

An Oasis Without Water:

A Hydro-Social Investigation into How Agricultural Water Use and Management Influences Water Scarcity in the Ferghana Valley, Central Asia

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Abstract

Water scarcity can have severe implications for society; endangering human health and food security whilst also exacerbating social conflict around the world. These issues are exemplified in the case of the Ferghana Valley in Central Asia, where much of the valley suffers from water scarcity and conflicts despite having adequate water sources. This scarcity is primarily due to how water is used, managed and distributed rather than a lack of supply. Accounting for 90% of water withdrawals, agriculture has a key role in altering the flow and availability of water in the region. This thesis used a mixed method approach to better understand how agricultural water use and management may influence water scarcity on the regional and local scale in the valley. The approach utilised hydrological methodology to measure crop water consumption (CWC) and demand (CWD) for the whole valley in 2016 and social methodology to investigate water management challenges and stakeholder perceptions of water scarcity in water user associations (WUAs). The results were integrated and compared to assess spatial differences in scarcity within WUAs. The results revealed that agriculture consumes and demands a significant amount of water, accounting for 81% of water withdrawn for the valley. Furthermore, the findings suggest that water scarcity varies spatially within and between different WUAs. Furthermore, several shared and unique challenges were discovered for management in the WUAs. Three main management challenges were discovered: distributional, technological and support based challenges. This thesis concludes that agriculture within the valley has an important role in driving the flow and altering the availability of water in the valley. Moreover, management within WUAs may have a significant impact on different dimensions of water scarcity through water use inefficiency, distributional inequity and by reinforcing temporal vulnerability to scarcity. Based on these results a number of intervention points and applications of the research are highlighted. Future research can expand and build on this research to enhance understandings of water scarcity and advance potential solutions.

Keywords:

water scarcity, Ferghana Valley, water user associations, remote sensing, mixed methods, sustainability science

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List of Abbreviations

~	= Approximately
CWC	= Crop water consumption
CWD	= Crop water demand
ENVSEC	= Environment and Security Group
Et _a	= Actual evapotranspiration
ET _f	= Evaporative fraction
ET _{pot}	= Evapotranspiration potential
FAO	= Food and agriculture organisation of the united nations
GIZ	= Deutsche Gesellschaft für international zusammenarbeit
ICG	= International Crisis Group
ICRAF	= World Agro-forestry Centre
IWRM	= Integrated water resource management
LST	= Land Surface Temperature
NDVI	= Normalised Difference Vegetative Index
RQ	= Research question
SD	= Standard deviation
S-SEBI	= Simplified surface energy balance index
USGS	= United states geological Survey
WHO	= World health organisation
WUA	= Water user association

1. Introduction

Water is one of the most fundamental resources for life on earth. Yet millions of people are without water for drinking, sanitation and food production, with four billion people predicted to experience water scarcity for at least one month in a year (Mekonnen & Hoekstra, 2016; WHO, 2015). This scarcity of water has several implications for society; threatening human health and food security whilst also exacerbating social conflict around the world (WHO, 2015; Gleick & Heberger, 2014; ICG, 2014). This is an issue that will become increasingly problematic if global trends in population growth, consumption and climate change continue to increase (Haddeland, 2014; Schewe *et al.*, 2014; Alcamo *et al.*, 2007). For example, it is estimated that 1.8 billion people will be living in a water scarce area by 2025 (FAO, 2012). Although water scarcity mainly occurs in arid areas, it is also experienced in many areas that are not arid or physically lacking supply (Mekonnen & Hoekstra, 2016). In these areas, a lack of water is also caused by additional factors such as how the water is used and managed by society (Rijsberman, 2006).

One of the biggest examples of anthropogenic use is in agriculture. Globally, agriculture accounts for 70% of fresh water use, with irrigated agriculture estimated to use ~2500 km³ of water to produce ~40-50% of food annually (Shiklomanov & Rodda, 2003; Döll & Siebert, 2002). Additionally, much of this water is not used efficiently and cannot be reclaimed directly because of losses to the ground and pollution with agro-chemicals (Wallace, 2000). Consequently, irrigated agriculture has an extremely influential role in altering the flow and availability of water globally (Alcamo *et al.*, 2007). As stated by the FAO (2012,p2) *“Agriculture is both a cause and a victim of water scarcity... causing water scarcity even in areas that are relatively well endowed with water resources”*. With water use in agriculture expected to increase because of demographic, consumptive and climatic pressures aforementioned, these influences are likely to intensify (Haddeland, 2014; FAO, 2012; Godfray *et al.*, 2010).

These issues are exemplified in the case of the Ferghana Valley in Central Asia. The valley, part of the wider Aral-Sea basin, is a fertile area of land spanning across multiple countries including Kyrgyzstan, Tajikistan and Uzbekistan. The region, and much of Central Asia, suffers from water scarcity despite having adequate sources of water (Zhupankhan *et al.*, 2017; Savoskul *et al.*, 2000; FAO, 2003). This scarcity is primarily a result of how the water is used and managed within the valley and a result of historical development and hydro-climatic change (ICG, 2014; Sorg *et al.*, 2014; Savoskul *et al.*, 2003). Accounting for up to 90% of water withdrawals, agriculture is the largest user of water (ICG, 2014; Frenken, 2013). As a result, the management of water is largely controlled and influenced by agricultural management institutions. Much of how this water is consumed and managed by local

water user associations (WUAs) and by national governments is very inefficient (Moss & Hamidov, 2016; ICG, 2014). This is reflected in the region having some of the highest rates of water consumption per capita in the world (Varis, 2014).

Thus, improvements in agricultural water use and management is vital for reducing water scarcity, vulnerability and social conflict in the region (ICG, 2010; ENVSEC, 2005). However, to improve agricultural water use, the factors that drive water use inefficiency need to be better understood and identified. Hence, a more exact understanding of what the current water management challenges are, combined with a spatial assessment of crop water consumption (CWC) and crop water demand (CWD) across the valley, is essential for understanding the impacts of agriculture on water and ultimately understanding and improving water scarcity in the valley.

1.1. Aim, Research Questions and Objectives

The main aim of this thesis is to better understand how agricultural water use and management influences water scarcity in the Ferghana Valley, in order to highlight leverage points from which agricultural water use and management can be improved. The research questions (RQ) used to guide the investigation are as follows:

1. What is the water consumption and water demand of agriculture in the Ferghana Valley for 2016?
2. How do stakeholders perceive their water availability in WUAs?
3. How do water availability perceptions correlate spatially with crop water consumption and crop water demand?
4. What are the main challenges for water management in WUAs?

As described in the introduction, it is well known that agriculture is a driver of water scarcity. However, a more specific understanding of how local management may influence this, combined with up-to-date information on CWC and CWD and how this varies across the valley, will help achieve a greater understanding of agriculture's role in water scarcity and help target efforts aimed at improving it. By quantifying agricultural CWC and CWD, my objective in RQ-1 is to gain a greater understanding of the current usage and demand of water in agriculture for the valley. Furthermore, by mapping this spatially, my objective is to see how this varies both on the regional scale and on the local scale in WUAs. Secondly, in RQ-2, my objective is to gauge the extent of water scarcity as a problem in WUAs

and ascertain how perceptions differ within and between the WUAs. Thirdly, in RQ-3, my objective is to further investigate spatial differences in perceptions and how they relate with CWC and CWD maps. This is done to see if perceptions of scarcity are correlated with differences in the availability of water in agriculture. Lastly, through RQ-4 my objective is to better understand how certain challenges in management can influence and potentially cause water scarcity. Finally, focusing on the applicability and usability of sustainability science research (Jerneck *et al.*, 2011), an additional objective is to provide shareable information that can be utilised by users within society, and to show how social and hydrological methodology can be combined to create a greater understanding of a problem and inform solutions.

2. The Ferghana Valley – The Heart of Central Asia

Surrounded by arid and mountainous environments, the Ferghana Valley is an oasis at the heart of Central Asia. The valley forms the midstream part of the Syr Darya river basin and the north-eastern part of the larger Aral Sea Basin (Figure 1.). Three countries intersect the area of the valley: Uzbekistan in the central lowlands, Tajikistan in the west and Kyrgyzstan in periphery areas in the north, east and south. The valley is one of the most populated and ethnically diverse areas in Central Asia and represents one of the largest irrigated areas in the Syr Darya basin (Bischel, 2011). Agriculture is the dominant industry in the valley, forming the backbone of the economy with most people directly or indirectly dependent on agriculture (ICG, 2014; Bischel, 2011).

Originating in the Tien Shan mountains in Kyrgyzstan, the main water supply comes from the Naryn (14.5km³) and Kara Darya (3.9km³) rivers that join to form the major Syr Darya river (Figure 1.). A number of smaller transboundary rivers also contribute a significant amount of water collectively (7.8km³)(Wegerich *et al.*, 2015). Much of this supply comes from glacial and snow meltwater from the surrounding mountains in Kyrgyzstan (Savoskul *et al.*, 2003). The amount of surface water withdrawn in the valley is estimated to be around 10km³/year (Kenjabaev & Frede, 2016). The climate is typically arid and continental with a low annual precipitation of 100-300mm/year on average. Temperatures differ quite drastically annually ranging from up to 40°C in the summer and down to -10°C in the winter (Löw *et al.*, 2017). As a result of being surrounded by mountains and being dependent on meltwater, the area is particularly vulnerable to natural disasters and climate change (ENVSEC, 2005). Climate change is predicted to have substantial impacts on the hydrology of the area, the incidence of natural disasters and consequently on the vulnerability of the area (Sorg *et al.*, 2014; Bernauer & Siegfried, 2012; Savoskul *et al.*, 2003). Rises in population compound these vulnerabilities further (ENVSEC, 2005).

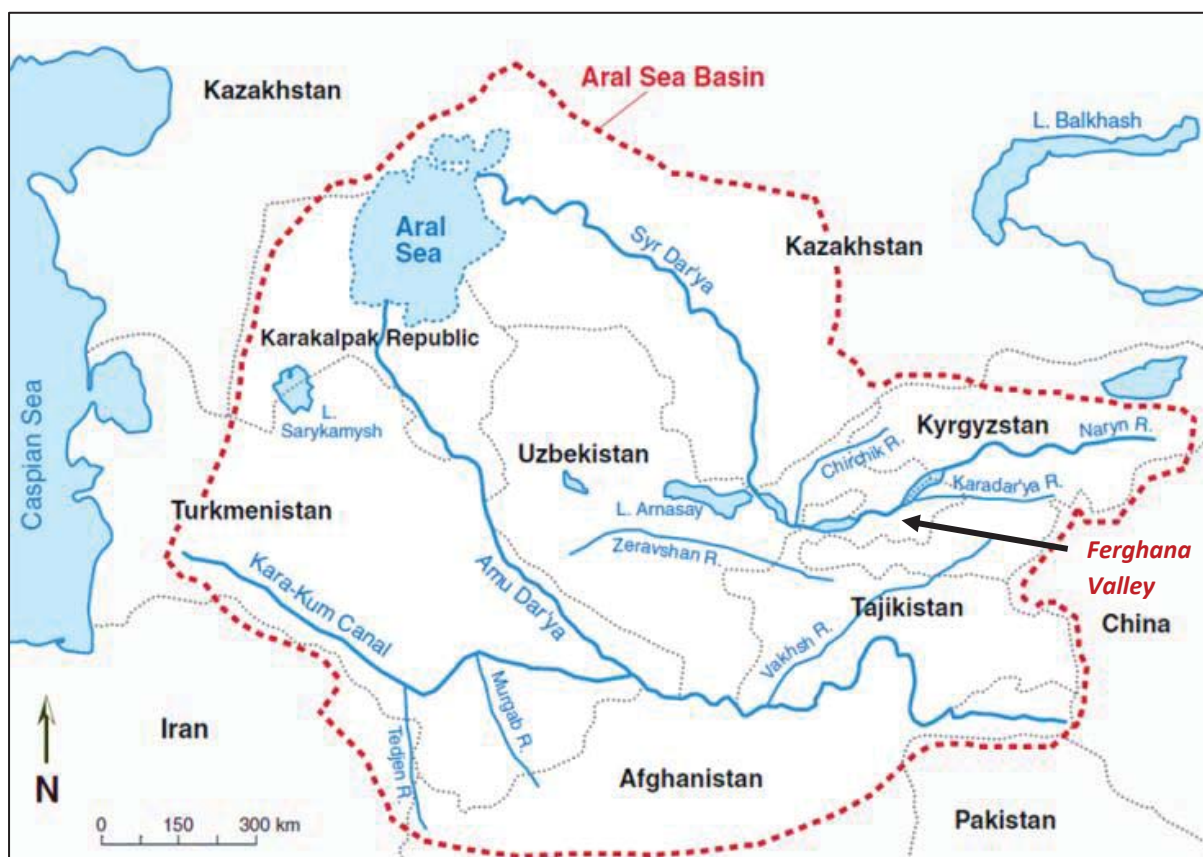


Figure 1. Map of the Aral Sea basin including major rivers such as the Syr Darya and tributaries Naryn and Kara-Darya rivers. The Ferghana Valley is indicated by the arrow (adapted from Quagliarotti, 2017).

2.1. Historical Development and Management of Water

The issue of water scarcity and the associated problems with water use efficiency and management, cannot be properly understood without an explanation of the contextual history of the valley. The most notable period of water use and development occurred when the valley was under control by the Soviet Union from the 1920s to 1990s (Kreutzmann, 2016). The Union took advantage of the valley's fertility and undertook large expansions in irrigation, primarily to expand the production of the cash crop cotton also known as 'white gold' (Kreutzmann, 2016). Cotton production is very water intensive. With radically increased production, the water demand for the area increased drastically; resulting in the redirection of most of the flow from the Syr Darya river and its tributaries (Bichsel, 2011). To accommodate this there was widespread construction of hydrological infrastructure such as large irrigation canal networks within the valley and hydropower reservoirs upstream of the valley in Kyrgyzstan (Guo *et al.*, 2016). This resulted in over 90% of the Syr Darya water being controlled by infrastructure (Kenjabaev & Frede, 2016). Furthermore, a management system of resource sharing was established between the valley's republics to facilitate the growth of cotton in the summer

(Kreutzmann, 2016). Essentially this system comprised of the provision of water and hydropower by upstream republics in the summer and the provision of fuel for winter heating by downstream republics (Sorg *et al.*, 2014). This management was conducted in a highly centralised and hierarchical manner and is representative of the 'hydraulic mission' view that water can be manipulated and shaped to fit the needs of society (Kreutzmann, 2016; Abdullaev & Rakhmatullaev, 2015). The result of this hydrological development, exponential growth of cotton and the form of management contributed greatly to the infamous depletion of the Aral Sea; known as one of the biggest ecological catastrophes in the world (Micklin, 2016;2007). When the Soviet Union collapsed in 1991, the countries within the valley had to grapple with the sudden responsibilities that came with independence after being in a single union for decades. With border delimitation, the unequal share of water and energy resources between constituent countries was reinstated and hydrological infrastructure became international and shared (Guo *et al.*, 2016). Uzbekistan now became reliant on water from upstream Kyrgyzstan, whilst Kyrgyzstan became reliant on energy exports from Uzbekistan. The newly independent countries tried to maintain the resource sharing agreements with water and energy exchanges, but this collapsed shortly after independence when countries began to prioritise national objectives (Bernauer & Siegfried, 2012).

Relics from the Soviet Union combined with newly formed clashes over resources forms the basis for many of the problems plaguing the valley today such as water scarcity and social conflict (ICG, 2014; Bernauer & Siegfried, 2012). Because of this historical development, the valley is completely reliant on agriculture dominated by cotton and the remnants of the hydrological infrastructure that support it (Kreutzmann, 2016). This has imposed a lock-in for the region as it struggles to move away from water intensive industries and lacks the resources to maintain infrastructure and improve technological efficiencies (ICG, 2014). High water demands of agriculture, large inefficiencies in use, coupled with ineffective national and international management compounds this reliance on water and exacerbates problems such as scarcity (ICG, 2014). Moreover, due to the transboundary nature of water sources, conflicting national interests with resources and border disputes along the peripheries of the valley, the area is prone to social conflict (ICG, 2014; Bischel, 2011). Post-independence, the management of water moved from a highly controlled and top-down bureaucratic process to a more decentralised and more autonomous process (Abdullaev & Rakhmatullaev, 2015). Central to this transition was the formation of WUAs as a potential way to improve irrigation management at the local scale, resolve conflicts and fill voids created from the withdrawal of the Soviet Union (Moss & Hamidov, 2016).

2.2. Water User Associations

WUAs are a collective, decentralised form of management tasked to manage, maintain and develop an irrigation network (Moss & Hamidov, 2016). They are usually made up of a group of users, such as farmers, to deliver and enforce water withdrawals amongst users in a specific hydrological unit or along a water source such as a canal. They were initially presented as means of decentralisation and irrigation management transfer to cope with the expansion of irrigated land and improve the management of irrigation systems (Garces-Restrepo *et al.*, 2007). The principle behind them is that if users assume the costs and responsibilities of operations, there is a higher incentive to improve the efficiency of management (Garces-Restrepo *et al.*, 2007). The concept was popular because WUAs allowed for local management to become autonomous (and therefore less financially burdening) and were championed to be good examples of how to incorporate principles of the heavily promoted integrated water resource management (IWRM) paradigm such as user participation and decentralisation (Moss & Hamidov, 2016).

In the Ferghana Valley WUAs emerged after the collapse of the Soviet Union. This was largely in response to outcomes of legal reforms, movements away from Soviet style governance structures, promotion by international donors and incentives to gain access to funding (Moss & Hamidov, 2016; Abdullaev & Rakhmatullaev, 2015; Wegerich, 2000). For example, to fill the void of management responsibilities created after reforms divided large collective farms into smaller units (Abdullaev *et al.*, 2010). The establishment and formalisation of WUAs in the valley differed according to the socio-political and legal context of each country (Moss & Hamidov, 2016; Wegerich, 2000). For example, the formation of WUAs in Kyrgyzstan and Tajikistan was both a bottom-up process from users and a top down approach from the help of international donors. Contrastingly, in Uzbekistan the formation of WUAs was mainly a top-down state-ordered process (Sehring, 2007; Wegerich, 2000). Whilst the underlying motivations behind their emergence may be the same, the formation and operation of the WUAs differ in relation to the socio-political and legal frameworks surrounding them and do not necessarily reflect full participatory management (Moss & Hamidov, 2016; Sehring, 2007). These differences, combined with a lack of support and resources, have called the effectiveness of the WUAs into question (Moss & Hamidov, 2016). As WUAs are the lowest level of governance, deficiencies in management and support may translate into significant influences and causes of water use inefficiency and scarcity. Thus, studying the challenges that WUAs in the valley face is important for both understanding and improving water scarcity.

3. The Hydro-Social Cycle: A Conceptual Framing

Traditionally, research on water scarcity has focused mainly on biophysical aspects of the resource (Bakker, 2012; Mehta, 2007). For example, water scarcity on a global scale is mainly measured hydrologically and defined using simple attributions of supply and demand (White, 2014; Martin-Carrasco *et al.*, 2013; Rijsberman, 2006). However, water scarcity is much more complex than simply changes in supply per capita or changes in demand in an area (Jaeger *et al.*, 2013; Mehta, 2007;2003). As mentioned in the introduction, water scarcity also occurs in areas that do not have a lack of supply such as in the case of this study, the Ferghana Valley (Rijsberman, 2006). Based on traditional indicators of supply per capita, the Ferghana Valley is above thresholds for scarcity having more water per capita than many countries in Western Europe with no scarcity (Varis, 2014; FAO, 2003). Therefore, water scarcity is not absolute but also driven by non-physical factors. In other words, water scarcity is, in part, socially constructed and can vary spatially and temporally according to how water is used, distributed and managed over time (Mehta, 2007;2003). Consequently, as stated by Mehta (2003, p6057) “...there is an urgent need to link water scarcity with socio-political, institutional and hydrological factors”. This has largely been acknowledged in the recent past with research and definitions shifting to better include these factors (White, 2014; Jaeger *et al.*, 2013; FAO, 2012; Mehta, 2007). However, due to the complexity involved in accounting for such factors, many studies such as those modelling water scarcity, still focus on hydro-climatic factors or broad socio-economic influences on demand (Gosling & Arnell, 2016; Schewe *et al.*, 2014; Hanasaki *et al.*, 2013). Whilst studying hydro-climatic and socio-economic factors are absolutely necessary (Veldkamp *et al.*, 2015), understanding influences from factors such as management is crucial for understanding and more accurately estimating water scarcity.

In order to address the complexity of water scarcity, I draw upon the hydro-social cycle concept to broadly frame and guide the research process. The hydro-social cycle is a framework stemming from a political ecology approach to water (Swyngedouw, 2009). Political ecology approaches focus on how socio-political and ecological factors interact to affect and produce a certain environment or environmental problem (Robbins, 2011). For water, the hydro-social cycle is presented in direct contrast to the hydrological cycle to highlight how the flow of water is also shaped and determined by society and not just by physical processes (Linton & Budds, 2014). The use of the word ‘cycle’ emphasises the nature in which water and society interact, with both water and society influencing each other in an infinite loop over time (Linton & Budds, 2014). In other words, social and hydrological systems are inextricably linked, where hydrological environments are determined by past and current socio-ecological interactions (Swyngedouw,2009).

In the case of the Ferghana Valley, the use and management of water by agriculture and hydropower forms the majority of these socio-ecological interactions and plays a large role in shaping the flow or cycle of water. The hydrological environment or state of water scarcity in the valley is thus determined not only by hydro-climatic components but also by hydro-social interactions such as those produced by irrigation. By emphasising the inseparability of water and social relations, the hydro-social cycle is useful for water scarcity research as the inclusion of social relations can help understand how and why water becomes scarce where water supply information on its own cannot (Budds, 2008). For example, in determining the distributional and temporally varied access to water or how the quality of water may inhibit use. Whilst emphasis is placed on understanding these social interactions, hydrological aspects also play a crucial role and should not be neglected. In fact, hydrosocial and political ecology research has been criticised for focusing too much on theory, not including enough biophysical research and for not engaging with the solutions to the problems addressed (Turner, 2016; Wesselink, Kooy, & Warner, 2016; Walker, 2005).

To translate these concepts and accommodate these criticisms into my research I also need to draw on principles embedded within sustainability science such as transdisciplinarity (Lang *et al.*, 2012). Lang *et al.*, (2012, p26-27) define transdisciplinarity as "...a reflexive, integrative, method driven scientific principle aiming at the solution or transition of societal [...] and [...] scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge". Incorporating both social and bio-physical dimensions requires methodological and theoretical integration from multiple disciplines and knowledge areas. Drawing on principles within sustainability science helps to incorporate these aspects by urging research to be interdisciplinary and solution-orientated (Lang *et al.*, 2012; Jerneck *et al.*, 2011).

Hence, using the hydro-social concept and principles within sustainability science to inform the research, I employ a combination of social and hydrological methodology, using different sources of knowledge, to investigate agricultural water use and management in the Ferghana Valley. By integrating social and hydrological aspects with these concepts in mind, I am able to carry out a better informed and contextualised study of water in the Ferghana Valley. Furthermore, by acknowledging the multi-dimensional nature of water scarcity, my investigation can explore beyond water supply factors and into other factors such as demand, distributional or temporal elements of water scarcity. Although, the hydro-social cycle emphasises how complex water related issues are, it also suggests that there are possibilities to improve them. The use as a conceptual framing may thus help to better understand water scarcity in the valley and help determine ways to improve it.

4. Methodology

To answer the research questions, a mixed method approach was applied including a combination of quantitative and qualitative components in a ‘concurrent triangulation strategy’ (Creswell, 2013). This describes a research design where both components are analysed separately and then integrated and compared to answer further research questions (see Figure 2.)(Creswell, 2013). This strategy was chosen based on the assumption that the combination of methods and philosophical underpinnings within them, produces a greater understanding of a problem that could not have been obtained from each method separately (Mayring, 2014; Creswell, 2013).

The quantitative part of the thesis involved the production and analysis of crop water consumption and demand maps of the Ferghana Valley using remote sensing. Remote sensing is a common technique that uses spectral information captured by satellites to better understand earth-system processes and objects on the land surface (Lillesand, Kiefer & Chipman, 2014). The qualitative approach consisted of a study of three WUAs within the valley, whereby multi-stakeholder interviews were conducted to gain information about WUA management and perceptions of water availability. To achieve this I collaborated with ICRAF and GIZ organisations to conduct field work in the valley. Collaboration with these organisations allowed me to meet with multiple stakeholders and receive much needed guidance and knowledge about the context within each WUA and location. Both qualitative and quantitative components were then combined to assess how spatial differences in perceived water scarcity relate with CWC and water availability in two of the WUAs studied (Figure 2.). The integration of the methods in a triangulation strategy fits my study well because it helps address the methodological requirements for transdisciplinarity research and the hydro-social cycle concept (Linton & Budds, 2014; Lang *et al.*, 2012; Jerneck *et al.*, 2011).

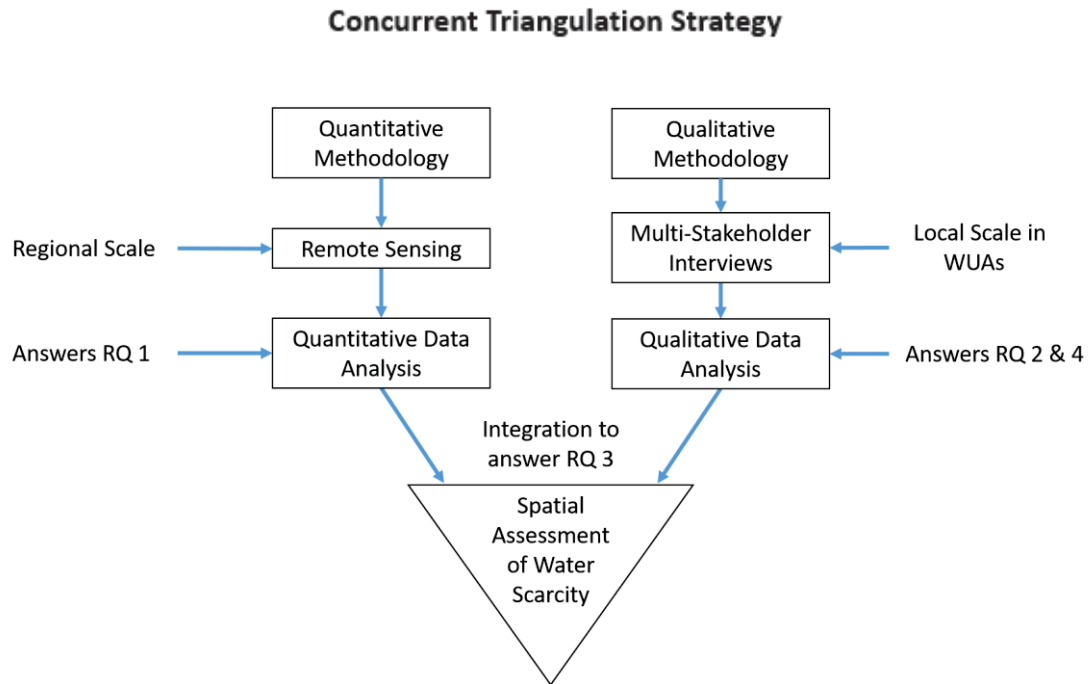


Figure 2. Visualisation and summary of the concurrent triangulation strategy employed in this thesis.

4.1. Study Locations: WUAs in the Ferghana Valley

Since the scope of this thesis prevents complete investigations in all three countries, the local WUAs studied were confined to the Kyrgyz part of the valley. This was based on the ability to freely work within the country and the ability to collaborate with research organisations. The WUAs investigated are within three rural communities in Kyrgyzstan (Figure 3.). These case studies were chosen to account for upstream and downstream differences and any potential affects related to the proximity to country borders. The ability to account for these differences are both important and interesting for contextualising the results obtained in this study. The location and geographical context of each WUA are described briefly in the following sections.



Figure 3. Locations of the WUAs studied in relation to elevation, major hydrological features and major towns in the Ferghana Valley. Hydrological features are represented in light blue and include major rivers, canals and reservoirs (Adapted from ENVSEC, 2005).

4.1.1. *Khalmion WUA*

Khalmion WUA manages the rural community of Khalmion ($40^{\circ}12'44''\text{N}; 71^{\circ}37'58''\text{E}$) in Kadamjai district, Batken province (Figure 3). This community is comprised of 13 villages and is situated directly next to the Uzbek border. Khalmion also includes a small 1.5km^2 Uzbek enclave known as Jangy-Alyll. Interviews with farmers were conducted in two villages, Khalmion and Chekelik. The area is $\sim 3,800$ ha with a population of $\sim 19,000$ (March, 2017). Batken province shares its borders with both Uzbekistan and Tajikistan and has six enclaves within it (Kreutzmann, 2016). This has made the region geopolitically tense with several violent, sometimes fatal, incidents in the past (ICG, 2014; ENVSEC, 2005). As observed in Figure 3. Khalmion WUA is upstream relative to small transboundary rivers but downstream from major hydrological features such as the Kara-Darya river, Naryn river, large canals and reservoirs. For the purpose of this study Khalmion is characterised as downstream.

4.1.2. *Alma-Suu WUA*

Alma-Suu WUA is within the rural community of Saydykum ($40^{\circ}55'59.7''\text{N}; 72^{\circ}36'08.9''\text{E}$) in Bazar-Korgon district, Jalal-Abad province. The community is made up of 12 villages, only four of which are managed by the WUA. Farmer interviews were conducted within two villages Jany-Abad and Chek. Like Khalmion, these villages also share its borders with Uzbekistan. The WUA is ~ 1610 Ha with a

population of ~4000 (March, 2017). As observed in Figure 3. the WUA is located in the north-eastern part of the valley at a similar elevation to Khalmion WUA. However, in contrast, Alma-Suu WUA is upstream relative to major hydrological features as it is close to the Andijan Reservoir, the Kara Darya river and other smaller transboundary rivers.

4.1.3. Toolose WUA

Toolose WUA is within the rural community of Toolose (40°18'17.4"N;72°14'07.0"E), Nookat district, Osh province. The area is ~3375 ha including eight villages and a population of ~21,700 (March, 2017). Farmers were interviewed from Kengesh village. The geographical and political context of Toolose is similar to Khalmion WUA. Osh province has also been at the centre of conflict in the past with several violent incidents taking place in cities and along the border (ICG,2014; ENVSEC,2005). As observed in Figure 3. Toolose WUA is near, but not adjacent, to small transboundary rivers but far from major hydrological features in the east of the valley (Figure 3.). Toolose WUA is also characterised as downstream in this study.

4.2. Estimation of Crop Water Consumption and Demand Using Remote Sensing

4.2.1. Evapotranspiration

Evapotranspiration is a combined measurement of the water evaporated from the soil surface and of the water transpired by plants. Both processes are governed by energy and are influenced by atmospheric conditions such as wind speed, air humidity and solar radiation (Allen *et al.*,1998). Consequently, evapotranspiration is a fundamental component of water and energy exchanges within the physical part of the hydro-social cycle (Oki & Kanae, 2006; Allen *et al.*,1998). Furthermore, it is directly related to crop water use and is therefore a suitable measure for CWC and CWD (Fisher *et al.*, 2017; FAO, 2012; Allen *et al.*, 2007;1998). Measurements of ET can therefore help achieve a greater understanding of the effects of agricultural socio-ecological interactions in the Ferghana valley. The two measures of evapotranspiration used in thesis are actual evapotranspiration (ET_a) and evapotranspiration potential (ET_{pot}). ET_a represents the real amount of water that is evapotranspired from a surface and indicates CWC, whilst ET_{pot} represents the maximal amount of evapotranspiration possible for a surface assuming water is not limited and indicates CWD (Allen *et al.*, 1998).

ET_a and ET_{pot} can be measured using several different techniques. However, many techniques are limited because they are either too expensive, require a lot of climate data, are point based, hold crop management assumptions or are only suitable for homogenous vegetation (Allen *et al.*, 1998). These

limitations are realised in the setting of the Ferghana Valley where there is data scarcity, heterogeneous vegetation and differences in crop management (Radchenko, 2014). Remote sensing approaches are currently the only accurate methods available for measuring ET_a and ET_{pot} over a large spatially heterogeneous area, with accuracies of up to 94% recorded for seasonal evapotranspiration estimations (Gowda *et al.*, 2008; Allen *et al.*, 2007). Moreover, remote sensing is particularly useful in this thesis as it overcomes limitations with data scarcity and can be conducted inexpensively, albeit not without some technical capacity.

The method used to calculate ET_a and ET_{pot} in this thesis follows the simplified surface energy balance index (S-SEBI) approach proposed by Roerink, Su & Menenti (2000). This method is based on assumptions about energy exchanges and energy balances at the surface (Liou & Kar, 2014; van-der Tol & Parodi, 2012; Bastiaanssen *et al.*, 1998). These assumptions are explained only briefly here. As previously noted evapotranspiration requires energy to vaporise (Allen *et al.*, 1998). This is known as the latent heat of vaporisation (λE_v) (MJ/Kg). S-SEBI works under the assumption that if this energy can be measured then the evapotranspiration of a surface can be measured. To measure this energy, the S-SEBI method utilises surface reflectance, land surface temperature and other metadata captured from satellite sensors (Liou & Kar, 2014). ET_{pot} is calculated as a precursor for ET_a in this method. Each satellite image was further broken down into three elevation zones to account for temperature differences. The method results in daily ET_{pot} and then daily ET_a (mm/day) values for each satellite image. From these values, average seasonal ET_a and ET_{pot} maps (mm/year) were made by summing monthly averages (mm/month). All remote sensing operations including image processing, analysis and statistics were conducted using GIS software (QGIS, 2017; GRASS GIS, 2017). Further explanations of these assumptions and the method employed by S-SEBI is in textbox-1. in Appendix C and in references cited.

4.2.2. Satellite Imagery and Boundary Definition

For the remote sensing analysis, Landsat-8 satellite images were used. They were chosen because they are freely accessible, they cover the entire study area, have a small spatial resolution, a regular capture frequency (~16days) and include the required metadata. These images comprise of 11 spectral bands including two thermal bands (USGS, 2016). All bands used have a spatial resolution of 30m except the thermal bands at 100m (USGS, 2016). Bands B2-B7 & thermal band B10 were used for the remote sensing. Images were downloaded from <http://glovis.usgs.gov/>. To cover the entire valley and growing season, 29 images were downloaded from four Landsat 'scenes' identified by the WRS-2 path/row: 153/32, 152/32, 151/32, and 152/31 between 1st April - 31st October, 2016. Images with high cloud

cover (>40%) were excluded, whilst remaining clouds/cloud shadows were masked. The area was then limited to only the flat parts where agriculture is most likely to grow. This was defined as the area with a slope of less than two degrees and was created using topology data from the Shuttle Radar Topography Mission (SRTM)(Farr *et al.*, 2007). Furthermore, SRTM data was used to create three overlapping elevation zones <500m, 500-700m and 700-1000m as previously mentioned. After ETa and ETpot was calculated, the values for agriculture were extracted by excluding non-vegetated areas. This was done using normalised difference vegetation index (NDVI) maps of the Ferghana Valley for 2016 (Kozhayeva, 2017). These maps show the vegetated versus non-vegetated land areas and can therefore be used to mask non-vegetated areas. The assumptions and method behind NDVI are in textbox-2 in Appendix C.

4.3. Stakeholder Interviews and Analysis

During the field work, I conducted 18 semi-structured interviews with different stakeholders within the WUAs including WUA directors, local government leaders, technical experts and farmers (Supplementary Table 1., Appendix A). Interviews were conducted in March 2017 (Khalimion: 13/03/17 – 14/03/17, Alma-Suu: 23/03/17, Toolose: 25/03/17 – 26/03/17). Unfortunately interviews with local government leaders and experts was only possible for Khalimion WUA. These groups were chosen to get accurate information about WUAs and to get an inclusive and diverse set of opinions. Before these interviews a brief focus group was conducted with 6-8 farmers in Khalimion WUA. This information was not analysed but used to gain a preliminary perspective of farmer views and used to adapt interview questions. WUA directors, local government leaders and the technical expert were selected through purposive sampling, whereas farmers were gathered through snowball sampling.

The interviews consisted of a mixture of open-ended qualitative questions focusing on water management and water availability. Questions on management focused on gaining descriptive information about the structure of the WUAs, procedure of water delivery and opinions on the main water management challenges. Questions on water availability were focused on understanding water availability issues for the whole WUA and for individuals as an indication of water scarcity. Example questions can be seen in Appendix B. For the purpose of this study and due to language constraints, I did not investigate how perceptions differ semantically or are affected by the social environment such as power. Overall, I followed an iterative process where questions were adapted based on participant reactions and responses. To draw direct comparisons in the spatial assessment of perceptions, GPS points were taken from two farmers' fields. These fields were chosen because they are in the same village sub-unit, they receive water from the same irrigation channel and both grew the same crop in 2016. These variables were kept the same so that the comparison between perceptions and water availability can be more accurately made. GPS points were taken with a Garmin eTrex GPS device.

Prior to the start of the interview the participants were informed of the aims of the research, how the information will be used or shared and their rights as a participant. Such rights included the right to refrain from answering a question and the right to withdraw at any point. Informed consent was given verbally. Interviews were not recorded on recommendation from ICRAF and local GIZ staff but conducted with a research assistant and translator from ICRAF and using extensive notes. These notes were then transcribed electronically on the same day with the translator.

To analyse the interviews, an inductive content analysis was used whereby a set of categories were discovered from the data (Mayring, 2014). This analytical method was chosen to ensure the analysis is structured and replicable, whilst also ensuring the qualitative and contextual content remains intact (Mayring, 2014). First transcripts were compiled and organised according to location, stakeholder group and main question topic area (water management, water availability). This was done to compare answers within and between stakeholder groups of different locations. Next keywords or phrases were highlighted to get a better idea of the main themes discussed in each question topic area and to create subcategories. These were then compared within each location to generate an overall picture of what was discussed and to create final overarching categories of the answers for each question topic area for all WUAs.

4.4. Spatial Assessment of Water Scarcity Perceptions

As explained previously, both qualitative and quantitative components were combined in order to assess perceptions of water scarcity spatially in relation to CWC and CWD (Figure 2.). CWC and CWD can give indications about the spatial variability of water use. The difference between them indicates the amount of evapotranspiration that was not realised, or in other words, the amount of water that would have been needed to achieve maximal evapotranspiration. This is an indication of the water shortage and thus can reflect the water availability and water distribution of an area (Karatat *et al.*, 2009; Bos *et al.*, 2005; Perry, 1996). This information is useful in assessing whether the perceptions of scarcity are due to differences in water availability or due to other factors. The investigation focused on Khalmion and Alma-Suu WUAs. Unfortunately, due to cloud cover, Toolose WUA was unable to be investigated. For Khalmion WUA additional assessments were made for the specific field plots measured and for the Uzbek enclave, Jangy-Alyll. The maps were assessed using visual and statistical observations to see how perceptions of scarcity relate to both water use and water availability across the WUAs. Statistical observations include average and standard deviation (SD). Assessments of differences between CWC and CWD (water shortage) were only done visually.

5. Results

5.1. Agricultural Water Use and Demand in the Ferghana Valley

The results from the remote sensing revealed that the water consumption and water demand of irrigated agriculture in 2016 for the whole valley amounts to a seasonal sum-total average of $\sim 8.1 \text{ km}^3$ and $\sim 14.8 \text{ km}^3$ respectively. This is shown spatially on a pixel by pixel basis in Figure 4 where Figure a) shows the CWC (ETa mm/year) and b) shows the CWD (ETpot mm/year). As the figure shows, CWC varies across the valley with consumption being higher overall in the eastern part of the valley and lower in the western part of the valley. This seems to be in accordance with demand, where the CWD follows a similar pattern from east to west. However, as observed in Figure 4, there are some areas where consumption and demand do not match. This difference indicates areas that may have a water deficit, suggesting disparities in water availability or distribution of water across the valley. This is discussed further in 5.1. The CWC and CWD of the WUAs studied is investigated in more detail in section 4.3.

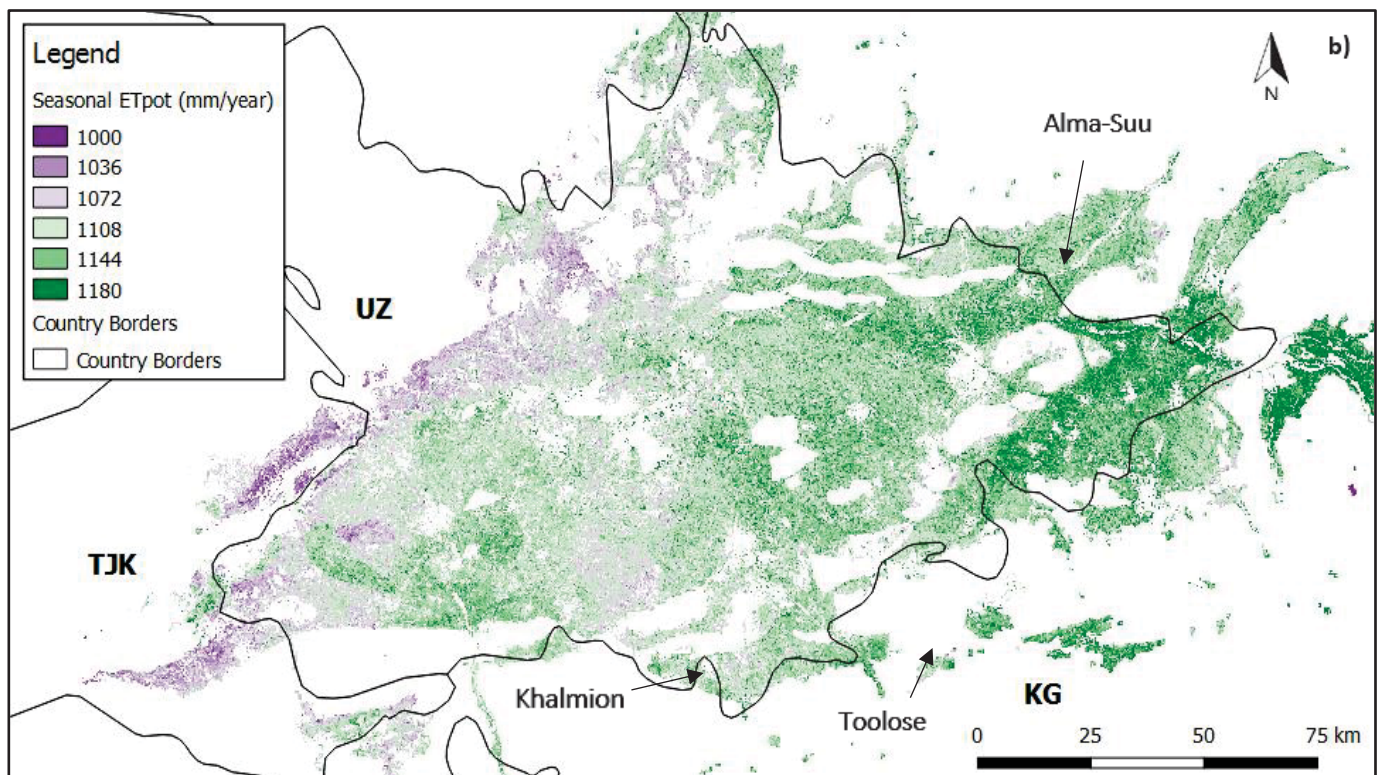
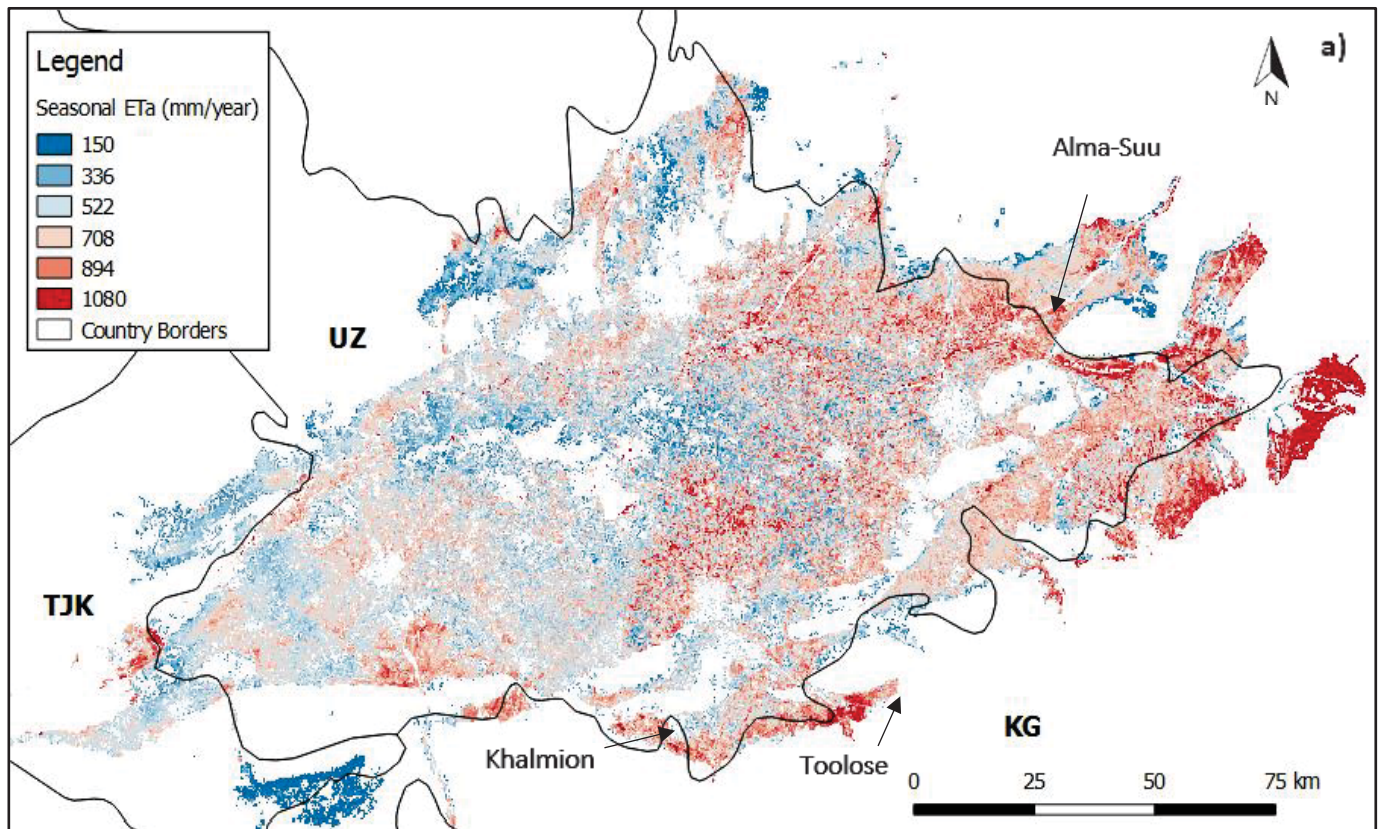


Figure 4. Showing a) the seasonal ETa and b) seasonal ETpot of irrigated agriculture in the Ferghana Valley for 2016. The WUAs studied are shown for reference. Country borders are included where KG = Kyrgyzstan, TJK = Tajikistan, UZ = Uzbekistan. Areas in white are either non-vegetated, covered by clouds or are outside of the defined boundary of the valley.

5.2. Perspectives on Water Scarcity

The results from the content analysis revealed that there was a variety of different perspectives surrounding water availability in each of the WUAs. As previously mentioned, the interview questions focused on understanding water availability and related issues as an indication of water scarcity for the whole WUA and for individuals. Correspondingly, the perceptions are presented separately for each WUA.

5.2.1. *Khalmion WUA*

Overall, a lack of water availability was a primary concern of all stakeholder groups with only a few farmers considering themselves to have enough access to water. Whilst the majority of water concerns were focused on irrigation, there was a large proportion of farmers and the local government that also voiced concerns about drinking water. For example, it was reported that many people are forced to drink water from the channels and often get ill after doing so. Based on the interviews it seems that these concerns about water availability are disproportionately shared within the WUA. The WUA director noted that there are more water availability issues with downstream village subunits 7,9,12 and 13 (figure 5.). This is reflected in the farmer interviews where more farmers in zone 9 reported to have not enough access to water compared with farmers upstream in zone 5. Interestingly, one interviewee has land upstream and downstream in the WUA. This farmer has different experiences with water availability, with the upstream land receiving more water than the downstream land. Many of the concerns highlighted by downstream farmers were made in reference to the Uzbek enclave, Jangy-Alyll; where farmers in Khalmion attributed their lack of water to this enclave, stating that the enclave uses too much water. As noted, two field plots were measured with a GPS device in zone 9 (Figure 5.). Although both field plots are in zone 9 and downstream of the enclave, the perceptions of the farmers for each field differed with one farmer experiencing difficulties with water availability whilst the other does not.

Water was discussed as one of the main limiting factors for crop yield by all stakeholder groups and one of the most important factors considered when deciding what crops to grow for the following year. In fact, many farmers have already or are considering switching to growing fruit trees because they believe trees are easier to manage, are more drought resistant and are less dependent on the timing of irrigation. The main concerns for water availability in the future reflects much of what is highlighted in the management challenges in section 4.4, with a lack of water supply, population growth and climate change being the most discussed factors between stakeholder groups.

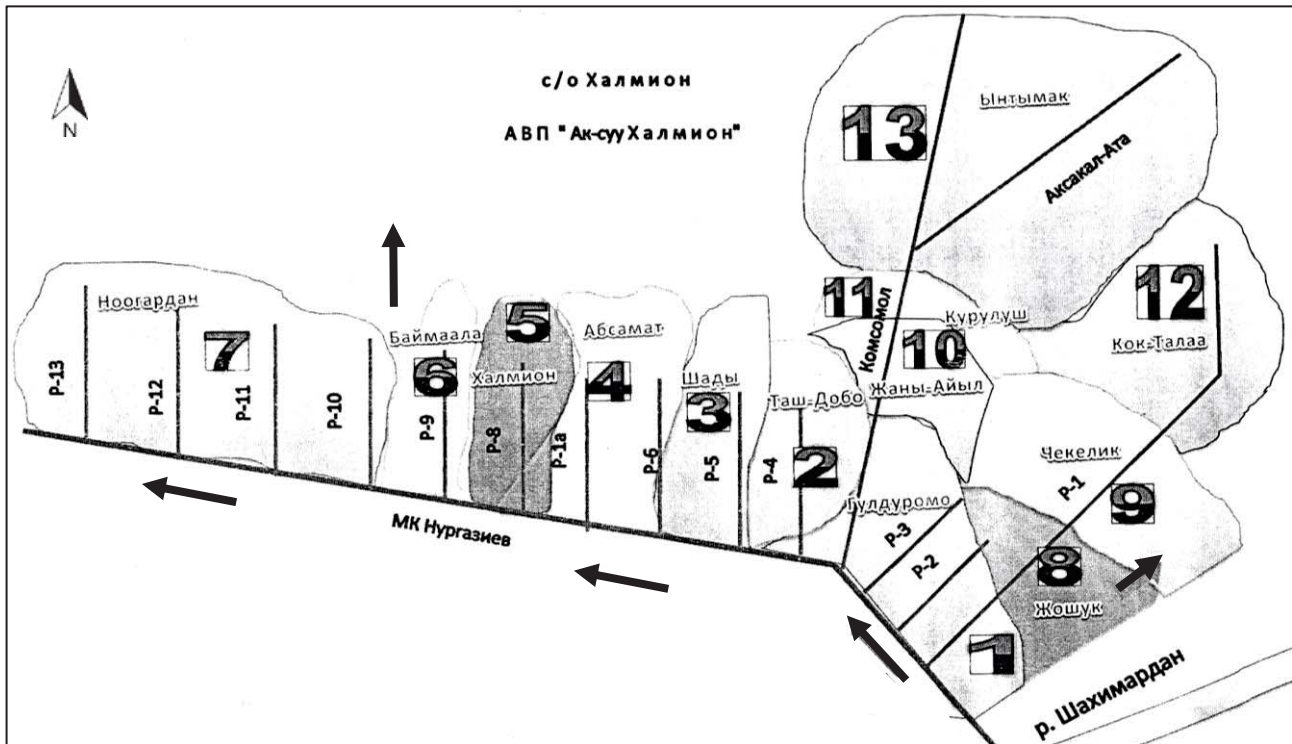


Figure 5. Map of Khalmion WUA showing the 13 village subunits and the 15 main irrigation channels that supply them. Village subunits 7,9,12 and 13 are downstream. Irrigation channels are labelled by number (e.g. P-1) and villages in Kyrgyz. Arrows indicate the direction of water flow. (adaptation of official document, 03/17).

5.2.2. Alma-Suu WUA

Contrastingly, stakeholders within Alma-Suu did not perceive water availability as a problem. The WUA director said they can satisfy most water demands annually and only in the event of a landslide does water availability become an issue. Drinking water is also not a problem with most people receiving water directly to their home. This is reflected in the interviews where farmers from both villages reported that water availability was not a problem. Furthermore, any spatial disparities with water availability within the WUA was not obvious from the interviews. A lack of fertilizers, weeds and pests are the main limiting factors for yield, with water only becoming noticeable during a dry year or during a landslide. The main concerns for the future revolve around landslides with fears that an increase in frequency in the future from climate change will start to cause serious problems with water availability during the growing season.

5.2.3. Toolose WUA

Based on the interview responses, water availability seems to be a main concern for Toolose WUA. Analogous to Khalmion, this seems to affect downstream users more strongly than upstream users. The WUA director said the WUA struggles to satisfy demands and receives many complaints from the farmers. No comments were made about drinking water. The director also reported that there are

more problems with downstream villages where these villages complain upstream villages do not abide by water withdrawal agreements. Of the farmers interviewed, all said they do not have access to enough water and declared water as the main limiting factor for yield amongst other factors such as soil quality. The main concerns for the future proved difficult to communicate with two farmers answering that they cannot think about the future if they do not have water now. In reference to water availability, another farmer mentioned that people are migrating to Russia because agriculture is getting too difficult.

5.3. Spatial Assessment of Water Scarcity in WUAs

In this section results from 5.1 and 5.2 are integrated using the concurrent triangulation strategy (Figure 2.), to assess how perceptions of water scarcity within Khalmion and Alma-Suu WUAs relate spatially with CWC (ETa) and CWD (ETpot) maps. Based on the results provided in 4.2, there are clear differences in perceptions of water availability both between different WUAs and within them. Firstly, spatial observations are made for Khalmion WUA and specific field plots. Secondly, since many farmers in zone 9 attributed their lack of water to Jangy-Alyll, this enclave is also assessed. Lastly, spatial observations are made for Alma-Suu WUA.

CWC and CWD maps for Khalmion WUA can be seen in Figure 6. This figure includes Jangy-Alyll and the specific field plots investigated where field 1 corresponds to the farmer who did perceive water availability as a problem and field 2 corresponds to the farmer that did not. Downstream village subunits experiencing problems with water availability (7,9,12 and 13) and upstream subunits without problems (5), are included in Figure 6 for reference. As Figure 6a) shows there is a visible difference in CWC across the WUA. The highest levels of consumption seem to be clustered in the southernmost part of the WUA, whereas consumption seems to be lower in downstream areas from the centre to the north of the WUA. With a standard deviation (SD) of 204.34, there is a high degree of variance in consumption. As shown in Figure 6b) CWD is relatively homogenous across the WUA with no observable differences between upstream and downstream areas. This is reflected in a low S.D. of 22.80. This is interesting as the figures suggests demand for water is not being met in the downstream areas of the WUA. Since there is a disparity between demand and consumption these differences are likely to be caused by differences in water availability as opposed to crop type. These visual observations suggest that there is a difference in water availability within the WUA. On the surface this supports the spatial disparity highlighted in the interviews. These being that downstream users were reported to have more problems and perceived water availability as a bigger problem than upstream users.

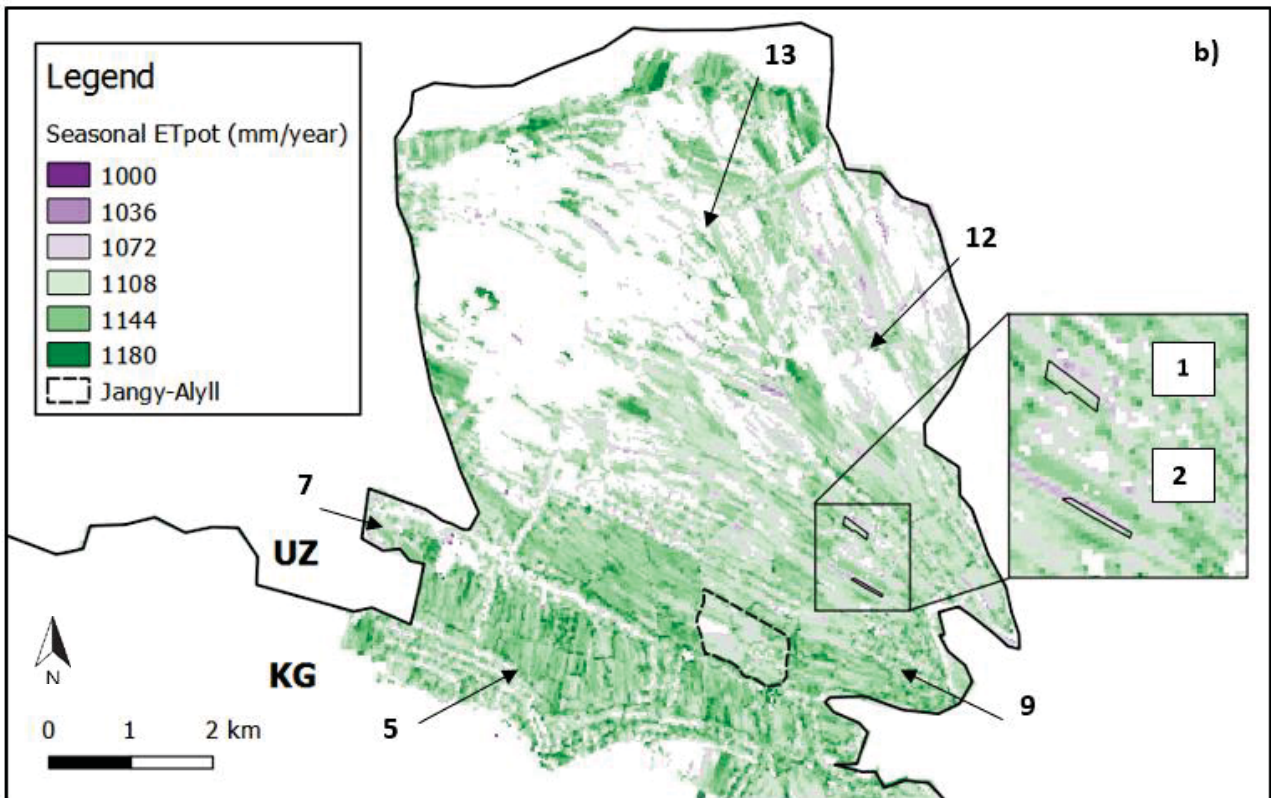
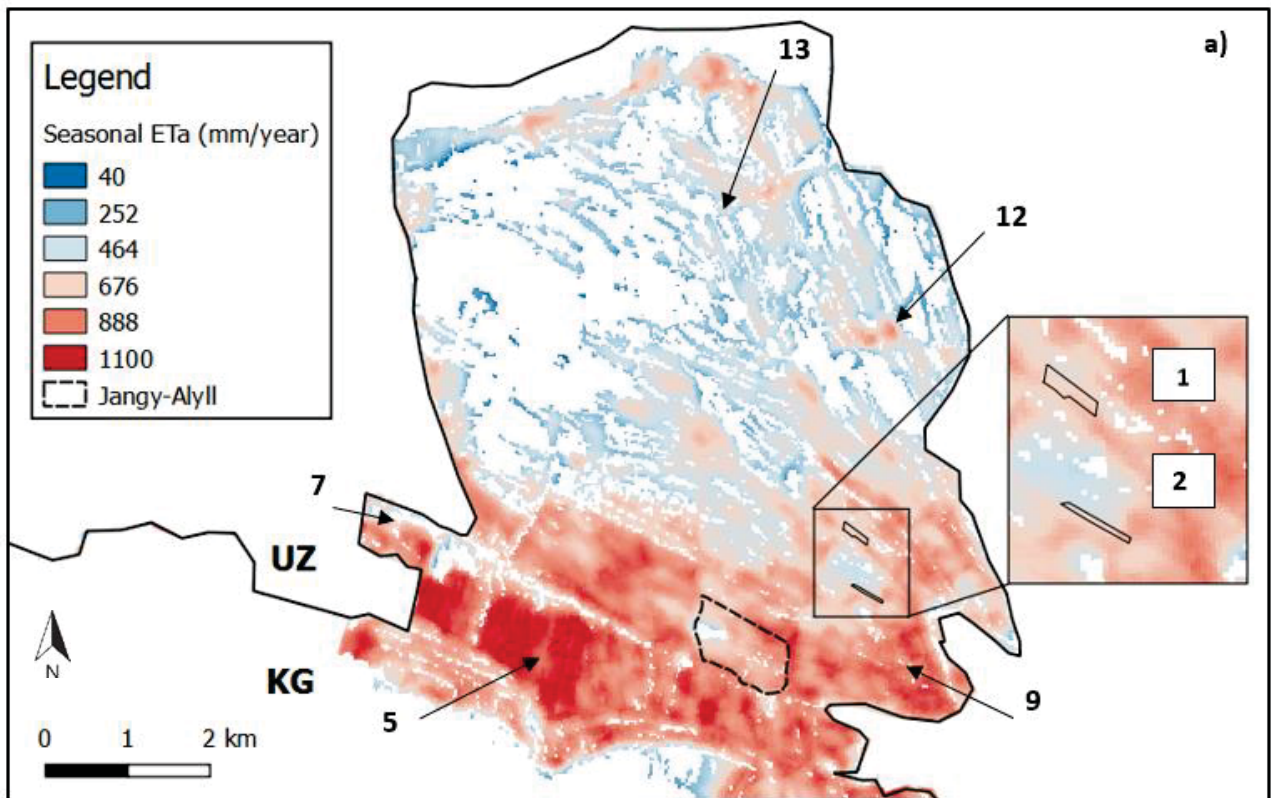


Figure 6. Showing a) seasonal ETa and b) seasonal ETpot maps of agriculture in Khalmion WUA for 2016. The enclave Jangy-Alyll and upstream zones 5 and downstream zones 7,9,12 and 13 are included for reference. Numbers 1-2 correspond to the two specific field plots studied.

Statistically, the average of CWC and CWD for fields 1 and 2 are 672.93mm/year (SD=34.11), 1110.30mm/year (SD=17.47) and 642.51mm/year (SD=56.21), 1089.93mm/year (SD=22.34) respectively. This indicates that the consumption and demand between the field plots are not statistically different. Furthermore, both field plots seem to have a large water deficit and therefore may be limited by water. As shown in Figure 6. the enclave seems to have a lower CWC (ETa) and a similar CWD (ETpot) than immediate surrounding areas. The average CWC and CWD of the enclave is 762.33mm/year (SD=98.92) and 1115.00mm/year (SD=19.73). This suggests that there is a water deficit in the enclave and that the consumption is not overwhelmingly higher than surrounding areas.

To reiterate, Alma-Suu did not report any problems with water availability and there were no differences in perceptions between the villages. The two villages interviewed are shown in Figure 7 for reference. As shown in Figure 7 both CWC in a) and CWD in b) seems to be homogenous across the WUA. Compared to Khalmion there are no obvious differences across the area and it is not obvious which areas are upstream and which are downstream. The SD of CWC and CWD are 131.00 and 23.11 respectively. The SD of CWC is lower than that of Khalmion and the SD of CWD is very similar. The slight differences in consumption observed between field plots seem to be in line with slight differences in water demand. This suggests that there is not much variance across the WUA and that the differences observed are likely to be due to crop type rather than water availability. These spatial observations align with what was reported in the interviews where no spatial disparities were reported and all stakeholders said that water availability was not a problem.

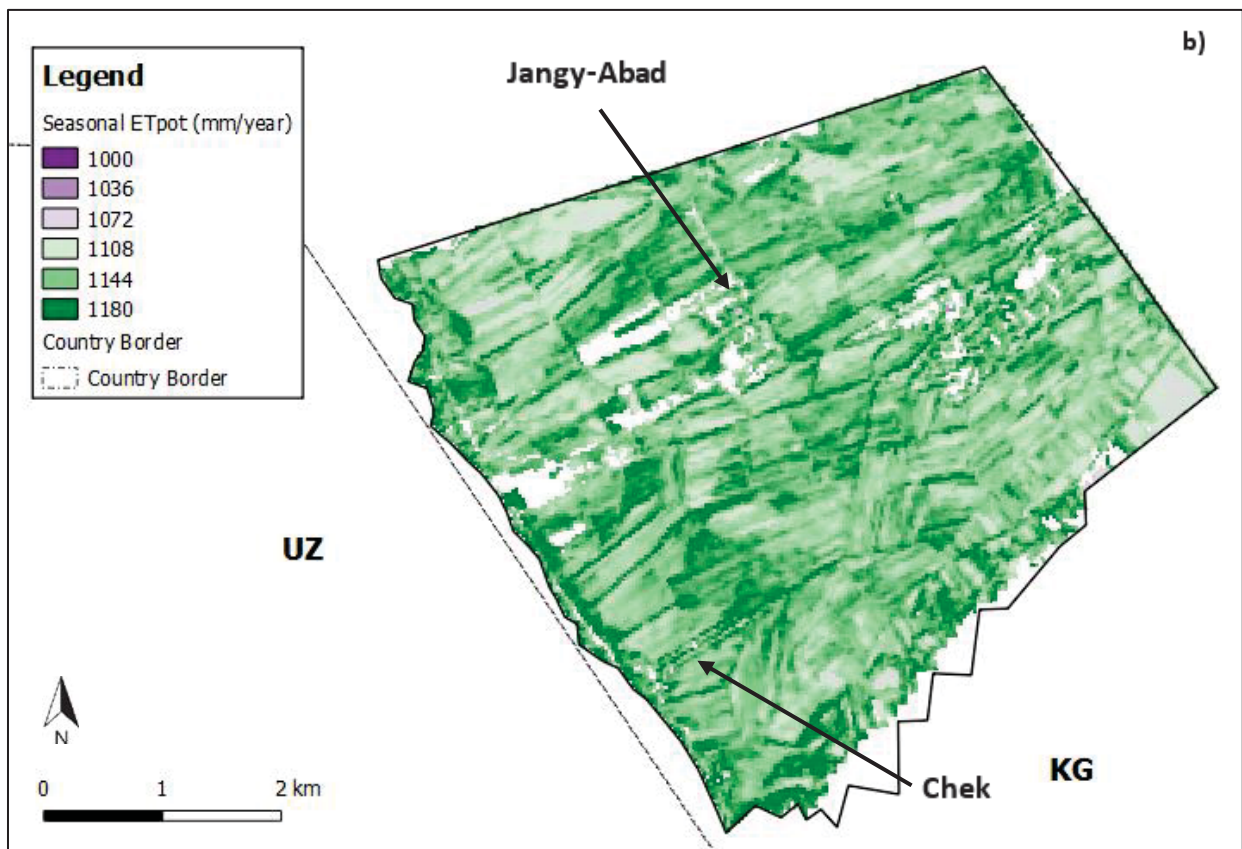
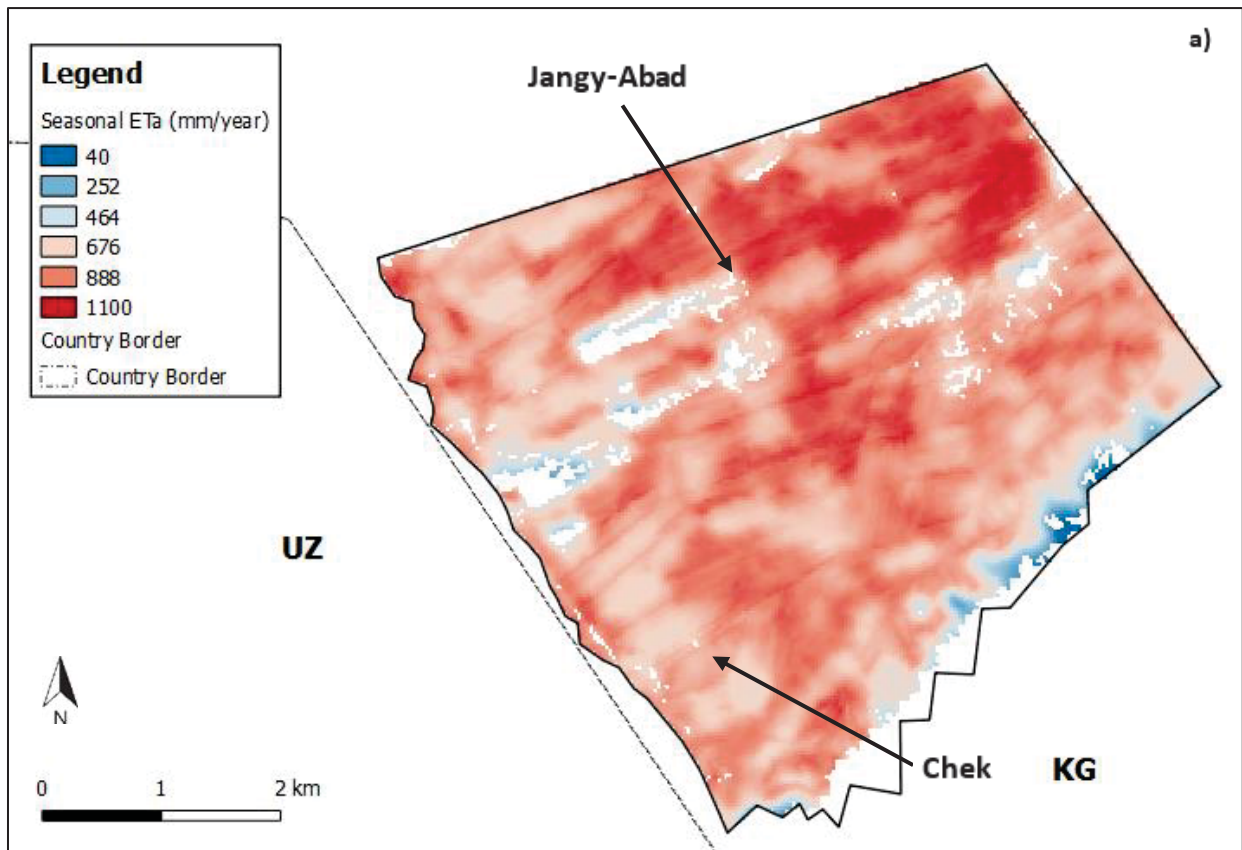


Figure 7. showing a) seasonal CWC and b) seasonal ET_{pot} maps of agriculture in Alma-Suu WUA for 2016. The villages interviewed Jangy-Abad and Chek are shown for reference.

5.4. Water Management Challenges

The results from the interviews revealed multiple shared and unique challenges experienced by the WUAs. From the content analysis, I grouped the main challenges experienced by all WUAs into three interlinking categories: distributional, technological and support based challenges. Each category has several subcategories which are summarised in Table 1. The particular subcategory discussed in each WUA is shown in Figure 8. The figure shows which subcategories were mentioned and shared by each stakeholder. These challenges are discussed briefly per category, including more detail about the shared and unique subcategories experienced in the WUAs.

Table 1. Summary of the main management challenges experienced by the WUAs, organised into categories and constituent sub-categories.

Distributional	Technological	Support
<ul style="list-style-type: none"> • Poor Channel quality • Lack of Transboundary Cooperation • Land fragmentation • Corruption • Natural Disasters • Deficient groundwater pumps 	<ul style="list-style-type: none"> • Outdated information • Insufficient Monitoring & control • Irrigation inefficiency • Lack of Expertise 	<ul style="list-style-type: none"> • Inadequate governmental support • Insufficient financial support



Figure 8. Display of the main subcategories discussed by each stakeholder group in each WUA.

5.4.1. Distributional Challenges

The first and most prominent distributional issue shared by all WUAs is the poor quality of irrigation channels and related infrastructure like channel gates. As observed in figure 8, every stakeholder group in all WUAs discussed this as a concern. The main problems communicated included the level of deterioration, lack of cementation, inability to control flow, high amount of losses to the ground, susceptibility to blockages and the overall low holding capacity. To deliver agreed amounts of water to users, Khalmion WUA needs to overestimate water demand to account for these losses. A related issue discussed by farmers in Toolose was the lack of working groundwater pumps and the subsequent reliance on the channels as the main source of water. Since most of the water comes from these channels, water availability is tightly linked to channel supply. Farmers in Toolose complained that cuts in channel supply occurs too often and are left with not enough water as a consequence.

This leads into the issue of natural disasters discussed by Alma-Suu and, to a lesser extent, Toolose WUAs. Landslides occur frequently in both areas, blocking irrigation channels and limiting the supply of water. According to the WUA director in Alma-Suu this has stopped the flow of water for 15 days in the past. Since the WUAs are reliant on channels, when this happens water must be sourced from other areas which costs money and time. This was mentioned as being especially problematic for farmers who need water at critical times during the season. Furthermore, the water is usually highly sedimented and can cause health problems if used for drinking.

For Khalmion, a prominent concern revealed was a lack of transboundary cooperation between the small Uzbek enclave, Jangy-Alyll. All stakeholder groups mentioned this as a problem, claiming that the enclave uses too much water, pollutes the remaining water and does not maintain irrigation networks (see Figure 9). It was revealed that one channel (P-1, see Figure 5, p20) runs through this enclave before reaching Khalmion farmers in zones 9 and 12. The WUA must send surplus amounts so that the users downstream of the enclave can receive water. Many stakeholders complained that the enclave is uninterested and does not want to talk or cooperate. A related issue that is likely to exacerbate this lack of cooperation, is the suspicion of corruption at the upper government level discussed by the local government. It was hinted that the district government is selling water to the enclave illegally. Lastly, a problem discussed in Khalmion by local government and farmers is the fragmentation of land caused by population growth and the increased demand to work in farming. The local government and farmers complained that water needs to be divided amongst more users and more (usually small and uncemented) channels need to be created to water these fragmented fields.



Figure 9. Showing a highly littered and sedimented channel immediately downstream of the enclave (left) and broken channel gates (right) in Khalmion WUA (03/17).

5.4.2. Technological Challenges

It is quite clear from the analysis that all WUAs lack the technological capacity needed to fully optimise the effectiveness and efficiency of management. One of the core issues apparent in all WUAs is the inability to effectively monitor and control water delivery and water use. One of the most prominent technological weaknesses attributed to this, is the lack of measurement devices on the channels. Based on the information received about the procedures of water delivery, all WUAs estimate water delivery by time and deliver water in an order. Without measurement devices the WUA directors reported that allocating water accurately and fairly to individual users is difficult, with a high probability that some farmers may get more or less than was agreed and that some users may be disadvantaged by the irrigation order. This limitation is compounded by the fact that WUAs cannot properly enforce or monitor this allocation. One farmer in Toolose, mentioned that there are water codes in place to prevent the misuse of water but this is not monitored or enforced. Some farmers in Khalmion mentioned in their interviews that they must watch the gates for the whole duration of allocation in case someone closes the gate to water their own field.

Another major hindrance discussed by all WUA directors is the lack of updated information on crop water demand. WUAs use regional crop water demand information created by the Soviet Union. However, the directors complained that this information was too old and may be inaccurate now. Similarly, a concern communicated in Alma-Suu and Toolose WUAs is the lack of technical experts within the WUAs and in the upper government. Based on responses about WUA structure, most WUA directors are accompanied by experts such as hydrologists, accounts and engineers. However, many people believed that there are not enough experts for the WUA to work optimally and the lack of experts in the government makes this problem worse. A further issue that is quite apparent in all WUAs, but only discussed in Khalmion and in relation to salinization, is the lack of technical irrigation systems. There was only one farmer who had installed drip irrigation for their farm in Khalmion WUA. This farmer discussed a lack of water use efficiency in irrigation as a major challenge for management and water use in the WUA. Similarly, in Toolose irrigation inefficiencies were mentioned in relation to issues with soil salinity where 300ha of land are affected. The WUA director of Toolose attributed this salinization of soil to irrigation inefficiency and a lack of improved systems.

5.4.3. Support Challenges

Lastly, a lack of support was highlighted as a significant impediment to management. The lack of support experienced is relatively similar between the WUAs with some placing a larger significance on certain aspects than others. One of the biggest challenges shared by all WUAs and mentioned by all stakeholder groups was a lack of financial support. The detrimental effects of which are related to

many of the challenges previously discussed. This point is separate from governmental support because these financial difficulties are also caused by water users paying too little, too infrequently or too late at the end of the season. For Toolose the money they receive is quickly lost to the government who takes more than half of the irrigation service fee paid by farmers. Insufficient funds prevent the WUAs from improving or making repairs on the channels, hiring more experts during pivotal times in the season and obtaining technical equipment or machinery. For example, all the WUAs have plans to improve the channels but cannot afford it themselves and need to apply for funding from the government or international donors. Similarly, Toolose WUA can only afford to hire the hydrologists intermittently and Alma-Suu have to hire machinery privately as they cannot afford to buy their own machines. Additionally, many people believed that the WUA staff and technical experts are underpaid and thus cannot work as effectively.

For all WUAs it was stressed that they receive very little support from the government. Most complaints focused on aspects related to management, planning, finances and a lack of conflict mitigation. For example, the Toolose WUA director discussed a lack of adequate planning by the government as a severe hindrance to management. In the past they used to deliver plans stating which crops to grow and for how many hectares. Now, no such plans are provided and the WUA is unable to cope and adapt management plans in accordance with changes in the crops grown every year. With financial restrictions limiting the extent the WUA can work and hire experts, this limitation is made worse.

6. Discussion: Implications for Water Scarcity and Potential for Improvement

6.1. Agricultural Water Use

As reported in section 4.1, agriculture within the valley consumes and demands large volumes of water. No studies thus far have quantified the consumption of agriculture specifically for the valley for 2016 in absolute terms. However, if compared with the average volume of water available from surface water in the valley (26.2km^3) and the estimated annual withdrawals for the valley (10km^3), agriculture consumes ~30% of total surface water available and ~81% of withdrawn water respectively. These results are in line with previous literature, suggesting that agriculture consumes large quantities of water and represents the majority of withdrawals within the valley (Wegerich *et al.*, 2015; ICG, 2014; Frenken, 2013). This supports the assertion that agriculture has a large role in altering the flow and availability of water within the valley and thus water scarcity (ICG, 2014). Furthermore, this supports the use of the hydro-social cycle as a conceptual framing; showing that socio-ecological interactions can significantly drive the flow of water in an area or system (Linton & Budds, 2014). Mapping this spatially adds another dimension to this information, revealing precisely how and where CWC and CWD differs across the valley. Based on the maps produced, there are clear differences in CWC and CWD demand across the valley.

As noted in the results, there are some areas where CWC and CWD do not align, suggesting differences in water availability for agriculture across the valley (Karatat *et al.*, 2009; Bos *et al.*, 2005). Observations of these differences can give some indications about areas with water shortage and subsequently water distribution, as shown within the WUAs in section 4.2. In absolute terms, the difference between CWC and CWD is quite large, suggesting that the whole valley has a potential water deficit of 6.7km^3 . However, it is more likely that this deficit is a result of distributional deficits from allocation and conveyance inefficiencies in channels rather than supply based deficits. On the regional scale, differences might depict certain allocation decisions for 2016 or may reflect past hydrological development by the Soviet Union where the distribution was prioritised to areas growing certain crops like cotton (Kreutzmann, 2016).

However, without accurate validation from ground measurements, the estimations of ET_a and ET_{pot} can only give broad indications and require further study before concrete conclusions can be drawn. Although the method has proven to be quite reliable (Gowda *et al.*, 2008), due to the size of the area it is likely that there are inaccuracies with certain estimations of climatic variables, such as with temperature. Although accuracies may not be 100%, this is the only method to calculate ET_a and ET_{pot}

over such a large and spatially different environment. Furthermore, the maps still provide valuable insights into the recent consumption and spatial variance of consumption within the valley. This information helps to better understand how water use in agriculture impacts water scarcity and helps highlight target areas for improved or altered water management decisions. Whilst these maps are presented on the regional scale, as is shown in the next section, these maps can be very useful for understanding the spatial variability of water scarcity on the local scale.

6.2. Perceptions and Spatial Assessment of Water Scarcity in WUAs

The results in section 4.2. and 4.3. uncovered some very interesting insights into water scarcity in the valley. Both Khalmion and Toolose WUAs experienced significant problems with water availability whilst Alma-Suu WUA only experienced problems in the event of a natural disaster. Furthermore, the results in Khalmion and Toolose highlighted that water scarcity was not equally shared within the WUAs, with downstream areas reported to have more problems than upstream areas. Interestingly, these results suggest that there is a high degree of spatial variation in water scarcity both on the regional scale and on the local scale within the WUAs.

The use of a triangulation strategy allowed me to compare the results from the remote sensing and the interviews to further investigate whether these perceptions are related spatially with CWC and CWD maps. The initial spatial observations from Khalmion and Alma-Suu WUA seem to support the perceptions discussed in section 4.2, showing that perceptions of scarcity are correlated with consumption and indications of water availability. On the surface this suggests that water availability for agriculture is an important determinant for water scarcity in an area. The differences in the spatial distribution of water availability between Khalmion and Alma-Suu can be explained by the management challenges discovered in section 4.4 or differences in hydrogeography. However, as discovered in the analysis of the field plots, even when water availability is very similar, the perceptions differed. This indicates that there are other factors than water availability that influence the perceptions of water scarcity for individuals. This can be explained by other socio-political influences on perceptions such as those induced by their socio-political environment (Mehta, 2007,2003). For these field plots, the difference in perception might be attributed to different perceptions about the Uzbek enclave. As noted, all stakeholder groups in Khalmion WUA blamed the enclave for much of their water availability problems and seemed to have a very negative attitude towards the enclave. This negative disposition may lead stakeholders to assume that the enclave uses too much water and as a result leaves them without enough water. However, as found in section 4.3, the consumption of the enclave seems to be only slightly higher than the field plots downstream. This

suggests that the extent of the complaints about the enclave are somewhat unwarranted. The difference in perceptions between the field plots may be explained by different influences on opinions from their respective socio-political environments (Mehta, 2007).

The differences in perceptions between the WUAs can be, in part, explained by differences in hydro-geography and size. Since the management challenges were very similar across WUAs, the differences observed are more likely to be due to hydro-geography and size. Both Khalmion and Toolose are downstream whilst Alma-Suu is upstream (Figure 3, p12). Alma-Suu may therefore receive more water than the two downstream WUAs. Furthermore, the area and population size of Alma-Suu is much smaller than the other WUAs. Alma-Suu may therefore have more water to distribute to fewer people. This assumed difference in water availability is reflected in observations in the field. In Khalmion and Toolose WUAs the main crops were wheat, corn, vegetables and fruit trees, whilst in Alma-Suu the main crops are cotton, rice and wheat. During the field work in Alma-Suu I observed many field structures for rice and large amounts of cotton crop residues in houses, on fields and along roadsides (Figure 10.). Moreover, the timing of the fieldwork coincided with the planting of crops, of which is a crucial time for water. During fieldwork in Alma-Suu most of the channels and fields were well watered, whilst the channels and surrounding areas in Khalmion and Toolose were dry in comparison. Cotton and rice crops are very water intensive and the comparative lack of these crops indicate differences in water availability. These observations indicate that there might be differences in water availability between Alma-Suu and the downstream WUAs. However, to more accurately assess this, more exact information on water availability and a larger comparison between upstream and downstream WUAs is needed.



Figure 10. Showing temporary cotton crop residue fences (left) and cotton residue piles (right) in Alma-Suu WUA (03/17).

6.3. Water Management in WUAs

As described in the results, there are a number of different challenges experienced and shared by the WUAs. Many of the challenges identified such as poor channel quality, insufficient expertise, outdated information, lack of monitoring and control and irrigational inefficiencies are in accordance with other studies assessing WUAs in the valley (Moss & Hamidov, 2016; Kazbekov *et al.*, 2009) and elsewhere in Central Asia (Awan *et al.*, 2011). I discuss how the challenges have a role in driving water scarcity in the Ferghana Valley; arguing that they may contribute to supply based, distributional and temporal water scarcity. This discussion is not exhaustive but focuses on the most influential challenges and relations to scarcity.

All WUAs suffered from the poor quality of the irrigation channels and had a low adoption rate of efficient irrigation systems such as drip irrigation. Both problems can lead to large losses of water and an unnecessary usage of water (ICG, 2014; Pereira *et al.*, 2009). For example, it is estimated that over half of withdrawn water is lost through leakages from channels and irrigation uses 1.5 times more water than recommended (Zhupankhan *et al.*, 2017; ICG, 2014). This loss of water is typical of irrigated systems in Central Asia and elsewhere in the world (Arumí *et al.*, 2009; Pereira *et al.*, 2009). As a result, this can reduce the total amount of water that can be distributed within WUAs and establish an unequal gradient where those furthest away from the channels or last in the irrigation order may have reduced access. Similarly, on a regional scale, these conveyance and irrigational losses can reduce the amount of water available for users downstream in the valley. Since surface water and groundwater systems are linked, these losses can be reclaimed from groundwater (Sophocleous, 2002). However, as observed in the interviews groundwater does not form a major source of water for the WUAs (Pereira *et al.*, 2009). Instead of being reused, this water builds up and raises the groundwater table level (Fernald & Guldan, 2006). This poses very dangerous risks of salinization, which can have disastrous consequences for agriculture and livelihoods (Saysel & Barlas, 2001). Salinization issues were reported in the interviews in Toolose WUA, and it is estimated that 28% of irrigated land suffer from salinization with 31% of land having a water table within 2m (Savoskul *et al.*, 2003). Whilst this problem is a consequence of inefficient irrigation management, it can also contribute to scarcity directly if large volumes of water are used to flush the salts in problem areas (Podmore, 2009).

Furthermore, upstream users might primarily employ inefficient practices as there is less pressure to invest in technologies compared with downstream users. In fact, the only user of drip irrigation in Khalmion WUA was in the downstream subunit 9 and was forced to invest because water availability was such a limiting factor. A further indirect effect of inefficient irrigation practices is the pollution of water from field sediments, salts and agro-chemicals (Cai *et al.*, 2003). This was not studied explicitly

but alluded to in interviews about water availability. As noted in section 4.2, downstream farmers in Khalmion reported that many people rely on the irrigation channels for drinking water. This reflects a failure of drinking water initiatives and the enduring influence of the breakdown of the Soviet Union where lack of funds and support has led to the decline in drinking water infrastructure (Rost, Ratfelder & Topbaev, 2015). As a consequence, many farmers said that people's health is at risk and many get ill. This raises questions about the quality of water in the channels. Irrigation may pollute water in earthen and unlined channels through run-off and seepage (Cai *et al.*, 2003). This reduction in water quality can exacerbate existing scarcity if pollution prevents people from using it for uses such as drinking (Rijsberman, 2006). Downstream WUAs and downstream users within WUAs are also at further risk as the pollutants are likely to accumulate as water travels through the irrigation networks and fields.

Similarly, a lack of monitoring and control in all WUAs may also create an unequal gradient of access. For example, users upstream may receive more water because the WUA cannot measure the allocation accurately or because the WUA cannot stop upstream users from taking more than they need. This was reported in Khalmion and Toolose WUAs where downstream users complained that upstream users take more water than agreed, leaving them with not enough. This inequity in access may also mirror and exacerbate differences in power between water users. Power can be broadly defined as the ability to obtain and exercise leverage or influence so that interactions between other people or the environment are more favourable (Turner, 2005). Simply from geography upstream users may have more power over downstream users because they have more access and potentially control over water resources. Differences in water availability may translate into differences in wealth and consequently power and influence (Turner, 2005). Furthermore, there may be lingering power relations from the Soviet Union that still have an influential role in current management (Sehring, 2007). Whilst WUAs are a collective form of management, this inequity in power relations may influence the representation of certain users within the WUA and influence collective decision making, such as those concerning the enforcement of water withdrawals or allocation decisions (Turner, 2005). Upstream users who have a greater power over downstream users may influence the decisions to be in their favour to the disadvantage of downstream users. This may be compounded by the lack of technical information and measurement devices which prevents users with less power from being able to prove if they have been disadvantaged (Faysse, 2006).

Population growth and the subsequent fragmentation of land can also have large implications for water scarcity. Although this issue was only reported for Khalmion, the population is expected to double in the valley by 2030 and is therefore likely to become problematic (ENVSEC, 2005). An

increased number of water users will reduce the absolute amount of water that can be distributed amongst people and will make the management and fair distribution of water harder to accomplish. This is likely to deepen existing inequalities in distribution and access to water in the valley. Furthermore, as discovered in Khalmion WUA, more channels need to be built in order to water these fragmented fields. Increased channels and the subsequent increase in water losses may exacerbate many of the problems previously discussed. Power may also have a role in determining the location of fragmented fields. If upstream users have more power than downstream users, they are less likely to need to sell their land to others or may influence the decisions made by the government on where land should be divided. If more fields are divided in downstream areas where users have less power and wealth, this would exacerbate inequalities previously discussed.

However, without further information measuring losses, water delivery per user or power relations, the extent of these problems and their relation to water scarcity is hard to gauge. Nonetheless, the spatial observations of perceptions of scarcity can give some insights into how these problems may affect water availability. For example, in Khalmion WUA I observed that overall perceptions of scarcity correlate with lower CWC and lower water availability across the WUA. This can be explained by the problems associated with the channels, irrigation efficiency and a lack of monitoring and control discussed. Reductions in water availability caused by these problems can account for the lower water consumption in downstream areas observed in Khalmion WUA. A study assessing the performance of WUAs in the valley support this, showing that WUAs performed badly when it came to the equity of distribution (Kazbekov *et al.*, 2009). However, as observed in the specific field plots in Khalmion WUA and interviews in Alma-Suu WUA, these problems might not necessarily lead to water scarcity. As explained in 5.2, this may be due to different socio-political influences on perceptions of water scarcity or in the case of Alma-Suu, hydro-geographic and demographic differences.

I also argue that the reliance on irrigation channels observed in the WUAs can contribute to temporal water scarcity even if water scarcity is not usually an issue. This reliance makes the users vulnerable to further deterioration of the channels and cuts in supply; affecting the ability to supply water in the future and in an unexpected event such as a natural disaster. For example, as discovered in Alma-Suu WUA, the blockage of channels from landslides can have quite damaging effects on water supply. During this time, the competition for water is likely to be very high, reducing the total amount that can be shared amongst the same number of people and potentially exacerbating current inequalities in access. Furthermore, the valley is predicted to have increased natural disasters such as landslides and flooding due to increased snow and glacial meltwater (ENVSEC, 2005; Savoskul *et al.*, 2003). These

natural disasters can have devastating effects on the Ferghana Valley, especially in areas close to the mountains (ENVSEC, 2005).

The issues mentioned thus far are further compounded by a lack of financial and governmental support. If the WUAs do not have the ability to improve the channels, the amounts of water lost will only increase as the channels deteriorate further. Similarly, unless adequate measurement devices are installed or the enforcement of allocation improves, the distribution of water may continue to be unequal across the WUA. An indirect outcome from this lack of support, is the reliance on aid from donors. Khalmion and Alma-Suu WUAs receive support from either international or national donors. Based on the interviews and conversations during field work it seems the most of the noteworthy progress achieved in the WUAs is related to this support from donors. This reliance on donors and lack of governmental support suggests that either the government doesn't have the capacity to adequately deal with these issues or they are not prioritised.

It is important to note that all study locations were within Kyrgyzstan. Therefore, much of the results are within the Kyrgyz context and socio-political differences between the more state controlled countries of Uzbekistan and Tajikistan and the more democratic Kyrgyzstan are unaccounted for. Socio-political and legal differences surrounding the WUAs may result in different challenges and require different solutions (Moss & Hamidov, 2016). For example, differences in land reforms between Kyrgyzstan and Uzbekistan have resulted in large differences in farm size (individual vs collective state owned) (Wegerich, 2000). Similarly, the growth of crops in Uzbekistan is state controlled compared with Kyrgyzstan where farmers have the freedom to choose (Moss & Hamidov, 2016; Wegerich, 2000). These differences may require different management strategies and solutions. However, the study locations still account for various spatial and geo-political differences within the valley including upstream vs downstream locations, proximity to borders and even the inclusion of an enclave. These study areas therefore provide valuable insights into WUAs that vary hydro-geographically and socio-politically. Nevertheless, the remote sensing was produced on the regional scale and therefore is not restricted by administrative boundaries or socio-political differences. These maps can be applied within the socio-political context of each respective country and can therefore extend beyond the scope of this study and be used in regional and transboundary management or research.

6.4. Potential for Improving Agricultural Water Use and Management

Research within sustainability science aspires to be “solution-oriented, socially robust [...] and transferable to both the scientific and societal practice” (Lang *et al.*, 2012, p27). Hence, in this section

I briefly outline how this thesis can point to potential solutions and how it can be used beyond the academic nature of the thesis itself. The results from each method alone can provide useful information for improving water use and management in agriculture. However, the combination and application of the 8588 results from each method can better highlight problem areas, target points of intervention and evaluate existing projects or solutions. The potential to improve agricultural use and management, within the overarching aim to improve water scarcity, is discussed briefly here.

Firstly, the remote sensed evapotranspiration maps allow consumption to be assessed spatially, giving indications of areas that are consuming a lot of water and areas that may have a shortage. Consequently, these maps can help improve water scarcity by helping to inform water management and planning decisions and facilitating the evaluation of existing management or solutions (Droogers & Immerzeel, 2008; Bastiaanssen & Harshdeep, 2005). For example, the remote sensed maps can help target and adapt water allocation over an area, aid the monitoring and enforcement of consumption and help assess how consumption or water shortage is influenced by certain solutions (Fisher *et al.*, 2017; Thevs *et al.*, 2014; Allen *et al.*, 2007). Remote sensing can also increase the transparency of management as it presents unbiased information, showing exactly how much is being consumed and where (Lopez-Gunn & Ramón Llamas, 2008). If combined with existing management, this can help ensure unbiased monitoring and control of consumption and thus may also help alleviate potential consequences of unequal power relations previously discussed. Remote sensing of evapotranspiration is used in a number of studies to evaluate the performance of irrigation delivery in WUAs (Awan *et al.*, 2011; Kazbekov *et al.*, 2009; Karatas *et al.*, 2009). However, these studies focus mainly on hydrological indicators of performance and are not able to fully assess the impacts of management on areas such as water scarcity. As demonstrated in my thesis, the addition of social aspects can provide valuable information that can help better understand and subsequently assess management in WUAs. For example, in understanding why and how there may be differences in consumption in an area and understanding problems that extend beyond irrigation performance.

By investigating the major challenges for management in WUAs, I highlight multiple points of intervention for improving local water management. Solutions and initiatives can focus on the three main categories and subcategories identified in section 4.4 as a starting point. The results indicate that both technical and socio-political orientated solutions are necessary for improving management. For technical solutions it is likely that improvements to channels, irrigational efficiencies, the utilisation of ground water and enhanced technological capacity are likely to have substantial positive effects on both the management and use of water within WUAs. For example, the repair and construction of new groundwater pumps within the WUAs can help address many of the problems discussed. Firstly,

the sustainable abstraction of groundwater can help address the unequal gradient of access by increasing the amount of water that can be supplied to users, especially if installed in downstream areas (Pereira *et al.*, 2009). If managed properly this extraction can be matched with the recharge rate of groundwater from channel leakage and irrigation. This will help to recycle the water lost from conveyance and irrigation inefficiencies whilst ensuring the groundwater is not depleted (Pereira *et al.*, 2009). Furthermore, this can help to regulate water-table levels and consequently reduce or prevent the salinization of soils (Ayars *et al.*, 2006). Lastly, by providing an alternative to surface water, groundwater can help reduce the vulnerability associated with the reliance on channels, such as in Alma-Suu.

Although the results do not indicate the relative importance of each challenge explicitly, the fact that technically based problems were highlighted by multiple stakeholder groups in every WUA signifies the necessity to improve them. This is in line with current efforts to improve management. For example, much of the work conducted by the WUAs are focused on improving channels whilst farmers are beginning to invest in more efficient irrigation systems such as drip irrigation (Field work, personal communications). Similarly, work implemented by donors focuses on either improving the channels (Figure 11.), installing technical equipment, delivering training and/or providing technical assistance (Bischel, 2011; Helvetas, Rural Advisory Service & GIZ, personal communication, 03/17).

It is important to note that the application of the remote sensing maps may be limited without external support from other actors or improvements in expertise. As highlighted in the results, the WUAs lack the technical capacity to measure required information such as water delivery and lack technical expertise. This may prevent the WUAs from conducting or utilising the remote sensing maps by themselves. This further highlights the limitation of a lack of technical capacity and the lack of financial or governmental support. In addition to improving technical capacity, research and donor organisations can help improve this through participatory research and management, for example in participatory geographical information systems knowledge generation (Lopez-Gunn, & Ramón Llamas, 2008; Rambaldi *et al.*, 2006). Participatory approaches have shown to improve the inclusiveness and ownership of management by involving stakeholders in the generation and analysis of information (Rambaldi *et al.*, 2006). Through this process stakeholders may become more empowered whilst also learning valuable technical skills that may help them replicate the information generation processes (Rambaldi *et al.*, 2006).



Figure 11. New irrigation channel and gates constructed using European funding in Alma-Suu WUA (03/17).

Whilst many of the more technically orientated challenges are being targeted, the information from this thesis also points to other, more socio-political, areas which may prove to be invaluable in improving water management and water scarcity. For example, a lack of governmental support was highlighted as a major limitation for management. Although my study did not investigate the relationships and influences of upper government, my study can still contribute to initiatives addressing this challenge. For example, I argue that the dissemination of information gained in this thesis to other actors can help improve government support by improving the integration between upper and lower management levels. One of the aims within sustainability science is to extend research beyond academia to “establish profound understandings that can be harnessed and used by society” (Jerneck *et al.*, 2011, p80). I achieve this aim by producing local and regional information that can be applied beyond the scope of this study and by sharing the results with other actors such as ICRAF, GIZ and Kyrgyz upper government. For example, the results are planned to be shared with a Kyrgyz governmental unit implementing the [Kyrgyz] national water resources management project phase-1 (NWRM-1). The project is primarily focused on making information about water resources available across Kyrgyzstan and making improvements to water management (project director, personal communication). For example, it is composed of three components to 1) strengthen national water management capacity, 2) improve irrigation service delivery to WUAs and 3) improve irrigation management by WUAs (project director, personal communication). The results can be useful for components 1) and 3) especially; where component 1 includes creating a fully accessible database of information regarding water and other hydrological aspects in Kyrgyzstan and component 3 includes assessing and strengthening of WUAs. Hence, I hope that sharing information with this project will

help to achieve these objectives and improve the integration of knowledge and support between levels of governance levels.

6.5. Future Direction

In this thesis I was able to investigate many factors within agriculture and water scarcity. However, there are a number of additional factors that may have significant influences on scarcity and which may unveil other points of intervention. For example, I was unable to map the consumption of water for specific crops. As is well known, cotton is a water intensive crop that dominates the region (Bischel, 2011). Therefore, it would be interesting to see where it is grown in the valley and how much water is consumed relative to other crops and the total consumption of agriculture. This would give important insights into how crop choice may influence water scarcity in absolute terms and spatially. Secondly, the investigation within the WUAs can be expanded on by investigating socio-political factors that may influence the management of water in agriculture. For example, the influence from upper government or institutions within and between different countries, potential power relations between users and potential misrepresentation of gender within WUA governance structures (Garces-Restrepo *et al.*, 2007; Abdullaev & Yakubov, 2006). Future research should expand on the remote sensing and investigate these socio-political differences further to gain additional knowledge on how water management and influencing factors may drive water scarcity in the region.

7. Conclusion

Despite having adequate sources of water, the Ferghana Valley suffers from water scarcity. This scarcity is highly complex and is influenced by many interconnected factors from history, the climate and society. Through the integration of both hydrological and social methodology this thesis was able to gain more detailed and contextualised insights into agriculture's role in driving water scarcity in the valley. Based on the results presented, I conclude that both the use and management of water has profound influences on various dimensions of water scarcity in the valley, including impacts on water availability, access, distribution, water quality and temporal vulnerabilities to changes in supply. By creating a multi-scalar research design, I could delve deeper into the complexities of water scarcity and the role of agriculture on both the local scale and on the regional scale.

Through the results presented, I show how the multi-faceted nature of water scarcity and the socio-ecological interactions with water cannot be ignored in research or practice. Furthermore, the insights gained in this thesis support the concept of the hydro-social cycle, suggesting that societal interactions with water, such as those in agriculture, has a large role in driving the flow and altering the availability of water in an area. Through this methodological design and the incorporation of concepts from sustainability science I produced replicable and applicable results whilst also commenting on potential solutions and applications of the research. This thesis therefore compliments existing research whilst forming a good foundation for future research and applications.

8. References

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Appendix A

Table 2. The number of stakeholders interviewed in each WUA

Khalmion	Alma-Suu	Toolose
<ul style="list-style-type: none">• WUA director• Head of Local Government• Land Use Expert• Farmer (x8)	<ul style="list-style-type: none">• WUA director• Farmer (x2)	<ul style="list-style-type: none">• WUA director• Farmer (x3)

Appendix B

Example questions on water management to WUA directors:

- *What services does the WUA provide?*
- *How is the water distributed within your WUA?*
- *Are you able to satisfy the water demands of all users?*
- *How would you assess current water management by the WUA?*
 - o *What are the challenges?*
- *What are the main concerns for water in the future?*

Example questions to farmers:

- *Do you consider yourself to have access to enough water?*
- *What are the main factors limiting crop growth?*
- *What are your main concerns for water in the future?*
- *How would you assess current water management by the WUA –*
 - o *What are the challenges/ what can be improved?*

Appendix C

Text Box 1: S-SEBI Estimation of ET_a

To measure λE , the energy balance equation needs to be solved (equation 1) (van der Tol & Parodi, 2012; Bastiaanssen *et al.*, 1998).

$$R_n = G + H + \lambda E \quad (1)$$

where R_n is net radiation, G is soil heat flux, H is sensible heat flux and λE is latent heat flux [w/m^2]. Energy balance methods are referred to as residual methods because it solves the energy balance equation by calculating λE as a residual of the equation (equation 2) (Bastiaanssen *et al.*, 1998).

$$\lambda E = R_n - G - H \quad (2)$$

The S-SEBI method utilises the evaporative fraction (ET_f) and ET potential (ET_{pot}) to estimate λE as ET_a as follows (Roerink, Su & Menenti, 2000)

$$ET_a = ET_f \times ET_{pot} \quad (3)$$

Firstly, ET_{pot} is calculated by dividing R_n by the λE_v . Using spectral reflectance data and metadata, R_n is calculated from estimated components such as albedo and diurnal solar radiation (R_s) (Liou & Kar, 2014; van der Tol & Parodi, 2012; Thevs *et al.*, 2013). Scripts containing the relevant equations were used for the estimation of ET_{pot} (ICRAF, personal communication). Secondly, ET_f represents the realisation of ET_a from ET_{pot} . It works on the basis that land surface temperature (LST in Kelvin) and ET are linearly linked. It assumes that wet areas will realise the maximum ET_{pot} and have a low LST and that dry areas will experience the minimum ET_{pot} and have a high LST (Roerink, Su & Menenti, 2000). The method locates the extremes of temperature by finding cold (wet vegetated) and hot (dry non-vegetated) pixels in the images and calculates ET_f using equation (4),

$$ET_f = \frac{T_h - T_s}{T_h - T_c} \quad (4)$$

where T_h is the LST of the hot pixel, T_s is the LST of the pixel in which ET_f is calculated and T_c is the LST of the cold pixel (Roerink, Su & Menenti, 2000). Pixels were found for each elevation zone in each image using NDVI to help locate vegetated vs non-vegetated areas. These pixels were then averaged per image and elevation zone to find T_h and T_c . However, not all images had suitable hot and cold pixels to choose from. To rectify this, missing hot and cold pixels were linearly interpolated from neighbouring images and elevation zones. ET_f and ET_a calculations were done per elevation zone to account for temperature differences in elevation.

Appendix C (continued)

Text Box 2: NDVI

NDVI is a technique used to determine the distribution, density and health of vegetation in an area and can be used to create land classifications (Usman *et al.*, 2015; Lunetta *et al.*, 2006; Tucker, 1979). The method uses the following equation (5) to find the ratio of absorbed vs reflected light.

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \quad (5)$$

where NIR is near infrared (750 -1300nm) and VIS is visible red (600-700nm). The assumption is that densely foliated or healthier plants will reflect more NIR and absorb more VIS than unhealthier or less foliated plants. Here, NDVI is used to differentiate between vegetated and non-vegetated areas.