portfolio returns.

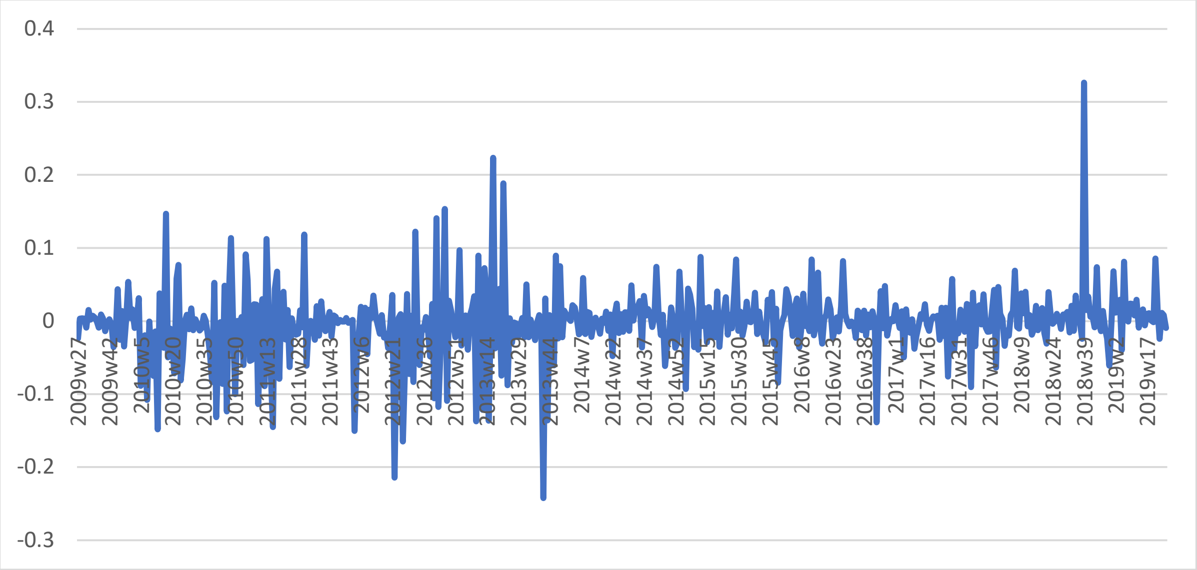

Figure C. 9 Realized returns of the weekly-rebalanced optimal portfolios in the investor model, estimated with the **Mean-Semivariance** optimization framework and **1-year** estimation window.

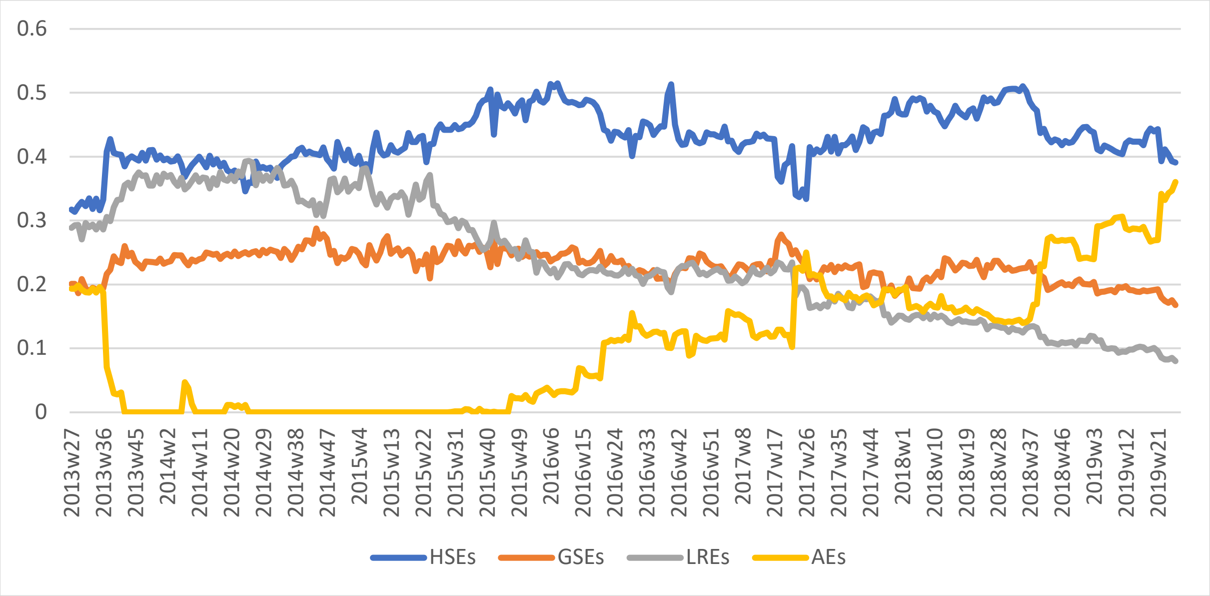

Figure C. 10 Optimal weights of entitlements by security levels in the weekly-rebalanced portfolios for the **investor model**, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window.

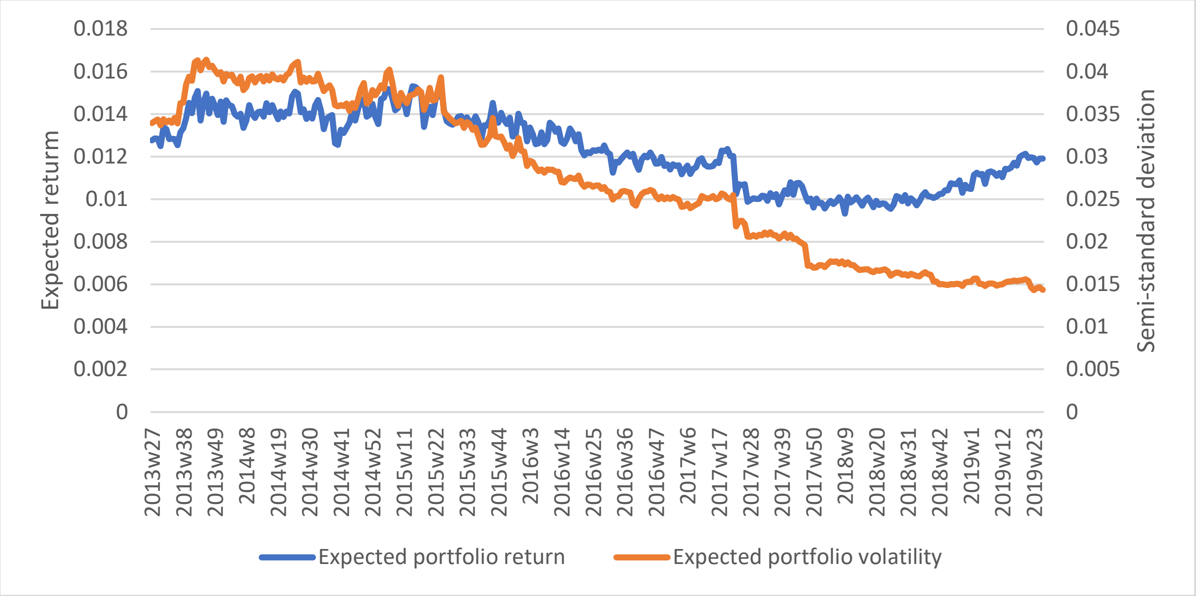

Figure C. 11 Expected return and expected volatility of the weekly-rebalanced optimal portfolios in the **investor model**, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window. Expected portfolio volatility is measured in the semi-standard deviations of the expected portfolio returns.

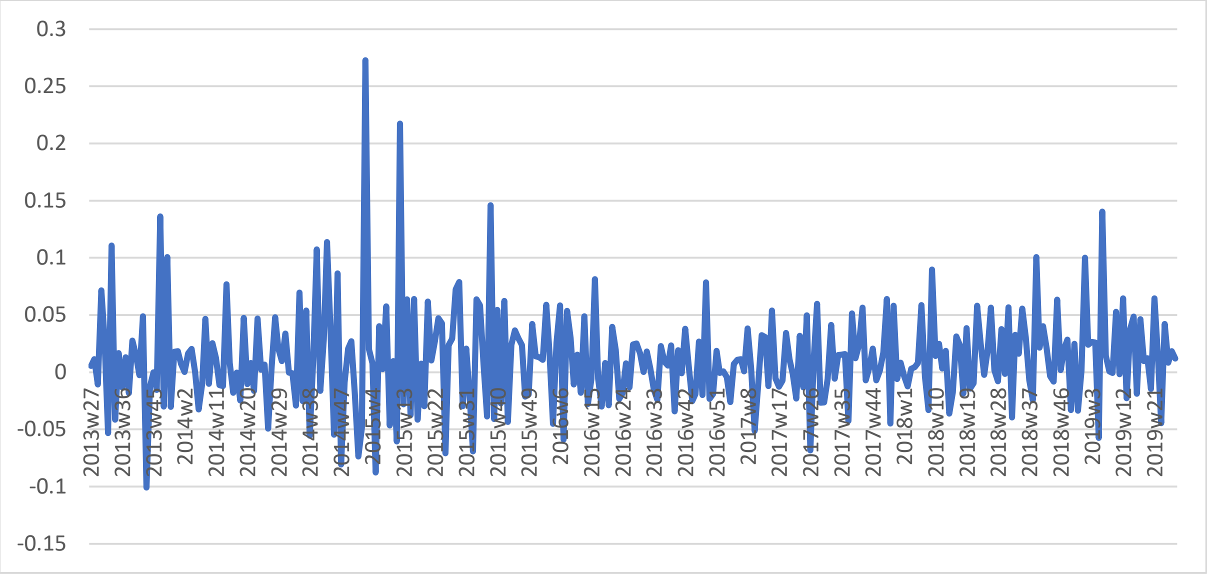

Figure C. 12 Realized returns of the weekly-rebalanced optimal portfolios in the investor model, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window.

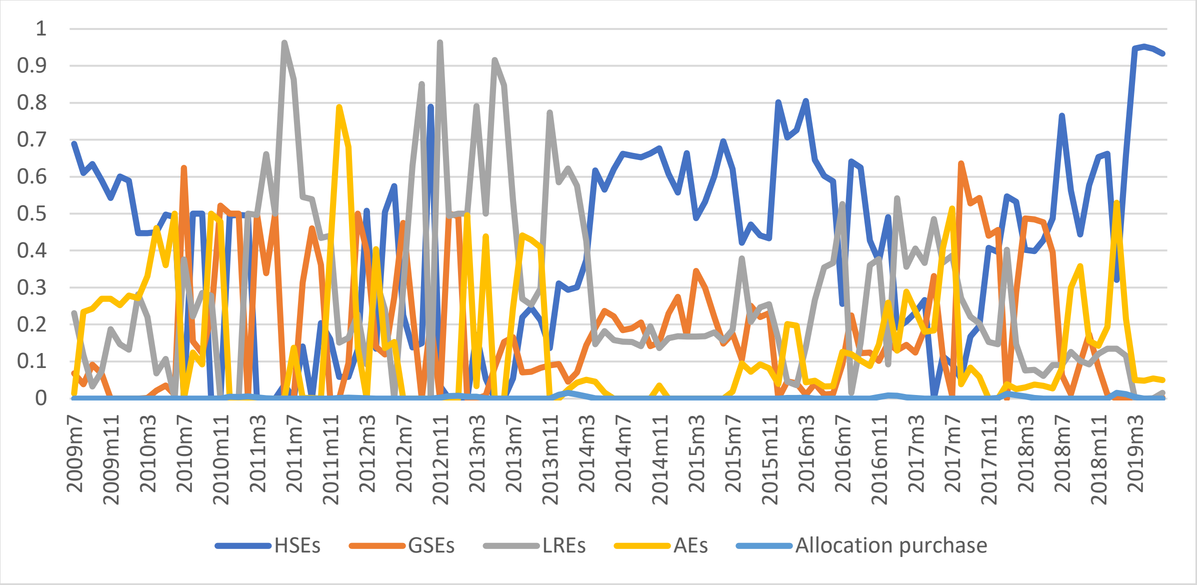

Figure C. 13 Optimal weights of entitlements by security levels in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **1-year** estimation window.

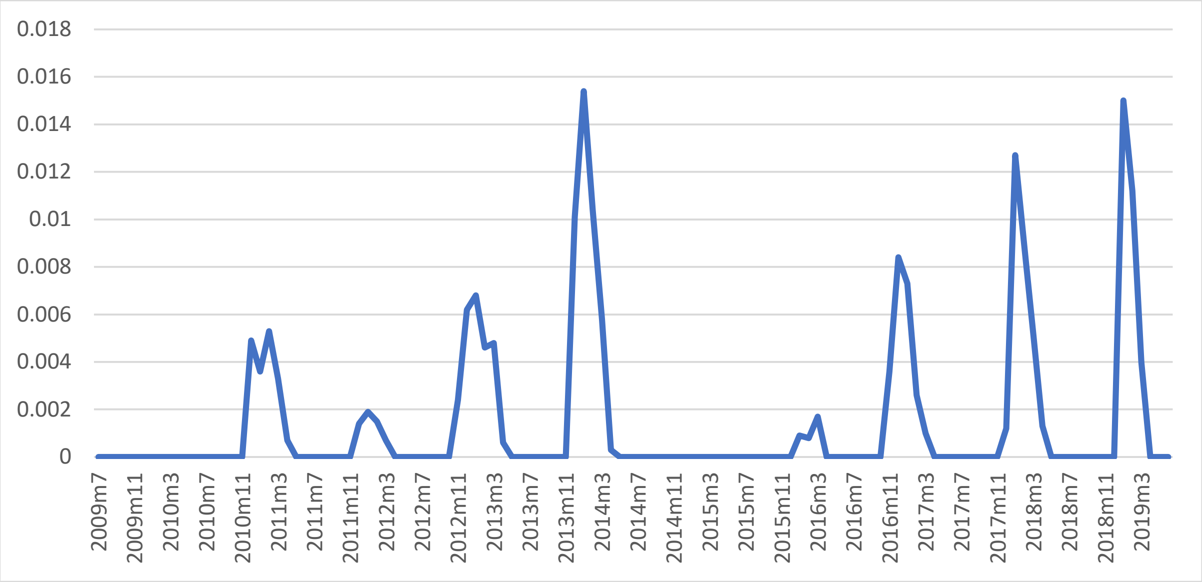

Figure C. 14 Optimal weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and the **1-year** estimation window.

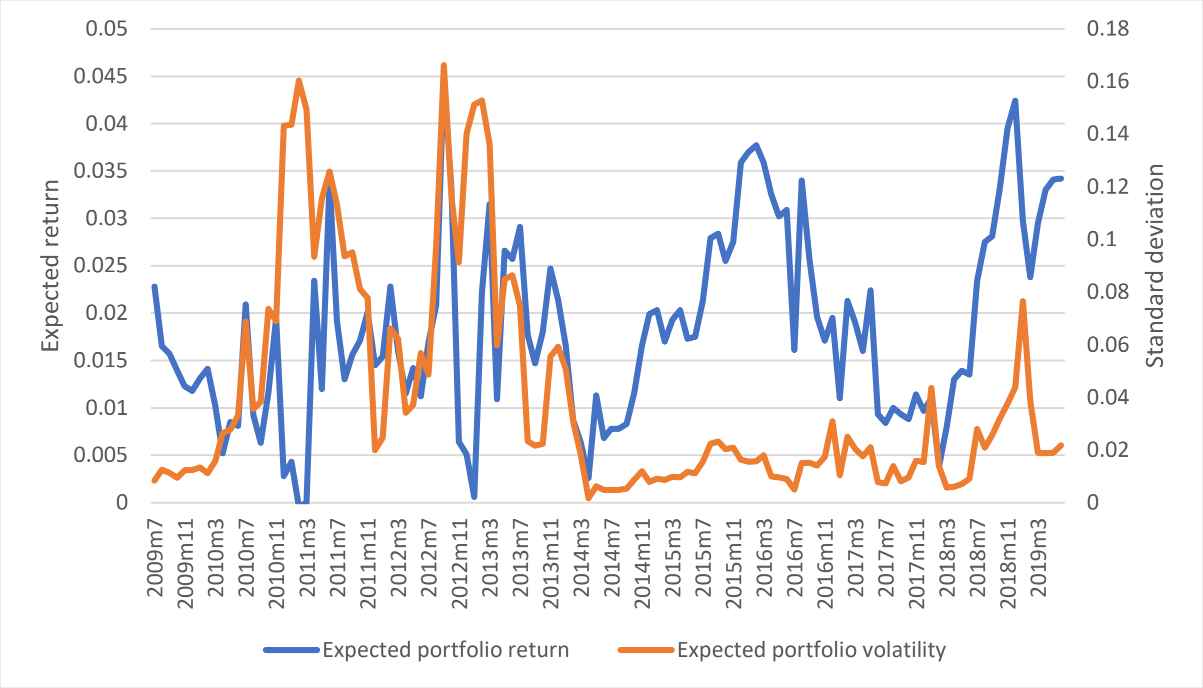

Figure C. 15 Expected return and expected volatility of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **1-year** estimation window. Expected portfolio volatility is measured in the standard deviations of the expected portfolio returns.

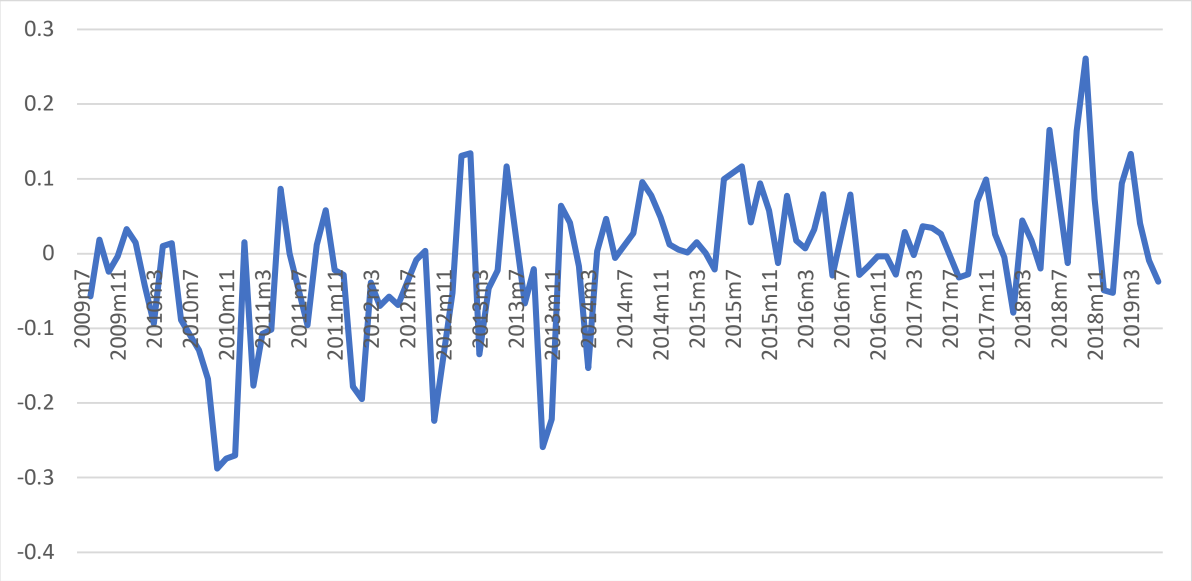

Figure C. 16 Realized returns of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **1-year** estimation window.

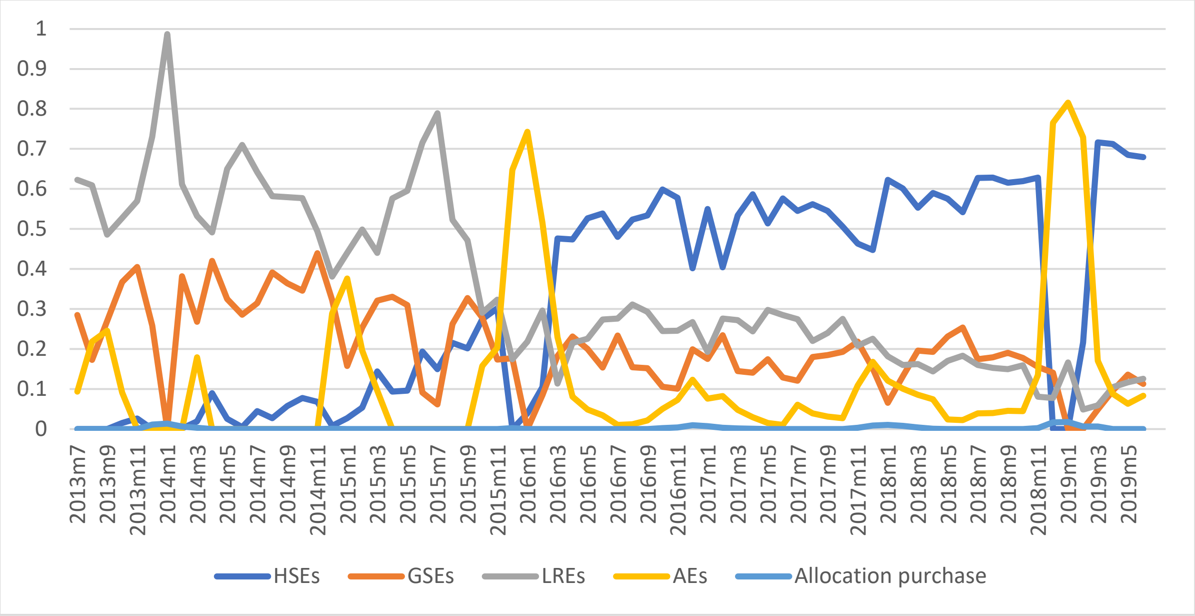

Figure C. 17 Optimal weights of entitlements by security levels in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window.

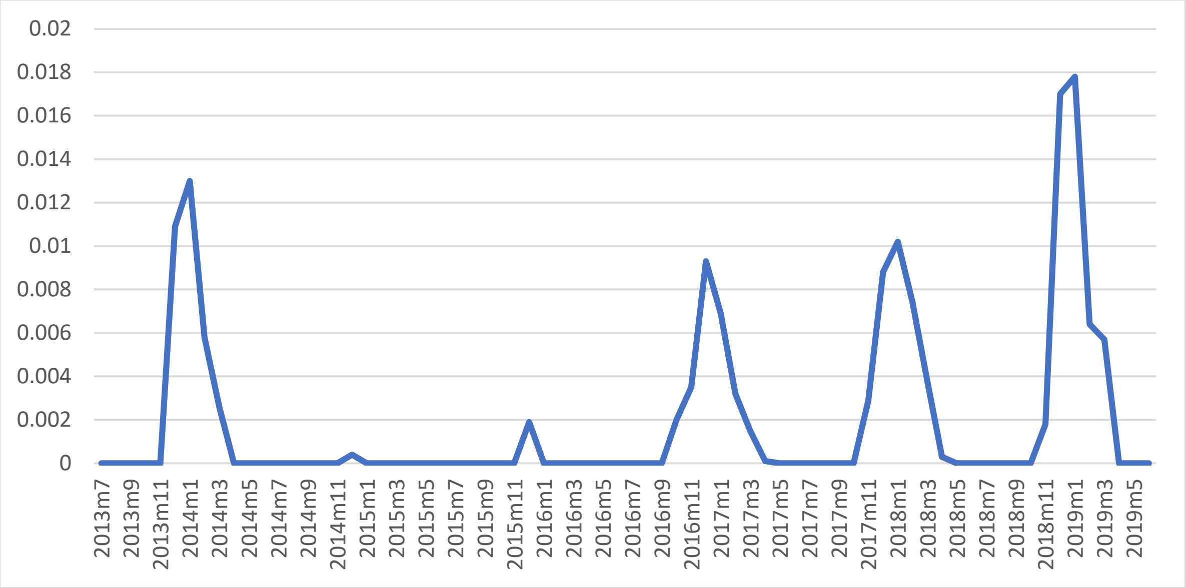

Figure C. 18 Optimal weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Variance** optimization framework and the **5-year** estimation window.

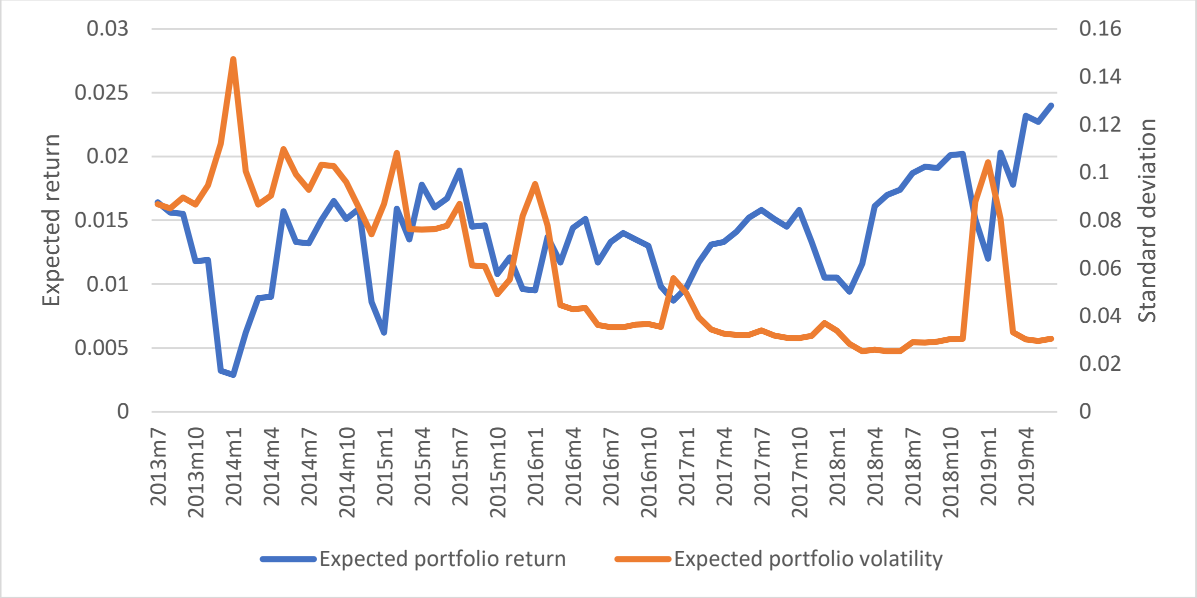

Figure C. 19 Expected return and expected volatility of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window. Expected portfolio volatility is measured in the standard deviations of the expected portfolio returns.

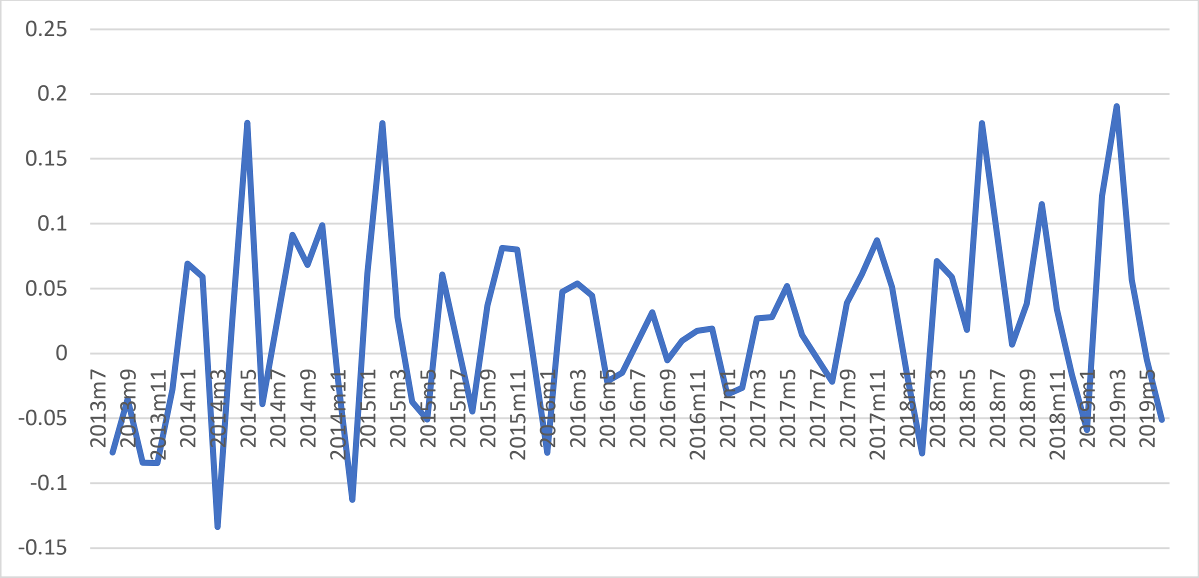

Figure C. 20 Realized returns of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Variance** optimization framework and **5-year** estimation window.

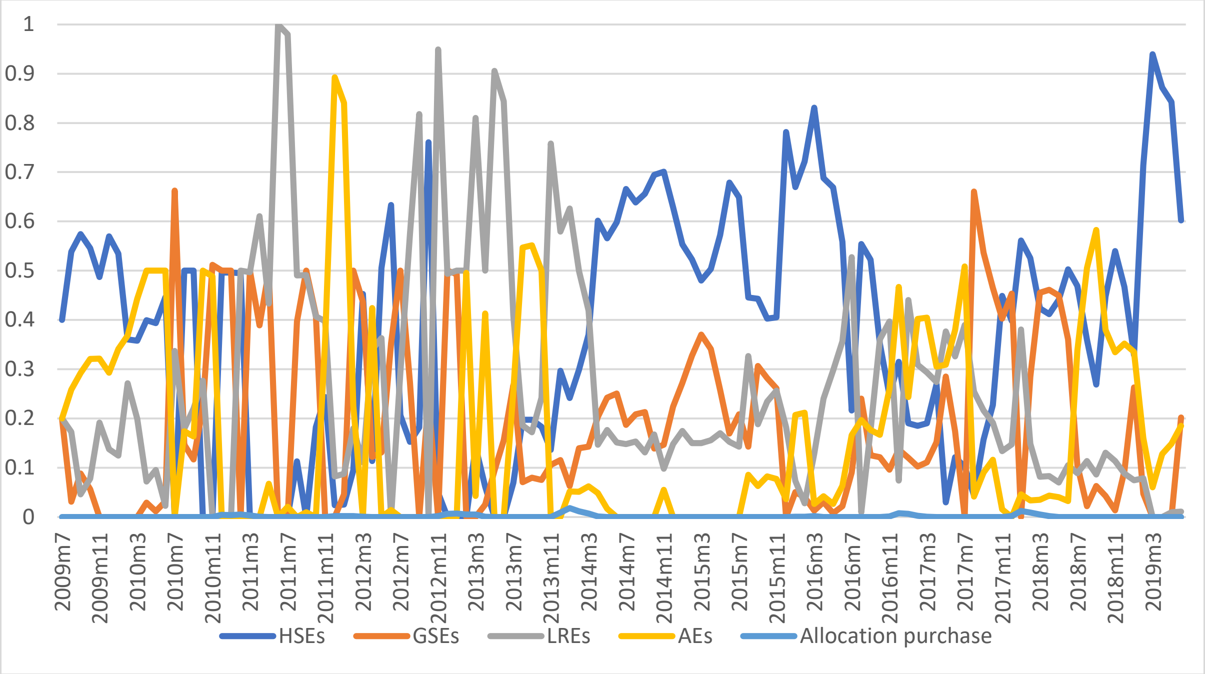

Figure C. 21 Optimal weights of entitlements by security levels in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and **1-year** estimation window.

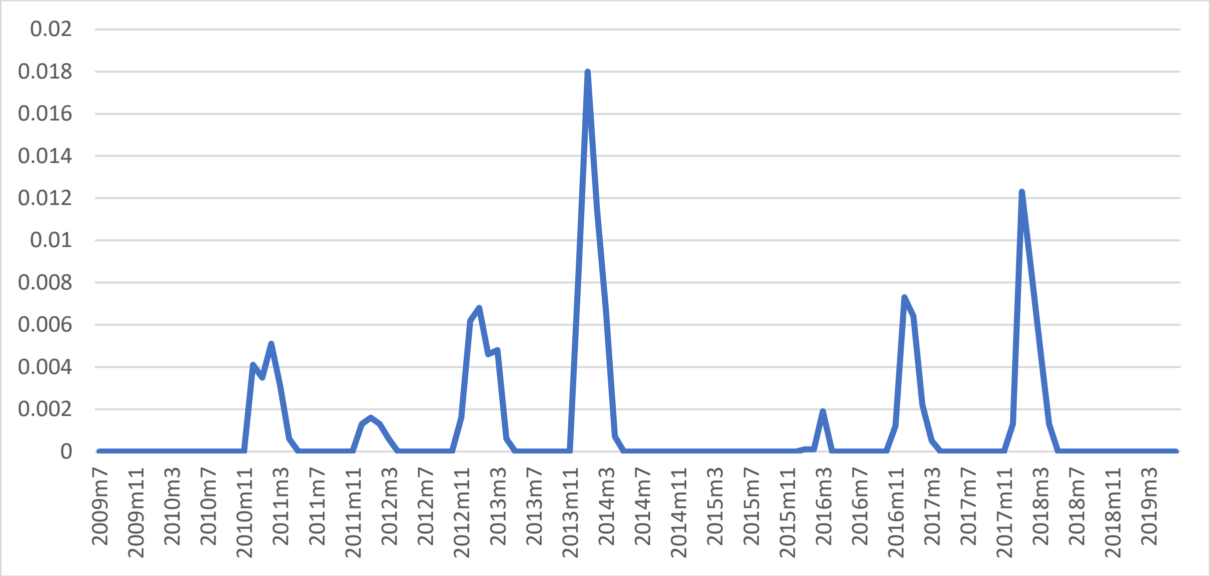

Figure C. 22 Optimal weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean- Semivariance** optimization framework and the **1-year** estimation window.

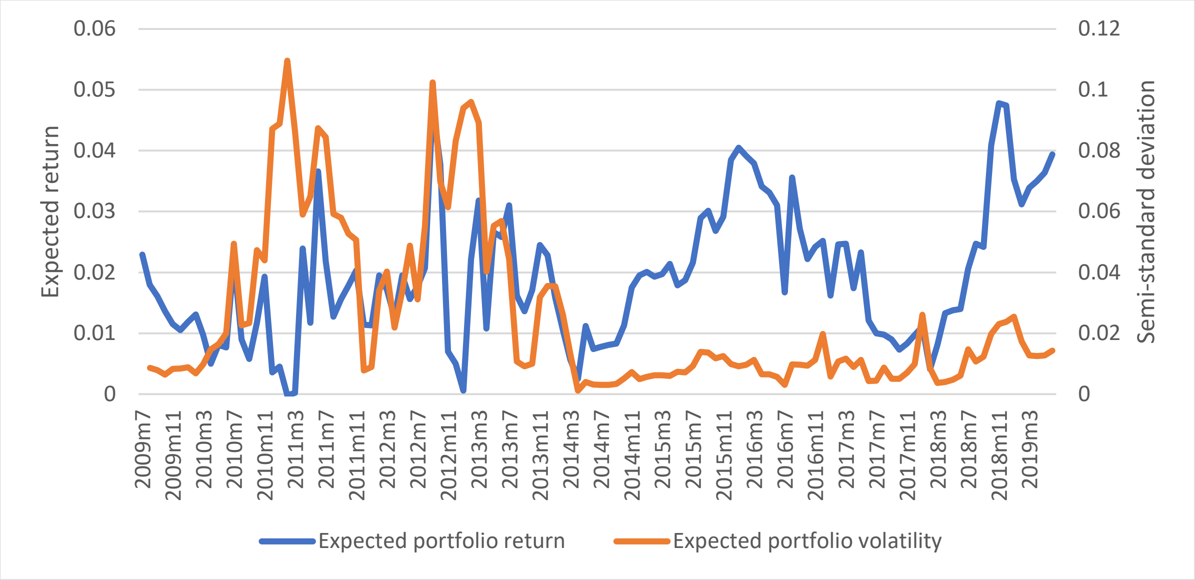

Figure C. 23 Expected return and expected volatility of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with **Mean-Semivariance** optimization framework and **1-year** estimation window. Expected portfolio volatility is measured in the semi-standard deviations of the expected portfolio returns.

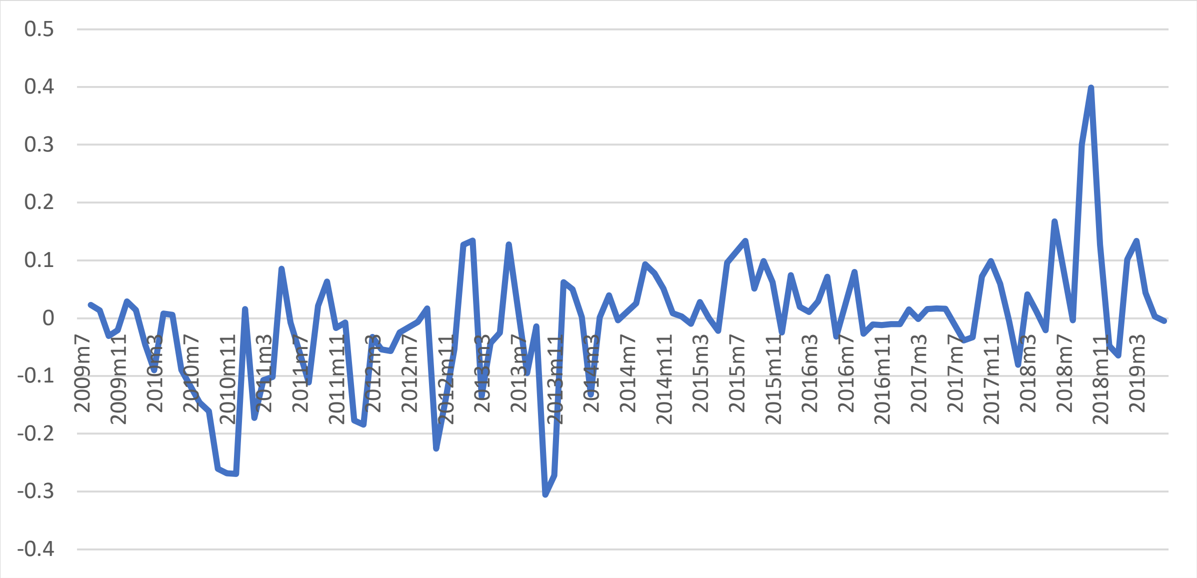

Figure C. 24 Realized returns of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with **Mean-Semivariance** optimization framework and **1-year** estimation window.

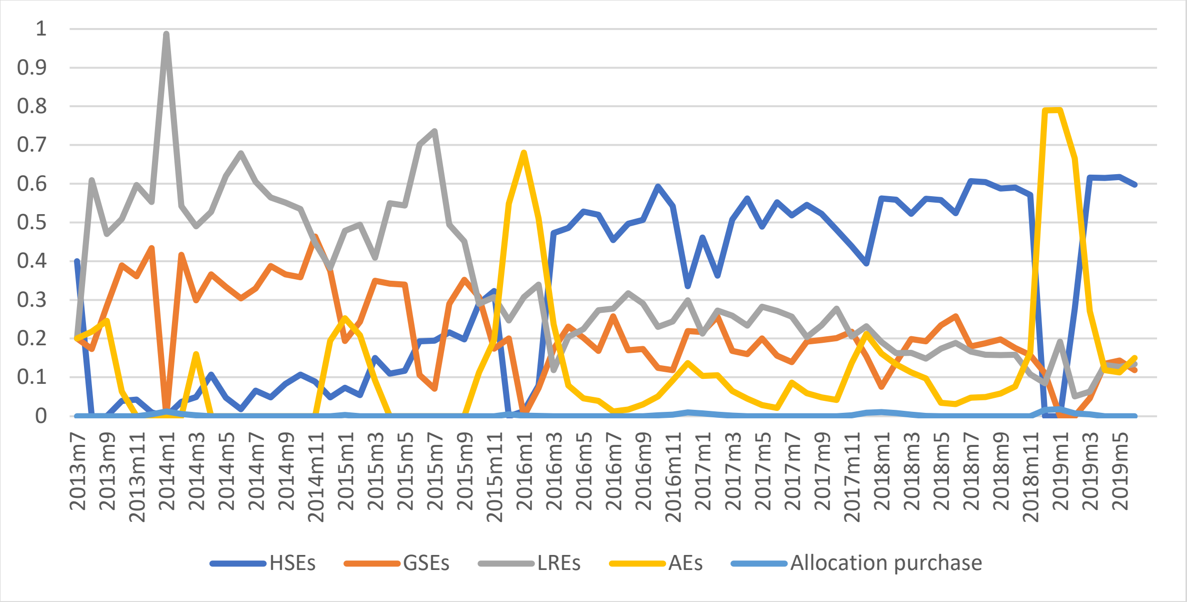

Figure C. 25 Optimal weights of entitlements by security levels in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window.

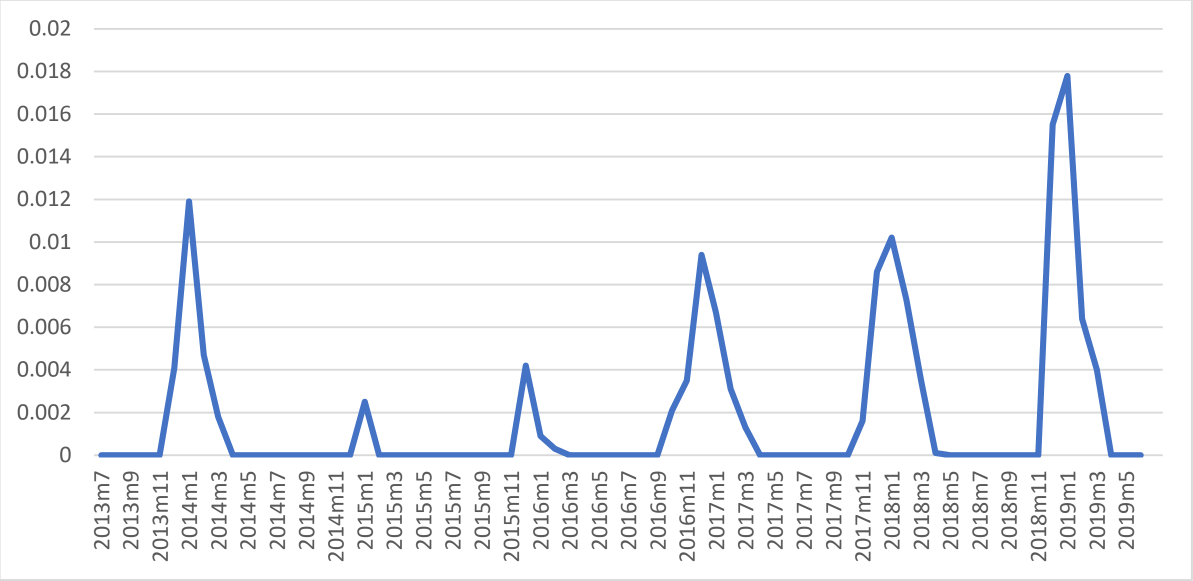

Figure C. 26 Optimal portfolio weights of **allocation purchases** in the monthly-rebalanced portfolios for the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and the **5-year** estimation window.

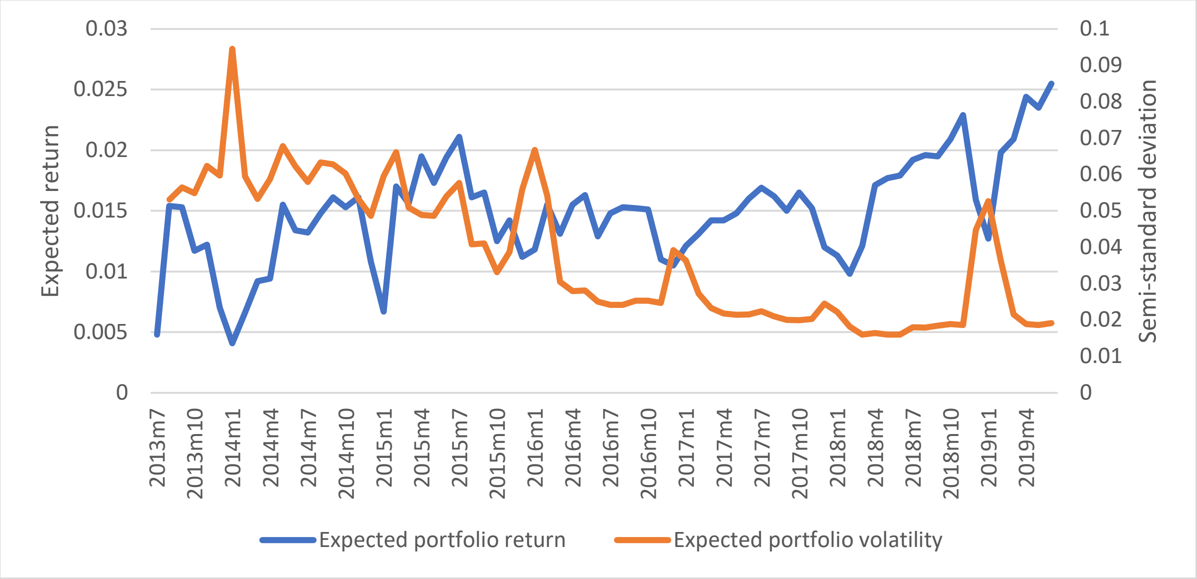

Figure C. 27 Expected return and expected volatility of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window. Expected portfolio volatility is measured in the semi-standard deviations of the expected portfolio returns.

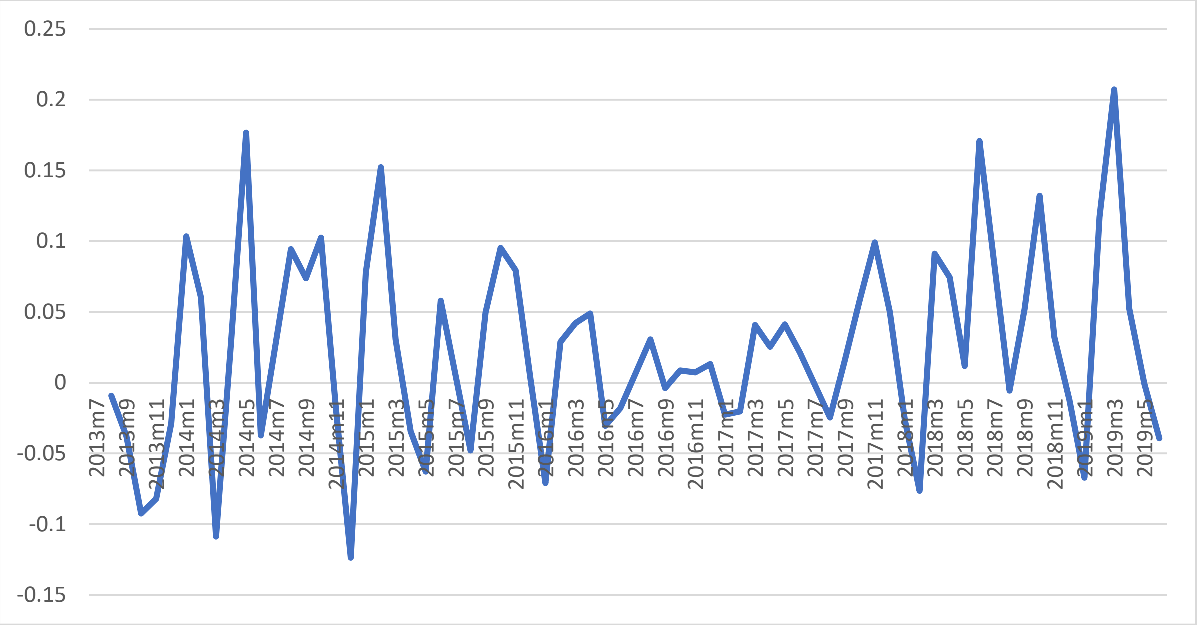

Figure C. 28 Realized returns of the monthly-rebalanced optimal portfolios in the **irrigator model**, estimated with the **Mean-Semivariance** optimization framework and **5-year** estimation window.