Opportunities to improve operation of smallholder canal schemes in Vhembe, Limpopo Province

Report to the
Water Research Commission
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EXECUTIVE SUMMARY

Background and rationale

Irrigation has been found to have positive impacts on primary production and livelihoods. The expansion of irrigated smallholder agriculture could therefore be one of the strategies for realising the job creation potential of agriculture in rural areas as part of South Africa's National Development Plan 2030. Whilst some of these smallholders would probably access water for irrigation independently, it is likely that the majority would be settled on smallholder irrigation schemes (SIS), to enable a shared use of the water source and irrigation system. However, the success of SIS in South Africa has been variable; many significantly improving the livelihoods of farmers while others have under-performed, with several of these in a state of total collapse.

Expansion of smallholder irrigation through the establishment of new SIS could help reduce structural unemployment and high levels of poverty that prevail in rural South Africa. However, in order to increase the potential for their success, the design and management of new SIS needs to be based on best practice distilled from lessons learnt on existing SIS. It is therefore imperative that the factors influencing underutilisation of existing SIS are investigated, and that opportunities for improved operation of these SIS are identified.

Studies in South Africa have identified a range of factors that affect SIS performance including inappropriate scheme design, ineffective operation and maintenance of irrigation systems, institutional and organisational deficiencies, and low levels of competency among SIS participants. However, farmers on SIS consistently highlight limited access to water, problems with access to land, and lack of access to markets as the main challenges they face. In general, social relations and institutional processes are the principal factors limiting access to land and water in SIS. However, little is known about the content of the institutions and the make-up of the organisational structures which smallholders would like to see in SIS. Moreover, since many SIS are old, various degrees of deterioration to the irrigation infrastructure has occurred, causing the systems to deliver water at levels that are below their design capacities. The factors affecting the performance of SIS, including the challenges faced by farmers in these schemes, form the basis for the aims and objectives of this study. Since these span across the human (institutional, social) and water domains, socio-hydrology, a recently conceived approach of integrating and coupling human-water dynamics was considered a realistic approach for exploring and finding effective solutions to the challenges faced by SIS.

Aims and objectives

The general aim and objectives of the study are:

General aim:
To assess the opportunities for improving the operation of smallholder irrigation schemes in Vhembe, Limpopo Province.

Objectives:

1. Review factors causing underutilisation of existing SIS with specific reference to water, land and irrigation infrastructure
2. Document and assess (i) existing design, operation and management of water resource distribution and (ii) existing institutions and organisations governing access to land and water on selected canal schemes.

3 Identify opportunities for improved design, operation and management for equitable water resource distribution and for institutional and organisational reform on these schemes.
4 Assess the applicability of socio-hydrologic modelling to aid decision making to improve the design, operation and management of SIS.

Approach and steps to achieving objectives

In attempting to achieve the study objectives, the approach taken consisted of the following main steps:

1 A review of the literature to examine existing knowledge on factors affecting underutilisation of smallholder irrigation schemes in South Africa. The factors of specific interest were the design, operation and management of canal schemes and the land and water institutions that exist in them.
2 The selection of appropriate smallholder irrigation schemes for the study. The Vhembe district of in the Limpopo province has a large number of small holder irrigation schemes and the contractual undertaking required the study to be conducted on three smallholder canal schemes in this district.
3 Desktop data collection of the selected smallholder irrigation schemes and the determination of other data required for the study. This task was undertaken at the time of the COVID-19 lockdown (when field visits were not possible) and was integrated with the search and selection of the modelling approaches and methods for achieving the study objectives. Some data analysis and preliminary modelling were also undertaken at this stage.
4 A detailed diagnosis of the current condition of the infrastructure of the study schemes.
5 The collection of field data consisting of a detailed hydraulic survey of the irrigation infrastructure and a questionnaire survey of the selected smallholder irrigation schemes.
6 The formulation of a detailed smallholder canal scheme conceptual socio-hydrologic model.
7 The search for opportunities for improving the performance of the study smallholder canal schemes and an evaluation of the applicability of socio-hydrologic modelling for this. This included:
   a. The assessment of the existing governance structures and how these could be improved for better scheme performance.
   b. Assessment of the applicability of socio-hydrological modelling for searching for improvements of scheme performance.
   c. Hydrologic modelling for a statistical determination of the expected water inflows in the study schemes.
   d. Hydraulic modelling of the study scheme for determining the levels of water supply to the schemes and for searching for modifications to the canal infrastructure and operation schedule for improving water supply
   e. Determination of the adequacy of water supply to the farms based on crop water requirements.

The literature review included a description of the history canal design, operation and management in South Africa and the existing social, water and land institutional structures that govern smallholder canal schemes. This enabled the identification of i) the factors causing underutilisation of the smallholder schemes; and ii) the likely opportunities for improving the operation of smallholder canal schemes with specific reference to design, operation and management and governance. A review of socio-hydrological modelling was also carried out and socio-hydrology was posed as a realistic approach for identifying opportunities for improving scheme performance.

The selection of the smallholder canal schemes for the study involved the shortlisting of potentially suitable schemes in Vhembe district based on set criteria. Thereafter, a week-long field visit was conducted and the most suitable schemes were selected based on additional criteria. The Raliphaswa, Mandiwana and Mamuhohi complex was selected as the study site. This complex of three schemes, each belonging to a different village but linked to each other by a shared water source of water and irrigation infrastructure, was particularly well suited to investigate opportunities for improved operation and management for equitable water resource distribution and for institutional and organisational reform. Water for the scheme is obtained from the Mutshedzi River through a diversion structure (Raliphaswa weir) and the main canals are 1.74, 2.11 and 1.96 km long for the Raliphaswa, Mandiwana and Mamuhohi Smallholder Irrigation Schemes respectively. The system consists of 14 long weirs for flow control, 19 furrows for diverting water into the farms and 2 flow measurement structures. Raliphaswa, Mandiwana and Mamuhohi have areas of 17, 66 and 92 hectares and hold 13, 40 and 61 farms respectively.

The lockdown during the COVID-19 pandemic prevented field visits for situation analysis and, therefore, desktop data collection and the selection of modelling approaches for meeting the study objectives were undertaken. The lockdown also provided an opportunity for the project team to undertake preliminary hydrologic, hydraulic and conceptual socio-hydrologic modelling, as these were not directly dependent on field data. The determination of the required data and the development of questionnaires for data collection were also undertaken at this stage. The development of the detailed socio-hydrologic model was undertaken at a later stage.

Field work was carried out in two days in November 2020 to diagnose the state of the canal and storage infrastructure at the study schemes. The field work was mainly focused on

i. determining the locations of flow control structures and their state of functionality and maintenance
ii. determining the functionality of the canal infrastructure based on the existence of blockages by objects, vegetation, sediments, leakages and overflows, condition of canal lining and stability of canal surroundings
iii. searching for the existence and locations of illegal/ informal abstraction. Significant observations on the management, governance and institutional aspects were also made during the field trips

In January 2021, a hydraulic survey and assessment of the irrigation infrastructure for purposes of calibrating the hydraulic modelling was carried out. The piloting of the questionnaire survey was carried out in March 2021 and this led to a restructuring and refinement of the questionnaires and the approach of conducting the survey. The main questionnaire survey was conducted over the months of July to October 2021.

Findings and opportunities for improving scheme performance

Governance structures

Data from the questionnaire survey revealed that the Scheme Committee was the main water governance structure of the schemes, while traditional leadership and informal water institutions (groups of farmers) also have significant recognition and roles. The results indicated that most of the farmers considered the management and governance to be satisfactory in most aspects. The occurrence of illegal water abstractions, the ineffective low fines for penalising farmers who do not follow the rules, and vandalism of infrastructure were highlighted as some of the inadequacies in management and governance. Shortage of water for irrigation also prevailed and led to low crop yields and reduced land utilisation for farming.

Based on the above challenges, the strategies for improving water governance in the schemes included:

i. engaging an independent full-time overseer of scheme operation
ii. increasing the fines for failure to comply to the rules and regulations
iii. registering the unregistered farmers to enable better control of water allocation
iv. ensuring that those vandalising canal infrastructure are held accountable for the required repairs

Socio-hydrological modelling

The search for quantitative socio-hydrologic relationships for the implementation of the socio-hydrologic conceptual model did not find any realistic relationships and changes in the approach to incorporating the social (human) aspects into the analysis were therefore made. Since the social (human) aspects relating to governance and management impact on the operation, maintenance and adequacy of infrastructure of the scheme, these were used as surrogates for the social (human) aspects. Three scenarios that correspond to various levels of adequacy of operation, maintenance and infrastructure (and therefore the quality of governance and management) of the study schemes were used to incorporate social aspects into the modelling. These were: a scenario depicting the current state; a moderately improved scenario; and a comprehensively improved scenario of the state of infrastructure, maintenance and operation.

Hydrological and hydraulic modelling to determine inflows into study schemes

The expected water supply inflows into the study schemes were determined using available historic and modelled hydrological data for the period September 1996 to January 2022 and the hydraulic capacity of the canal inlet works upstream of the first water diversion into the farms. The maximum possible inflow into the scheme was found to be 0.186 m^3/s which is expected 63% of the time making it the most common and therefore the most representative flow. The expected inflows then decline quickly and for 26% of the time, no water is expected to be available for the study schemes.

Hydraulic modelling and alterations to infrastructure to improve water supply

After calibrating the hydraulic model, the flow rates diverted into each of the furrows supplying the farms were determined for the entire system for the three scenarios. Information and data from the hydraulic survey of the irrigation system were used for the scenario corresponding to the current state. For the moderately improved and comprehensively improved scenarios, an iterative approach was used to determine the additions and alterations to infrastructure and operating schedules that could improve water supply and its equity across the schemes.

The current state scenario revealed that for the most common water inflow rate of 0.186m^3/s, the most upstream scheme, Raliphaswa receive proportionately much more water (12.61 mm/day) than Mamuhohi and the tail end Mandiwana scheme that receive 2.11 and 2.57 mm/day of water respectively. For the same water inflow rate (0.186m^3/s), the comprehensive improvements scenario led to supplies of 13.27, 6.56 and 8.94 mm/day for Raliphaswa, Mandiwana, and Mamuhohi schemes respectively and equitable water delivery across the schemes under low flow conditions. The comprehensive improvement scenario consisted of three new formal canal regulating structures (long weirs), alterations to nine of the existing long weirs, and an iterative optimisation of the operating schedule.

Crop-water balance to assess adequacy of water supply to farms

Based on the crop water requirements of maize, the dominant crop in the schemes, reductions in average crop water deficit of 3%, 35% and 34% could be achieved through the comprehensive improvements for Raliphaswa, Mandiwana, and Mamuhohi respectively. However, even with the comprehensive improvements, there would still be significant crop water deficits averaging 3.3, 4.5 and

4.0 mm/day with high peak values (in January) of 10.9, 14.7 and 13.3 mm/day for Raliphaswa, Mandiwana, and Mamuhohi schemes respectively. If the land utilisation dropped to 50%, the respective crop water deficits for the three schemes would reduce to 3.0, 3.4 and 3.1 mm/day with high peaks of 7.2, 11.0 and 8.6 mm/day. The total water losses for the comprehensive improvements scenario were low at 10-15% implying that more capital and resource-intensive measures including the increase in the canal capacity and the creation (or allocation) of water storage for the schemes would be required to further reduce the crop water deficits.

Conclusions and recommendations

Overview of project outcomes

The general aim and the four objectives of the project were broadly met. The factors causing under-utilisation of smallholder irrigation schemes (SIS) were comprehensively reviewed to achieve the first objective, and field work that involved a questionnaire survey, a hydraulic survey and qualitative diagnosis of the selected study schemes achieved the second objective. It was found that quantitative socio-hydrological relationships were not obtainable from the data collected from the questionnaire survey and the conceptual socio-hydrological model for the SIS performance assessment that was developed in this study could therefore not be applied. By consideration of how social factors (governance and management) are expected to impact on the state of infrastructure, its maintenance and operation, social aspects were indirectly incorporated into quantitative hydrologic and hydraulic modelling and opportunities for improving water supply and its distribution to the study schemes were identified. Thus, the third and fourth objectives were also met.

The hydraulic and hydrologic analysis revealed a large inadequacy of the current infrastructure for supplying water and large inequity of supply to the individual schemes. Furthermore, it was found that even with improvements to enhance water supply and its equity, significant crop water deficits would still be experienced even at 50% land utilisation. Hydraulic analysis revealed that the proposed hydraulic improvements would reduce water wastage within the canals to low levels of 10-15% indicating that only major infrastructure developments could achieve adequate levels of water supply to the study schemes.

The questionnaire survey informed that the Scheme Committee was generally considered to manage and govern the scheme reasonably well by farmers in most aspects, except those relating to competition for the inadequate water resource. Understandably, several of the farmers in the schemes proposed punitive measures such as increasing the severity of penalties for breaking the set rules in order to improve governance.

Novelty of the study

This study aimed to assess the opportunities for improving the operation of smallholder irrigation schemes (SIS) in a manner that closely integrates the human (social) and the water (hydrological and hydraulic) aspects. The detailed hydrological and hydraulic analysis undertaken in this study and the practical recommendations of infrastructural improvements for increased and more equitable water supply for the study SIS has not been undertaken in other studies on SIS in South Africa available to the project team and is therefore considered novel. Although data limitations did not allow the use of the conceptual socio-hydrological model for SIS developed in this study, the model is itself a distinct contribution to knowledge that is available for researchers on SIS and social hydrology in South Africa and beyond.

Study limitations and recommendations for future work

The study found that major infrastructural interventions including an increase of the capacity of the canals and the creation or allocation of water storage for the study schemes would be required to significantly minimise water deficits. Time and resource constraints of the current project could not enable an analysis of how this may be achieved and it is therefore recommended that these aspects be included in future work geared to improving the performance of the study schemes and other smallholder irrigation schemes in Vhembe and other parts of South Africa. Such analysis would however need to be preceded or integrated with comprehensive hydrologic and hydraulic analysis of water supply availability as carried out in this study.

Many farmers in the study schemes recommended punitive measures such as increasing fines for non-compliance to the agreed-upon rules to improve governance and the project team supports this. It is however recognised that improving water supply needs to be prioritised as is likely to lead to more significant and more sustainable improvements of scheme performance and a diminished need for punitive governance.

The study found that quantitative socio-hydrology could not be carried out as no realistic quantitative socio-hydrologic and socio-economic relationships could be obtained from the field data. The quantitative data were collected from verbal interviews during the questionnaire surveys and were therefore estimates with high likelihood of large margins of error. There were also large data gaps as many of the interviewees did not answer several of the questions of the survey. Recorded socio-economic, operational and management data could not be acquired within the time and resource-limitations of the study and it is recommended that the acquisition of recorded data be included in future attempts to undertake quantitative socio-hydrological modelling that has substantial action research orientation.

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Prof NS Mpandeli	Water Research Commission
Dr SN Hlophe-Ginindza	Water Research Commission
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Mr MF Rabothata	Department of Agriculture, Land Reform and Rural Development
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CAPACITY BUILDING

One PhD student Nhlakanipho Mkhize; one MSc student, Vhahangwele Mbaimbai; one MA student, Rudzani Nedombeloni; and three BSc Honours students; Toscar Ntakadzeni, Kabo Setogang and Lesego Makgene were engaged in this project.

Toscar graduated at the University of Venda with BSc (Hons) in Hydrology and Water Resources in 2021 while Kabo and Lesego graduated with BSc (Hons) in Civil and Environmental Engineering from the University of the Witwatersrand in 2021. Rudzani is currently registered in the Institute for Rural Development of the School of Agriculture at the University of Venda and has submitted her MA dissertation for examination. Vhahangwele is registered in the School of Hydrology and Water Resources of the University of Venda and intends to submit her MSc dissertation for examination in 2023. Nhlakanipho also intends to submit his PhD thesis for examination in 2023 and is registered in the School of Civil and Environmental Engineering of the University of the Witwatersrand.

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ACRONYMS

CBNRM	Community based natural resource management
DAFF	Department of Agriculture Forestry and Fisheries
DEM	Digital Elevation Model
DWA	Department of Water
DWS	Department of Water and Sanitation
FAO	Food Agricultural Organisation
HRU	Hydrologic response unit
IMT	Irrigation Management Transfer
SCS	Smallholder Canal Scheme
SEBAL	Surface energy balance
SES	Social-ecological systems
SETS	Social, ecological and technological systems
SIS	Smallholder Irrigation Scheme
SWAT	Soil Water Assessment Tool
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WAS	Water Administration System
WRC	Water Research Commission
WUA	Water User Association

1 INTRODUCTION

1.1 Background and rationale

Access to reliable irrigation water has enabled farmers in developing countries to adopt new technology and intensify cultivation, leading to increased productivity, higher overall production, and greater returns from farming. This growth in agriculture has created new employment opportunities on-farm and off-farm, raised rural incomes, created more sustainable livelihoods, and improved the quality of life in rural areas (Bhattarai, Sakthivadivel and Hussain, 2002; Hussain and Hanjra 2004; Smith, 2004; Namara et al., 2010). Similar positive impacts of irrigation on primary production and livelihoods linked to irrigated farming have been documented in selected areas of South Africa (Mohamed, 2006; Manyelo et al., 2015; Denison et al., 2016). This warrants the placement of expanding irrigated smallholder agriculture, through better use of existing water resources and the development of new water resources, at the centre of the recommended strategy that seeks to exploit the job creation potential of agriculture in rural areas as part of South Africa's National Development Plan 2030 (NDP 2030) (National Planning Commission, 2011). The primary objective of smallholder irrigation agriculture is to improve rural livelihoods through sustainable crop production for food security and poverty alleviation (Denison and Manona, 2007; Sinyolo et al., 2014; Moyo, 2016; Christian, 2017).

According to the NDP 2030 (National Planning Commission, 2011), expansion of irrigation targets the establishment of 247 500 smallholders, referred to as 'labour-intensive winners', on plots ranging between 0.5 ha and 5 ha. Whilst some of these smallholders would probably access water for irrigation independently, it is likely that the majority would be settled on smallholder irrigation schemes (SIS), because scheme arrangements enable groups of farmers to make use of a shared water source and irrigation system. However, the success of SIS in South Africa has been variable (Van Averbeke et al., 2011). Whilst some of the 302 SIS that existed in 2010 have significantly improved the livelihoods of farmers and their communities (Denison et al., 2016), others have performed well below their potential (Mnkeni et al., 2010; Fanadzo et al., 2010; Van Averbeke and Denison, 2013). More disconcerting was that nearly one third (90) of these 302 SIS were in a state of complete collapse (Van Averbeke et al., 2011). Underutilisation of land and water is common at these schemes (Van Averbeke, 2008), and seemingly on the rise, as indicated by a decline in cropping intensity (Denison et al., 2016).

Expansion of smallholder irrigation through the establishment of new SIS could help to reduce structural unemployment and high levels of poverty that prevail in rural South Africa. However, in order to increase the potential for their success, new and improvements on existing SIS must be designed based on best practice principles. These principles can be distilled from lessons learnt on existing SIS. Accordingly, it is imperative that factors influencing underutilisation of existing SIS are investigated, and that opportunities for improved operation of these SIS are identified.

The Water Research Commission (WRC) has been instrumental in drawing research attention on South African SIS. Researchers identified a range of factors that affected their performance. Broadly, these included inappropriate scheme design, ineffective operation and maintenance of irrigation infrastructure and equipment, institutional and organisational deficiencies pertaining to a wide range of aspects associated with irrigated farming, and low levels of competency among SIS participants, be they farmers or people mandated to assist them (Bembridge, 2000; Crosby et al., 2000; de Lange et al., 2000; Denison and Manona, 2007; Mnkeni et al., 2010; Denison et al., 2016). Farmers on SIS, on the other hand, consistently raise three issues that affect their aspirations and goals, namely problems with access to land, particularly those seeking expansion or entry to schemes, inadequate access to water, especially at the tail end of schemes, and lack of access to markets, the latter affecting the smallholder sector at large. The current project pays attention to two of these themes, namely access to land and water. In general, access to resources is function of social relations, institutional processes and organisational structures (Scoones, 1998; Ellis, 2000). Research has shown that ineffective institutional processes and organisational structures are principal factors limiting access to land and water on smallholder schemes (Letsoalo and Van Averbeke, 2006a, 2006b; Denison et al., 2016), but little is known about the content of the institutions and the make-up of the organisational structures which smallholders would like to see on these schemes. Moreover, since many smallholder irrigation schemes are old, various degrees of deterioration to the irrigation infrastructure have occurred, causing the systems to deliver water at levels that are below their design capacities.

The factors affecting the performance of SIS, including the challenges relating to water and land faced by farmers in these schemes, were the basis for the aims and objectives of this study. Since they span across the human (institutional, organisational) and water domains, socio-hydrology; a recently conceived approach of integrating and coupling human-water dynamics was considered a realistic approach for exploring and finding effective solutions to these challenges.

The early irrigation SIS schemes in South Africa were all gravity fed concrete lined canal water supply and furrow systems otherwise known as smallholder canal schemes (SCS). SCS are also the most widely utilised infrastructure systems amongst smallholders in South Africa. They are durable, cheap to maintain, easy to operate and are not affected by energy price externalities like pumped schemes. Furthermore, they accommodate the full spectrum of farming objectives, they permit farmers to choose between the use of local resources (i.e. manure, animal draught) and external resources (i.e. fertiliser and mechanisation) in their farming systems, and they support large numbers of farmers albeit on smaller plots, as consolidation is not essential for ongoing farming operations (van Averbeke et al., 2011). The focus of this project will therefore be limited to SCS.

1.2 Aims and objectives

The general aim and objectives of the study are:

General aim

To assess the opportunities for improving the operation of smallholder irrigation schemes in Vhembe, Limpopo Province.

Objectives:

1. Review factors causing underutilisation of existing SIS with specific reference to water, land and irrigation infrastructure
2. Document and assess (i) existing design, operation and management of water resource distribution and (ii) existing institutions and organisations governing access to land and water on selected canal schemes.
3. Identify opportunities for improved design, operation and management for equitable water resource distribution and for institutional and organisational reform on these schemes.
4. Assess the applicability of socio-hydrologic modelling to aid decision making to improve the design, operation and management of SIS.

2 LITERATURE REVIEW

2.1 Aim and structure of literature review

Aim of chapter
The general aim of this review is to examine existing knowledge on factors affecting underutilisation of smallholder irrigation schemes in South Africa. The main focus of the review is on smallholder canal schemes and the two factors that are of specific interest are the design, operation and management of these canal schemes and the land and water institutions that exist on them.

Structure of chapter
In the first section of this document, the project team and project aims are summarised. The second section details the aims of the review and explains how the document is structured.

The aim of the second section is to set the scene by providing a summary of the latest information on smallholder irrigation in South Africa and an overview of the people, agriculture and irrigation in the Vhembe District of Limpopo Province, which is the study area of the project.

The third section reviews the factors affecting the functioning of smallholder schemes while the fourth describes the range of factors that have been identified as causing the general underutilisation of smallholder schemes globally and in South Africa.

The aim of the fifth section is to describe the existing social, water and land institutional structures that govern smallholder canal schemes while the sixth section reviews governance systems of smallholder canal schemes.

The seventh section summaries the opportunities to improve the operation of smallholder canal schemes identified in the literature with specific reference to design, operation and management and land and water institutions, separately and conjointly, as well as lessons learnt on best practices of investigating these opportunities through engagement with relevant stakeholders.

The last section of the literature review briefly reviews socio-hydrology and poses it as a realistic approach for finding opportunities to improve the performance of small holder irrigation schemes.

2.2 Scene setting - smallholder irrigation schemes in Vhembe District

2.2.1 Concept definitions

Irrigation is the practice of transferring water from a source, either continuously or opportunistically, and applying this water to agricultural land to enhance plant growth (Molden et al., 2007; Van Averbeke et al., 2011; Denison, 2018). Irrigation enables crops to be grown in areas otherwise too dry, and for crop yields to be increased and produce quality to be raised by reducing or eliminating water stress.

Furthermore, irrigation allows for multiple cropping cycles during a single year where the temperature regime is favourable (van Averbeke et al., 2011). Multiple cropping cycles raise the labour requirement per unit area and distribute it more evenly over the year than in the case of dryland farming. By reducing or removing the risk of water deficits, irrigation enables intensification but this necessitates greater investment of time and resources on the part of farmers. (Van Averbeke and Denison, 2013).

Farmers can either irrigate independently or share an irrigation system with others. Accordingly, Reinders et al. (2010) defined **irrigation scheme** as 'an agricultural project involving multiple farm units that depend on a shared water supply and irrigation system'. Reinders et al. (2010) considered an irrigation scheme to consist of the hydraulic command area and to exclude surrounding villages, farms and grazing areas, despite the inter-linkages between these areas and the scheme. Reinders et al. (2010) identified three elements of water-management on irrigation schemes, namely the water source, the bulk conveyance system and the command area that contains the farms.

Hunt (1988) defined **canal irrigation system** as being composed of a main intake structure (gate, offtake), which takes water from a natural channel and moves it away from its natural downhill course, and of the subsequent control works (canals, gates, fields) that guide the water flowing on the surface to the agricultural plants, until that water either soaks into the earth or flows on the surface out of the control works. In the context of the current study, a **canal scheme** is defined as an irrigation scheme in which water is diverted from its natural course and conveyed and distributed by way of an open channel system, which may include over-night storage facilities, to the plots, where it is applied to the land by means of surface irrigation.

'**Smallholding**', and '**smallholder**', the latter referring to the occupant of a smallholding, are normative concepts, because a holding can only be called small in relation to a farm size distribution. Such a distribution is only meaningful at a local level, because when looked at more broadly, the wide diversity of farm enterprises in terms of agroecology, the object of farming, and the production systems used, make it impossible to formulate size limits that allow for a meaningful separation of farm categories. Reviewing the meaning of the term 'smallholder' in the South African context, Cousins (2009) found that the term 'smallholder' had been defined and used in an inconsistent manner, referring, *inter alia*, to producers who occasionally sold products for cash as a supplement to other sources of income; to those who regularly marketed a surplus after their consumption needs had been met; and to those who were small-scale commercial farmers, with a primary focus on production for the market. Denison (2018), who sought to define 'smallholder' for a study of smallholder irrigation schemes in Limpopo Province, also identified a lack of consistency in the definition of 'smallholder', and, for this reason, ended up not defining the concept.

In the context of the current study, a **smallholder** was defined as an occupant of a plot on a smallholder irrigation scheme, and **smallholder irrigation scheme** was defined as an irrigation scheme that was constructed specifically for occupation and use by black farmers (Van Averbeke et al., 2011).

2.2.2 Smallholder irrigation schemes in South Africa

Whilst irrigation in South Africa is widely seen as technology introduced by western colonisers, there is substantial evidence that irrigation was known and used by selected African groups before colonisation occurred (Tempelhoff, 2008). The Vhembe District is one of a few localities where physical evidence of irrigation works was recorded. Stayt (1968), who conducted anthropological research among the Venda during the late nineteen-twenties, and published the first account of his work in 1931, wrote, 'In the northwest of Vendaland there are traces of some very ancient occupation. Colonel Piet Moller, who was an early settler in the Zoutpansberg, has found what he considers indisputable evidence of ancient irrigation works. Most of the old furrows are near Chepisse and it appears that the water was diverted from a small stream there in a series of furrows to a distance of about four and a half miles south. Traces of furrows are also discernible at Sulphur Springs, and at several places by the Nzhelele River, where some of them have been reopened and are utilised by the BaVenda today. Colonel Moller says that when he first came across these some forty years ago (around 1880), there was no doubt about their antiquity. Today they are very difficult to trace, as roads, modern agriculture, and furrows have altered the face of the country considerably and have particularly hidden the ancient workings.'

Black farmers in South Africa also learnt about irrigation from the missionaries (Tempelhoff, 2008). For example, in the Ciskei region of the Eastern Cape, Bundy (1988) reports on irrigated agriculture by African peasants during the second half of the 19th century. Bundy (1988) referred to these smallholder irrigation developments as being mostly private initiatives or small mission station schemes and involving river diversion.

State-driven development of the smallholder irrigation schemes that are still in existence dates back to the 20th century. The early schemes were all canal schemes in which concrete was used to line the conveyance and distribution channels. In 1952, the Commission for the Socio-Economic Development of the Bantu Areas within the Union of South Africa (1955) identified 122 of these smallholder canal schemes covering a total of 11 406 ha. Construction of smallholder canal schemes continued until 1975, when there was a shift to overhead irrigation (Van Averbeke et al., 2011). Rapid expansion of the smallholder irrigation scheme area occurred during the period 1975 to 1985, when 27 758 ha of irrigated land was developed. Most of this land was located on large (>500 ha) state-managed projects (Van Averbeke et al., 2011).

In 2010, there were 302 smallholder irrigation schemes in South Africa covering an area of 47 667 ha, which represented 3.4% of the total area that was annually irrigated in South Africa at that time. Among these smallholder schemes, 81 were gravity-fed canal schemes, 20 were pumped schemes on which surface irrigation was practised, 170 were overhead irrigation schemes, 25 were micro-irrigation schemes and 6 were without information on the irrigation method being used. With the exception of Ncora Irrigation Scheme in the Eastern Cape, all overhead and micro-irrigation schemes were pumped. Significant was that even though canal schemes were the oldest type, the proportion among them that was still operational in 2010 (83%) was higher than among overhead irrigation schemes (65%) and micro-irrigation schemes (56%) (Van Averbeke et al., 2011). Also significant was that 170 of the 302 smallholder irrigation schemes (56%) were located in Limpopo Province.

2.2.3 Vhembe District: background to study area

2.2.3.1 Vhembe District

The Vhembe District is located in the Limpopo Province of South Africa and is the most northern district of the Limpopo Province (Figure 2.1). The district borders Zimbabwe in the north and Mozambique in the east. It incorporates four local municipalities, namely Thulamela, Makhado, Collins Chabane and Musina (Figure 2.2). Vhembe covers an area of 25 596 km^2. In 2011, the district was home to 1.294 722 million people. In 2016, the human population had grown to 1 393 949 people, an increase of 1.68% per annum (Municipalities of South Africa, 2019). In 2016, Vhembe counted 382 357 households, an increase of 47 081 households from the 335 276 households recorded in 2011. The annual rise in number of households during this five-year period amounted to 2.81%, and is explained partly by the increase in population mentioned earlier, and partly by the reduction in the average household size from 3.8 to 3.6 persons per household during this period. Significant also is that in 2016, just over half of the households in Vhembe (51.0%) were female-headed (Municipalities of South Africa, 2019).

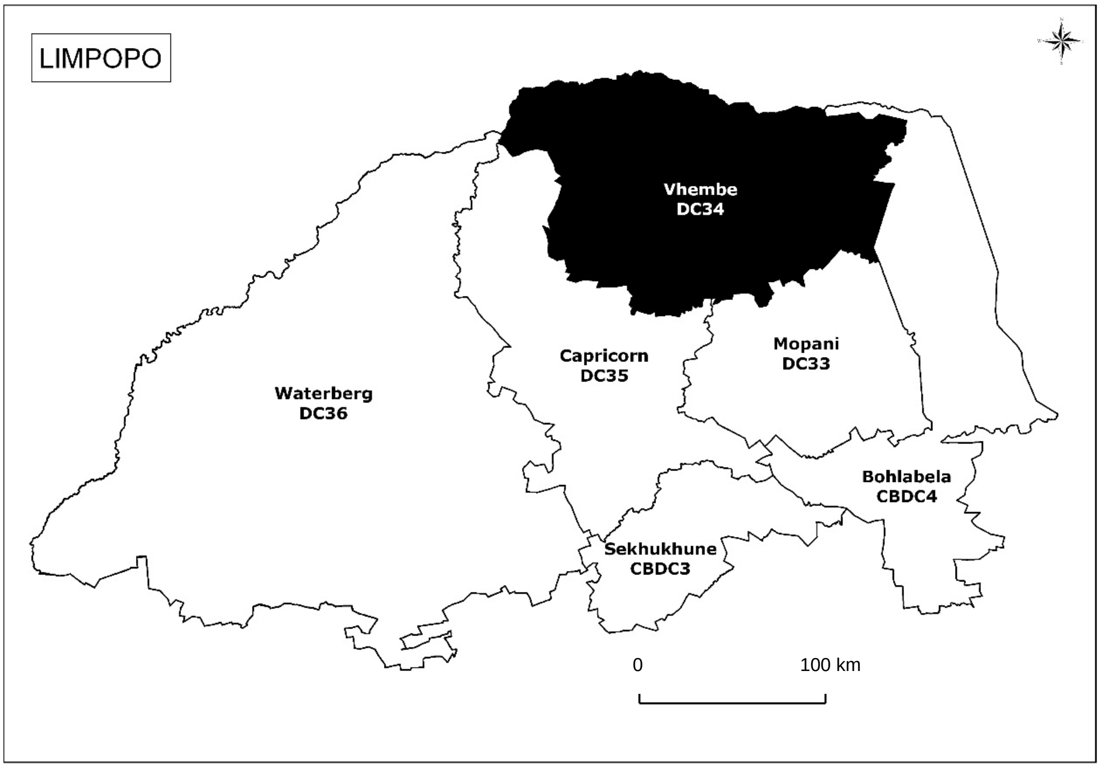

Figure 2.1: Location of the Vhembe District in the Limpopo Province

About two-thirds of the people living in Vhembe speak TshiVenda and a quarter speak Xitsonga. Most of the people speaking Xitsonga reside in the Collins Chabane Local Municipality. The town of Thohoyandou is the administrative capital of the district. The two other large towns are Louis Trichardt (Makhado) and Musina.

Besides the tertiary sector, mining and agriculture also make important contributions to the economy of the district. The arable land area in the district is limited to about 10% of the area (249 757 ha) but the availability of water for irrigation enables the production of high value crops, including macadamia nuts, bananas and other subtropical fruits. About 70% of the arable land belongs to large-scale farms and 30% is in the hands of smallholders (Vhembe District Municipality, 2017).

Figure 2.2: The four local municipalities that make up the Vhembe District (extracted from Municipalities of South Africa, 2019)

2.2.3.2 People in Vhembe

Since the dominant language in Vhembe is TshiVenda, the description of the people presented in this review has been limited to the Vhavenda. As with every 'origins' narrative, that of the Vhavenda continues to be a subject of debate amongst historians and sociologists, but it shares some of the characteristics of those of the other African societies in South Africa. The Vhavenda are said to have migrated from either Central Africa or the Great Lakes areas of East Africa (Lahiff, 2000). Their migratory process led to a number of groups breaking away from the original group. Lahiff (2000) and Stayt (1968) have suggested that the language, Tshivenda, shows a strong affiliation with and influence of East African languages, such as Swahili, and McNeill (2011) adds that the language has also been greatly influenced by Shona and Lozi, reflecting the long period in which the group spent in the regions which are now known as Zambia and Zimbabwe (Lahiff, 2000; Stayt, 1968, McNeil, 2011). While Kirkaldy (2002) agrees that TshiVenda has a strong resemblance to the Shona language, he adds that it also resembles Sesotho, whose people were settled in the Soutpansberg region and with whom there was much interaction and mixing.

In a description of their cultural practices, Benso and RAU (1979), Lahiff (2000) and Stayt (1968) liken those of the Vhavenda to those of the Shona and the Sotho people, adding that much of the influence on Venda culture came from the Sotho communities who occupied areas in the south and south-west of the Venda dominion. The authors concur that there were also cultural aspects (mainly Shona) that were adopted from the communities that the Vhavenda encountered during the migration process to South Africa (Benso and Rau, 1979).

While white settlement in the area occupied by the Vhavenda has a fairly long history, among the different African groups in South Africa, they were the last to be subjugated by white colonialists and this occurred during the period 1898-1902. The first party to arrive in "Vendaland" around 1820, was led by Coenraad De Buys and it had migrated from the Ciskei, which formed part of the, now, Eastern Cape Province. Subsequent Afrikaner groups under the leadership of Louis Trichardt, Andries Hendrik Potgieter and Johannes van Rensburg entered the territory of the Vhavenda in 1836. Potgieter and his followers established the first substantial white settlement in Venda in 1848. The settlement established by Potgieter was initially called Zoutpansbergdorp and later, it was renamed Schoemansdal. This settlement served, primarily, as a hunting and trading centre, with ivory serving as its principal commodity. The increasing monetary demands of the Zoutpansberg community on the Vhavenda, coupled with violent military campaigns in an attempt to gain greater access to hunting land within the region, led to a revolt against the settler community. The Vhavenda, under Chief Makhado, attacked and defeated this Zoutpansberg community, destroying their settlement in 1867. When Chief Makhado died in 1895, he was succeeded by his son Chief Mphephu. Conflict arose between Mphephu and other Venda chiefs, however, they one by one submitted to the Transvaal authorities, leaving Mphephu and his followers as the only group of Vhavenda to resist white authority. In 1898, Mphephu and his people were defeated by a commando of Afrikaners, forcing Mphephu to flee to present-day Zimbabwe and in 1902, the Venda nation was disarmed by the British administration following the end of the Anglo-Boer War (Lahiff, 2000; Kirkaldy, 2002).

In 1902, the territory of the Venda was subdivided into three Native Commissioner's areas, namely, Sibasa, Louis Trichardt and Spelonken. The southern and western parts of this territory were made available for white settlement, reducing the part held by the Vhavenda to a fraction of its original size (Lahiff, 2000). Following additions of land, in line with the 1936 Trust and Land Act, the total area held by the Vhavenda first increased to about 525 500 ha and ultimately to 680 700 ha during the homeland era, which lasted from 1971 to 1994. This era underwent an initial period of self-governance (1971-79) and a subsequent period of independence (1979-94).

The 1991 census showed the human population of Venda to be 558 797 people. This meant that, towards the end of the homeland era, the population density in Venda was 82 people per km^2. At that time, Venda counted 103 481 households with an average size of 5.4 persons per household. Dividing the total area of Venda by the number of households, the average area of land available per household was 6.58 ha. Of the total land area, only 11% was considered arable, which when divided equally over all households would provide an arable land allocation of 0.72 ha per household (Lahiff, 2000).

2.2.3.3 Agriculture in Vhembe

The economic life of the Vhavenda was dependent on agriculture and continues to be so. Its main agricultural activity is poultry production and fruit production with 37 901 and 64 100 households recorded to be involved in this production (Netshifhefhe et al., 2018; Stats SA, 2015). Musetha (2016) adds that the Vhembe District produces "4.4% of South Africa's total agricultural output, including 8.4% of the country's sub-tropical fruit and 3% of its citrus".

Like most of the Bantu groups of South Africa during the pre-colonial period, homesteads had livelihoods that were almost exclusively land based. They used hand tools to cultivate land, which limited the area that was planted to crops (Bundy, 1988). For food, homesteads also relied on the milk produced by their cattle herds, but not as much as among the Nguni-speaking groups that settled along the eastern seaboard. The introduction of iron hoes and the animal drawn plough following colonisation enabled homesteads to expand the area under cultivation (Bundy, 1988). For African homesteads, increasing crop production became a necessity to maintain food security because of the loss of land to the colonisers and the spread of new diseases among the cattle herds. However, the areas that African homesteads cultivated after adopting the plough remained limited in size and from a contemporary perspective it was still small-scale (Bundy, 1988).

The Land Act of 1913 divided South Africa into areas where land was held by whites and others where the land was held by African people. The parts that were allocated to African people were called the "Native Areas". Combined, they covered about seven per cent of South Africa. At that time, traditional land tenure still largely prevailed in the “Native Areas”. Characteristic of that tenure system was that homesteads were allocated land by the tribal leadership in accordance with their needs (Cokwana, 1988). The technology that was available at that time limited the scale of farm operations and as a result, land allocations tended to be small. From about 1910 onwards, when the white farming sector was increasingly being commercialised, but particularly after 1960, when tractors replaced draught animals, white farmers expanded the cultivated area on their farms. This particular development did not occur in the “Native Areas”, because when tractors were made available to African farmers, most of the available arable land had already been distributed among the growing population. In this way the small scale of African farms persisted and remains prevalent at present (Van Averbeke, 2008).

Historical factors also affected the orientation of African farming in South Africa. Following colonialisation of the country during the nineteenth century, there was a brief era of peasantisation among African people. During this era, which lasted from about 1860 until about 1910, selected African homesteads increasingly engaged in commodity production, such as wool and wheat, competing effectively with their white counterparts (Bundy, 1988). Politically, this development was encouraged because the integration of Africans in the broad social and economic networks of colonial society was adopted as a strategy to pacify the African groups (Bundy, 1988). African peasantisation developed along two trajectories. In the Eastern Cape and KwaZulu-Natal, African peasants farmed their own land, which in some cases was held by individual title. In the Free State and the Western Transvaal (North-West Province), African peasants were involved in various share cropping arrangements with white farmers. Van Onselen (2005) presents a detailed account of the life of one of these sharecroppers who farmed in the area around Bloemhof, Wolmaranstad and Schweizer Reneke.

During the first decades of the twentieth century, change in policy curtailed the emerging African peasantry. By that time, the African groups no longer posed a serious military threat and economically there was more need for the labour of African people than for their agricultural produce. Rapid mining development and the commercialisation of the white farming sector created demand for cheap labour and the African population was viewed as a suitable source of supply. Various policies, including territorial segregation based on race, prohibiting African people from accessing white-owned land through tenancy arrangements, restricting the size of farms held by Africans and raising taxes were introduced to make it difficult for African homesteads to maintain their agrarian livelihood (Bundy, 1988). However, unlike in other parts of the world, the natural processes of proletarisation and urban migration of the rural population were not allowed to occur in South Africa. Instead, policies and practices were implemented to access rural labour without bringing about its permanent displacement.

This approach gave rise to the male migrant worker system, which characterised South Africa for most of the twentieth century. This system involved the employment of African men during their prime years, whilst their spouses, children and parents remained behind in the rural areas. In the case of the mines, workers were housed in male-only hostels and provided with meals that kept them fit for the heavy work they had to do. When their most productive years were over, their contracts were no longer renewed, leaving them with few options other than to retire to their rural homesteads. During their years of employment, migrant workers invested in their rural homesteads. They built up cattle herds in preparation for their retirement and also supported the annual production of crops, not only financially by remitting money to pay for inputs but often also physically by taking leave during the time of ploughing and planting. Smallholder farming became increasingly subsistence oriented, responding to the new way in which African homesteads constructed their livelihood. In the case of crop production, the emphasis was on meeting the food requirements of the homestead during the absence of the male head (Ferguson, 1990).

During the period between 1910 and World War II, indicators of quality of life, such as life expectancy, child mortality and the absence of diseases associated with severe malnutrition, such as pellagra and kwashiorkor, showed that the social and economic status of the "Native Areas" was deteriorating (Bundy, 1988). At the same time, agricultural production in these areas was declining. For example, during the period 1921-30, the average annual production of maize in the "Native Areas" was 290 000 tons. This dropped to an average of 220 000 tons during the subsequent decade (Bundy, 1988). There was also alarming evidence of rapid degradation of the natural resources in the form of denudation of the landscape and soil erosion (Bundy, 1988). To release pressure on the land, the state intervened by increasing the size of the "Native Areas" through the promulgation of the Land and Trust Act of 1936.

On newly released land, also called "Trust Land", *Betterment*[*] was implemented to protect the natural resources. One of the elements of "Betterment" was to subdivide the land into residential, arable and grazing areas. Land conservation measures included the subdivision of fenced camps on the rangeland to enable rotational grazing, imposition of restrictions on livestock densities and the construction of contour banks and contour ploughing to check soil erosion on arable land (Beinart, 2001). These new measures did not reverse the overall decline in agricultural production in the "Native Areas", mainly because structurally the function of these areas was to serve as labour reserves for the mining, industrial and white commercial farming sectors and not to act as centres of agrarian production. This was abundantly clear from the results of the census conducted in 1936, which revealed that 54 per cent of the adult male population in the "Native Areas" was absent from their rural homes (Bundy, 1988).

The policies of the National Party, which came to power in 1948, stood out by their preoccupation with racial separation of South African society. For the "Native Areas", which were now called "Bantu Areas", policy was aimed at establishing self-government for each of the different African groups. The Bantu Authorities Act of 1951 and the Bantu Self Government Act of 1959 were all legislative expressions of the intent of the National Party to implement separate development. For this policy to succeed, it was important to improve the economic and social conditions in the "Bantu Areas". The Tomlinson Commission was established to develop an overall master plan for the economic development of the "Bantu Areas". The Commission proposed the establishment of a class of peasants on farm units that were economically viable, but the relocation of large numbers of rural homesteads, which the implementation of this proposal demanded, was unacceptable to the government. Instead, implementation of "Betterment" was extended to land held under traditional tenure (Van Averbeke, 2008). In practice this meant that dispersed settlements were consolidated into villages bringing about the spatial separation of homesteads from their different land resources, particularly their arable land. Several scholars have argued that this reorganisation of the rural space further reduced African smallholder production (De Wet, 1989; Yawitch, 1981; McAllister, 1988).

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[*] *Betterment* is the term commonly used to refer to the Native Trust and Land Act No 18 of 1936 land use planning programme. The aim of the land use planning programme was the protection and rehabilitation of natural resources and to prevent "further degradation of land" in areas designated for Africans. One solution by the state was to make available and allocate additional land ("trust land") and this was done by relocating a number of African families and groups. One way in which the state believed it would achieve its aim was by restricting livestock numbers on this "trust land". The plan may have protected natural resources but it was met with much resistance in certain areas of South Africa because, for example, it threatened the sense of economic security one placed in the size of one's herd of cattle. Further, in re-settling groups and their members, it created new social boundaries and heightened the sense of displacement amongst African families. Betterment here, is used to illustrate the context in which the specific Irrigation Schemes were constructed and the policies imposed on its plot holders and homesteads.

As in other former homelands, the role of farming in the livelihood of Venda people also declined during the twentieth century, but visitors to the area usually comment on the intensity with which the available land is being cultivated. Fruit trees, particularly mangoes and bananas, also feature more prominently in the Venda cultural landscape than in that of other former homelands. Another distinguishing feature of the Venda region is the presence of large numbers of informal enterprises, which provide a range of goods and services to local people. This suggests a relatively highly developed spirit of entrepreneurship, which is often lacking in other rural parts of South Africa (Van Averbeke, 2008).

During the period of self-government and particularly during the era of independence, the Venda homeland administration through its agricultural parastatal Agriven, initiated a wide range of commercial agricultural development projects. However, the majority of these projects collapsed when Agriven was closed down following the reincorporation of Venda into South Africa (Du Toit, 2005). Land reform, more specifically land restitution, has resulted in the transfer of considerable tracts of land that were allocated to whites back to the descendants of the earlier Venda owners (Du Toit, 2005).

2.2.3.4 Irrigation schemes in Vhembe

The Vhembe District has 42 smallholder irrigation schemes within its borders (Vhembe Municipality, 2017). This represents 14% of the national total, and one quarter of the Limpopo Province total. The high concentration of schemes makes it the ideal study area for smallholder scheme investigations. Among the 42 smallholder schemes in the District, Tshiombo stands out, not only for its large size (795 ha) relative to the others, but also because in one of its seven units the method of water application was changed from surface to overhead irrigation. For this reason, the seven hydraulic units of Tshiombo are treated as separate schemes in Table 2.1, explaining the total of 48 schemes in this table.

The 48 smallholder schemes listed in Table 2.1 covered a total area of 3 344 ha, which is 7% of the national smallholder scheme area. A total of 3 265 people occupied a plot on these schemes. Accordingly, the average plot size was 1.02 ha. Just over half of the schemes (26) were gravity-fed canal schemes. In 2010, all 26 canal schemes were considered operational. Since then, Block 4 of the Tshiombo Scheme has become dysfunctional, because it no longer receives water (Denison et al., 2016).

Table 2.1 Overview of smallholder irrigation schemes in Vhembe District

(from Van Averbeke, 2012)

Scheme name	Operational	Command area (ha)	Number of plot holders	Average plot size (ha)	Hydraulic head	Irrigation method
Nesengani	Yes	13.7	28	0.415	Pumped	Surface
Nesengani B1	No	20.6	116	0.178	Pumped	Overhead
Nesengani B2	No	40.9	116	0.352	Pumped	Overhead
Nesengani C	No	31.2	131	0.238	Pumped	Overhead
Dzindi	Yes	136.2	102	1.285	Gravity	Surface
Khumbe	Yes	145.0	138	0.623	Gravity	Surface
Dzwerani	No	124.0	248	0.500	Pumped	Overhead
Palmaryville	Yes	92.0	70	1.296	Gravity	Surface
Lwamondo	No	15.0	75	0.200	Pumped	Micro
Mauluma	Yes	38.0	30	1.267	Gravity	Surface
Mavhunga	Yes	47.5	32	1.532	Gravity	Surface
Raliphaswa	Yes	15.0	13	1.154	Gravity	Surface
Mandiwana	Yes	67.0	40	1.675	Gravity	Surface

Scheme name	Operational	Command area (ha)	Number of plot holders	Average plot size (ha)	Hydraulic head	Irrigation method
Mamuhohi	Yes	77.0	61	1.262	Gravity	Surface
Mphaila	Yes	70.6	59	1.197	Pumped	Overhead
Luvhada	Yes	28.8	79	0.365	Gravity	Surface
Rabali	Yes	87.0	68	1.279	Gravity	Surface
Mphepu	Yes	132.8	133	0.998	Gravity	Surface
Tshiombo Block 1	Yes	60.5	47	1.287	Gravity	Surface
Tshiombo Block 1a	Yes	128.6	100	1.286	Pumped	Overhead
Tshiombo Block 1b	Yes	122.0	115	1.061	Gravity	Surface
Tshiombo Block 2	Yes	126.0	98	1.286	Gravity	Surface
Tshiombo Block 2a	Yes	173.5	114	1.522	Gravity	Surface
Tshiombo Block 3	Yes	128.4	100	1.286	Gravity	Surface
Tshiombo Block 4	Yes	56.0	112	0.500	Gravity	Surface
Lambani	No	260.0	16	16.250	Pumped	Surface
Phaswana	No	16.7	16	1.044	Pumped	Surface
Cordon A	Yes	43.7	38	1.150	Gravity	Surface
Cordon B	Yes	82.3	65	1.266	Gravity	Surface
Phadzima	Yes	102.3	103	0.993	Gravity	Surface
Makuleke	Yes	37.3	29	1.286	Pumped	Overhead
Rambuda	Yes	170.0	132	1.288	Gravity	Surface
Murara	Yes	70.0	7	10.000	Gravity	Surface
Dopeni	Yes	30.0	6	5.000	Gravity	Surface
Makhonde	No	83.0	58	1.431	Pumped	Micro
Sanari	No	17.0	11	1.870	Pumped	Micro
Tshikonelo	No	10.0	15	0.670	Pumped	Overhead
Chivirikani	Yes	68.3	112	0.609	Pumped	Overhead
Gonani	Yes	8.5	30	0.295	Pumped	Overhead
Folovhodwe	Yes	70.0	24	2.197	Gravity	Surface
Klein Tshipise	Yes	60.0	60	1.000	Gravity	Surface
Morgan	Yes	56.7	35	1.620	Gravity	Surface
Makumeke	Yes	17.0	63	0.269	Pumped	Micro
Dovheni	Yes	60.0	14	2.143	Pumped	Overhead
Mangondi	No	48.0	38	1.260	Pumped	Micro
Xigalo	Yes	22.0	24	1.080	Pumped	Micro
Garside	Yes	13.7	28	0.415	Gravity	Surface
Malavuwe	Yes	20.6	116	0.178	Pumped	Overhead

In Table 2.2, an overview is provided of the 25 operational smallholder canal schemes in Vhembe, keeping in mind that the five operational canal units of Tshiombo belong to the same Scheme.

On average, an operational smallholder canal scheme in Vhembe is 57 years old, has a command area of 88 ha, which is occupied by 70 plot holders, who each hold 1.3 ha of land.

Table 2.2 Overview of operational smallholder canal schemes in Vhembe District

(from Van Averbeke, 2012)

Scheme name	Number of years of operational by 2019	Command area (ha)	Number of plot holders	Average plot size (ha)
Dzindi	65	136.2	102	1.285
Khumbe	68	145.0	138	0.623
Palmaryville	65	92.0	70	1.296
Mauluma	54	38.0	30	1.267
Mavhunga	54	47.5	32	1.532
Raliphaswa	55	15.0	13	1.154
Mandiwana	55	67.0	40	1.675
Mamuhohi	55	77.0	61	1.262
Luvhada	58	28.8	79	0.365
Rabali	58	87.0	68	1.279
Mphepu	58	132.8	133	0.998
Tshiombo Block 1	54	60.5	47	1.287
Tshiombo Block 1b	54	122.0	115	1.061
Tshiombo Block 2	54	126.0	98	1.286
Tshiombo Block 2a	54	173.5	114	1.522
Tshiombo Block 3	54	128.4	100	1.286
Cordon A	54	43.7	38	1.150
Cordon B	54	82.3	65	1.266
Phadzima	54	102.3	103	0.993
Rambuda	67	170.0	132	1.288
Murara	51	70.0	7	10.000
Dopeni	55	30.0	6	5.000
Folovhodwe	63	70.0	24	2.197
Klein Tshipise	45	60.0	60	1.000
Morgan	40	56.7	35	1.620
Mean	57	87.7	70	1.257

2.3 Factors affecting functioning of smallholder irrigation schemes

2.3.1 Global situation

Denison (2018) describes the global evolution of factors affecting the functioning of smallholder irrigation schemes. He explains that previous evolutions have focused on infrastructure and agricultural production factors. As a result, inadequate attention has been given to institutional challenges, competing water needs, market linkages as well as the interrelation of these factors with the scheme infrastructure (Veldwisch, 2006; Denison, 2018). Given the shift in the current era towards farmer managed schemes, there is greater appreciation that increased focus on these factors is necessary for scheme sustainability (Denison, 2018).

2.3.2 South African situation

The multi-factorial nature of irrigation performance is also widely appreciated in South Africa (Denison, 2018). Seasonal water shortages as well as unequitable distribution are a major cause of conflict (Bembridge, 2000; Bjornlund et al., 2016). According to de Lange et al. (2000) and Speelman (2009), the plot holders' ability to use water efficiently and productively on farm is low. In their contribution to the factors affecting the functioning of smallholder schemes, Bembridge (2000) and van Averbeke and Mohamed (2006) highlighted water reliability and reticulation problems, poor infrastructure, limited knowledge on crop production, limited farmer participation in the management of water, ineffective extension and mechanisation services, lack of reliable markets and effective credit services, deterioration of infrastructure, institutional and management problems as well as socio economic constraints. Denison (2018) identified the performance of gravity systems and land-exchange in relation to commercialisation as the two most dominant factors, whilst water resource constraints and distance to markets were significant but of lessor importance. Despite these challenges, irrigation development in South Africa remains central to rural development (Denison, 2018).

2.4 Design, operation and management of canal irrigation systems as factors affecting smallholder canal scheme utilisation

2.4.1 Introduction

Rainfall characteristics are a pivotal factor in irrigation design (Denison, 2018). The spatial, temporal and uneven distribution of rainfall in most of South Africa limits rain fed agriculture (van Averbeke et al., 2011; Sithole et al., 2014). Within the semi-arid zones, rainfall typically ranges from 400 – 600 mm per annum, is highly erratic and often falls as intensive, convective storms of short durations (Rockstrom, 2000). Changing weather conditions in Southern Africa have resulted in shorter growing seasons, increased frequency of dry spells, increased variability, droughts and floods (Mkuhlania et al, 2018). Mkuhlania et al. (2018) reported that up to 50% of the maize yield losses in Southern Africa over the past 25 years were attributable to rainfall variability. Rockstrom (2000), who reviewed water resource management on smallholder farms in Eastern and Southern Africa, found that in the semi-arid regions, severe crop reductions caused by dry spells occurred once to twice every five years, and total crop failure caused by annual droughts occurred once every 10 years. His work indicates that dry spells are more of a cause of concern for crop failure than absolute water scarcity due to low cumulative annual rainfall. Repeated crop failures lead to low levels of income and prevent farmers from purchasing labour, fertilisers or high yielding crop varieties that may otherwise help them to stabilise crop production (Pande and Sivapalan, 2017).

Irrigation is widely accepted to be one of the strategies used by small scale farmers to manage their dependency on rainfall, especially in semi-arid zones (Sithole et al., 2014; van Averbeke and Denison, 2011). It enables the production of horticultural crops and can be used in climate variability management (Mkuhlania et al., 2018). The water source is critical from the perspective of water supply adequacy and reliability to the scheme (Denison, 2018). Furthermore, infrastructure type, condition and operational management has a significant influence on the adequacy and reliability of water supply at the plot holder's boundary (Denison, 2018).

Studies by Muchara et al. (2014) and Lopus et al. (2017) show that the quality of water delivery drives member satisfaction, which influences farmer's participation in collective water management, which, in turn, affects the systems sustainability. Muchara et al. (2014) for instance established that the number of consecutive days that farmers spend without access to irrigation water per week, is a significant determinant of farmer participation in collective action activities. On this basis, system failure is a conceivable result of member's displeasure with the water delivery outcomes of a scheme.

Water is the economic lifeblood of the farmers and if it is delivered in an uncertain and unreliable manner, collective action disintegrates and each farmer fends for themselves (Crosby et al., 2000). Similarly, Nkhomo and Kayira (2016) in their study in southern Malawi, found that poor water delivery can potentially accelerate the vandalism of the infrastructure as farmers scramble for the water that reaches them. Sustained water resource management in irrigation schemes relies on the user's satisfaction with the performance of both the infrastructure and governance (Lopus et al., 2017). According to Gomo et al. (2014), addressing the short comings in the water distribution system may raise the performance of irrigation schemes. To explore this further, the following sections review the technical factors affecting the performance of smallholder irrigation schemes.

2.4.2 Design aspects of smallholder canal schemes

The canal is the most frequently used water delivery system to convey water from the source to the farmland for irrigation. In a study of 206 smallholder irrigation schemes in South Africa, canal schemes were found to have the highest functionality in relation to pumped irrigation schemes, which are vulnerable to functional and financial failure, are less resilient to factors such as water stress and have lower lifespans (van Averbeke et al., 2011; van Koppen et al., 2018; Denison, 2018). Canal schemes are durable, better suited to local control and are not affected by energy price externalities (van Averbeke and Denison, 2011). In South Africa, canal schemes are typically older than 40 years and combined they contribute approximately 25% to the total smallholder irrigation scheme command area (Mohamed, 2006).

The aim of hydraulic design of canal schemes is to ensure that the conveyance structure and its related structures, perform their functions efficiently and competently with minimum maintenance, ease of operation and minimum water loss (USBR, 1978). The history of canal design at the Department of Water and Sanitation dates back to the early 1900s, with emphasis on the design of canals for large commercial government water schemes. The main references include the Design of small canal structures (USBR, 1978) and the Design of canals and related structures (DWA, 1980).

Infrastructure design in the nineteenth and twentieth century was characterised by a command-and-control attitude towards natural systems, promoting ideas of stability, efficiency, monofunctionality and permanence (Lokman, 2017). The canal design capacity is primarily based on the crop pattern, the area irrigated, water rotation system, water losses from evaporation and seepage and the anticipated efficiency of water application to crops (USBR, 1978 and DWA, 1980). Based on these considerations, the net average peak water requirement is calculated. Provision to meet maximum peak demand is made by extending the irrigation time and/or controlled overloading of the canal system (DWA, 1980). The management and operation of the canal schemes is usually centralised and undertaken by Water User Associations (WUAs). Consequently, the social habits relating to the normal working week are fairly static and difficult to change (DWA, 1980). This implies that farmers must sow, till, weed and harvest at the times determined by the engineer (Diemar et al., 1991). The effectiveness of this approach is being gradually diminished by many challenges including climate variability and unpredictability, changes in demographics and preferences, complexity and interconnectedness within infrastructure systems, and unpredictable human behaviour (Markolf et al., 2018).

Smallholder irrigation projects in sub-Saharan Africa have been largely funded by development institutions whose professional staff tend to be engineers, who tend to focus on technical issues in isolation from social considerations (Harrison, 2018). These engineers work without consulting smallholder farmers as their mandate is to design a scheme against a single criterion of meeting the water requirements of irrigation schemes, without considering the politics associated with their maintenance (Diemer et al., 1991; Harrison, 2018). Smallholder canal schemes are typically developed in what is generally referred to as a "hierarchical" layout design in irrigation engineering literature (Yu et al., 2015). These infrastructure design features configure a series of arenas for water distribution interaction with large spatial extent that is difficult to police and a static system with limited options for flow regulation (Mollinga, 2014). The structure is that of a set of queues wherein those located upstream have a strategic local advantage (Molinga, 2014). The lack of flow regulation devices and storage facilities means that the possibilities for flexible forms of management responding to local demands and needs are circumscribed. The system is designed for stable and continuous flow, in tune with the protective objective of a thinly and widely spread irrigation, but not with the actual use of the system in mind (Molinga, 2014). Two regularities emerge from this type of layout, the critical importance of infrastructure maintenance and the challenge of fair, reliable water distribution (Yu et al., 2015). Most of the scheme identification and development efforts were decided without considering the hydrology and water budget of the catchment. Consequently, in many cases, decisions regarding site location were made with only one surface flow measurement, or based on rainfall data from a distant weather station (Amede, 2015).

The case-specificity of smallholder irrigation schemes arises from the multitude of factors that affect them including scheme objective, natural resource base, technology, scheme and plot size, farmer profile and marketing opportunities. According to Lokman (2017), infrastructure has the agency to structure relationships between humans and the environment. Consequently, an evaluation of smallholder irrigation schemes from just a technical perspective is not enough (Crosby et al, 2000). Diemer et al. (1991) thinks that planning and design must be based on the norms identified during the study of the local production to identify the organisational criteria for designing the hydraulic network and political systems to identify the criteria for allocating plots. Plusquellec et al. (1994) suggests that the design of the water delivery network should be based on an understanding and satisfaction of the agricultural and social requirements at all levels and stages of the design and operation process within overall resource availability. Denison and Manona (2007) recommend that engineers interrogate water management issues jointly with the scheme users to develop creative changes to the water system. Designs should align with the community needs and resources (Bembridge, 2000).

Numerous control strategies are in use in irrigation systems throughout the world, these include proportional control, adjustable flow rate control, upstream control, downstream control, remote monitoring and remote control (Plusquellec et al., 1994). The selected control strategy must be compatible with the required flexibility of the water supply and with the social, political, geographical and economic conditions under which it will be used (Crosby et al., 2000). Most of the canal schemes in South Africa are upstream controlled (or supply driven). This means that a control structure (typically structures such as long weirs), provides a constant head at the offtakes for a constant discharge to be achieved (DWS, 1980). Once the flow diversion from the source is adjusted, the unsteady state of the system requires that the discharge and water level regulators be adjusted accordingly, which can be a very time consuming and resource intensive activity (Ankum, 1997). These types of systems were designed for strong centralised control by a managing authority and not for operation by the farmers themselves (Denison and Manona, 2007). They leave little flexibility for downstream users in choosing cropping patterns, planting calendars and water delivery schedules. In addition, these systems encounter operational difficulties because of their response times and operational losses may become high due to frequently changing discharges (Ankum, 1997). These designs also make self-management difficult or favours some farmers over others (Denison and Manona, 2007). Downstream controlled systems solve the problems related to response times and operational losses and therefore do not require centralised control (Ankum, 1997). However, the required infrastructure system is larger and more expensive than upstream controlled systems. A combination of different control philosophies may therefore lead to the optimum control method (Ankum, 1997).

Plusquellec et al. (1994) developed the principles for modern (i.e. contemporary) water control in irrigation. He suggests that a good irrigation system design should increase reliability of water supply (i.e. timely supply of water), ensure equity and flexibility to adjust water delivery to farmers, reduce conflict amongst water users and between water users and the irrigation agency. In systems with several levels of operation, the reliability and equity at each level should be the same however the flexibility may be different. It should be designed around the local rainfall conditions to maximise returns on investment. The system should be able to respond quickly and accurately to a sudden fall in demand of irrigation water. The design must consider the turnout size, the number of turnouts downstream, the gross flow rate needed for continuous irrigation, the probability of the farmers changing crops to ones with higher water requirements, the probability of not having enough capacity in the canal to provide flow at a turnout when needed, operational storage and the rejection of water by upstream turnouts. Farmers should not be obliged to accept more water than is required. The system needs to be designed for unsteady flow operation with structures that will ensure reliability and responsive control for a variety of flow conditions.

The question of design appropriateness for smallholder farmers and their environment has not been adequately addressed locally. Instead, irrigation design practitioners concentrate on optimising perceived engineering standards or goals adopted from western professional institutions. Markolf et al. (2018) challenges infrastructure designers to see infrastructure systems from a perspective of interconnected social, ecological, and technological systems (SETSs), to prevent maladaptive issues and highlight effective infrastructure adaptation strategies that may not have been traditionally considered. SETS approaches are technologically - ecologically and socially oriented, and not focused on one over the others. They can help us identify vulnerabilities within infrastructure systems over time. Markolf et al. (2018) argues that without broader consideration of social and ecological aspects, physical infrastructure systems may be implemented and managed in an inequitable manner. They posit that infrastructure systems be treated as complex social, ecological, and technological systems (SETSs) where feedback between humans, infrastructure, and the environment dictate failures and their consequences.

2.4.3 Operational aspects of smallholder canal schemes

The successful sharing of a water source on a canal scheme requires farmers to be well organised and equipped to control (i.e. regulate water flow), operate and maintain the infrastructure (Crosby et al., 2000). If the decisions made on these aspects are incorrect, the sustainability of the smallholder irrigation scheme is adversely affected.

The operation of canal schemes is concerned with adjusting the setting of structures in a consistent and timely manner in order to deliver water of a predetermined quantity/flow rate at a desired point. Each one of the manually operated flow regulators should be adjusted at a suitable frequency as the flow change moves downstream. The operation needs to consider some basic laws of hydraulics such as lag time, unsteady nature of flow, fluctuations of water levels and the hydraulic interactions of the open channel infrastructure. It is complex task requiring sequenced and coordinated actions and is demanding in terms of effort and resources (i.e. staff, coordination, transport, communication etc) (Renault et al., 2007). The complexity of these requirements often makes it very difficult for local people, with local knowledge, to negotiate on an equal basis with officials and actors with scientific knowledge, as a result, the operation of many of these schemes are shaped by outsiders (Tantoh and Simatele, 2017). The nature of the efforts needed to operate the system should be adjusted according to the local technical and socio-economic context (Renault et al., 2007).

Irrigation systems should be designed with a certain mode of operation in mind which is based on two decisions, the scheduling of water deliveries (i.e. the frequency, rate, and duration of water deliveries at all levels within an irrigation conveyance system), and the determination of the interactive movement of various control structures to satisfy the requirements of the desired schedule (Plusquellec et al., 1994). There are different types of water-delivery schedules including continuous supply, rotation schedule, centralised scheduling, arranged schedule and limited rate demand (Plusquellec, 2002). The rotational method of supply is the most commonly used amongst smallholder irrigation schemes, where a fixed supply is normally selected and changes in irrigation requirements are met by adjusting the duration and interval of supply. On the continent there is evidence of over-application of water by plot holders where water is supplied on this basis (Bjornlund et al., 2016). This method is not well adapted to a diversified cropping pattern or sudden large changes in supply requirements (Crosby et al., 2000). It provides water with no flexibility in frequency, rate or duration (Plusquellec, 2002). Crosby et al. (2000) and Veldwisch (2006) amongst others are of the opinion that continuous proportional distribution of water would be a more manageable arrangement for smallholders, with equal daily division of water between blocks that are small enough to allow flexibility among close neighbours.

Ankum (1997) agrees that proportional control is simple and more manageable. He also mentions however that these types of systems react slowly to changes in supply and will only suffice in certain conditions of mono-cropping, extensive irrigation or when drainage water can be re-used. The rotational method in the South African commercial irrigation sector was refined with a transition towards on-demand scheduling of water and the use of night storage (DWS, 1980). The Water Administration System (WAS) (Benade, 2017) has been used by a number of commercial schemes in South Africa to facilitate on demand scheduling. The WAS minimises water distribution losses on canal networks and in river systems, calculates water releases for the main canal including all branches, allowing for lag times and water losses such as seepage and evaporation, determines operational procedures for a dam with varying downstream inflows and abstractions in a river (Benade, 2017). There is no reported use of the systems system by any smallholder irrigation schemes in South Africa.

In canal schemes with several levels of operation (i.e. primary (or main) canal, secondary canal, tertiary canal), improved water control must begin in the main canals, otherwise the flows in the secondary and tertiary canals will be erratic (Plusquellec, 2002). Furthermore, the reliability at each level should be the same although the flexibility at each level may be different, restricted by the flexibility of the next higher level (Crosby et al., 2000). Improved reliability and flexibility of water deliveries to the farm, result in improved on-farm use and less spillage in the conveyance system, thereby decreasing the volume of water required at the source for the same crop yield (Crosby et al., 2000). However, flexible delivery results in unsteady flow conditions which increase the risk of siltation of canals as well as strain on maintenance, deteriorating the operation of the canal (Plusquellec, 2002).

Maintenance is one of the main concerns to sustainability of irrigation development in Africa (Chidenga, 2003; Amede, 2015). Chidenga (2003) defines maintenance as all the activities carried out to ensure that the system is kept in working order and retains the capacity to operate as and when required. Maintenance is typically subdivided into three categories: routine maintenance (i.e. removal of plants and sediments from canals, maintenance of gates and valves and removal of sediments from overnight dams), special maintenance (i.e. usually refers to the repair or replacement of primary or secondary canal sections, gates or structures) and deferred maintenance (i.e. large modifications of canal systems) (van Averbeke, 2008). Routine maintenance is a major concern for canal schemes (Plusquellec et al., 1994). There are typically three options for the removal of sediment including removing sediments before they enter the canals, making it easy to remove the sediments from the canals or keeping the velocities in the system sufficiently high to keep the sediments in suspension. Faulty cleaning and sediment accumulation in the canals leads to an increase in canal roughness and a reduction of the canal capacity, which increases the risk of water requirements for farming (Ankum, 1997; Totina, 2014).

Continual use of irrigation systems requires farmers to routinely maintain the infrastructure, which involves collective action by plot holders. If too few farmers contribute towards this maintenance, then the capacity of the infrastructure to deliver water is reduced thereby increasing the risk of water shortage for farming (Yu et al., 2015 and Totin et al., 2014). Yu et al. (2015) refers to the point at which water shortage starts as the maintenance threshold, which is a function of the biophysical and natural environment. Infrastructure design features can significantly affect this threshold. Care must be taken not to increase this threshold by over designing, leading to a lower maintenance cost and an increased likelihood of total collapse or reduction to this threshold, increasing the cost of maintenance and affecting the sustainability of the project (Crosby et al, 2000 and Yu et al, 2014). Furthermore, incentives for water users need to be availed and improved to encourage farmer participation in collective action activities like the maintenance of famer managed irrigation schemes. The understanding of the determinants of farmer participation informs this basis (Muchara et al, 2014). Muchara et al (2014) points to the need to strengthen local water management systems and institutional policies and to further understand the institutional dynamics in which smallholder irrigation farmers operate. The interplay between social, technological, economic and natural processes has a strong influence on the capacity of groups to overcome the collective action problem that maintenance poses in farmer managed systems (Yu et al, 2015).

The perspectives of the various role players (i.e. the farmer, operator, scheme project manager, government) in an irrigation scheme vary. The operational plan combines these perspectives and reflects an understanding of the climatic, cropping pattern and soil types of the project area (Plusquellec et al., 1994). However, in many irrigation schemes in South Africa, formal operating rules have not been properly documented and implemented.

2.4.4 Management aspects of smallholder canal schemes

The duty of irrigation management is to ensure adequate supplies of water are made available where and when lawful irrigation users need it (DAFF, 2015). The two key aspects are adequacy and assurance of supply. Adequacy is concerned with the extent at which water supply availability at the source meets crop water requirements (Denison, 2018) and is critical during the peak water requirement period of the crop growth. Assurance of supply is important during the phenological stages at which crops are sensitive to water stress (DAFF, 2015). According to de Lange et al. (2000), scheme managers are essentially service providers to the farmers. Therefore, they need to have a deep understanding of the institutional relationships and decision-making mechanisms that determine the day-to-day operation of the scheme and farming activities.

Historically, the management of water sharing and maintenance of smallholder irrigation schemes in South Africa was the responsibility of the government (van Averbeke, 2008). In the 1980s there was an appreciation that farmers were not sufficiently involved in the schemes they were an integral part of, resulting in policy changes towards more participatory approaches (Harrison, 2018). The review of the smallholder irrigation policy in 1994, resulted in the transfer of the management, operation and maintenance responsibility from the government to farmer communities or management committees, constituted during the scheme revitalisation initiatives, through the adoption of irrigation management transfer (IMT) (van Averbeke, 2008; Letsoalo and van Averbeke, 2006; Denison and Manona, 2007).

The typical management organisation of the committee was a Trust or a Water User Association (WUA) (Denison and Manona, 2007). IMT requires the cooperation of the group of farmers sharing water resources in order to maximise benefits from the resource (Muchara et al., 2014). Totin et al. (2014) summarises the factors that contribute to successful cooperation as the physical and technical characteristics of the resource around which the group work is organised, characteristics of the user group (e.g. number, homogeneity), and the attributes of the institutions that govern the interaction among the different users of the resource (e.g. rules that govern collective well-being). According to van Averbeke (2008), successful cooperation depends on functional institutions and organisations to guide collective action. The level of individual participation in collective water management activities is influenced by personal attributes, resource attributes, institutional setting and the incentive systems.

The water distribution management requirements of smallholder irrigation schemes are unique as they involve a number of individuals with different crops and varying water requirements throughout the farming season (Crosby et al., 2000). It is easier in smaller areas, where social pressures help keep participants accountable, however, when distances become larger, management becomes more difficult as the ability to act quickly when there is a problem is diminished (Crosby et al., 2000). These challenges are exacerbated during water shortage periods or during the failure of a canal section or regulation structure (Crosby et al., 2000).

Water User Associations (WUAs) were formalised to enable a community of water users to organise and pool financial and human resources to carry out more effective water related activities for their mutual benefit (Mukovhe, 2007). The National Water Act 36 of 1998 defines a WUA as a “co-operative association of individual water users who wish to undertake water related activities for their mutual benefit”. The Act provides a framework which it expects WUAs to follow, these typically include protecting water resources and preventing unlawful use, constructing, operating and maintaining waterworks, monitoring water use and keeping records of water levels (Saruchera, 2008).

WUAs in South Africa however are characterised by high social inequities and disorganised groups that lack financial and technical capacity to make the WUA viable (Saruchera, 2008). They bring two notable stakeholders together, namely the commercial and smallholder farmers. Commercial farmers are happy to include emerging farmers who are paying members in the WUA, or those located upstream of them and can therefore affect their water quantity and quality. However, the involvement of many smallholder farmers is low and most of them find themselves at a loss in these organisations despite their superior numbers (Saruchera, 2008). Consequently, these associations are unable to articulate and address the needs of smallholder farmers.

In addition, conventional methods of assessing water delivery performance all depend on flow measurements at various levels and points of the irrigation system (Sam-Amoah and Gowing, 2001). However, no measurements of field data are available in most smallholder irrigation schemes (Manero et al., 2019). Reasons for lack of data may vary from lack of equipment, equipment malfunction, lack of motivation on behalf of the staff and lack of knowledge. Government Gazette No. 40621 requires that all water users taking water from a water resource for the purpose of irrigation, to measure such water. This notice obligates water users to measure water taken from a water resource and must, at the water user's expense install, maintain and use a water measuring device. Any water user who negligently or intentionally fails to comply with the provisions of this notice are guilty of an offence. Various proxy indicators are used in literature for assessing water delivery performance amongst smallholder farmers. Key amongst these are the farmer’s perceptions and farmer’s satisfaction. Lopus et al (2017) identified farmer’s satisfaction as a potential key factor in shaping resilient agricultural systems. They determined that this factor was strongly associated with the relative water delivery of one’s peers. Lopus et al. (2017) also identified the water delivery relative to one’s past as a strong predictor of farmer’s satisfaction.

There has been a lag in the development of appropriate institutions to deal with the equitable allocation of water amongst competing users and to strategically integrate the management of different stakeholders to meet the different needs of smallholder farmers in Africa (Mutambara et al, 2016). Ostrom (1992) suggested the establishment of a WUA that could undertake most routine maintenance and articulate the needs and interests of the plot holders to project officials. van Averbeke and Denison (2011) recommended the involvement of a commercial partnership based on the consolidation of a number of smallholders, to take the responsibility of operation and management of the schemes as the plot holders themselves cannot. Community natural resource management (CBNRM) has been recognised as one of the avenues for the sustainable management of common pool resources (Tantoh and Simatele, 2016).

The management challenge on canal schemes is to ensure that water is shared equitably amongst the plot holders and that the scheme infrastructure is maintained (van Averbeke, 2008; Chami et al., 2014). Current water management practices and institutional arrangements on smallholder irrigation schemes seem to jeopardise the sustainability of the scheme (Amede, 2015). For natural resource management to succeed, it is important that new power-sharing relationships between communities, the state and other actors are worked out and established (Tantoh and Simatele, 2016). Without strong irrigation management it is impossible to have a working maintenance strategy and fair, reliable and timely delivery of water (Ulsido and Alemu, 2014). Well managed smallholder irrigation schemes have the ability to improve the resilience of its members to climate shocks (Lopus et al., 2017).

2.5 Land and water institutions and their effects on smallholder canal scheme utilisation

2.5.1 Introduction

Institutions are structures and systems that "matter the most in the social realm" (Hodgson, 2006) because they are the "prescriptions [used by] humans to organise all forms of [their] repetitive and structured interactions" (Ostrom, 2005). They range from legal structures to informal social arrangements backed by moral pressure or sanctions (Bromley, 1982).

Institutions clarify the rights, responsibilities, and obligations of individuals and groups in a society by indicating what individuals must or must not do (compulsory or duty), what they may do without interference from other individuals (permission or liberty), what they can do with the aid of collective action power (capacity or right) and what they cannot expect the collective action power to do on their behalf (incapacity or exposure) (Eicher, 1999; Commons, 1936). They structure social interaction, defining the behaviour of individuals and groups, as such, institutional factors may be seen to "affect our expectations of the behaviour of others and their expectations of our behaviour" (Ostrom, 2005).

Institutions, therefore, are structures built on sets of rules which are instructive ("provide individuals with strategies for ongoing situations"), preceptive ("the cultural prescriptions known as norms") and principled ("physical laws") (Ostrom, 2005) and they persist because the "patterns of norms and behaviours [they create, are] valued and useful" (Bandaragoda, 2000). Ostrom (2005) defined rules as the "shared understanding by [individuals] about enforced prescriptions concerning what action (or outcomes) are required, prohibited or permitted" thus ordering the human being and creating predictability in his society. To achieve an ordered and predictable society, the value system of that society is used a framework for the content of its institutions and its social norms are used to enforce that content and realise those values.

Values are the abstract self-conception of groups and they refer to a group's aspirations and desirable goal (Baurmann et al, 2010; Schwartz, 2012). They are an expression of what a group perceives to be, morally, desirable or undesirable, good or bad (Macionis, 1991; Frese, 2015) and represent basic convictions of particular modes of conduct or end-states of existence that are personally or socially preferable to others (Stolley, 2005) which are transmitted from generation to generation through various socialisation practices. Schwartz (2012) theorises that values are interdependent and should be seen to "form a circular structure that reflects the motivations each value expresses [and] that this structure captures the conflicts and compatibility" between them. Her theory of values demonstrates that values have both content and intensity attributes- the content attribute is concerned with the mode of conduct or end-state of existence, whilst the intensity attribute specifies how these are. The description put forward by Schwartz of the relationship between people and values also highlights the way in which values are ranked in terms of their intensity form where they are classified according to their magnitude of flexibility and may be absolute or relative.

Absolute values tend to be prescriptive and binding (Deacon and Firebaugh, 1981) and they are reinforced through people's own experiences and by the expectations of those around them. They are resistant to change because they interpret what is desirable or of worth in spiritual or other fundamental structures, often prescribing solutions or 'ways to deal' with recurring situations (Deacon and Firebaugh, 1981). Relative values, on the other hand, refer to an individual or group's evaluation of circumstances (Ostrom, 2002). In groups where relative values are most active, the notion of change or new alternatives is always acceptable (Deacon and Firebaugh, 1981). Conversely, when groups primarily adhere to absolute values long-standing attitudes are closed to alternatives, narrowing options for change or adoption potential.

Schwartz's (2012) six key elements explaining the relationship between values and people:
- "Values are beliefs linked inextricably to affect." Schwartz explains this relationship as one "infused with feeling" and that much importance is attributed to this value because it defines a person's state of being. She writes, "people for whom independence is an important value [for example] become aroused if their independence is threatened, despair when they are helpless to protect it, and are happy when they can enjoy it."

- "Values refer to desirable goals that motivate action*."* This relationship is associated with acts or practice of social morality, people motivated to pursue this set of goals perceive social order, justice and helpfulness as important values.

- "Values transcend specific actions and situations*."* This relationship is associated with norms and attitudes expressed in specific context, outside of the private realm- it is values such as obedience and honesty which may only be active in the workplace or school, in business or politics, with friends or strangers.

- "Values serve as standards or criteria*."* In this relationship, a group's absolute values are at play. It looks at what a group of people decided on what is "good or bad, justified or illegitimate, worth doing or avoiding, based on possible consequences for their cherished values" and, these values guide "the selection or evaluation of actions, policies, people, and events".

- "Values are ordered by importance relative to one another*"* and "The relative importance of multiple values guides action*."* These relationships are concerned with the individual's relative values, his normative behaviour and his attitude. The first, looks at what the individual prioritises versus group priorities- "does he/she attribute more importance to achievement or justice [for example, or] to novelty or tradition?". The second of these relationships looks at weighing one's options in interdependent values, it is a relationship of "trade-offs among relevant, competing values [that] guide attitudes and behaviours [and] influence action when they are relevant in [specific] context, important to [an individual]."

The relationships presented by Schwartz are daily interactions between individuals and the groups they form a part of with values and interpretations of these values and resultant behaviours, are regulated by norms.

Norms are derived from values (Stolley, 2005) and should be seen "instruments of value realisation" (Baurmann et al, 2010). They are the shared, beliefs, ideas, rules or expectations which prescribe appropriate behaviours and rules of conduct in various situations (Newman, 1995; Macionis, 1991). Norms are descriptions of a concrete course of action for what is regarded as desirable with an injunction to make certain future actions conform to this course- in effect, they specify what people should do and not do and how they should pursue values (Newman, 1995; Macionis, 1991).

Norms include formal rules and laws, as well as informal social controls. They encourage or give permission to behave in certain ways and they sanction undesirable behaviour (Ellickson, 1991). A system of social norms mimics a legal system or vice versa. They are unwritten rules of conduct related to society's values and rules that influence people's behaviour, explaining the expected behaviour, including its procedural characteristics which clarify how aberrant behaviour is dealt with (Marsh, 2000; Eggertsson, 2001). Hechter and Opp (2001) and Kanazawa and Still (2000), distinguish between moral norms and coercive norms. Moral norms prescribe behaviour that most people would practise anyway or proscribe behaviour which most people would not practise even in the absence of such norms and the associated threat of sanctions; whilst coercive norms prescribe behaviour that most people would not otherwise practise or proscribe behaviour that most people would practise in the absence of such norms.

Social norms are enforced by group (surrounding people) sanctions, which are either rewards for carrying out those actions regarded as correct or punishments for carrying out those actions regarded as incorrect (Coleman, 1990; Nordlund, 2009). Social enforcement is an essential component of norms (Parsons, 1952; Nordlund, 2009). A rule advocated by an individual is not a norm at all but a personal idiosyncrasy (Horne, 2001) and individuals apply sanctions to their own behaviour and respond to these internally generated rewards or punishments in the form of good or bad conscience (Coleman, 1990; Nordlund, 2009). Norms may also be internalised when individuals come to value the behaviour specified by norms for its own sake. In such instances, they follow social norms because they want to. Internalisation can be an enforcement mechanism that is brought by external sanctions.

A person who violates a norm can receive punishment in three different ways:

- i) from an actor who is directly affected by the violation;
- ii) from a third party who acts to uphold community standards and;
- iii) from the violator's own consciousness (Eggertsson, 2001).

Norms can either be legal or social- public order and enforcement of rules, for example, are highly depending on social norms (Eggertsson, 2001). Some norms govern substantive entitlements whilst others, govern remedies and procedures where controller-selecting rules specify each type of activity to achieve social order. In some contexts, control-selecting norms even forbid a grievant from using the legal system (Ellickson, 1991).

Legal norms are created by "classes of persons (positions)" in deliberative processes. What is required, permitted and forbidden in these norms with their sanctions, is captured in written texts and enforced by specialised bureaucracy (Coleman, 1990; Ostrom, 2005). Social norms, by contrast, are, often, spontaneous rather than deliberately planned, hence their uncertain origin. Social norms are unwritten and their content and rules for application are often imprecise (Hechter and Opp, 2001) and they are enforced informally even though the resulting sanctions may sometimes be a matter of life and death (Hechter and Opp, 2001).

In this study, the institutions that are analysed, are those of smallholder canal irrigation scheme communities whose farming success is largely dependent on the group's collective action. Institutions are important in collective action because collective action occurs with the aid of rules (Bromley, 1982). Although the rules imposed here, are externally crafted and, often, ignore the cultural orientations of recipients (Chambers, 1997), they can be internalised by the intended recipients. Internalisation is assisted when the rules are compatible with the recipients' way of life and when they govern the use of a new resource that is of benefit them and for which there was a need in the community (Roggers, 1995). The formal (de jure) institutions of a small holder irrigation scheme may be compared be compared to the structure of organisations where the organisation is a social entity that has members, resources, structures, authority and boundaries (Mullins, 1999). Decision-making on execution of the rules and conventions of collaboration and co-operation is usually done in an organised manner by groups of people referred to as organisations (Gabriel, 1999). Within the organisation, there is often a hierarchy of positions known as the organisational structure (Gabriel, 1999) and, selected and appointed people fill positions in this structure (North, 1990). The functions of structures in an organisation are to reinforce and enforce the institutions in order to maintain social order.

In the last two decades, research conducted on and literature of smallholder irrigation schemes has highlighted a systematic break down of the institutions that maintain the social order of these schemes, particularly, those that activate unconscious participation in collective action by members of a group. Bates and Plog (1990) explain that one of the most basic conflicts in community politics is between those seeking to conserve social order and those seeking social change. If this is, indeed, the case, then it needs to be verified for smallholder irrigation schemes in Vhembe. The question that needs to be asked about the erosion of institutions on small holder irrigation schemes is, "what kind of change does one group of individuals seek for 'return' of order?" and "what are the implications of change for the group of individuals who seek to converse the status quo?" "Which of the sets of values and norms of these groups hinder the individual?"

2.5.2 Case of water institutions

The water institution structure comprises three institutional components- water law, water policy and water administration (water-related organisation) - which are concerned with the "formal and macro-level arrangements [as well as] the informal and micro level arrangements [which are] reflected in local customs, conventions, and informal contracts" (Saleth, 2004). Saleth (2004) explains what each of these institutional components is concerned with:

1. water law [is concerned with] (a) inter-governmental responsibility, (b) water rights, and (c) accountability provisions and mechanisms;
2. water policy [is concerned with] (a) project selection criteria, (b) pricing and cost recovery, and (c) user and private sector participation policy and;
3. water administration (the organisational dimension of water institutions) [is concerned with] (a) organisational structure and the relative role of government layers, (b) financing and management, (c) regulatory mechanisms, and (d) conflict resolution arrangements.

Saleth (2004) explains that analysis of the rules that each water institutional component is concerned with shows that they can be "approximated respectively by laws (legal rules), policies (policy guidelines), and organisations (organisational rules) [because] laws are the outcome of constitutional choice and policies are the results of a collective choice through the political process, whereas the operational rules come into play when the laws and policies are operationalised by the administrative mechanisms involved in their implementation, monitoring, and enforcement."

Smallholder canal irrigation schemes in South Africa are characterised by a multitude of plot holders who share irrigation resources in the form of water and infrastructure. For canal schemes to operate efficiently, plot holders must manage the social systems that provide for the fair distribution of irrigation water and the maintenance of the canals. The achievement of common goals of smallholder irrigation communities is dependent on the effectiveness of their collective action. In smallholder agriculture, the practice of collective action extends beyond irrigation resources and it is central in smallholder cooperatives and the management of commonage land of these canal schemes.

The concept definition of Collective Action, irrespective of the disciplinary perspective, has the common that it involves multiple individuals (a group), who are engaged in an activity (action), which is aimed at achieving a common goal.

Philosophers define collective action as “acting together with the intention of achieving immediate goals in everyday life” (Searle, 1990), that is “individuals with ‘we-intention’ in mind, working together to attain an everyday goal” (Searle, 1990). The ‘we-intention’ in the definition of Searle (1990), is similar to that of ‘joint commitment’ contained in the definition of Gilbert (1989), with both terms referring to ‘collective action intentionality’ (Searle, 1990; Gilbert, 2006). The implication of collective action intentionality is that those in that commitment are in a position to demand corrective action of members deviating from the collective action intentionality (Searle, 1990).

In sociology, collective action is defined as the “structured or unstructured involvement of a group of people towards attaining an intended common goal” (Sills, 1972; Perry and Pugh, 1978; Sullivan, 2001). Sociological theories of collective action aim to explain the behaviour of groups that is associated with social arrangements and is concerned with identifying the factors that result in the setting of standards of social integration and factors that lead to deviance and conflict.

Political scientists and economists studying collective action have been concerned with the provision of public goods and other collective action consumption by more than one individual. Marxwell and Oliver (1993), for example, defined collective action as “an action taken by two or more people in pursuit of the same collective action good”. Collective action featured prominently in studies that investigated property rights in rural development. In this context, Bates and Plog (1990) and Meinzen-Dick and Di Gregorio (2004) defined collective action as “voluntary action taken by a group to achieve common interests either directly on their own or through an organisation”. Ostrom (2001) added that “collective action occurred when more than one individual was required to contribute to an effort in order to achieve an outcome”. Collective action has also been studied in contexts in which the goal of a group was to attain power- Olson (1971), for example, studied collective action in relation to markets and identified its goal to be the attainment of bargaining power.

When studying cooperatives, Texier (1976) defined collective action as “a non-conventional form of cooperation that emanates from mutual aid constituted by various traditional practices in collaborative functions”. The ‘mutual aid’ Texier (1976) refers to, occurs socially, when people collaborate in assisting each other without immediate and direct reward- friends consoling and lending their hands to a bereaved friend are seen to be involved in social collective action. When several individuals, for example, put their resources together, attaining that which individually the resources would not achieve is economic collective action.

These definitions of collective action can be synthesised to define collective action as “the function of two or more people with common intention(s) applying the decided methods and techniques in attaining synergic tangible or non-tangible outputs”. This concept definition of collective action can, in turn, be transformed into a theoretical framework for use in the analysis of collective action as shown in Figure 2.3.

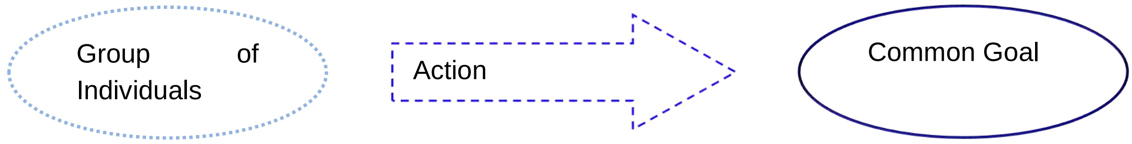


Figure 2.3 Collective action concept

The understanding of any form of collective action, therefore, requires an analysis of these three components. Groups studied, must be profiled in terms of their composition and dynamics and ascertaining the methods and techniques used by a group to achieve group goals is essential. Decisions made on the techniques and methods in collective action are determined by the dynamics of the group, for example, various leadership styles influence the quality of group decisions. The ultimate outcomes of collective action can be either tangible (for example, production of maize) or non-tangible (for example, resolution of a conflict).

Collective action manifests in formal or informal contexts. The informal context of collective action originates from spontaneous unaided self-help groups whose aims were associated with the enhancement and upgrading of societal relations (Sills, 1972). In the informal context of collective action, the benefits that members obtain are indirect and come in the forms of social unity, cohesion, and well-being Sills (1972). A universal example of informal collective is that of two strangers working together to assist a person involved in an accident where direct benefit is offered to for his or her participation.

Formal collective action pursues meta-economic aims and, the rights and duties of members of formal collective action are clearly recognised by officially permitted conduct (Kirch et al., 1984). Formal collective action is observed, for example, in agricultural cooperatives where the collaborative behaviour of farmers is aimed at improving access to markets and in in the institutions created for canal water management (Reddy and Shiferaw, 2014). Cooperatives offer the potential to provide positive synergies and advantages of economies of scale because in market access, transaction costs of marketing are reduced and the bargaining power for discounted prices on bulk purchases of farm inputs are increased relative to when farmers operate as individuals (Chancellor et al., 2003). Membership of agricultural cooperatives require contributions of money, attention to cooperative arrangements and taking part in duties associated with the cooperative (Kirch *et al*., 1984). The collective action in this case is governed by the cooperative's constitution and the rules are enforced by its members.

The motives for participation in collective action are located in the moral or the political economy. Olson (1971) theorised the motive of individuals involved in collective action is moral when members are less concerned with individual material benefit than with knowing that they will be protected during times of distress. Participants in collective action that has a moral motive assign priority to the (moral) value of being a member of a society that culturally envelopes and protects them through communal sharing during times of adversity and accord less value to their individual or family interests. This type of collection action is commonly encountered in African societies, particularly in rural areas, as in the case of the voluntary contribution of money, goods or assistance with funeral arrangements to a bereaved neighbourhood family. Here, there is no rule that coerces people to help, support and comfort are offered in anticipation of receiving reciprocal assistance when experiencing bereavement in their own families. In contexts where communities place great emphasis on moral collective action, it is contained in culturally defined rules that encourage sharing because the sharing behaviour of the group levelled out distinctions of wealth (Bates and Plog, 1990). Social status, reciprocity relations, solidarity, and kinship play an important role in moral collective action (Ostrom, 1998), where one's social status within the group is defined, largely, by his or her background (Ostrom, 1998). Expected contribution to the collective action is regarded in terms of the social status. High social status in the group is, typically, attributed to those members that are wealthy, holding high qualifications, etc. and these members are expected to make material contributions. The elder and those with experience, on the other hand, are expected to contribute their wisdom to the group. The strength of reciprocity is determined by sticking together (solidarity) of members of the group. Those that are not wealthy, for example, reciprocate by providing their physical ability in the collective action.

In the political economy, also called the rational foundation of collective action, individuals are seen to participate in a joint venture only when they expect to derive benefits for themselves or for their immediate families and will decline to participate when they see no benefit from taking part (Bates and Plog, 1990). They premeditate their self-interest rather than the likelihood of reinforcing community ties (Bates and Plog, 1990). In other words, in collective action of rational foundation; participants are not motivated by abstract notions of communal well-being but by self-interest rather, the incentive to contribute depends on the balance between the private benefits and the costs of participation being positive (Baland and Platteau, 1999).

Whether motive of collective action is in the moral or political economy, Ostrom (1998) points out that every collective action has in common, fair contributions and rewards. In the context of rural resource sharing, Ostrom (1998), Ostrom (1990), Agarwal (1994), Kurien (1995), Meinzen-Dick et al., (1997) and Marshall (1998) all agree that the sustainability of collective action was enhanced when participation of members was deliberate, group members shared socio-cultural values, work units were small and both membership and the boundaries of the resource being shared were clearly defined. Other attributes contributing to the sustainability of collective action were honest measurement of the contributions by participating members and net benefits arising from the collective action being large, relatively certain and equitably allocated. Members of successful collective action were characterised by dependency on common resources and a history of co-operation (Ostrom, 1998).

The effective functioning of collective action is based on rules and obligations that have to be clearly defined and adapted to local conditions and, members should be able to modify rules and obligations in response to changing circumstances (Meinzen-Dick et al., 1997). Meinzen-Dick et al. (1997) argued that adequate monitoring systems (through functioning organisations) should be in place, preferably with enforceable sanctions that were graduated to match the seriousness and context of offences. The actions of the organisation against offenders should not be challenged or undermined and this organisation should ensure that effective mechanisms for conflict resolution were in place (Meinzen-Dick et al., 1997).

Theoretical consensus on the functioning of any group is that it is determined by its cultural configuration (‘cultural make-up’) and its social structure (Stolley, 2005; Marsh, 2000; Newman, 1995). Cultural configuration refers to the groups’ institutions, its values and its norms (explained in 6.1) and it occurs through protocol that acknowledges positions and roles in a group. The positions held by members and roles that members play in the functioning of a group are called social structure and social structure sums up the common elements summed up in norms. As such the water institutional structure and the cultural configuration of a group should provide the basis of an analytical framework in the analysis of break down in collective action.

2.5.3 Case of land

In research and policy circles, it has long been the view that that the traditional tenure systems that prevail in Africa are inadequate to protect the land rights of local people and are poorly adapted to changing conditions (Ault and Rutman, 1979; Barrows and Roth, 1990; Deiniger and Jin, 2006; UN HABITAT, 2015), The current debate on improving the security of land tenure systems in Africa is largely between advocates of the extension of freehold tenure and supporters of alternatives, which, while formal, should be considerate of local conditions and be crafted specifically to serve the needs of existing land users. Extending freehold title to African smallholders is aligned with the view of de Soto (2000), who argued that awarding freehold title to the poor would increase their capital base and incenti*viz.*se them to take better care and make better use of the land they now own. Backers of alternatives to the freehold idea point out that wherever freehold tenure in Africa was implemented there was no real evidence of improved productivity and that freehold failed to take into account the importance of shared land resources and land use patterns that are aligned to local ecology, thereby sowing the seed for conflict over land (Besley, 1995; Deiniger and Feder, 2009; Sjaastad and Cousins, 2008; Toulmin, 2008; Sitko, Chamberlin and Hichaambwa, 2015). Further, Reddy and Shiferaw (2014) point out that awarding smallholder canal scheme farmers individual property rights may not resolve conflict arising from the sharing of resources.

They explain that an "efficient system of property rights should have three features**:**

i. Universality
ii. Exclusivity
iii. transferability" where the individual rather than the community decides on allocation of resources (Reddy and Shiferaw, 2014)

This system of privatisation is not only in direct conflict with the institutions of a smallholder canal irrigation scheme but Reddy and Shiferaw (2014) argue that it does not "necessarily lead to an efficient allocation of resources" and that, often, an "uneven distribution of rights would increase the ecological stress on the land if the majority of poor farmers were allotted rights in marginal and degraded lands [further aggravating] the existing inequalities due to the inequitable distribution of resources attached to [privatised] land".

In line with the general concern about the security offered by African tenure systems, studies that investigated land tenure systems on smallholder irrigation schemes in South Africa concluded that the security provided by existing systems was inadequate and that they were an impediment to agricultural growth (Masiya, 2018). Tenure on irrigation schemes is a special case, because of the intimate link between land and water. Whilst it is the norm on South African smallholder schemes that farming is done on an individual basis, the irrigation water and the infrastructure that provides farmers with access to water are shared. As a result, the institutions and organisations that govern land and water on irrigation schemes must not only specify and protect the land rights of participants in the scheme but also ensure that water is distributed fairly among participants and that the infrastructure providing access to water is maintained (Meinzen-Dick, 2014).

During the nineteen-fifties and sixties, when the state established large numbers of smallholder canal schemes, primarily in Limpopo Province, it imposed a paternalistic tenure system that took into account all of these requirements. This system, referred to as the '*Regulations for the Control of Irrigation Schemes in the Bantu Areas*', stipulated a wide range of conditions which participants in these schemes had to meet in order to retain access to irrigation land. By applying strict control and the use of sanctions, the state ensured that participants abided by the rules (Masiya, 2018). Over time, government control was progressively relaxed and participants responded by adapting the tenure system to suit their needs but the *de facto* changes they made eroded the practices that were in place to share water equally (Letsoalo and Van Averbeke, 2006) and maintain the irrigation infrastructure (De Beer and Van Averbeke, 2013).

Accordingly, the current institutional setup on smallholder irrigation schemes is a *de jure* system in the form of the '*Regulations*,' which is an anachronism that no longer suits contemporary needs and expectations of participants, and a *de facto* system characterised by uncertainties about the rights and obligations of participants pertaining to land and irrigation water.

2.6 Governance system of irrigation schemes

2.6.1 Introduction

The most commonly used definition of water governance is a "range of political, social, economic and administrative systems that are in place to develop and manage water resources and the delivery of water services, at different levels of society" (Rogers and Hall, 2003). Essentially, governance systems determine who gets what water, when and how, and who has the right to water and related services and their benefits (Allan, 2001). The representation of various interests in water-related decision-making and the role of power and politics are important components to consider when analysing governance dynamics (Jacobson and Wilde, 2013). These dynamics are complex. Venot and Hirvonen (2013) inform that water governance is crucial in enforcing rules and regulations in SIS to ensure sustainable use of the resource. Thus, some of these rules and regulations are driven towards fairness and equity in an irrigation scheme (Akuriba et al., 2019). Akuriba et al. (2020) further allude that these rules and regulations are crucial to achieve different scopes of governance, namely, participation, transparency, accountability and cooperation in the management of resources. Tropp (2006) identified four fundamental dimensions of water governance which can be used when performing assessments of water governance systems. These include social dimension; economic dimension; political dimension; and environmental dimension (Figure 2.4).

The social dimension focuses on equity of access to and use of water resources. This includes issues such as the equitable distribution of water resources and services among various social and economic groups and its effects on society. The economic dimension highlights efficiency in water allocation and use. The political dimension focuses on providing stakeholders with equal rights and opportunities to take part in various decision-making processes, while the environmental dimension emphasises sustainable use of water and related ecosystem services. When assessing the governance systems, one considers possible governance reforms that need to be taken into consideration to improve the system. Water governance reforms often contain similar elements, such as: decentralisation, integrated and coordinated decision-making, stakeholder participation, irrigation scheme management and increased roles for the private sector through public-private partnerships (Jacobson and Wilde, 2013).

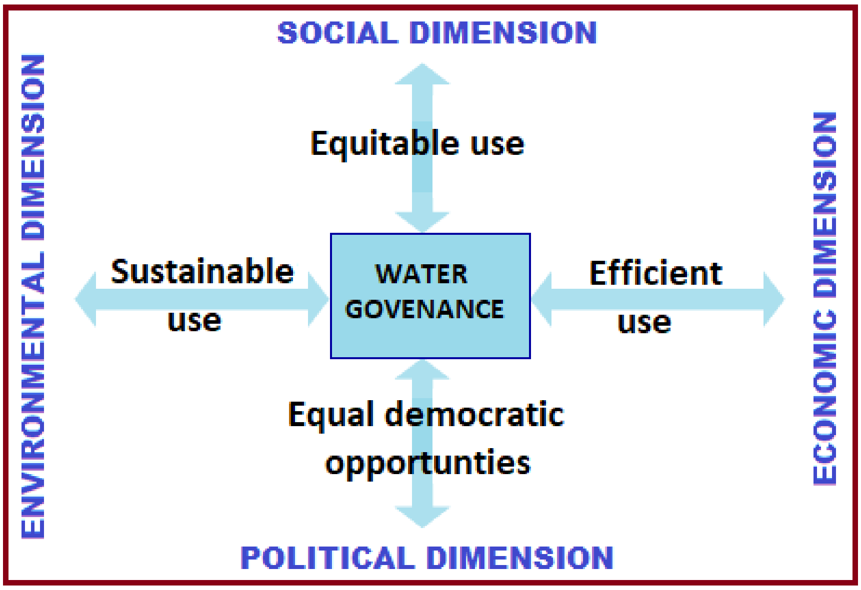


Figure 2.4: Four dimensions of water governance (Tropp, 2006)

The assessment of the water governance systems at the irrigation schemes is based on the approach of Howarth et al (2007) who identified four key features of governance.

Firstly, governance involves ***processes for making and implementing decisions***. Decision-making processes can involve among others, mass meetings, committee deliberations, elections, or the independent judgements of a powerful individual. Decisions can be implemented by *ad hoc* or regularly organised groups of irrigators, or by irrigation scheme management members or employees.

Secondly, the processes and decisions are the outcome of ***relationships between different categories of people***. This includes a range of relationships, e.g. between irrigators, between irrigators and scheme committee members, between irrigators and agency staff, between national politicians and donor agency representatives among others. The nature of communication and access to information, with its implications for trust and transparency, is an important aspect of relationships.

Thirdly, the way that people in these relationships make decisions is shaped by ***values, institutions (laws and rules), and policies***. For example, governance of water distribution is shaped by values surrounding equity and mutual obligation, rules about water theft, and policies that determine the legal powers of enforcement given to the irrigation scheme.

Fourthly, governance involves the ***exercise of authority***. Individuals, groups and organisations involved in irrigation determine whether the schemes have the authority to implement decisions. Irrigation scheme authority depends on relationships, influence, power, legitimacy and compliance.

2.6.2 Land tenure arrangements

The land tenure system under which most smallholder irrigation schemes (SIS) operate in South Africa is considered as one of the major institutional challenges leading to poor performance (Tlou et al., 2006; Denison and Manona, 2007; Fanadzo, 2010; Fanadzo et al., 2010; Mnkeni et al., 2010, Van Averbeke et al., 2011). In Mamuhohi, Mandiwana and Raliphaswa irrigation schemes, the farming land tenure is communal. Land tenure security is very important for SIS because tenure insecurity discourages land transactions that make it possible for successful farmers to increase their land sizes (Fanadzo and Ncube, 2018). Land tenure security is defined as the individual's perception of his/her rights to a piece of land on a continual basis, free from imposition or interference from outside sources, as well as the ability to reap the benefits of labour or capital invested in land, either in use or upon alienation (Roth and Haase, 1998). The previous scholars argue that, in agriculture, tenure security presents several advantages, including increased credit use through greater incentives for investment, improved creditworthiness of projects, and enhanced collateral value of land. It is further argued that, clearer definition and protection of rights that comes with secure tenure reduces the incidence of disputes and raises productivity through increased agricultural investment and an increased demand for complementary short-term inputs (Roth and Haase, 1998).

The trust tenure system was by far the most prevalent tenure system on smallholder irrigation schemes in Vhembe. The implication was that land identified for the development of irrigation schemes had been detribalised and transferred to the state before the scheme was constructed. Trust tenure is regarded as the least secure of all systems that applied to African land holding and has been identified as a possible reason for the lack of land exchanges on smallholder irrigation schemes (Van Averbeke, 2008).

Schemes with traditional tenure were usually established quite recently but there was one exception. Luvhada, a project developed in 1952 by the community of Mphaila without state assistance also had traditional tenure. Despite the prevailing Trust system of tenure, land exchanges occurred on 72% of the schemes, which was more common than expected. On schemes where land exchanges occurred the basis for the exchange in order of importance was cash (82%), free land preparation of own parcel (52%), a share of the crop (27%) and just as a favour (9%). The maximum duration of land exchange arrangements on schemes where such arrangements occurred was more than two years in 67% of the cases, up to two years in 12% of the cases and limited to a single season in 21% of the cases.

2.6.3 Capacity building to support governance systems

Building the capacity of smallholder irrigation systems (SIS) is one of the missing links in smallholder irrigation development and many failures of SIS have been attributed to lack of adequately trained farmers and extension staff (Fanadzo and Ncube, 2018). Smallholder farmers generally lack technical expertise in irrigated crop management. Training is probably one of the most important requirements for successful development and management of smallholder irrigation schemes in South Africa.

Institutional and organisational capacity-building is one of the critical elements for sustainable poverty reduction among the poor (Audinet and Haralambous, 2005). There is general recognition that the main constraints of poor performance of irrigation schemes are deficiencies in management and related institutional problems, rather than the technology of irrigation (Kirpich et al., 1999).

Water governance relates to institutions and organisation, rules, regulations, policies laws. Edquist and Johnson (1997) define institutions as sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups. Farmers on irrigation schemes are dependent on each other because they share the water distribution system. This interdependence requires a willingness on the side of farmers to work collectively in order to achieve their individual objectives (Van Averbeke et al., 2011), while at the same time also sustain the collective. Rules to govern collaboration (institutions) and structures to enforce these rules (organisations) are necessary for effective and sustainable functioning of collective action (Van Averbeke et al., 2011). Van Averbeke et al. (2011) argue that, one of the challenges of irrigation scheme governance is that irrigator communities and their scheme leadership structures find it difficult to enforce rules. Quite often farmers pursue their individual instead of collective goals and in so doing challenge institutions and erode organisations of irrigator communities (Letsoalo and Van Averbeke, 2006).

2.7 Opportunities to improve performance of smallholder canal schemes

2.7.1 Design, operation and management

Denison (2018) in his study to identify the factors that influence the performance of smallholder irrigation schemes in the Limpopo Province, identified the inter-relationship between the infrastructure and water and land institutions as key to understanding why schemes fail. Furthermore, technological systems will need to operate under a wider range of operating conditions in response to emerging ecological (i.e. climatic conditions) and social (i.e. preferences and demand) change (Markolf et al., 2018). These complexities compel planners to give careful consideration to the sustainability of a smallholder irrigation scheme.

Sustainable development through the prudent use of natural resources is a key development priority for the whole Africa (Alemaw and Sebusang, 2019). It has the potential to influence a farmer’s capacity to adapt to changing environmental conditions and may help in raising the performance of smallholder irrigation schemes to enable them to reach their full potential (Lopus et al., 2017 and Gomo et al., 2014). The achievement of sustainable development poses a combination of technical, social, economic, political and environmental challenges (Alemaw and Sebusang, 2019).

Smallholder irrigation systems are one of the oldest widely viewed forms of infrastructure mediated social-ecological systems (SESs), containing hard human-made infrastructure, soft human-made infrastructure (i.e. institutional arrangements and organisational forms), and natural infrastructure (i.e. watersheds and agricultural land) (Yu et al., 2015; Denison, 2018). According to Lokman (2017), SESs are driven by non-linear dynamics and feedbacks between entities at different hierarchical levels and constantly changing external drivers (e.g. environmental variability, climate change, global economy). The design features of these systems fundamentally shape the dynamics of coupled social and natural processes and therefore are central to the sustainability of SESs (Yu et al., 2015). The design criteria, therefore, need to consider how aspects of the infrastructure affect the capacity of SESs to maintain vital functions during unexpected events such as water shortages and the attractiveness of alternative livelihood opportunities (Yu et al., 2015). It is critical to discover how contemporary infrastructure, which is designed and built on a principle of command and control, can be (re)designed to fit within this framework (Lokman, 2017).

Understanding the complex feedbacks between water resource availability, infrastructure design, local social structure, crop production and income under volatile commodity markets is a prerequisite to explaining the failure of many smallholder irrigation schemes in developing countries (Pande and Sivapalan, 2017; Denison, 2018). In these complex environments, models can play an essential role in providing insight into these complex interactions, and assist policy makers to develop effective and sustainable management strategies. Such models are able to predict the outcomes of 'what-if' scenarios, and enable a deeper understanding of the possible consequences of interventions (Alemaw and Sebusang, 2019).

Socio-hydrology is considered a new and appropriate discipline to address these types of water related challenges (Sivaplan et al., 2014). Socio-hydrological models allow for the explicit inclusion of two-way feedback loops between the assets applicable to a given system. Pande et al. (2016), for example, used socio- hydrological modelling to couple the dynamics of six main assets of a typical smallholder schemes including water storage capacity, capital, livestock, soil fertility, grazing access, and labour.

The feedbacks that are applicable to the system can be selected by identifying gaps in our understanding of the system through the iterative process of hypothesis building, data evidence and hypothesis update (Pande and Sivapalan, 2017). This also provides a holistic view of smallholder dynamics required to understand the location-specific constraints critical for scheme sustainability (Pande et al., 2016). Successful socio-hydrological models require an understanding of the human interaction on smallholder canal irrigation schemes.

2.7.2 Land and water institutions

Water institutions and land tenure on smallholder irrigation schemes gives us insight on the interaction of groups of individuals within socially constructed institutionalised values, rules and norms. They present a picture of how individuals, as members of groups/communities, behave within "rule-structured [contexts] and situations" and they explain the consequences for these individuals and those around them when the "actions and strategies that they employ are based on the confines in which they find themselves" (Ostrom, 2005; Mwangi and Markelova 2008).

Sustainable collective action requires cooperative interaction within groups. This kind of interaction occurs only when trade-offs are acceptable to all individuals expected to participate in it. For example, on a smallholder canal irrigation scheme "tail-end" farmers who receive less irrigating water than those farmers at the head of the canal have little incentive to participate in collective action because they have no equal share in vital resources. A break-down in collective action or non-cooperative interaction, is an indication of dissatisfaction amongst group members with the rules that were crafted in a context no longer applicable to present day situations and life. To analyse these breakdowns, one must "know enough about the structure of a situation to select the appropriate assumptions about human behaviour to fit the type of situation under analysis" (Ostrom, 2005). In this context, that is to determine the farming and social aspirations of the individuals who form part of this community and to determine whether the farming individual perceives his or her growth/success as part of a collective or as individually attained. Further, one must investigate which values and norms of the institutional structures individuals no longer perceive important (Cardenas and Ostrom, 2001) and why individual success is perceived to have a greater pay-off than collective success.

This information is collected by using game theory models on participants under analysis. Game theory in economics helped the economist "understand and predict economic contexts" (Kreps, 1990) and, in social science, it is the analytical tool of rational choice research on social dilemmas (Buskens and Raub, 2013). The assumption of rational choice theory is that individuals are "motivated by the wants or goals that express their [personal] 'preferences'" (Scott, 2000) and that individuals, by nature, make decisions and set goals that maximise their personal utility rather than the public or collective good.

Game theory is used to "model interdependent situations, providing concepts, assumptions, and theorems that allow specifying how rational actors behave in such situations (Buskens and Raub, 2013). The content of these games asks participants pertinent questions on their perceptions of values and norms, specific to existing institutional structures and, which changes are acceptable and which forms of incentives or punishment are suitable to them (Ostrom, 1998). The types of strategies put forward to participants are designed to understand which payoff is deemed greater, individual or group and the responses of participants explain their cooperation or non-cooperation (Kreps, 1990; Ostrom 1998).

The breakdown of collective action on smallholder canal scheme may be looked on as a social dilemma, because it is considered vital in the management of common pool resources (Muchara et al, 2014). The information gathered from these games and solutions provided, guide how policy may be re-crafted and give indication of how groups believe their shared physical structures may be "restored"/fixed.

2.7.3 Opportunities to improve self-governing canal schemes in Vhembe District

2.7.3.1 Design, operation and management

The design, operation and management opportunities for improving canal schemes in Vhembe are concerned with raising the performance and sustainability of the infrastructure within the socio-economic context. They aim to improve scheme resilience through understanding the interconnectedness of the infrastructure and the farmers' decisions and actions within the range of socio-economic and hydrological conditions that are likely occur in the short and long-term. It is therefore essential to interrogate the design, operation and management issues jointly with the scheme users in order to comprehend their experience, socio-economic conditions and needs and the practical opportunities relating to scheme design, operation and management.

For the smallholder irrigation schemes in Vhembe district, the opportunities could include:

- Developing measures to increase the reliability of water supply
- Developing measures to ensure equitable water distribution at all levels
- Improving the flexibility of the physical infrastructure to enable adjustment of water delivery to the irrigators when and as required;
- Organising and equipping farmers to control, (i.e. regulate water flow), operate and maintain the infrastructure.
- Determining appropriate decision-making tools to support the day-to-day and longer-term management of the schemes. These could be in the form of technologies, methodologies and/or indicators for:
    - Monitoring of water use and preventing unlawful use;
    - Planning water allocations including the application of forecasting;
    - Record keeping;
    - Ensuring satisfactory operation and maintenance of the scheme infrastructure

Maximising the benefits of the quantifiable aspects of these opportunities can be posed as an optimisation problem within the socio-hydrologic context and this study will be seeking to find out if formal optimisation approaches will be applicable for this. The suitability of the WAS model that has been applied for the operation commercial irrigation schemes in South Africa will also be investigated.

2.7.3.2 Land and water institutions

Sustainable interventions in land and water institutions for the improvement of smallholder canal schemes must be developed by stakeholders who are selected and trusted by the farming community (Liedtke et al, 2013).

In the domain of water institutions, opportunities for improving smallholder canal schemes include:

- The crafting of water sharing arrangements that consider equity over equality in return for participation in collective action;
- The development or strengthening of a farmer-based organisation that performs the roles of the various actors identified by (Kay, 1986) as being essential for the proper functioning of a canal scheme. These actors and their roles are:
    - The irrigation engineer, who is responsible for the operation of the scheme;
    - The irrigation assistant, who offers irrigation training to gate operators, water guards and irrigators and coordinates and oversees the work of water guards (bailiffs);
    - The gate operators, who are responsible for adjusting gates on head and cross regulators and canal outlets to carry out maintenance on these gates and,
    - The water guards (bailiffs), who check water use efficiency, collect requests for water from irrigators, pass instructions to gate operators and report on problems with land preparation and canal maintenance.

In the domain of land institutions, opportunities for improving smallholder canal schemes include:

- Defining and formalising a bundle of rights pertaining to land tenure security i.e. user rights, transfer rights, exclusion rights and enforcement rights, which serve the diverse interests of canal scheme communities. Specific attention should be given to:
    - Institutional arrangements that enable farmers to obtain additional land within the scheme;
    - Provision of two-way security of rental contracts pertaining to irrigation land; and
    - Development of a recognised and trusted structure that acts as adjudicator (and enforcer) when the tenure rights of plot holders or lessees are infringed upon.

2.8 Applicability of socio-hydrology in identifying opportunities to improve performance of smallholder canal schemes

Socio-hydrology acknowledges the coevolution of human and water systems and is therefore considered an appropriate framework to evaluate and explore the influence of biophysical and socio-economic factors on the performance of smallholder canal schemes (SCS) (Sivapalan et al., 2014; Troy et al., 2015). Liu and Tian (2016) used a coupled socio-hydrologic model which includes water and land policies to analyse how agriculture water conservation develops with different policy scenarios. Jeong and Adamowski (2016) used a socio-hydrologic model to study and describe the causal relationships and dynamics between social and hydrological systems related to agricultural wastewater reuse. Pande and Savenije (2016) used socio-hydrologic modelling to couple the dynamics of six assets of a typical smallholder scheme in India including water storage capacity, capital, livestock, soil fertility, grazing access, and labour. The feedbacks applicable to the system were identified based on gaps in our understanding of the system through the iterative process of hypothesis building, data evidence and hypothesis update (Pande and Sivapalan, 2016). Dziubanski et al. (2019) used a socio-hydrologic modelling approach to better understand the effects of land-use changes driven by economic and human behaviour on hydrologic responses.

Socio-hydrology is however a new science (Sivapalan et al., 2014; Srinivasan, 2015; Garcia et al., 2016) and, unlike developed sciences, initial hypothesis is still being generated (Troy et al., 2015). The understanding of coupled systems has largely been driven by the study of socio-ecological (also referred to as coupled natural-human) systems and socio-economic systems. Studies of these systems also has a much longer history. Therefore, in accordance with the recommendations by Troy et al. (2015) and Srinivasan et al. (2018), the development of the socio-hydrology model for SIS in this study could be benchmarked against socio-ecological systems (SES) theories.

There are several modelling approaches that can be used for socio-hydrological modelling with different strengths and weaknesses (Troy et al., 2015; Srinivasan, 2015). These approaches are categorised as either top-down, bottom-up, pattern-oriented and coupled approaches.

Top-down approaches focus on high-level system outlook and outcomes and are by design abstract and generalisable (Sivapalan and Bloschl, 2015; Srinivasan, 2015). Examples of top-down approaches include “toy” models and system dynamic (SD) models. Bottom-up modelling techniques involve the representation of system processes, thus require good knowledge of site-specific processes, in both a spatial and temporal sense, to develop system behaviour (Sivapalan and Bloschl, 2015). These approaches focus on the behaviour and decision-making of individual “agents” within a system (Blair and Buytaert, 2016). Examples include agent-based models (ABMs) and game theory. Pattern-oriented approaches, observe multiple patterns in the real system at different hierarchical levels and scales and are used systematically to optimise model complexity and to reduce uncertainty. The most common pattern-oriented model (POM) is the “stylised” model. Coupled approaches or coupled component models (CCM) inherit the features of the component models that comprise them (Kelly et al., 2013).

The characterising of human behaviour is central in common pool resource systems like smallholder canal schemes (SCS). Therefore, the use of agent-based models (ABMs) is desirable. ABMs consist of a set of algorithms that encapsulate the behaviours of agents interacting to produce emergent outcomes within a defined system (Kelly et al., 2013; Troy et al., 2015; Dziubanski et al, 2019). ABM approaches however, tend to be data intensive, requiring site specific data for calibration and validation based on observations made on site, to inform individual agent’s decisions (Srinivasan, 2015).

Consequently, they tend to have high numbers of parameters requiring significant computational resources (Kelly et al., 2013). Pattern-oriented modelling (POM) approaches overcome the need for detailed knowledge of the base level processes by focussing on explaining the observed patterns in complex SES, thereby reducing model complexity and uncertainty (Grimm et al., 2005). POM results are matched to multiple patterns of behaviour at different hierarchical levels and (spatial and temporal) scales during the model calibration and validation stage (Blair and Buytaert, 2016). These patterns describe the behaviour rules or set of actions each agent might take and the conditions under which these actions take place (Grimm et al., 2005). The modelling here will therefore seek a pragmatic balance of data requirements and model complexity in seeking the project objectives.

3 SCHEME SELECTION

3.1 Aim and structure of chapter

Aim of the chapter

The aim of this chapter is to provide an account of the process leading to the selection of the Raliphaswa-Mandiwana-Mamuhohi complex of smallholder canal schemes as the study site for this project. The selection of this complex corresponds to the contractual undertaking to conduct the study on three smallholder canal schemes in Vhembe. The chapter explains the criteria that were used to reduce the population of smallholder irrigation schemes in the Vhembe district to a shortlist of potentially suitable entities for investigation. Schemes on the shortlist were explored by the research team during a week-long field visit to Vhembe. The chapter provides an illustrated description of the observations that were made during this field visit. Finally, selection of the Raliphaswa-Mandiwana-Mamuhohi complex as the preferred choice, is justified.

Structure of the chapter

The first section of the chapter describes the aim and structure of the current. This is followed by an explanation of the process that was used to develop a shortlist of possible schemes for consideration as study sites for the project and elaborates the criteria that were used to develop this shortlist. The third section describes the observations that were made by the team during the week-long field visit to the schemes on the short list, while section 4 justifies the choice of the Raliphaswa-Mandiwana-Mamuhohi complex of smallholder canal schemes as the preferred study site.

3.2 Short listing of canal schemes in Vhembe for possible selection as study sites

3.2.1 Smallholder irrigation schemes in Vhembe

In the Limpopo Province, the Provincial Department of Agriculture is the custodian of the smallholder irrigation schemes located within that Province. The Vhembe District Office of the Limpopo Department of Agriculture holds a data base of the smallholder schemes in the Vhembe District that are under the jurisdiction of the Department of Agriculture (Masiya and Van Averbeke, 2013). In 2009, this data base contained 42 farming projects that were considered to be smallholder irrigation schemes. In Table 3.1, all of these projects are listed but the seven units that make up Tshiombo Irrigation Scheme are presented separately, explaining why 48 schemes appear.

Table 3.1: Smallholder irrigation schemes in Vhembe

(from Van Averbeke, 2012)

Scheme name	Operational	Command area (ha)	Number of plot holders	Average plot size (ha)	Hydraulic head	Irrigation method
Nesengani	Yes	13.7	28	0.415	Pumped	Surface
Nesengani B1	No	20.6	116	0.178	Pumped	Overhead
Nesengani B2	No	40.9	116	0.352	Pumped	Overhead
Nesengani C	No	31.2	131	0.238	Pumped	Overhead
Dzindi	Yes	136.2	102	1.285	Gravity	Surface
Khumbe	Yes	145.0	138	0.623	Gravity	Surface
Dzwerani	No	124.0	248	0.500	Pumped	Overhead
Palmaryville	Yes	92.0	70	1.296	Gravity	Surface

Lwamondo	No	15.0	75	0.200	Pumped	Micro
Mauluma	Yes	38.0	30	1.267	Gravity	Surface
Mavhunga	Yes	47.5	32	1.532	Gravity	Surface
Raliphaswa	Yes	15.0	13	1.154	Gravity	Surface
Mandiwana	Yes	67.0	40	1.675	Gravity	Surface
Mamuhohi	Yes	77.0	61	1.262	Gravity	Surface
Mphaila	Yes	70.6	59	1.197	Pumped	Overhead
Luvhada	Yes	28.8	79	0.365	Gravity	Surface
Rabali	Yes	87.0	68	1.279	Gravity	Surface
Mphepu	Yes	132.8	133	0.998	Gravity	Surface
Tshiombo Block 1	Yes	60.5	47	1.287	Gravity	Surface
Tshiombo Block 1a	Yes	128.6	100	1.286	Pumped	Overhead
Tshiombo Block 1b	Yes	122.0	115	1.061	Gravity	Surface
Tshiombo Block 2	Yes	126.0	98	1.286	Gravity	Surface
Tshiombo Block 2a	Yes	173.5	114	1.522	Gravity	Surface
Tshiombo Block 3	Yes	128.4	100	1.286	Gravity	Surface
Tshiombo Block 4	Yes	56.0	112	0.500	Gravity	Surface
Lambani	No	260.0	16	16.250	Pumped	Surface
Phaswana	No	16.7	16	1.044	Pumped	Surface
Cordon A	Yes	43.7	38	1.150	Gravity	Surface
Cordon B	Yes	82.3	65	1.266	Gravity	Surface
Phadzima	Yes	102.3	103	0.993	Gravity	Surface
Makuleke	Yes	37.3	29	1.286	Pumped	Overhead
Rambuda	No	170.0	132	1.288	Gravity	Surface
Murara	Yes	70.0	7	10.000	Gravity	Surface
Dopeni	Yes	30.0	6	5.000	Gravity	Surface
Makhonde	No	83.0	58	1.431	Pumped	Micro
Sanari	No	17.0	11	1.870	Pumped	Micro
Tshikonelo	No	10.0	15	0.670	Pumped	Overhead
Chivirikani	Yes	68.3	112	0.609	Pumped	Overhead
Gonani	Yes	8.5	30	0.295	Pumped	Overhead
Folovhodwe	Yes	70.0	24	2.197	Gravity	Surface
Klein Tshipise	Yes	60.0	60	1.000	Gravity	Surface
Morgan	Yes	56.7	35	1.620	Gravity	Surface
Makumeke	Yes	17.0	63	0.269	Pumped	Micro
Dovheni	Yes	60.0	14	2.143	Pumped	Overhead
Mangondi	No	48.0	38	1.260	Pumped	Micro
Xigalo	Yes	22.0	24	1.080	Pumped	Micro
Garside	Yes	13.7	28	0.415	Gravity	Surface
Malavuwe	Yes	20.6	116	0.178	Pumped	Overhead

3.2.2 Initial elimination of schemes

The projects listed in Table 3.1 covered a total area of 3 344 ha, about 7% of the national smallholder scheme area at that time (van Averbeke, 2012). Of the 48 entities listed in Table 3.1, 12 had ceased to operate in 2009. Among the 37 operational entities, 10 relied on pumping to supply irrigation water, which excluded them from the population of smallholder canal schemes looked at by the Project, leaving 26 potential entities for selection as study sites.

Early on, the decision was made to exclude the six canal units of Tshiombo Irrigation Scheme. The reason for this decision was that Tshiombo, as a whole, was too large and complex for the limited scope of the three-year project. Moreover, Tshiombo has ongoing conflicts among the communities at the various units. One of the factors fuelling these conflicts is that the two-tail end blocks no longer received water, adding them to the list of ‘non-operational schemes. The remaining 20 canal in Vhembe schemes that were operational in 2009, were then considered as potential study sites. These schemes are listed in Table 3.2, which also presents some salient information on the criteria that were used to compile the short list of schemes. These criteria are elaborated in the next section of this chapter.

Table 3.2: Selected characteristics of canal schemes in Vhembe that were potentially suitable to serve as study sites

(Data extracted from the data base compiled by W van Averbeke during a Vhembe scheme survey in 2009)

Scheme name	**Age in 2019 (years)**	**Command area (ha)**	**Number of plot holders**	**Average plot size (ha)**	**Revitalisation status**	**Source of irrigation water**	**Cropping intensity (%)**	**Utilisation level in 2015**[1]	**'*De jure*' land tenure system**	**Scheme fence effectiveness**
Dzindi	65	136.2	102	1.285	Partially revitalised	River & weir	130	Full	'Irrigation tenure'	Partly effective
Mauluma	54	38.0	30	1.267	Revitalised	River & weir	110	Full	'Irrigation tenure'	Not effective
Raliphaswa	54	15.0	13	1.154	Revitalised	River & weir	110	Moderate	'Irrigation tenure'	Effective
Mandiwana	55	67.0	40	1.675	Revitalised	River & weir	80	-	'Irrigation tenure'	Partly effective
Mamuhohi	55	77.0	61	1.262	Partially revitalised	River & weir	100	-	'Irrigation tenure'	Effective
Rabali	68	87.0	68	1.279	Revitalised	River & weir	80	Low	'Irrigation tenure'	Effective
Mphephu	58	132.8	133	0.998	Revitalised	River & weir	80	Moderate	'Irrigation tenure'	Not effective
Khumbe	68	145.0	138	0.623	Not revitalised	River & weir	80	Non	'Irrigation tenure'	Partly effective
Palmaryville	68	92.0	70	1.296	Not revitalised	River & weir	140	Low	'Irrigation tenure'	Not effective
Mavhunga	54	47.5	32	1.532	Not revitalised	River & weir	90	Non	'Irrigation tenure'	Effective
Luvhada	67	28.8	79	0.365	Not revitalised	Spring	130	Full	Traditional	Effective
Cordon A	54	43.7	38	1.150	Not revitalised	River & weir	130	Non	'Irrigation tenure'	Effective

[1] Data extracted from Van Koppen et al (2017)

Scheme name	Age in 2019 (years)	Command area (ha)	Number of plot holders	Average plot size (ha)	Revitalisation status	Source of irrigation water	Cropping intensity (%)	Utilisation level in 2015[1]	'*De jure*' land tenure system	Scheme fence effectiveness
Cordon B	54	82.3	65	1.266	Not revitalised	River & weir	80	Non	'Irrigation tenure'	Effective
Phadzima	54	102.3	103	0.993	Not revitalised	River & weir	80	Non	'Irrigation tenure'	Partly effective
Murara	51	70.0	7	10.000	Not revitalised	River & weir	90	Moderate	'Irrigation tenure'	Not effective
Dopeni	51	30.0	6	5.000	Not revitalised	River & weir	80	Full	'Irrigation tenure'	Not effective
Folovhodwe	63	70.0	24	2.197	Not revitalised	River & weir	130	Full	'Irrigation tenure'	Effective
Klein Tshipise	45	60.0	60	1.000	Not revitalised	Spring	155	Full	'Irrigation tenure'	Partly effective
Morgan	49	56.7	35	1.620	Not revitalised	River & weir	100	Low	'Irrigation tenure'	Partly effective
Garside	54	13.7	28	0.415	Not revitalised	River & weir	90	Low	'Irrigation tenure'	Partly effective
Mean	57	74.5	60	1.794			103			

Criteria used in the compilation of the short list of potentially suitable study sites

The objective of compiling a short list of smallholder canal schemes was to identify schemes or hydraulic units that would enable the attainment of the study objectives. For this reason, the following criteria were considered when compiling the short list:

Reasonable level of irrigated farming: In order to achieve the objectives of the study, it is important that schemes selected as study sites are functional, meaning that irrigated farming is taking place, thus creating a demand for irrigation water and possibly for irrigation land. In a recent survey of a sample of 76 public smallholder irrigation schemes in Limpopo Province, Van Koppen et al (2017) found that during the winter of 2015, 37% of the sampled schemes were not utilised at all; 26% were being utilised at low or moderate levels, and 37% were fully utilised. They defined non-utilisation as less than 10% of the command area being cropped; low utilisation as 10 to 49% of the command area being cropped; moderate utilisation as 50 to 89% of the command area being cropped, and full utilisation as 90% or more of the command area being cropped. The utilisation levels recorded by Van Koppen et al. (2017) for canal schemes in Vhembe are shown in Table 3.2. All but the Mamuhohi and Madiwana schemes listed in Table 3.2 were covered by the survey of Van Koppen et al. (2017). Of the 18 schemes that were reported on, five were not utilised in the winter of 2015, four had low utilisation levels, three had moderate utilisation levels and six had full utilisation.

Extraction of irrigation water directly from the river by means of a weir: Van Averbeke (2012) and van Koppen et al. (2017) reported that sourcing water directly from the river by means of a weir, was one of the most common ways in which smallholder irrigation schemes accessed water. This applied particularly to canal schemes in Vhembe, because 18 of the 20 schemes listed in Table 3.2 obtained their water in this way.

Irrigation infrastructure in reasonable condition: In order to enable realistic analysis of measures to improve water reliability and distribution, it was considered necessary to select schemes where the irrigation infrastructure was perceived to be in a fairly good condition (i.e. with no major leaks or dysfunctional infrastructure). It was therefore considered desirable to focus on recently revitalised schemes. Revitalisation of canal schemes, without changing the irrigation method used, characterised the first version of the RESIS (Revitalisation of Smallholder Irrigation Schemes) programme initiated by the Limpopo Department of Agriculture. This programme focused on smallholder canal schemes located in the Nzhelele River Valley. The reason for this was the devastation caused by cyclone Conny hit Mozambique and the Limpopo Province in 2000 (Christie and Hanlon, 2001). Heavy rains, which caused widespread floods, had damaged roads, bridges and the weirs that provided water to the smallholder canal schemes in the Valley (Khandlhela and May, 2006:279-282). This resulted in Limpopo Province being declared a disaster area and special funding to repair the damage to its infrastructure was allocated. Part of this funding was used to rebuild or repair the infrastructure of canal schemes in the Nzhelele River Valley. Table 3.2 shows that five of the 20 listed canal schemes had been completely revitalised. These schemes were Mauluma, Raliphaswa, Mandiwana, Rabali and Mphephu. Two of the 20 schemes had been partially revitalised, namely Mamuhohi and Dzindi.

Minimal interference in irrigation activity: In order to minimise the effects of littering, 'unauthorised' water use and vandalism, it was considered necessary to select schemes where access restriction measures, such as effective fencing were present, and extraction of canal water and interference with infrastructure by 'outsiders' was limited. Table 3.2 shows that in 2009, only eight of the twenty canal schemes had an effective fence, whilst on four of the schemes there was no fence or what remained of the fence was completely ineffective. Ineffective fences were also identified by Van Koppen et al. (2017) as a recurrent concern among plot holders on public smallholder schemes in Limpopo Province.

Effective gauging structures: To develop technology, methods and indicators that can be used to monitor and eventually better manage the use of irrigation water, it was considered desirable to have canal schemes with good-quality gauging structures that were in working condition. The survey data and pictorial evidence collected by Van Averbeke in 2009 suggested that only revitalised canal schemes in the Nzhelele River Valley were equipped with good-quality gauging structures that were in working condition.

Sufficient social complexity: In a canal scheme context, social complexity is associated with multiple irrigation blocks and social units sharing the same water resource and irrigation infrastructure. When smallholder irrigation schemes are established, "new" farming communities (or groups) are constructed, because members of these communities are expected to share a water resource and irrigation infrastructure and to cooperate as a collective in the maintenance of irrigation infrastructure. Whereas a smallholder irrigation scheme community may be considered as an economic and ethno-political construct, over time, these social units do create, develop and define their own group identity. Regardless of their shared ethnicity, group identity in these communities is necessary because in establishing one, social institutions in which individuals interact, are erected (Giddens, 1984; Otto and Pederson, 2005). These social institutions act as a source of authority within groups channelling human activity into an "accepted cultural norm" and as a "shared history of interaction." They stabilise social relationships across time and space (continuity). They are safeguarded because "[they] create social worlds that are experienced as an objective, [normative and structural] reality by individual actors (Giddens, 1984). The erection of social institutions in these communities does not, however, prevent contestation amongst group members. Literature on smallholder irrigation schemes has identified the head versus tail-end location of irrigated land as a major source of conflict amongst plot holders (Ostrom, 2002; Reddy and Shiferaw, 2014). The unequal division of water resources promotes antagonism between dominant [head] and subordinate [tail-end] groups, which leads to in-group conflict and a negative group identity (Tajfel and Turner, 1974). Social complexity and potential conflict are further enhanced when the same water source and irrigation structure is share by multiple groups as in the case of the Tshiombo (Denison et al, 2016) and Dzindi irrigation schemes (Letsoalo and van Averbeke, 2006). The only other arrangement that involves multiple groups sharing water and irrigation infrastructure is found in the Raliphaswa-Mandiwana-Mamuhohi complex of smallholder canal schemes. Each of these schemes is linked to a village of the same name, suggesting an interesting "us-versus-them" situation.

'**Irrigation tenure' as the *de jure* land tenure system**: 'Irrigation tenure' refers to the tenure system described in Proclamation No. R. 5, 1963, called the '*Regulations for the Control of Irrigation Schemes in the Bantu Areas*'. Irrigation tenure is a form of Trust tenure that was adapted specifically for smallholder (canal) schemes constructed by the South African Government in what were then called the native Areas, and which later on became the homelands. Trust tenure was first applied on land that had been bought by the South African Native Trust, later called the South African Development Trust (SADT) in terms of the Development Trust and Land Act, No 18 of 1936 (De Wet, 1987). Following the promulgation of the Act, the specifics of Trust tenure were gradually developed, refined and amended so as to suit particular circumstances. Relevant Trust tenure legislation pertaining to irrigation schemes located in the 'Native Areas' or 'Bantu Areas', included the Regulations: Grobler Irrigation Scheme, District of Thaba 'Nchu (Proclamation No. 173 of 1938); Taungs Irrigation Scheme Regulations (Proclamation No. 4 of 1943); Linokana Irrigation Scheme Regulations (Proclamation No 106 of 1948); Seodin Irrigation Scheme Regulations (Proclamation No 195 of 1948); Olifants River Irrigation Scheme Regulations (Proclamation No. 371 of 1948); and the Control of Irrigation Plots on South African Native Trust Land (Proclamation No 29 of 1951) (Masiya and Van Averbeke, 2013). In all situations where Trust tenure applied, allocations were made by means of 'Permission to Occupy' (PTO) certificates and land rights were granted conditionally. Land rights could be forfeited when the right holder broke any of the stated conditions, and this was the principal reason why Trust tenure was considered the least secure tenure system available to Black people in South Africa (Cokwana, 1988; Kille and Lyne, 1993;

Roth and Haase, 1998). According to Masiya (2018), the 'Irrigation tenure' system is the *de jure* tenure system on smallholder schemes that were established by the state before 1990. This is confirmed by the tenure system information in Table 3.2, which shows that Irrigation Tenure' was , the *de jure* tenure system on all the listed schemes except Luvhada, which is a scheme that was established by the Mphaila community with assistance of the state.

Based on these criteria, a short list of smallholder canal schemes that were potentially suitable for selection as study sites was compiled. This list is presented in Table 3.3, which also provides the justification for the elimination of all other smallholder canal schemes in the Vhembe District.

3.2.3 Short list of potentially suitable study sites

From Table 3.2, it is evident that all or most canal schemes meet certain criteria, such as obtaining water directly from a river by means of a weir (18 of the 20 schemes) and 'Irrigation tenure' as the de jure tenure system (19 of the 20 schemes). Criteria for which schemes differed substantially were their revitalisation status and the implications this had on the condition of the irrigation infrastructure and the presence of good-quality gauging structures; utilisation level recorded by van Koppen et al. (2017) and the effectiveness of the scheme fence. Using the latter criteria in decision making, seven smallholder canal schemes made it on the short list. The justification for inclusion of these seven schemes and exclusion of the other 13 is presented in Table 3.3.

A field visit to the short-listed schemes was made during the week of 16 June to 21 June 2019. The next section contains the report of that visit. Whereas the Mauluma Scheme was on the short list, and the scheme was visited on the 19th of June 2019, it proved to be impossible to locate the weir. For this reason, no description of this scheme appears in Section 3.

Table 3.3: Shortlist of canal schemes deemed potentially suitable for selection as study sites

Scheme name	**Reasons for inclusion**	**Main reasons for exclusion**
Dzindi	Partially revitalised, rich collection of information and good relationship with plot holders, full utilisation	
Mauluma	Revitalised, full utilisation	
Raliphaswa	Revitalised, moderate utilisation	
Mandiwana	Revitalised but no information on utilisation	
Mamuhohi	Partially revitalised but no information on utilisation	
Rabali	Revitalised, but low utilisation	
Mphephu	Revitalised, full utilisation	
Khumbe		Not revitalised, not utilised
Palmaryville		Not revitalised, low utilisation
Mavhunga		Not revitalised, not utilised
Luvhada		Not revitalised, spring as the source of water, traditional tenure
Cordon A		Not revitalised, not utilised
Cordon B		Not revitalised, not utilised
Phadzima		Not revitalised, not utilised
Murara		Not revitalised, ineffective fence
Dopeni		Not revitalised, ineffective fence
Folovhodwe		Not revitalised, extremely remote

Scheme name	Reasons for inclusion	Main reasons for exclusion
Klein Tshipise		Not revitalised, spring as the source of water
Morgan		Not revitalised, low utilisation level
Garside		Not revitalised, low utilisation level

3.3 Report on field visit to short-listed schemes

Field visits to the short-listed canal schemes/hydraulic units listed in Table 3.3 were conducted during the week of 16 to 21 June 2019. The physical features observed during these visits included the scheme layout, the condition of the weir, canals, storage facilities, gauging infrastructure, offtake structures, main furrows and the access/service roads. The condition of the access roads is crucial as it impacts on the ease and safely of the study activities.

The water abstraction and conveyance system at all six schemes is similar and consists of a weir, which diverts river water into a parabolic concrete lined main canal with branches that consist of concrete or earthen furrows, conveying water to the plots. There is no evidence of on-farm storage on any of the plots.

Like most irrigation schemes in South Africa, the canal schemes are designed for the roster or rotational leading turn system. In these schemes, water is released into the main canal continuously and is allocated to the irrigators in turns, requiring them to accept the water at predetermined times (DWS, 1980). The following sections present the findings made at each of the schemes.

3.3.1 Dzindi canal scheme

According to Letsoalo and van Averbeke (2006) the Dzindi smallholder irrigation scheme draws its water from the perennial Dzindi River, a tributary of the Levuvhu River, by means of a weir and consists of a main canal that is approximately 14 km in length. The weir is located at 23˚ 0’ 47.16’’S and 30˚ 23’ 51.41’’E, 20 km upstream of Nandoni Dam. The scheme is divided into four blocks and consists of one night storage dam from which one of the blocks relies for water (Letsaolo and van Averbeke, 2006). The scheme was constructed in 1954 and has only been partially revitalised, when a short but badly damaged part of the main canal was repaired. The main canal is parabolic and concrete lined and meanders through the village of Dzindi. Consequently, there is significant influence of the village on the scheme in the form of litter, unaccounted for water usage and recreation.

The Dzindi river intake (Figure 3.1) is located on the concave side of the river bend but the observed turbulence at the entrance of the structure is likely to result in the accumulation of litter/branches on the trash screens (Figures 3.2 and 3.3), particularly given the overhanging trees and other vegetation immediately upstream of the river intake, leading to the blockage of the intake, ultimately reducing the long-term water reliability of the scheme. It is unregulated and diverts water in the upper layers of the river. The Dzindi intake channel includes an overflow (Figure 3.4).


Figure 3.1: Dzindi Weir


Figure 3.2: Downstream view of Dzindi river intake with trash screen

Figure 3.3: Upstream view of Dzindi river intake with trash screen

Figure 3.4: Dzindi intake channel with overflow

At the Dzindi intake channel exit an impact stilling basin and (Cipolletti) sharp crested weir have been installed (Figures 3.5 and 3.6). The severe turbulence downstream of the baffle wall leads to significant fluctuation of the water levels and therefore inaccurate water level measurements and flow estimates upstream of the Cipolletti weir.

Mainly because of silt collecting near their crests, errors in Cipolletti weir measurements can be as high as 10% (DWA, 1980). The ability of sharp crested weirs to measure flow accurately is also affected by their sensitivity to variations in approach velocity (DWA, 1986). Consequently, these types of weirs were not installed by the Department of Water Affairs in South Africa after 1978 (DWA, 1986).

The more expensive water becomes, the more important it is to accurately measure the volume of water supplied to the consumers (DWA, 1980). According to DWA (1980), the objective should be to measure flows, which may vary between 10% and 100% of design flow, to an error not exceeding + - 5%. It is highly unlikely that the gauging structure at Dzindi can meet this criterion.

Figure 3.5: Downstream view of Dzindi intake channel exit, impact stilling basin and (Cipolletti) sharp crested weir

Figure 3.6: Upstream view of Dzindi intake channel exit, impact stilling basin and trapezoidal (Cipolletti) sharp crested weir

The offtake structures in Dzindi (Figures 3.7 and 3.8) consist of fixed overflow weir with no moving parts and no long weir. Consequently, fluctuations in water level in the main channel may vary to the extent of detrimentally affecting the required constant flow to the irrigator through the offtakes and result in erratic flow diversion (DWA, 1980). There are also no measuring devices for the diverted flows.

In addition, since there are no shut-off gates or valves at the offtakes, rocks are being used as shut-offs. This increases losses due operational wastage and does not allow for the man concrete furrow to be taken out of commission for maintenance without affecting the operation of the main canal (DWA, 1980).

The propagation of standing waves downstream of the disturbance caused by the offtake weir side walls, indicates that the flows in the canal are either in the supercritical or very close to the critical flow regime. In medium and large canals, near-to-critical flow conditions are undesirable and are avoided as unstable flow conditions could easily cause a hydraulic jump to occur, the canal lining being overtopped and damaged (DWA, 1980). Similarly, this type of flow regime is also a concern in small canals.

Similarly, to the offtakes, there is no level control structure at the bifurcation structures (Figure 3.9), therefore erratic flow distribution in the branch canals can be expected. Figure 3.10 shows a typical level control structure (i.e. long weir) used to control the flow being diverted into offtakes.


Figure 3.7: Typical offtake at Dzindi


Figure 3.8: Typical offtake at Dzindi and main concrete furrow

Figure 3.9: Typical bifurcation structure at Dzindi

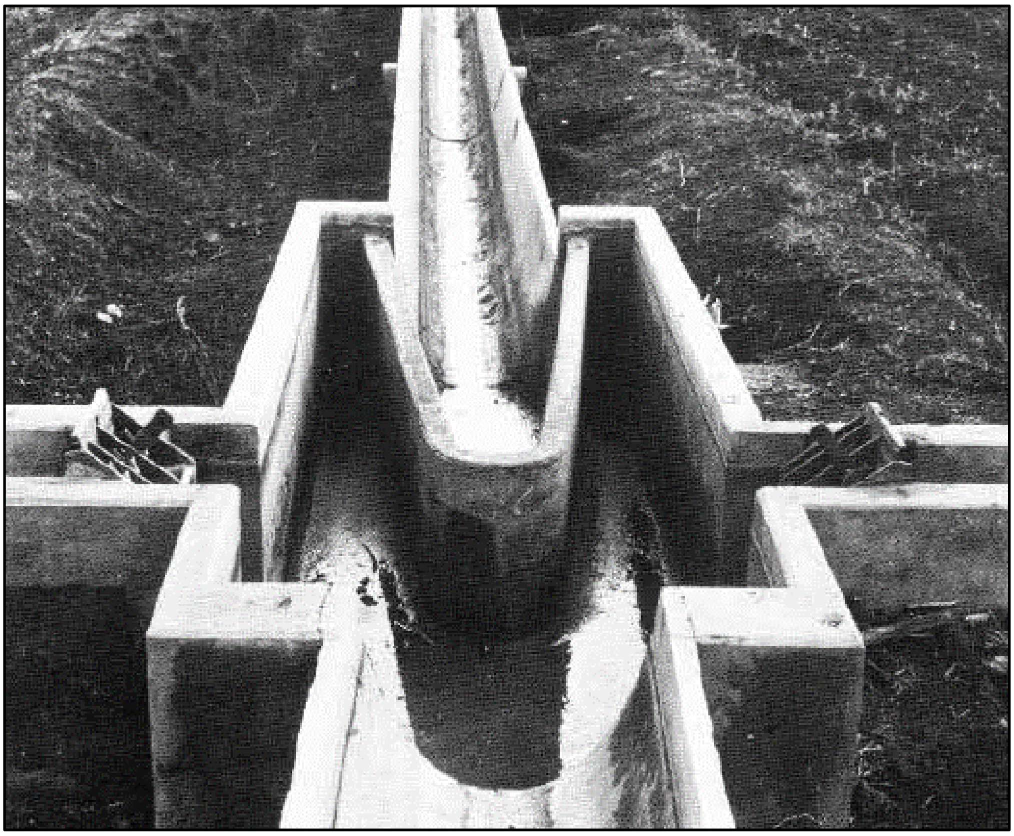


Figure 3.10: Duckbill weir installed downstream of offtakes (FAO, 1975)

3.3.2 Raliphaswa, Mandiwana and Mamuhohi complex of canal schemes

Raliphaswa, Mandiwana and Mamuhohi are hydraulic units of a single scheme. The scheme is a member of the Nzhelele Catchment Water Users' Association falling under the proposed Limpopo Water Management Area in the province (Mudau, 2010). The village of Mamuhohi is one of the villages falling under the Mphephu Territorial Council and shares a boundary with the Village of Mandiwana. Raliphaswa also shares a boundary with Mandiwana (Mudau, 2010).

Two night storage dams exist in the scheme of which Mamuhohi, the tail end hydraulic unit, relies on one. According to Mudau (2010), production at Mamuhohi irrigation scheme is extremely low, and the low reliability of irrigation water is one of the reasons attributed to this.

The weir and parts of the irrigation scheme were damaged during the February 2000 floods. The infrastructure was however revitalised in 2002. Mudau (2010) in his study to assess the sustainability of smallholder irrigation schemes observed incidences of water theft and vandalism at the scheme. The crops most commonly planted are maize, tomatoes, vegetables, sugar-beans, groundnuts and onions (Mudau, 2010).

Discussions with a local farmer during the field visit indicated that an irrigation schedule exists, according to which the farmers in Raliphaswa and Mandiwana are grouped into blocks that are each scheduled to utilise water at least twice a week between 06H00 and 16H00. This anecdotal evidence suggests that irrigation scheduling is inadequate as the consumptive water uses are much higher (Mhlanga–Ndlovu and Nhamo, 2017; Mudau, 2010). The farmer further indicated that the water is allowed to fill Mandiwana storage dam from 17H00 to 05H00.

According to Mudau (2010) there is also a water bailiff employed by the government to oversee water distribution; however, this could not be confirmed. The water bailiff and the extension officer together arbitrate any conflict relating water usage (Mudau, 2010).

The intake weir (Figure 3.11) is located in Raliphaswa on the perennial Mutshedzi River, a tributary of the Nzhelele River, at 22˚ 53’ 51.27S and 30˚ 08’ 00.14’’E. The Mutshedzi River has a slight bend at the location of the weir and the river intake is located on the concave side of the bend. The design philosophy of the Raliphaswa river intake is the same as those for the Mphephu river intake. The river intake resembles a frontal intake and the abstracted water is taken from the upper layers by means of a side overflow structure (Figures 3.12 and 3.13). Similarly, the sluice gate of the Raliphaswa scour channel was closed at the time of the visit (Figure 3.14). Consequently, manual maintenance of the sediment in the scour channel will be required to control sediment levels.

Figure 3.11: Raliphaswa Weir

Figure 3.12: Scour channel and overflow into intake chamber at Raliphaswa

Figure 3.13: Intake into scour channel and overflow into intake chamber at Raliphaswa

Figure 3.14: Leaking scour sluice gate at Raliphaswa

The scheme intake pipe from the intake chamber (Figure 3.15) is considerably long and underground and a Crump weir gauging structure is located at the outlet of the pipe (Figure 3.16). Flow at a Crump weir structure is not greatly affected by high approach velocities and by submergence and has a very smooth pattern of streamlines unlike the weirs with vertically cut-off crests (e.g. sharp and broad crested weirs). Energy losses in the upstream pool of Crump weirs are thereby very low and there is therefore sufficient energy for sediment to be transported over the crest instead of being deposited in front of it. Crump weirs should thus not silt up under normal conditions (DWA, 1986).

Downstream of the Crump weir, a sluice gate reject and reduction to scheme main channel has been installed (Figure 3.17) although it is not fully functional. Further downstream, a Parshall flume exists before the diversion of flow to Raliphaswa (Figure 3.18). The Parshall flume has been standardised and calibrated for a wide range of capacities in the United States (DWA, 1986). Therefore, once the dimensions of the flume in Figure 3.18 have been obtained, the rating curve for the structure could be established.

Figure 3.15: Scheme intake pipe from intake chamber at Raliphaswa

Figure 3.16: Intake pipe outlet and crump weir gauging structure at Raliphaswa

Figure 3.17: Sluice gate reject and reduction to scheme main channel at Raliphaswa

Figure 3.18: Parshall flume before Raliphaswa scheme offtake

The scheme has a number of offtake structures (Figures 3.19 and 3.20) that consist of fixed manually operated check (slide) gates with a long weir to maintain the upstream water level within relatively narrow tolerances (usually in the order of 5 to 10 cm). Similarly, to the Dzindi scheme, there are no measuring device for the diverted flow. The check gates function as orifices and it was not clear if they were constructed at standard dimensions for which rating is available. Orifice type check gates are more suitable when water level is to be controlled downstream from a structure, because of its more constant discharge (FAO, 1975).

The long weir should be able to deliver not less than 95% of the required flow under adverse conditions or more than 105% under favourable conditions (DWA, 1980). Therefore, at this point the head on the offtake opening should not vary by more than 20% (DWA, 1980).

A major advantage of fixed long weirs is their simplicity in construction and maintenance and their reliability in operation (FAO, 1975). Tampering is also almost impossible. However, they also trap silt efficiently, prohibiting their use where irrigation water is permanently charged with silt (FAO, 1975). Small quantities of silt can be avoided by providing a flush opening in the weir at the floor of the structure. The long weirs at Raliphaswa however, did not have these flush openings.

Figure 3.19: Long weir and first offtake at Raliphaswa

Figure 3.20: Silted long weir and typical offtake at Raliphaswa

Figures 3.21 to 3.27 show some of the other main features that were observed in the field trip including; the poor state of maintenance of road crossings, main furrows, canals and long weirs, and the presence of unplanned offtakes. Aquatic growth within the canal, which can drastically reduce its carrying capacity, was observed at several locations (e.g. Figure 3.27). Aquatic growth not only increases channel roughness, but also reduces the flow area. In some cases, the reduction in flow area can be as much as 20% (FAO, 1975).

Figure 3.21 Typical road crossing conduit at Raliphaswa

Figure 3.22: Typical concrete main furrow at Raliphaswa

Figure 3.23: Silted long weir and offtake structure at Raliphaswa

Figure 3.24: Unplanned offtake structure at Raliphaswa

Figure 3.25: Main concrete furrow of unplanned offtake structure at Raliphaswa

Figure 3.26: Unplanned main furrow and offtake structure at Raliphaswa

Figure 3.27: Sediment deposits and water grass along the Raliphaswa main canal

According to one of the farmers at Raliphaswa, the night storage dam (Figures 3.28 and 3.29) has not been receiving water from the Raliphaswa intake structure for several months as there is a blockage somewhere in the supply pipeline (Figure 3.30). Raliphaswa has meanwhile been obtaining water from the canal that also supplies Mandiwana scheme. Supply to this canal starts off with a syphon pipeline from the Raliphaswa intake (Figure 3.31) to an outlet (Figure 3.32) from which the Mandiwana canal starts (Figure 3.33). The canal has a number of long weirs (Figures 3.34 and 3.35) and other structures as those shown on Figures 3.36 to 3.39.


Figure 3.28: Night storage dam at Raliphaswa


Figure 3.29: Raliphaswa night storage dam outlet

Figure 3.30: Pipeline from Raliphaswa intake structure directly to Raliphaswa night storage dam

Figure 3.31: Syphon pipeline from Raliphaswa to Mandiwana

Figure 3.32: Raliphaswa syphon outlet

Figure 3.33: Start of Mandiwana canal

Figure 3.34: Typical long weir at Mandiwana

Figure 3.35: Last long weir structure and offtake at Mandiwana


Figure 3.36: Typical offtake structure at Mandiwana


Figure 3.37: Main concrete furrow at Mandiwana

Figure 3.38: Main concrete furrow split after the offtake structure at Mandiwana

Figure 3.39: Main concrete furrows at Mandiwana

The main canal to Mandiwana then eventually leads to Mamuhohi through a canal (Figure 3.40) to the Mamuhohi night storage dam (Figures 3.42 and 3.43). The main canal from the night storage dam has an outlet valve stilling basin and an overflow (Figures 3.44 and 3.45). Figure 3.46 shows a secondary canal in Mamuhohi.

Figure 3.40: Main canal from Mandiwana to Mamuhohi

Figure 3.41: Mamuhohi night storage dam


Figure 3.42: Mamuhohi night storage dam spillway


Figure 3.43: Mamuhohi night storage dam outlet valve


Figure 3.44: Mamuhohi outlet valve stilling basin and overflow


Figure 3.45: Main canal to Mamuhohi

Figure 3.46: A secondary canal in Mamuhohi

3.3.3 Rabali canal scheme

The weir of the Rabali smallholder irrigation scheme (Figure 3.47) is approximately 130 m upstream of the R523 bridge across the Nzhelele River in Ha – Raliphaswa. It is located at 22˚52'52.77''S and 30˚06'40.16''E. the length of the main canal is about 5 km.

According to Letsoalo and Van Averbeke (2006), the floods in February 2000 destroyed the original Rabali weir and cut away the bottom western part of the irrigated land. Consequently, the weir and the conveyance system were completely refurbished in 2001 – 2002 as part of a disaster relief programme. The canal section is parabolic and concrete lined. The water control and gauging infrastructure is in good working condition and well designed. The scheme lies along the boundary of the Rabali village, is fully fenced off and isolated from the surrounding communities.

The Rabali weir is located downstream of the Mphephu and Raliphaswa weir, after the confluence of the Nzhelele and Mutshedzi Rivers. Consequently, its catchment is substantially larger than that of the Mphephu and Raliphaswa weirs. The weir is located on the concave side of the Nzhelele River and includes a fish ladder (Figure 3.48) that encourages flow adjacent to the river intake.

Figure 3.47: Rabali Weir

Figure 3.48: Rabali weir fish ladder

The river intake is located outside the river main channel and is affected by sediment accumulation on the upstream side, this is evidenced by the dense reed growth upstream of the intake. The river intake also resembles a frontal intake with an inlet sill at the entrance of the intake, presumably to prevent the entrance of coarse sediment (i.e. the bed load). There is no mechanism for the clearing out of sediment upstream of the inlet sill and adjacent to the trash screens. Consequently, the management of sediment would have to be done manually or via sludge pumps.

After flowing through the trash screens (Figure 3.49), at 90 degrees to the direction of flow into a chamber, flow is regulated into the scheme via a sluice gate (Figures 3.50 and 3.51).

Figure 3.49: Intake into scour channel and trash screens at Rabali

Figure 3.50: Rabali intake chamber

Figure 3.51: Intake chamber and sluice gate at Rabali

Canal rejects are provided (Figure 3.52) so that upstream portions of main canals may be kept in operation while maintenance is being carried out in the lower reaches (DWA, 1980). Any excess flows can then overflow back to the river.

The Scheme has a well-maintained sluice gate (Figure 3.53) and gauging structure (Figure 3.54). The canals are not as well-maintained (Figures 3.55 to 3.57) and seem to have inadequate freeboards. Present practice in the case of sub-critical flow is to provide sufficient freeboard to accommodate a flow 20% in excess of design, plus the velocity head component (DWA, 1980).

Figure 3.52: Rabali canal reject (overflow structure).

Figure 3.53: Rabali sluice gate upstream of gauging structure

Figure 3.54: Reject and flow gauging structure at Rabali

Figure 3.55: Rabali main canal


Figure 3.56: Typical long weir at Rabali


Figure 3.57: Typical orifice offtake at Rabali

3.3.4 Mphephu canal scheme

The Mphephu smallholder irrigation scheme weir is located on the Nzhelele River at 22˚54’16.20’’S and 30˚10’26.40’’E, 860 m south of the R523 in Sedendza Village. The weir and the canal were revitalised in 2006/07 following the damaged caused by the February 2000 floods. According to data collected by Van Averbeke (2012), the infrastructure is prone to significant leakages and also has a few operable control gates. The scheme has a workable gauging structure just downstream of the weir and a night storage dam was also observed during the field visits. The infrastructure is easily accessible along the main routes, particularly near the first night storage dam which is in close proximity to the main road.

The Mphephu river intake (Figure 3.58) is located on the convex side of the Nzhelele River main channel. Like all the river intakes visited during the field visits (except for the Rabali river intake, which is regulated by means of a sluice gate in the intake chamber), the Mphephu river intake is unregulated.

The width of the scour channel intake is almost the same size as the width of the Nzhelele River main channel and is in the direction of the main flow. The abstracted water is taken from the upper layers by means of a side overflow structure (Figures 3.59 and 3.60).

The design of the Mphephu river intake resembles that of a frontal intake. These are particularly applicable where the majority of sediment carried by the river is bed load and where a large proportion of the flow continues down the original watercourse (Basson, 2006). An advantage of frontal intakes is that up to 90 % of the river flow can be diverted sediment free.

Continuous flushing is typically used in frontal intakes. This is done by keeping the sluice gate open to such an extent that the largest particle entering the gravel sluice may pass safely through it back to the main stream, with only a small amount of flushing water (Basson, 2006). However, the sluice gate of the Mphephu river intake at the time of the visit was closed (Figure 3.61). Consequently, manual maintenance of the sediment in the scour channel is required, to control sediment levels.

Water is released from the intake chamber through a pipe (Figure 3.62) to the main canal (Figure 3.63) that has a Crump weir installed a short distance downstream (Figure 3.64). The main canal is several kilometres long and seems to have an inadequate freeboard (Figure 3.65).

Figure 3.58: Mphephu Weir

Figure 3.59: Mphephu scour channel intake

Figure 3.60: Overflow into intake chamber from scour channel at Mphephu

Figure 3.61: Leaking sluice gate from scour channel at Mphephu

Figure 3.62: Scheme intake pipeline from intake chamber at Mphephu

Figure 3.63: Intake pipeline outlet to Mphephu canal


Figure 3.64: Crump weir flow gauging structure at Mphephu


Figure 3.65: Mphephu main canal

3.4 Study site selection and justification

Using the various criteria that were developed to assess schemes for their suitability to serve as study sites for WRC Project K5/2962, the decision was made to select the Raliphaswa, Mandiwana and Mamuhohi complex as the preferred study site. This complex of three schemes, each belonging to a different village but linked to each other by a shared source of water and irrigation infrastructure, is particularly well suited to investigate opportunities for improved operation and management for equitable water resource distribution and for institutional and organisational reform. The complex represents a high level of social complexity as it involves three communities, instead of the usual single village.

The field visit confirmed that it had effective gauging structures, fences that were effective, irrigation infrastructure that was in reasonable condition, and reasonable utilisation of the irrigation land was observed during the winter of 2019, even though the tail end scheme of Mamuhohi was utilised less than the other two. Another important advantage of selecting this complex as the study site was that it limits the need for travel and allows for the establishment of a home-base on site. Researchers staying on site for considerable periods of time assists the building of relationships of familiarity and trust, which benefits the research process.

Whilst selecting Dzindi as a study site had the important benefits of a rich data base and good relationships with the local community, the poor condition of the irrigation infrastructure and the absence of good-quality gauging structures led to its elimination.

Rabali had excellent gauging structures but the irrigation infrastructure was no longer in good condition and utilisation of irrigated land was low, as indicated by Van Koppen (2017) and confirmed during the field visit.

Mphephu irrigation scheme would have been a suitable site as well but ultimately it was considered less attractive than the Raliphaswa, Mandiwana and Mamuhohi complex for logistical reasons.

4 SITUATION ANALYSIS – DESKTOP AND REMOTELY SENSED DATA AND MODELLING FOR DIAGNOSIS OF SCHEME PERFORMANCE

4.1 Aim and structure of chapter

Aim of the chapter

The aim of this chapter is to provide an account of the activities undertaken to determine the current situation of the selected smallholder canal schemes and to enable an assessment of the opportunities for sustainable improvement of the performance of the schemes. The COVID-19 pandemic has led to significant delays to field data collection for the situation analysis but substantial desktop data for hydrological analysis has been obtained. The constraints of the COVID-19 pandemic also offered an opportunity for the project team to undertake the modelling activities that are not directly dependent on field data and these are also included in this chapter.

Structure of the chapter

This chapter contains five sections. Section 1 presents the aim and structure of the current chapter and Section 2 provides a brief description of the study schemes. Section 3 presents the acquired hydrological data and the associated hydrological modelling activities. The hydraulic modelling of the main canal is then described in Section 4 while Section 5 describes the initial socio-hydrological conceptual modelling.

4.2 Raliphaswa-Mandiwana-Mamuhohi smallholder canal schemes

The study is being conducted on three irrigation schemes located in Nzhelele area in Limpopo province namely, Raliphaswa, Mandiwana and Mamuhohi smallholder irrigation schemes. The schemes were established in 1964 and fall under the quaternary catchment A80B of the Nzhelele River Catchment although they obtain irrigation water from a weir located at the end of one of the tributaries of catchment A80A. The farms at Raliphaswa, Mandiwana and Mamuhohi are intrinsically linked by virtue of sharing this common water source, and a linked water conveyance infrastructure. They can therefore be considered as hydraulic sub-units of one unit.

The schemes form part of the Nzhelele Catchment Water Users' Association falling under the proposed Limpopo Water Management Area in the province (Mudau, 2010). The village of Mamuhohi is one of the villages falling under the Mphephu Territorial Council and shares a boundary with the Village of Mandiwana. Raliphaswa also shares a boundary with Mandiwana (Mudau, 2010).

The three schemes obtain water from the Raliphaswa Weir on the Mutshedzi river. Some of the water from the Raliphaswa Weir is transferred by a 600 m long pipe to the storage dam at Raliphaswa to supply the neighbouring Vhutuwa Nga Dzwebu scheme which is not included in this study. Water from Raliphaswa Weir is conveyed by a 600 m long canal to Raliphaswa scheme where it feeds a secondary canal network that is about 800 m long. Water from the main canal in Raliphaswa is conveyed by a siphon to feed the main ~ 1800 m long canal in Mandiwana. The main canal from Vhutuwa Nga Dzwebu also feeds the outflow from the siphon to supply Mandiwana. In Mandiwana, irrigation water is fed directly to the secondary canal network that is about 4300 m long. Night-flow from Mandiwana feeds a night storage dam at Mamuhohi which then feeds the farms of Mamuhohi scheme by a 1900 m main canal and a 4500 m long network of secondary canals.

4.2.1 Raliphaswa irrigation scheme

Raliphaswa irrigation scheme is the smallest of the three schemes. It has a total area of 17 ha farmed by 13 farmers with an average plot holding of 1.308 ha/farmer (UWP, 2005). Water use in the scheme is provided as 94 080 m^3/year by the National Irrigation Scheme Database of DWS. The irrigation method in the scheme is surface in a form of a furrow to grow maize which is a dominant crop farmed within the scheme (van Averbeke, 2012). The scheme is situated at the head of the multi-user system and thus, it is less vulnerable to the effects of low flow conditions in the Mutshedzi river than the other two schemes of Mandiwana and Mamuhohi, further down the system.

4.2.2 Mandiwana irrigation scheme

Mandiwana scheme comprises 40 farms occupying an area of 66 ha. The National Irrigation Scheme Database of DWS provides a water use estimate of 416 740 m^3/year for the scheme. Furrows are used as the irrigation method and maize is the predominant crop grown in the scheme.

4.2.3 Mamuhohi irrigation scheme

Mamuhohi is the largest of the three schemes with a land area of 92 ha cultivated by 61 farmers. The National Irrigation Scheme Database of DWS provides a water use estimate of 478 940 m^3/year for the scheme. Mamuhohi is on the tail-end of the three schemes and it is therefore likely that it is impacted more severely by water shortages than Raliphaswa and Mandiwana.

Figure 4.1 shows the main physical features of the three schemes

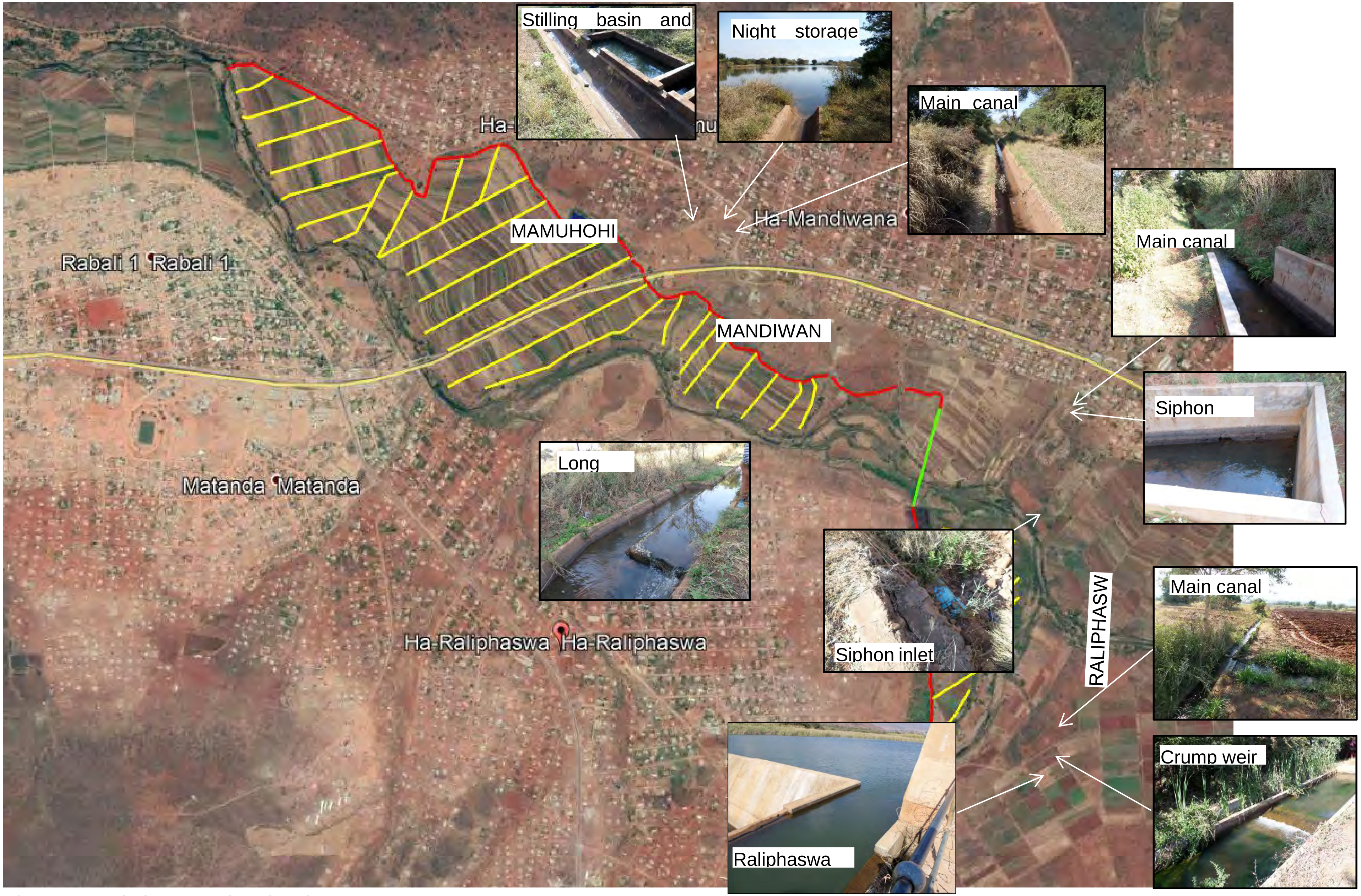


Figure 4.1 Main features of study schemes

4.3 Hydrological data acquisition and modelling

4.3.1 Introduction

This section describes the hydrological modelling for determining the water availability for irrigation supply and irrigation water requirements in the selected schemes. After consideration of the time step required for analysis, the data availability, the experience of the project team and availability of support, it was decided to use the QSWAT[2] and the Pitman model[3] for the hydrological modelling to estimate water availability. On similar considerations, it was decided to apply the SAPWAT model (Van Heerden and Walker, 2016) and remote sensing for the estimation of irrigation water requirements.

4.3.2 Hydrological modelling to estimate water availability

The study area falls under quaternary catchment A80A and A80B of the Nzhelele River Catchment (Figure 4.2), located in the northern most part of the Limpopo Province of South Africa on the leeward side of the Soutpansberg Mountains. It lies between the longitude 22º 54′ 00″ S and latitude 30º 12′ 00″ E and covers a surface area of approximately 2,436 km^2.

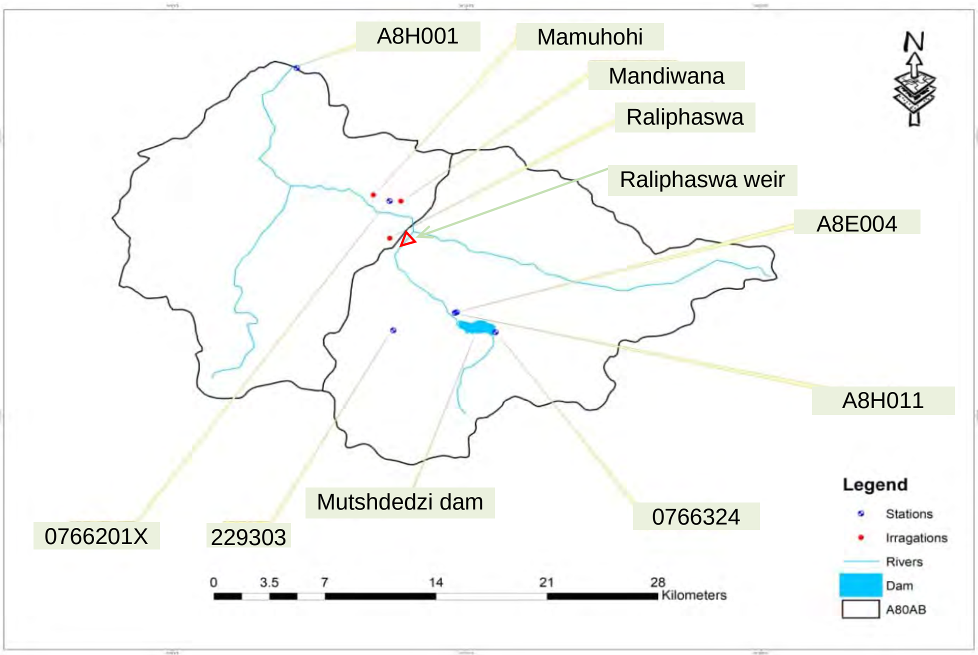


Figure 4.2: Catchment of study area including main storage features and hydrometric stations

The modelling aims to generate a realistic and daily streamflow sequence at the Raliphaswa weir (Figure 4.2) which is the irrigation water abstraction point for the three irrigation schemes. In order to incorporate hydrologic variability including inter-annual periods of low, normal and high flows, the modelling aims to generate a sequence that is as long as the data availability enables. A detailed search for hydrological data whether measured, patched or modelled from previous studies has therefore been undertaken.

Daily rainfall data for station 0766324 for the period 1903/10/01-2000/07/31 obtained from Lynch (2003) was extended by Makungo (2019) to cover the period up to 2014/02/10 (Figure 4.3). Station

[2] https://swat.tamu.edu/software/

[3] https://waterresourceswr2012.co.za/

229303 from the SWAT database has daily data which include minimum and maximum temperature, rainfall, wind speed, relative humidity and solar radiation for the period 1979/01/01-2014/07/31. Mutshedzi rainfall and evaporation station (A8E004) has daily rainfall and evaporation data from 1991/07/01 to 2020/02/29. The evaporation data which has some discontinuities is shown in Figure 4.4. Streamflow data for the period 1991/12/03-2000/12/04 is available for station A8H011 (Figure 4.5) downstream of Mutshedzi Dam obtained from South African Department of Water and Sanitation[4]. The gauging station A8H001 at the outlet of A80B only has recorded water levels for the period 1932/10/04 to 194612/28. A large proportion of these water levels were truncated at about 0.4m.

The periods of coverage of the various data are shown in Figure 4.6 and reveal that the classical calibration and verification approach to the modelling may only be applicable over a period of 10 years when streamflow data is available. Since the streamflow data is itself impacted by the operation of Mutshedzi dam, the classical calibration-verification would be further constrained. The application of a predominantly process-based rather than a statistical hydrological modelling approach may help to reduce the dependence on calibration and the Soil Water Assessment Tool (SWAT) model, that is widely used globally and in South Africa was therefore selected for the modelling. The SWAT model requires daily rainfall, temperature, relative humidity, solar radiation and wind speed as inputs. Other input data for model set up include a Digital Elevation Model (DEM), soil information, land cover data, and drainage network. The modelling procedure involves watershed delineation, definition of hydrologic response units (HRUs), editing of SWAT database, definition of weather data, application of default input files, model set up and running. Figures 4.8, 4.9 and 4.10 show, respectively, the DEM, the land-use and soil data that have been generated for the study area using QGIS. The 3 spatial data have been integrated to create the delineated watershed of the study area shown in Figure 4.10. The modelling applying the QSWAT version of the SWAT model is currently on-going.

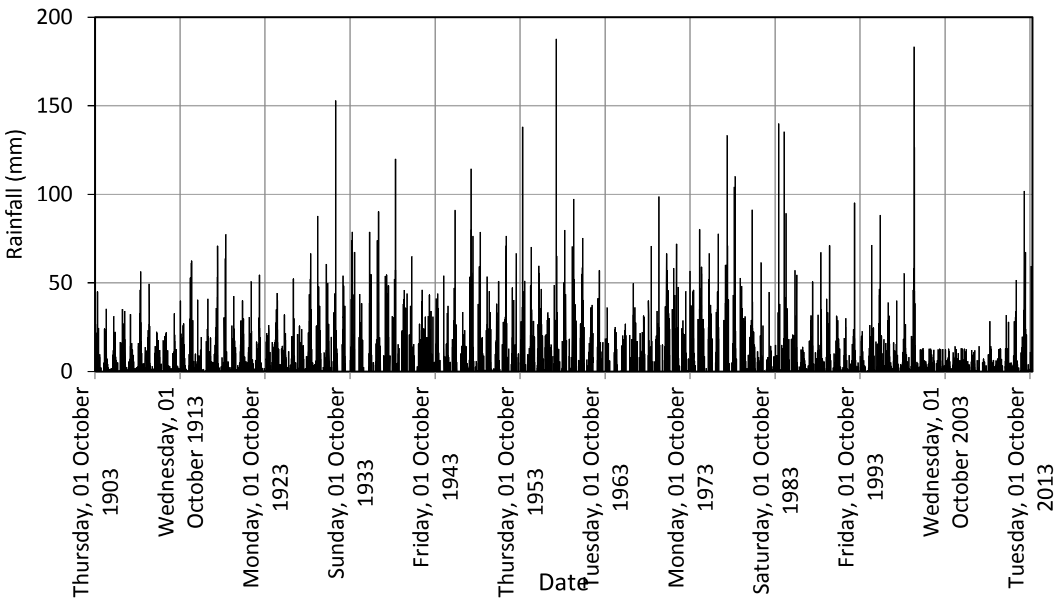


Figure 4.3: Daily rainfall at station 0766324

[4] http://www.dwa.gov.za/Hydrology/Verified/hymain.aspx

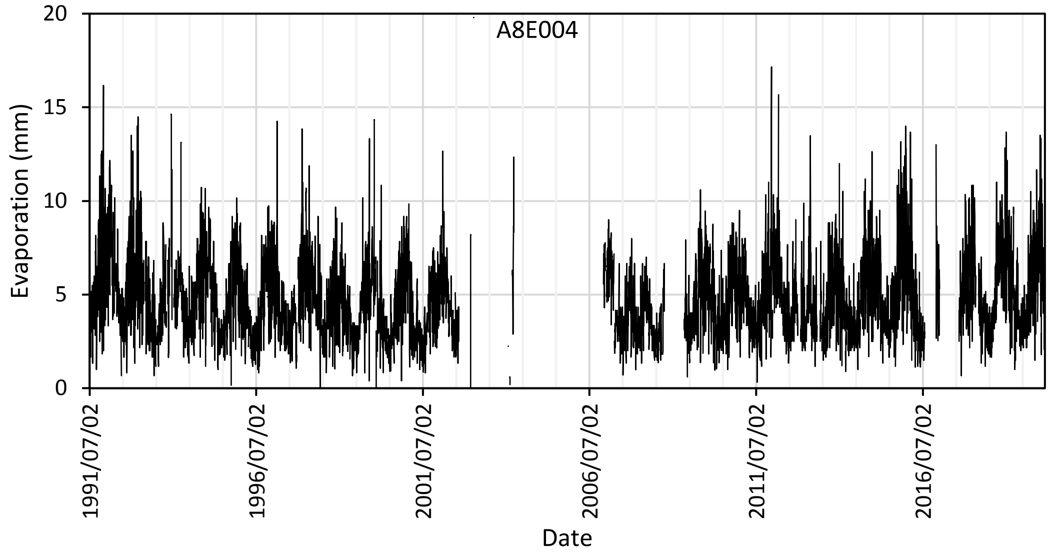
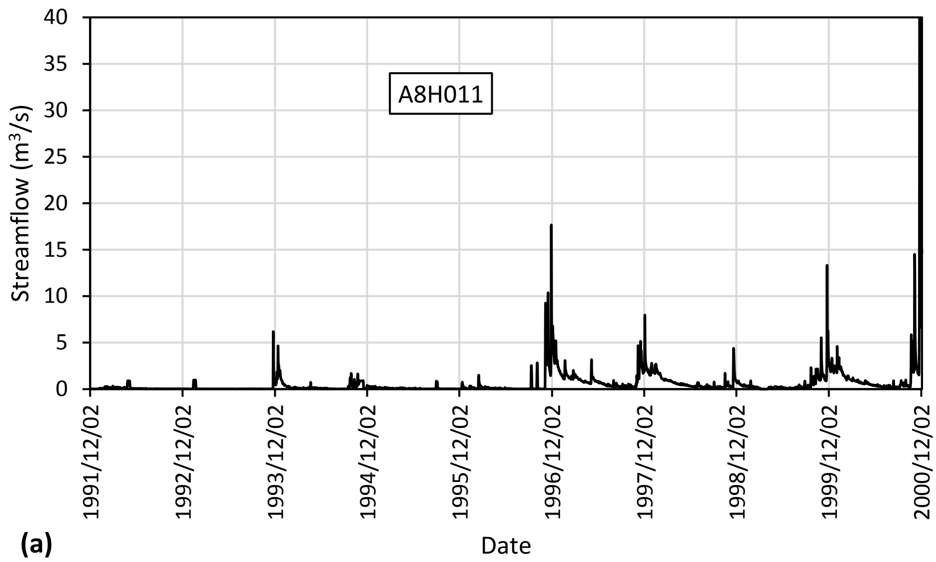


Figure 4.4: Daily evaporation at station A8E004



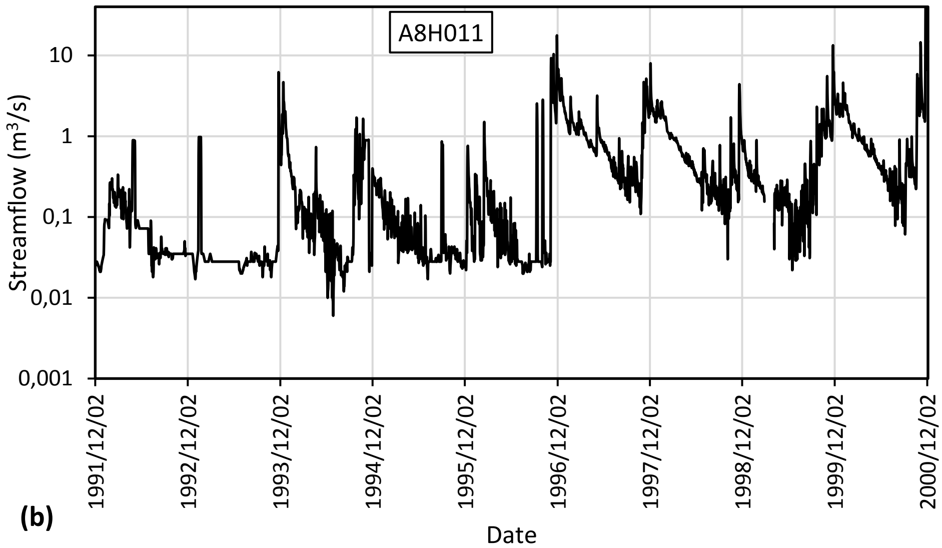


Figure 4.5: Daily streamflow at station A8H011 in linear (a) and logarithmic (b) scales

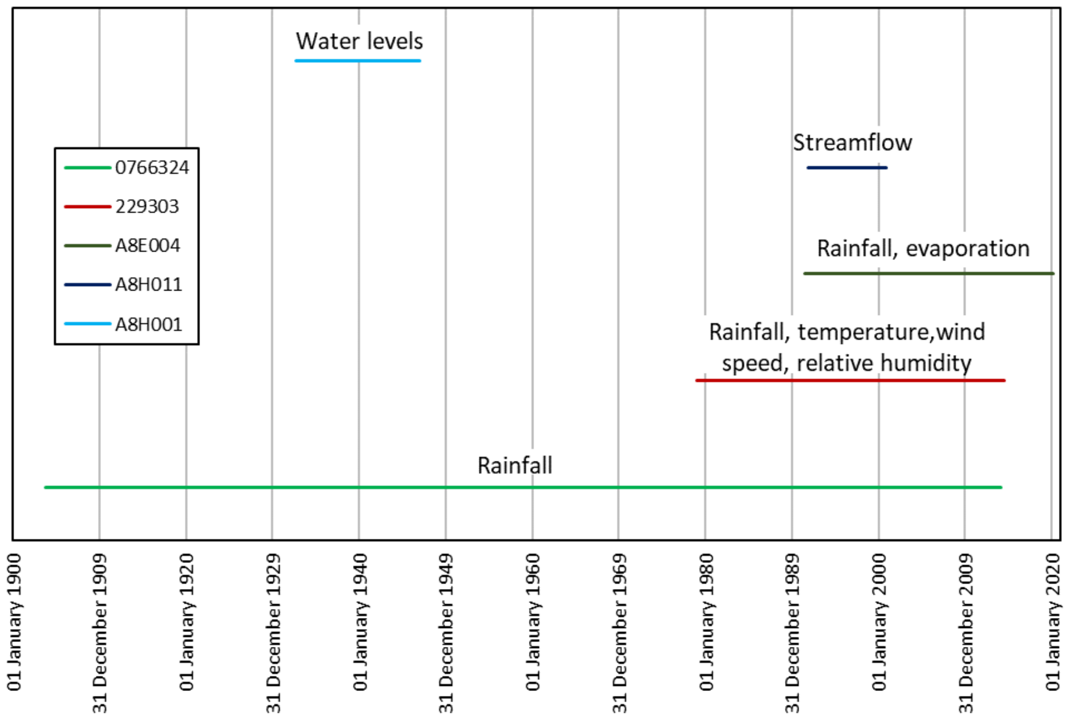


Figure 4.6 Temporal ranges of available hydrological data

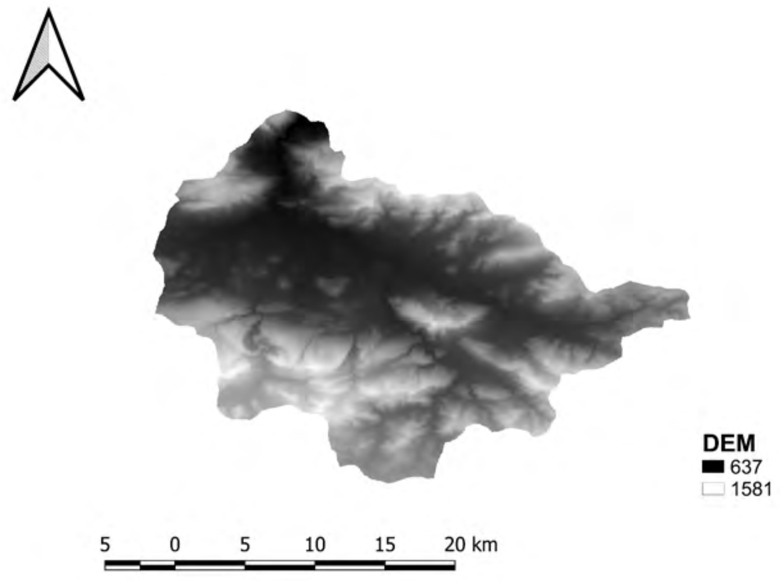


Figure 4.7 DEM of study area

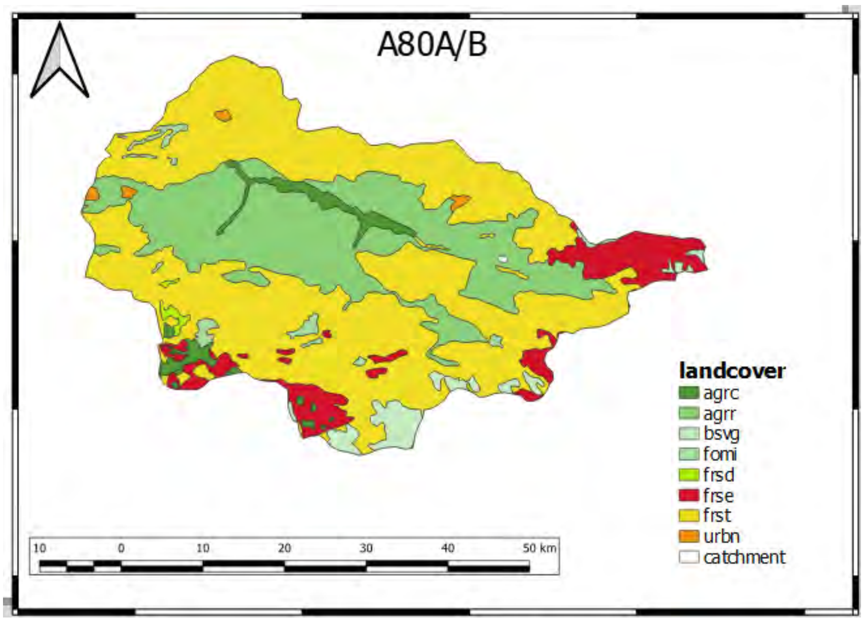


Figure 4.8 Land-use data input into SWAT model

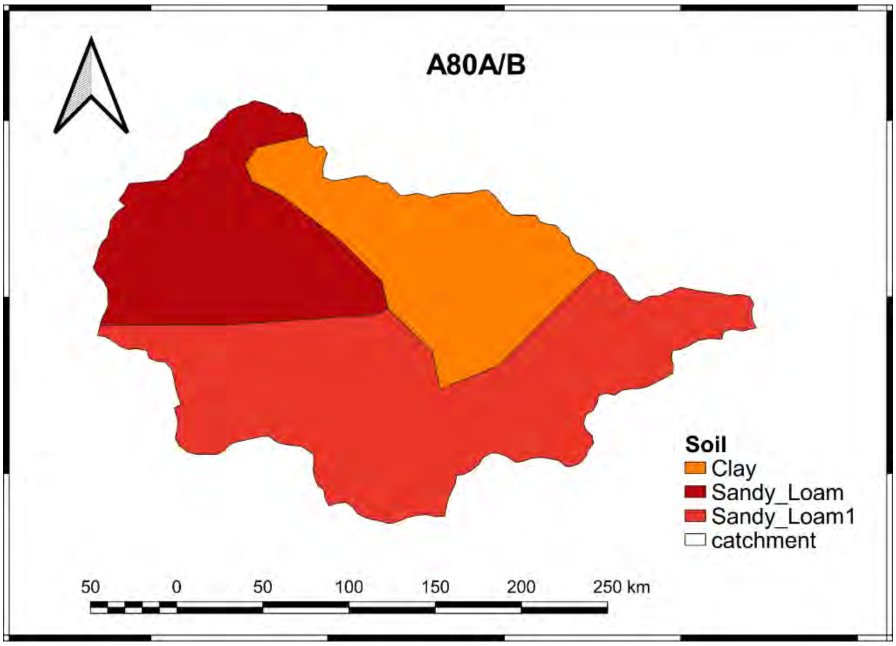


Figure 4.9 Soil data input into SWAT model

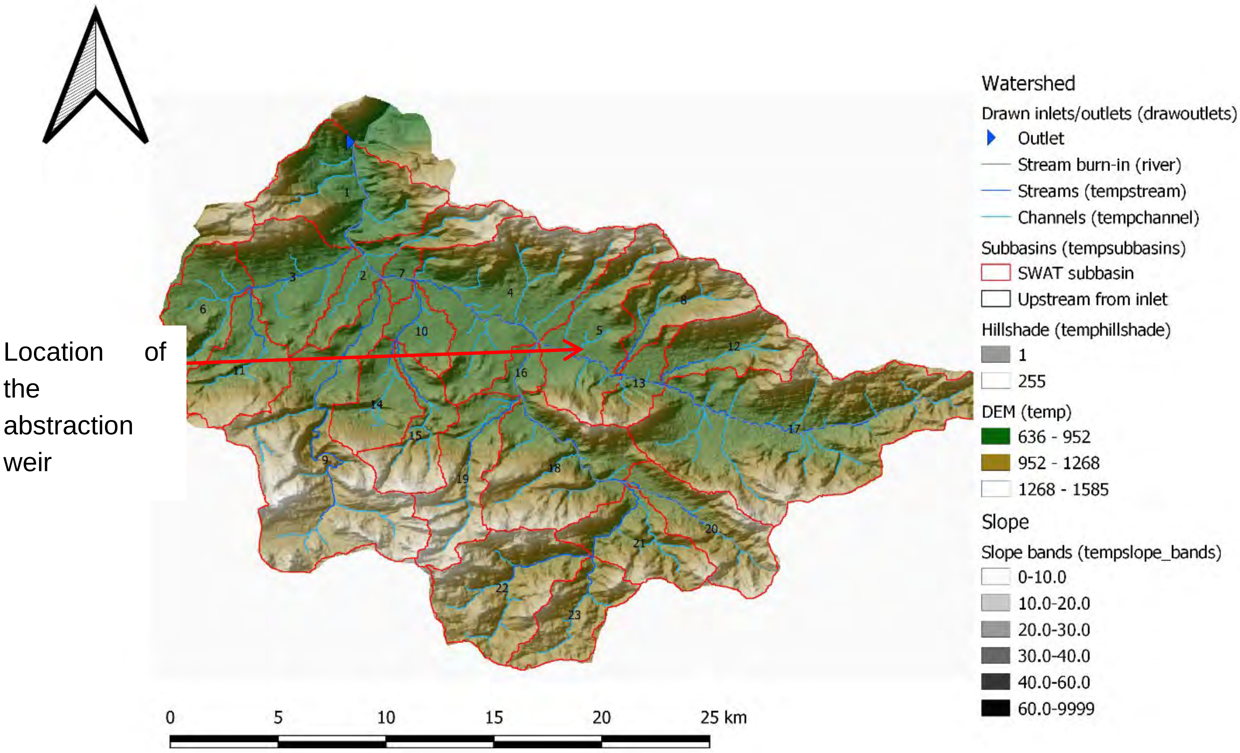


Figure 4.10 Delineated watershed of study area

Although the daily SWAT modelling could lead to a reasonably long daily streamflow series of 35 years if all the data from station 229303 is used, the Water Resources of South Africa study[5] has a much longer time span of 90 years (1920-2009) of monthly data including naturalised streamflows

[5] https://waterresourceswr2012.co.za/

for catchment A80A. The WR2012 study has a background of several decades of modelling experience (Hughes, 2013) since the development of the Pitman model (Pitman, 1973) and provides parameter values or ranges of the model for the whole of South Africa.

The modelling incorporates the effects of land use change and is applied widely for water resource systems analysis in South Africa. Monthly-time step water resource modelling tends to be simpler and more parsimonious than daily time analysis and is usually more amenable to long-term assessments of water availability. Three members of the project team have used the Pitman model for research previously (Ndiritu, 2009 a, b; Ndiritu and Mkhize, 2017; Makungo, 2019) and the team has a self-developed source code of the model. This code could be easily adopted to carry out Pitman modelling at a daily time to complement the on-going modelling using SWAT and also allows for flexibility in dealing with unique modelling requirements that may be needed for the current task.

Given all the above considerations, the Pitman model is selected for the assessment of long-term water availability at the schemes. The setting up and data requirements for the Pitman model are considerably lower than those of SWAT and it seems likely that a daily time step Pitman model simulation for the duration of the daily rainfall series of station 0766324 which is 112 years long (1903-2014) could be achievable. Table 4.1 provides the Pitman model parameter values and ranges while Figure 4.11 shows naturalised annual streamflows for catchment A80A aggregated from the monthly flows given in the WR2012 study[6]. The high hydrologic variability of the study area – which is also typical to other regions of South Africa is evident. Figure 4.12 is the WR2012 network for the study area and shows that the study schemes have been lumped with 3 other schemes to form one irrigation module RR2. Estimates of the irrigation demands for the individual schemes are available from the National Irrigation Scheme Database of DWS and from a scoping study (UWP, 2005) and would be utilised for the more refined analysis required here.

Table 4.1 Pitman model parameter ranges for catchment A80A[7]

Parameter	**Value / Range**
ST (mm): Maximum moisture storage capacity	500 – 1000
SL (mm) Lower limit of soil moisture below which no groundwater recharge occurs	0 – 1
FT (mm): Runoff from moisture storage at full capacity. Determines the balance between evaporation and runoff in humid areas.	10 – 20
POW: Power of the moisture storage-runoff equation. Controls the rate of runoff from the soil for any moisture state	3
ZMAX (mm) Maximum catchment absorption rates. Controls surface runoff generation	1000 – 1500
ZMIN (mm) Minimum catchment absorption rates. Controls surface runoff generation	25 - 50
GPOW: Power of the moisture storage-recharge equation. Controls rate of recharge from the soil from any given soil moisture state	3

[6] https://waterresourceswr2012.co.za/

[7] https://waterresourceswr2012.co.za/

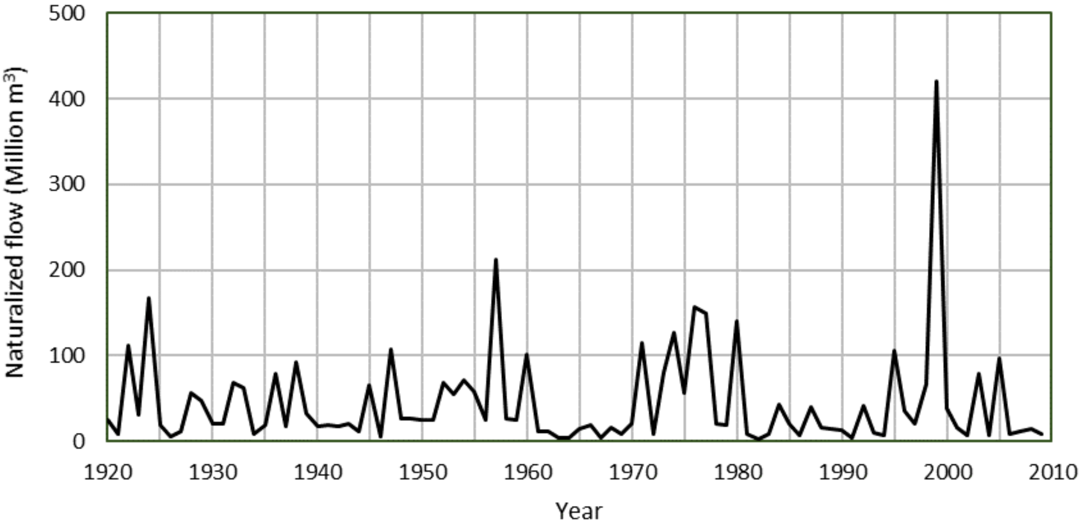


Figure 4.11 Naturalised annual streamflow for catchment A80A[8]

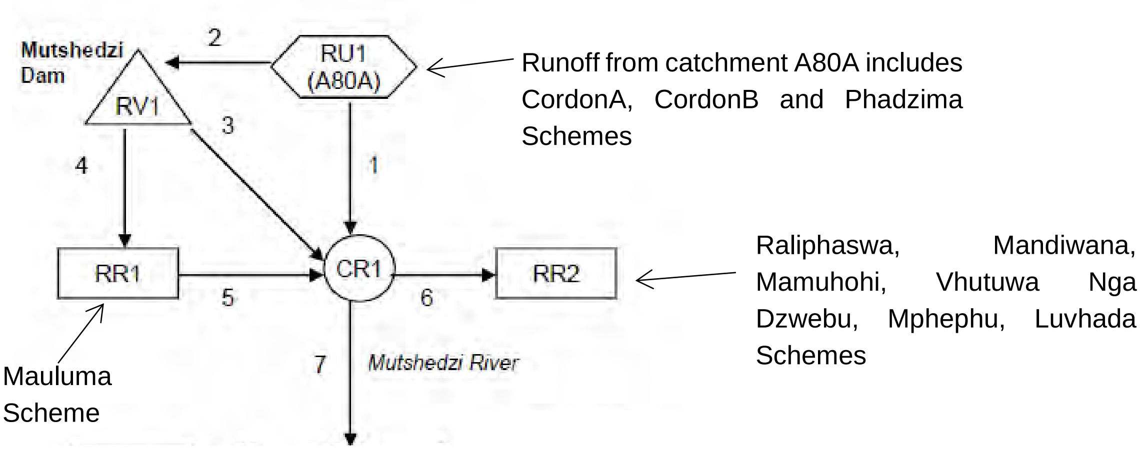


Figure 4.12 WR2012 network for study area[9]

Mutshedzi dam, with a capacity of 2.35 million m^3 is the main storage within catchment A80A. Streamflow measurements at the dam (Figure 4.5) ceased in year 2000 and the Department of Water Affairs and Sanitation has continued to undertake monthly water balance for the dam to the present. The monthly water balance data has been acquired and its main components are presented graphically in Figure 4.13. Although considerable portions of the time series are missing, it is evident that the sudden increase in municipal demand in 2017 has led to a sharp reduction in uncontrolled spillage, most of which would have served as inflow into Raliphaswa weir. A search for additional data to enable the computation of the streamflow over a longer period than seen on Figure 4.13b will be conducted as this computed streamflow would be very useful in model calibration.

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[8] https://waterresourceswr2012.co.za/

[9] https://waterresourceswr2012.co.za/

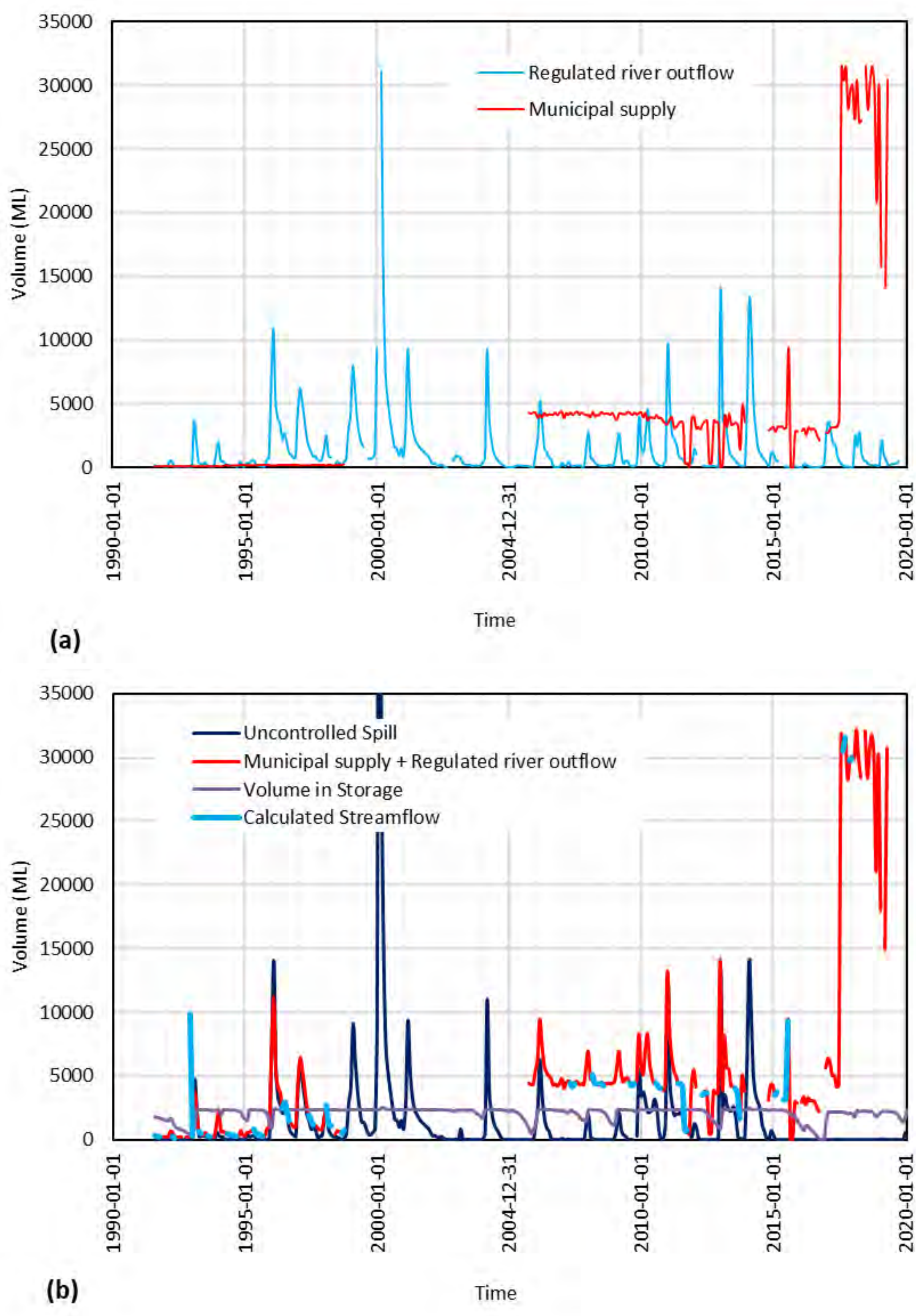

Figure 4.13 Monthly water balance of Mutshedzi dam

4.3.3 Estimating irrigation water requirements

4.3.3.1 Models for estimating crop water requirements

Application of the SAPWAT model to determine the amount of water required for irrigation requires various data including crop factors, the area under irrigation, the types of crops grown, the irrigation schedule and evaporation rates. The SAPWAT model, which is an improvement from CROPWAT model for determining crop water requirements (Van Heerden *et al*., 2001, Van Heerden, 2004, Smith, 1992), has been widely applied for planning irrigation schemes and management of irrigation water (Van Heerden et al*.,* 2001, De Lange *et al.*, 2010, Backerberg et al*.,* 2006). The SAPWAT follows the four-stage Food Agricultural Organisation (FAO) procedure to ensure a transparent and internationally comparable methodology. The key input data which include irrigation system data, precipitation, infiltration, surface runoff, evapotranspiration, soil data and crop data is used to drive the model. SAPWAT has inbuilt weather data required for model setup for the study area at daily, weekly or monthly time scales.

For situations where the data requirements for applying the SAPWAT model are not available, the data-scarce, Hargreaves equation (Hargreaves, 1981; Hargreaves and Samani, 1985) which is a widely applied temperature-based method for potential evapotranspiration could also be used. The Hargreaves equation is linked to solar radiation through terrestrial solar radiation (R_a) and considers the impact of radiation warming the surface near the ground via temperature difference, the equation provides reasonable estimates of reference crop evapotranspiration (Gavilan *et al.,* 2006; Yates and Strzepek, 1994). This equation could be used with crop factor values from the CROPWAT model to estimate the daily crop water requirements of different crops.

The daily crop water requirement could therefore be determined using equations 4.1 to 4.3.

$$ET_{crop} = K_c ET_0 \tag{4.1}$$

$$ET_0 = 0.0023 R_a TD^{0.5}(T_a + 17.8) \tag{4.2}$$

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega s \sin(\phi)\sin(\delta) + \cos(\phi)\cos\delta\sin(\omega s)\right] \tag{4.3}$$

Where ET_{crop} = crop water requirements (mm/day), K_c = crop factor, ET_o = reference crop evapotranspiration (mm/day), R_a is extra-terrestrial radiation (mm/day), *TD* = difference between the max and min temperature and T_a = mean daily temperature

For the study schemes, preliminary modelling was done using inputs corresponding to the schemes including the areas of irrigation, the irrigation system and soil types and the main crops grown. Weather data from 1950-1999 are used with crop data through the dual crop coefficient approach (K_{cb}+K_e) with reference evapotranspiration (ET_0) to calculate crop water requirement (ET_c) (Allen et al., 1998). The analysis will apply an assurance of supply (percent non-exceedance) of 80% and includes the iterative calibration of coefficient $K_{cb.}$

4.3.3.2 Remote sensing and GIS

The estimation of irrigation demand using remote sensing used surface energy balance approaches and a review of several models applied for this led to the selection of the SEBAL (surface energy balance) model which is highly recommended for estimation of crop water requirements (Bala et al., 2017). The empirical relationships of the SEBAL model can be adjusted to different geographical regions, are applicable to various climates, and require minimum ground-based data with no need for land use classification. The model is suitable for all visible, near-infrared and thermal-infrared radiometers indicating that it can be applied at different spatial and temporal resolutions (Ndara et al., 2017). Gibson et al. (2013) showed that the SEBAL model has been widely and successfully applied in a historical context in South Africa for crop water use efficiency studies. Some other studies have also used SEBAL model in South Africa (Singels et al., 2014; 2018; Ndara, 2017). The SEBAL has minimal input requirements which include satellite images and weather data utilising surface energy balance (Waters et al., 2002).

Weather data required in SEBAL include wind speed, solar radiation, air temperature, and precipitation. The wind speed at the time of the satellite overpass is required for calculation of sensible heat flux (H) (Waters et al., 2002). Precipitation data is used to evaluate the general “wetness” of areas based on the four- or five-days antecedent rainfall (Waters et al., 2002). Solar radiation data are useful for the estimation of the cloudiness of the image and for adjusting the atmospheric transmissivity. These weather data should be obtainable from a weather station situated within 50 km of the point of interest and two or more weather stations should be used if the terrain or land-use is widely varied. The ERDAS Model Maker tool is used to compute the net radiation (R_n). The SEBAL process uses two “anchor” pixels to fix boundary conditions for the energy balance (Waters et al., 2002) and the surface temperature and near-surface air temperature (dT) are assumed to be similar at this pixel (Liou and Kar, 2014). The main equations used in SEBAL model is as follows based on surface energy balance equation:

$$LE = R_n - G - H \quad (4.4)$$

Where LE is the latent heat flux (W/m^2), R_n is the net radiation (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux (W/m^2).

The net radiation at the earth’s surface is calculated using radiation balance equation as follows:

$$R_n = (1 - \alpha)\, R_{s\downarrow} + R_{s\downarrow} - R_{l\uparrow} - (1 - \varepsilon_o)\, R_{l\downarrow} \quad (4.5)$$

Where R_n is the net radiation (W/m^2), α is the surface albedo (dimensionless), $R_{s\downarrow}$ is the incoming shortwave radiation (W/m^2), $R_{l\uparrow}$ is the outgoing long-wave radiation (W/m^2), $R_{l\downarrow}$ is the incoming long-wave radiation (W/m^2), and ε_o is the surface emissivity (dimensionless).

Bastiaanssen et al. (2000) proposed an empirical equation for the ratio of G/R_n to be calculated providing values near midday (Elkatoury et al., 2019). The equation is:

$$\frac{G}{R_n} = T_s(0.0038 + 0.007 \propto)(1 - 0.98[NDVI]^4) \quad (4.6)$$

Where T_s is the surface temperature (°C), α is the surface albedo, and NDVI is the normalised difference vegetation index.

Sensible heat flux is calculated utilising the following equation for heat transport (Bezerra et al., 2015):

$$H = P_a C_p \frac{dT}{r_{ah}} \quad (4.7)$$

Where P_a = air density (kg/m^3), C_p = air specific heat (1004 J/kg^1/K^1) at constant pressure, r_{ah} = aerodynamic resistance to heat transport (s/m^1) between two near surface heights, h_1 and h_2, and dT (K) = near surface temperature difference between the levels h_1 and h_2 ($T_a - T_s$).

The evaporative fraction is estimated from the instantaneous surface energy balance at the satellite overpass on a pixel-by-pixel basis as follows and it expresses the ratio of the actual to the crop evaporative demand when the atmospheric moisture conditions are in equilibrium with the soil moisture conditions (Elkatoury et al. 2019).

$$EF = \frac{LE}{Le+H} = \frac{LE}{R_n - G} \quad (4.8)$$

Finally, daily evapotranspiration (ET_{24}) is computed as expressed below:

$$ET_{24} = \frac{86400000}{LEp_w} EFR_{n24} \quad (4.9)$$

Where R_{n24} is the 24 hours averaged net radiation (W/m^2), and p_w is the density of water (Kg/m^3).

Clear sky Landsat 8 satellite images from USGS for the period 2010 have been downloaded from the website[10]. These images are usually created with an associated "header" file for the satellite image which is a relatively small file that contains important information for the SEBAL process (Waters et al., 2002) which include satellite overpass date and time, coordinate location (latitude and longitude of the centre of the image) and sun elevation angle at the satellite overpass time, Gain and Bias levels for each band.

Figure 4.14 shows estimated daily evapotranspiration maps for selected dates determined by the SEBAL process. There are larger areas with relatively high evapotranspiration rates in the wet season (January and October) than in the dry season (August and September) indicating increased crop water use in the summer months. Figure 4.15. relates the image of 16/01/2016 to the locations of the irrigation schemes and reveals higher evapotranspiration rates in the schemes than other areas.

[10] https://earthexplorer.usgs.gov/

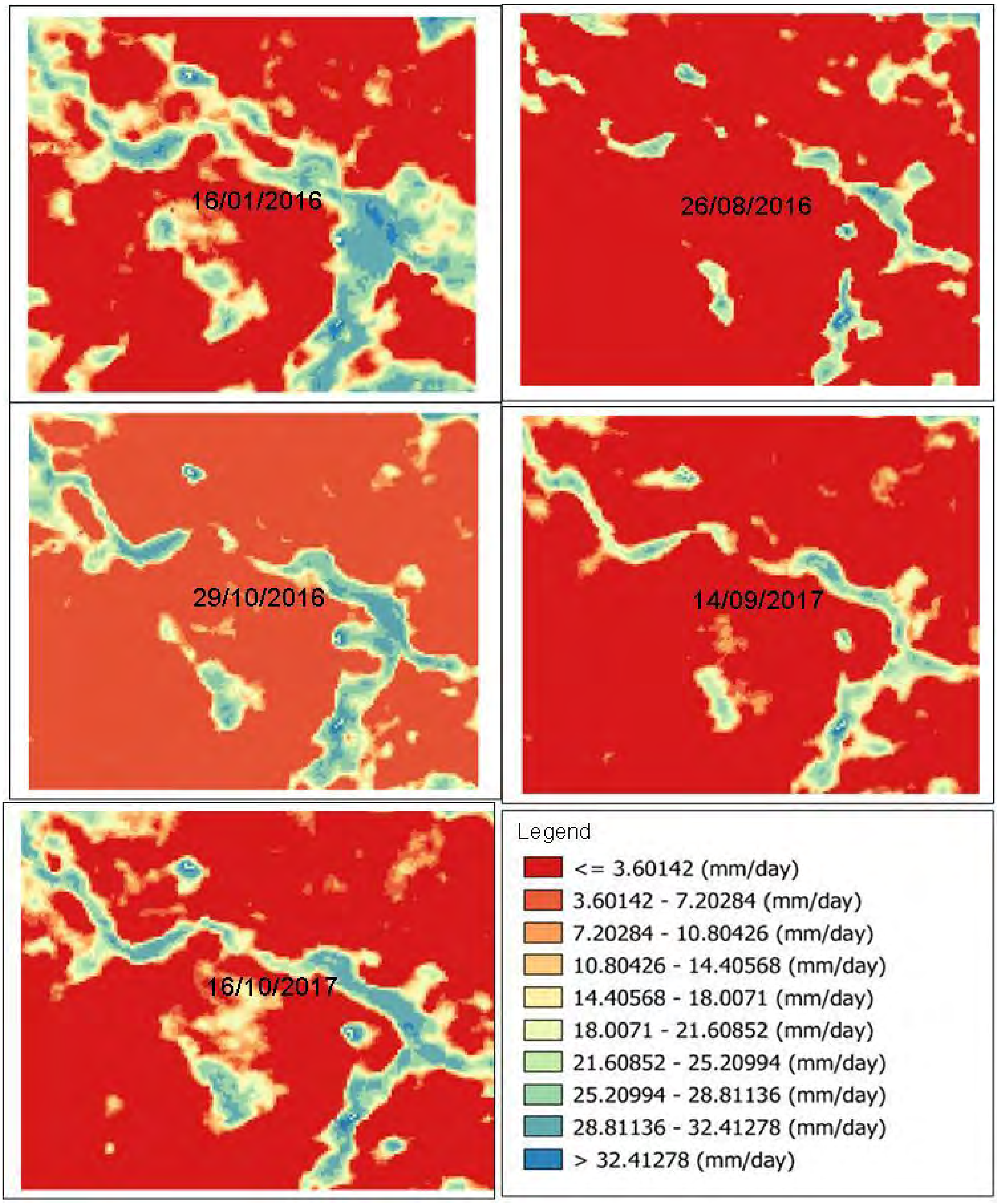

Figure 4.14: Evapotranspiration rates determined by SEBAL model for selected dates

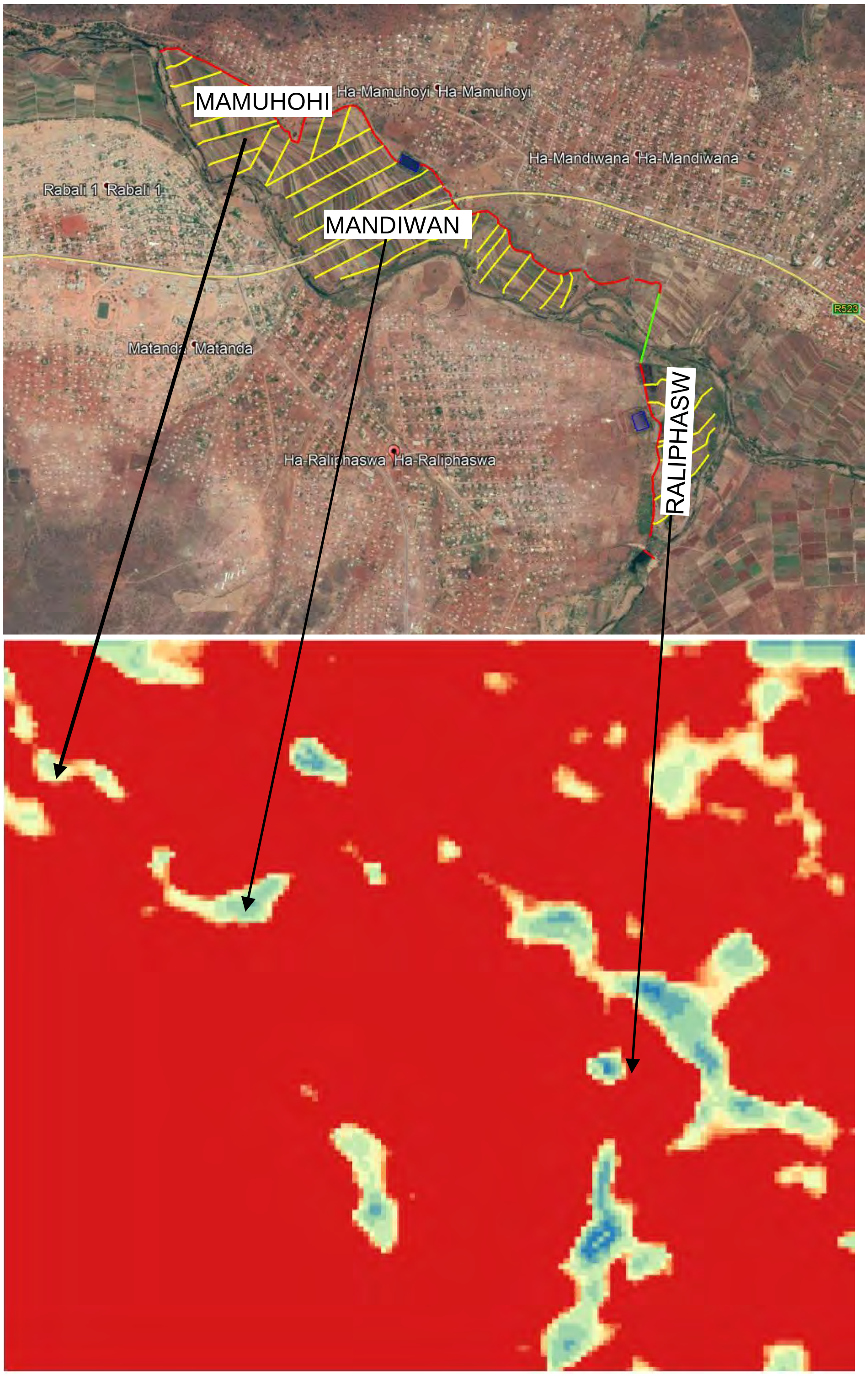

Figure 4.15: SEBAL Evapotranspiration map for 16/01/2016 in relation to locations of study schemes

4.4 Hydraulic modelling of main canals

4.4.1 Introduction

The irrigation system is the interface between the human and natural system and therefore a key element of irrigation scheme performance and the socio hydrological approach of assessing this performance. It shapes the water inflow from the source upstream and the delivered water volumes to the downstream users, based on the hydraulics of the system. Detailed hydraulic modelling that includes the effects of various states of maintenance that depend on human factors including socioeconomics, governance and skill on hydraulic performance and water supply is therefore desirable. This section describes the hydraulic modelling applied on the main canals of the study schemes.

Hydraulic simulation models are important tools for understanding the hydraulic flow characteristics of irrigation systems under different operating scenarios and obtaining information on actual hydraulic parameters of water flow (Islam et al., 2008; Serede et al., 2015; Patamanska and Grancharova, 2019). Patamanska and Grancharova (2017) used a hydraulic model to study the influence of management practices of the water distribution and operation conditions and maintenance of the canal on the size of operational losses. Kim et al. (2016) developed a hydraulic analysis model for an irrigation canal using the Storm Water Management Model (SWMM). Hydraulic simulation models are essential in contributing to an optimised irrigation operation and water allocation (Islam et al., 2016).

There are numerous commercially available computer models or software packages for flow modelling of irrigation systems (Huang and Fipps, 2009). Examples include SOBEK, CanalCAD, Mike 11, SIC, HEC-RAS and CanalMan, CANAL, PROFILE, FLOP, USM, MASSCOTE and ODIRMO. These models are for general use and are either expensive or difficult to customise for applications under specific conditions (Huang and Fipps, 2009). Furthermore, they differ in user-friendliness and in their ability to handle a variety of boundary conditions such as combination of weir/undershot gates, orifices, hydraulic gates, siphons, pumps, etc (Burt and Gartrell, 1993, Islam et al., 2016). The development of a suitable modelling tool is therefore necessary, that provides results comparable with commercially available models and software packages but that can also be configured to the specific needs of the study.

4.4.2 Hydraulic computation methods

In irrigation canals, water flows are typically categorised as either steady uniform flow (SUF), steady gradually varied flow (SGVF) and unsteady gradually varied flow (USGVF) (Huang and Fipps, 2009). A flow is steady if the characteristics describing that flow (i.e. velocity, discharge or depth) do not vary with time and uniform if the parameters (i.e. cross section, slope) describing the flow do not change with distance along the flow path (Chadwick et al., 2004).

Canals are typically designed based on the uniform flow criterion, even though uniform flow at all locations is not feasible due to the presence of various hydraulic structures such as gates, weirs, siphons, falls, rejects etc (Misra, 1995). Non-uniform flow is thus the prevailing flow condition in these systems (Huang and Fipps, 2009).

The flow in canal irrigation systems is described by unsteady, gradually varying, one-dimensional flow equations, commonly known as the Saint-Venant equations, based on conservation of mass and energy in a bounded system (Zhang and Shen, 2007; Islam et al., 2008). These equations are simultaneous nonlinear partial differential equations with a number of boundary conditions, making their implementation much more difficult and time consuming due to the extreme variability and unsteadiness of the flow, the presence of numerous hydraulic structures and dynamic gate movements (Forrest and Merkley, 1993; Huang and Fipps, 2009; Burt and Gartrell, 1993). USGVF are also very data intensive, as to define the instantaneous unsteady condition at a single moment, all gate positions, flow rates, and water levels throughout the system need to be known (Burt and Gartrell, 1993).

The SGVF is a special case of USGVF which can be more easily implemented (Huang and Fipps, 2009). The SGVF can be computed and analysed by observing the conservation of mass and energy with an ordinary differential equation (Huang and Fipps, 2009). In reality, steady flow rarely exists in an irrigation canal, however, it can be useful in solving problems in flow computation and analysis (Burt and Gartrell, 1993; Islam, 1995; Huang and Fipps, 2009).

The scheme rotation schedule and therefore the simulation time interval for the Raliphaswa, Mandiwana and Mamuhohi scheme are hours to days, therefore it is reasonable to assume that SGVF would establish at this time scale. Furthermore, the canals being analysed are shallow and have small hydraulic gradients such as in the study by Huang and Fipps (2009). Under these conditions, SGVF is the dominant flow type and USGVF is likely to be isolated at the offtakes. The simpler SGVF techniques will therefore be used in the development of the hydraulic modelling tool.

4.4.3 Irrigation system of study schemes

Many different types of canal structures are required in an irrigation system to effectively and efficiently convey, regulate, and measure the canal discharge and also to protect the canal from storm runoff damage. (USBR, 1978). The irrigation system at the study scheme includes conveyance structures (in addition to the main canal itself, structures such as siphons, culverts, drop or chute structures), regulating structures (this includes the turnouts, weirs, gates, check structures), water measurement structures, protective structures such as cross drainage structures and wasteways. The turnouts (or “offtake”) consist of a sluice-gate-controlled inlet, used to divert the water from the main canal into the farmers’ furrow systems.

The long weirs are built in the main canal just downstream of the turnouts. These structures maintain a water level over narrow limits at the head of the outlets, minimising the variability of the water head at the inlet of the turnout. They are typically built with a sluice or check gate set at canal bed level for purposes of scouring and dewatering, however this was not the case at the study scheme. An L – shaped long weir is typically used at the study schemes, consisting of a combination of a normal downstream frontal weir, connected by a side weir at 90˚ degrees to the frontal weir (Figure 4.16).

Figure 4.16 Typical L- shaped long weir at the study scheme

The canal lining is usually extended above the canal normal water surface as a safety measure (otherwise known as freeboard) to protect the conveyance system from overtopping.

With the passage of time and due to inadequate maintenance, the condition of canals deteriorates. The canals become irregular in shape due to silting, erosion and weed growth changing the roughness characteristics and seepage losses. The increased roughness increases the flow depth in the canal which in turn reduces the discharge from the upstream gate. On the other hand, the increase in seepage loss should decrease the flow depth which will lead to higher discharge from the upstream gate. However, the effect of increased canal roughness is usually more dominant compared to increased canal seepage. All these effects generally reduce the discharge carrying capacity of the canals, providing a higher canal water surface and increase the risk of canal overtopping. This is further exacerbated by temporary mis-operation of the canal system, excess flows caused by storm runoff entering the canal through drain inlets, and waves produced by wind or surges which accompany sudden changes in flow.

The reduction of operational water loss is important for increasing efficiency (Patamanska and Grancharova, 2017). The conveyance canal and its related structures should perform their functions efficiently and competently with minimum maintenance, ease of operation, and minimum water loss. The objective of the model is therefore to investigate the effect of sedimentation and obstructions in the canal on the magnitude of operational water loss. At a later stage following data collection, this can be expanded to include losses as a consequence of poor operating conditions. Various principles and methods of canal management can then be developed, aimed at reducing water loss and increasing efficiency of water allocation (Patamanska and Grancharova, 2017).

4.4.4 Computation procedure and preliminary modelling

In the computation of the SGVF profiles, the one-dimensional equation of energy (Bernoulli equation) is integrated by the standard step method. The standard step method divides the channel into small reaches and applies the hydraulic equations to iteratively calculate water surface profiles and energy grade lines. This method applies the conservation of energy in the calculation of water-surface elevations and energy lines along the reach between cross-sections as illustrated in Figure 4.17.

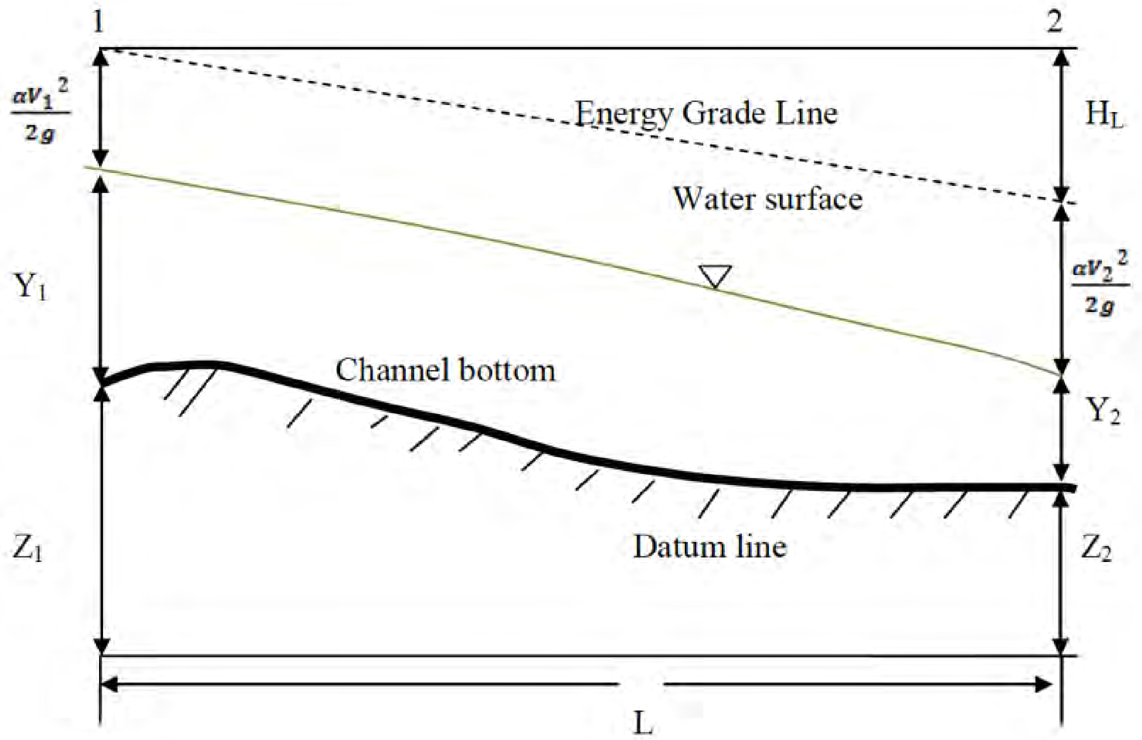

Figure 4.17 Water surface profiles and energy lines between two points (Serede et al., 2015)

The length of the reaches cannot be too big because this may cause the iterative procedure to fail, and cannot be too small either because this would increase the computational burden. With the divided reaches the computation starts from the downstream end of the channel for subcritical flow (which by and large prevail in irrigation canals) by applying the standard step equation to the reach:

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 - Fr^2} \qquad (4.10)$$

where x= distance along the canal; y = depth of flow; S_o = bed slope; Fr = Froude number; S_f = friction slope given by Manning's n equation written as,

$$S_f = \frac{n^2 Q^2}{A^2 R^{4/3}} \qquad (4.11)$$

where n = Manning's coefficient and R = hydraulic radius; Q = discharge and A = area of cross section.

Under subcritical flow conditions, at least one boundary condition is to be specified at the downstream end. The discharge equations from the control structures such as weirs, gates, siphons, falls etc. are therefore used as the boundary condition. In this case, the long weir was used.

The long weir structures are typically designed to operate under free flow conditions. Under these conditions the weir head-discharge relationship is governed primarily by the weir geometry and the approach flow conditions. A common equation for the head-discharge relationship calculations of such weirs is given by Henderson (1966):

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_t^{\frac{3}{2}} \quad (4.12)$$

Where C_d = dimensionless discharge coefficient; L = weir length; g = gravitational constant; total head (piezometric head plus velocity head) measured relative to the weir crest elevation.

It was assumed that the spillway behaves hydraulically similar to a rectangular labyrinth weir (RL) with a half cycle as discussed by Anderson and Tullis (2012). Anderson and Tullis (2012) conducted a number of experiments to develop a better understanding of the effects of Piano Key (PKL) weir geometry on discharge efficiency (as quantified by C_d), specifically the upstream and downstream overhangs and sloped floors. They compared the PKL weir discharge coefficients with the rectangular labyrinth weir (RL), the rectangular labyrinth with slopes in the outlet keys (RLRO), the rectangular labyrinth with slopes in the inlet keys (RLRI) weirs, and the rectangular labyrinth weir with slopes in inlet and outlet (RLRIO), as shown in Figure 4.18. The discharge coefficients for the RL were therefore used.

If the flow velocity over a weir is not high enough to transport the sediments over the weir, sediments are deposited in the inlet key of the weir in a ramp like shape (Gebhardt et al., 2018). The accumulation of sediment or floating debris is problematic at spillways. If neglected, debris or sediment could potentially reduce flow capacity and increase upstream flooding. Sediment accumulation has the effect of reducing the effective wall height (P) and therefore increasing the H_t/P ratio, and reducing the spillway efficiency (represented by C_d in Figure 4.18). A reduction of the spillway efficiency results in an increase in upstream weir pool elevation for the same discharge. Low-head long weir control structures installed on mild sloping channels or where the channel downstream of the weir is constricting and/or heavily vegetated can experience submergence. Under these conditions, for a given discharge over the weir, a higher upstream head is required to pass the flow relative to free-flow (or unsubmerged) conditions. Excessive increases in the driving head can lead to the overtopping of the canal structure, leading to water loss from the canal system as well as damage of the canal infrastructure as shown by the erosion patterns around the canal infrastructure illustrated in Figure 4.19.

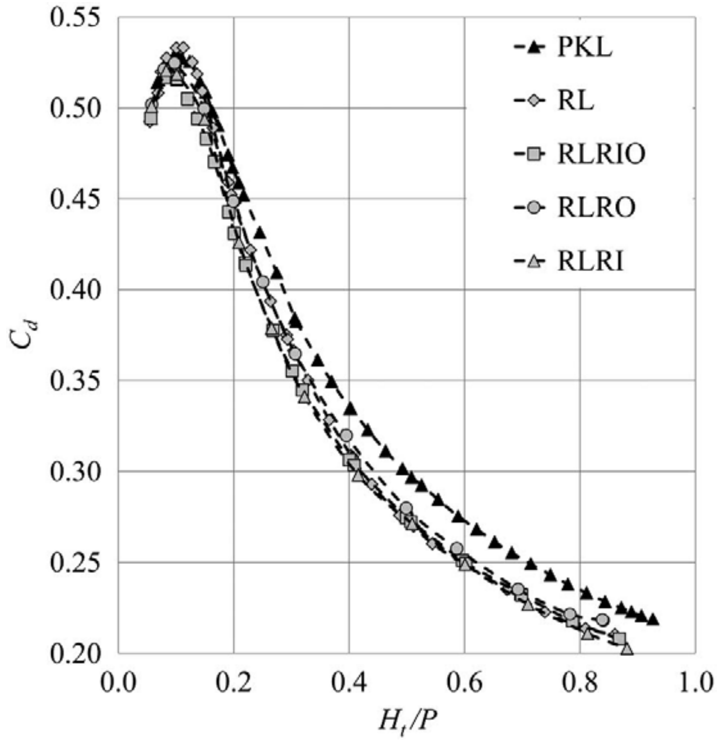

Figure 4.18 C_d versus H_t/P data for RL, RLRIO, RLRI, RLRO, and PKL weirs (where P is weir height) (Anderson and Tullis, 2012)

Figure 4.19 Typical long weir at Raliphaswa scheme with sediment accumulated at weir and erosion patterns around infrastructure

Tullis et al. (2007) developed dimensionless submerged head relationship for submerged labyrinth weirs. These expressions were derived for trapezoidal labyrinth weirs. However, given that these showed little variation for different sidewall angles (7°, 8°, and 20°), they are considered reasonable estimates for the submergence effects of rectangular labyrinth weirs too.

The labyrinth weir submergence equations are presented in equations 4.13 – 4.15.

$$\frac{H^*}{H_t} = 0.3320\left(\frac{H_d}{H_t}\right)^4 + 0.2008\left(\frac{H_d}{H_t}\right)^2 + 1 \quad \text{Where } 0 \leq \left(\frac{H_d}{H_t}\right) \leq 1.53 \tag{4.13}$$

$$\frac{H^*}{H_t} = 0.9379\left(\frac{H_d}{H_t}\right) + 0.2174 \quad \text{Where } 1.53 \leq \left(\frac{H_d}{H_t}\right) \leq 3.5 \tag{4.14}$$

$$H^* = H_d \quad \text{where } 3.5 \leq \left(\frac{H_d}{H_t}\right) \tag{4.15}$$

Where H^* = total upstream head on a submerged weir relative to the crest elevation; H_t = total head upstream of a weir operating in a free-flow condition and measured relative to the crest elevation and H_d = total downstream head on a submerged weir relative to the crest elevation.

To use the above equations, we begin with the unsubmerged discharge relationships, compute the spatially varied flow profile along the downstream channel section, if the computed tailwater (or downstream canal depth) for a given discharge exceeds the spillway crest, then the submerged discharge relationship is determined using the above equations.

The total head upstream of the weir (H_t) for a given flow, was assumed to be constant over the length of the spillway. However, losses due to end contraction (due to obstructions interfering with the flow) were applied at the interface of the side weir with the canal side wall and the normal weir with the canal side wall. These losses were approximated to be 0,1 × total head (H_t) (Knight, 1989). The effective length (L_{eff}) of the spillway at the design discharge was calculated by accounting for the effect of the approach head and end losses. According to Knight (1989), if the downstream end of the weir has characteristics different from the main weir, then the discharge over the different portions of the weir should be calculated separately. Furthermore, the effective length of the spillway will be greater where the water approaches more directly. Consequently, the full length of the normal portion of weir was assumed to be effective, and the corner losses were assumed to occur on the side weir, reducing the effective length of the side weir.

$$L_{eff} = L_w - 2\left(NK_p + K_a\right) \tag{4.16}$$

Where L_{eff} is the effective weir length; L_w = measured weir length; N = number of piers; K_p = coefficient for piers and K_a = coefficient for abutments (assumed to be 0,2).

Along the side weir, water flows over the control section into a downstream canal or trough usually at right angles to the main inflow. The inflow over the spillway section of the side weir is usually uniformly distributed and so the lateral inflow has a constant value. Along the downstream canal or trough, the flow is considered to be spatially varied and nonuniform, resulting from the addition of water along the course of the flow (see Figure 4.20).

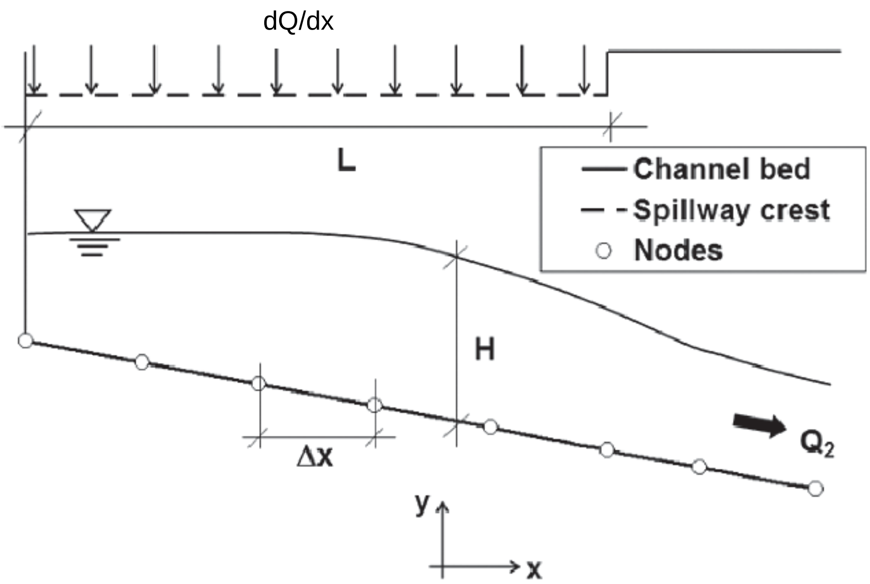

Figure 4.20 Definition sketch for spatially varied flow in lateral spillway channel with upstream dead-end (Zerihun, 2019)

The additional flow causes a disturbance in the energy or momentum content of flow. An appreciable portion of energy is also lost due to the turbulent mixing of the added water and the water flowing in the canal. Due to the high and uncertain losses, the momentum equation is found to be more convenient in solving this problem than the energy equation. The calculation procedure requires a step computation with successive approximations, using the equation below from Chow (1959):

$$\frac{d_y}{d_x} = \frac{S_o - S_f - \frac{2Q}{gA^2}\frac{dQ}{dx}}{1 - Fr^2} \quad (4.17)$$

where dQ/dx = lateral inflow

In the limiting case of no lateral flow (dQ/dx = 0), these equations reduce to the dynamic equation of SGVF.

The spatially varied flow (SVF) profile can be solved by a step-by-step method starting from a boundary condition or control point. There a three potential control points that need to be assessed for the irrigation canal: the overflow jet from the spillway, the SGVF due to the weir further downstream and the downstream contraction as the canal width reduces (see Figure 4.20). The water depth downstream of the impact from the overflow jet is obtained from Henderson (1966) (see equation 4.18). If the overflow is a control, a hydraulic jump will occur further downstream. The taper for the contraction is assumed to be 1:2, smooth and therefore with negligible energy losses. The water depth immediately before and after the transition are therefore determined using the specific energy equations.

$$\frac{y_1}{y_c} = 0.54\left(\frac{y_c}{\Delta z_0}\right)^{0.275} \quad (4.18)$$

Where Δz_o = elevation drop into the channel or trough; y_c = critical depth above the spillway and y_1 = downstream water depth after impact from drop.

To solve the above equations under subcritical flow conditions, which by and large prevail in irrigation canals, two boundary conditions are required: a specified depth at the downstream end and a discharge at the upstream end. At the study irrigation system, the discharge is controlled by the abstraction weir at the upstream end and is regulated by the long weirs at the downstream end.

The discharge was estimated to start the iterative procedure. Thereafter, the depth at the downstream end is computed using the long weir equation (equation 4.12). For this depth and discharge the SGVF and SVF computations are performed to obtain the water depth and water surface elevation of the canal interior points. The calculations are repeated assuming the effective weir height has been affected by sedimentation and assuming an obstruction is located midway between the long weir structures; for comparison between the water surface profile depths, and delivered water at the canal furrows.

The computed water surface profiles based on the realistic hydraulic variables given in Table 4.2 that have been assumed for the canals are illustrated in Figure 4.21.

Table 4.2: Assumed hydraulic variables for typical canal section

Variable	**Value**	**units**
Manning's n	0.015	
Slope, S	0.001	m/m
Parabolic coefficient, c	2	
Side weir length, L_w	3	m
Weir height, P	0.39	m
Normal weir breadth @ P	0.883	m
Total discharge, Q	0.15	m^3/s
Downstream step	0.15	m
Length between weirs	90	m
Canal depth	0.5	m
Starting elevation amsl	10	m
Chainage of obstruction	45	m
Transition depth	0.5	m
Transition base width	2	m
Sediment as a % of weir height P	60	%
Ka	0.2	
Obstruction depth, Δz	0.3	m

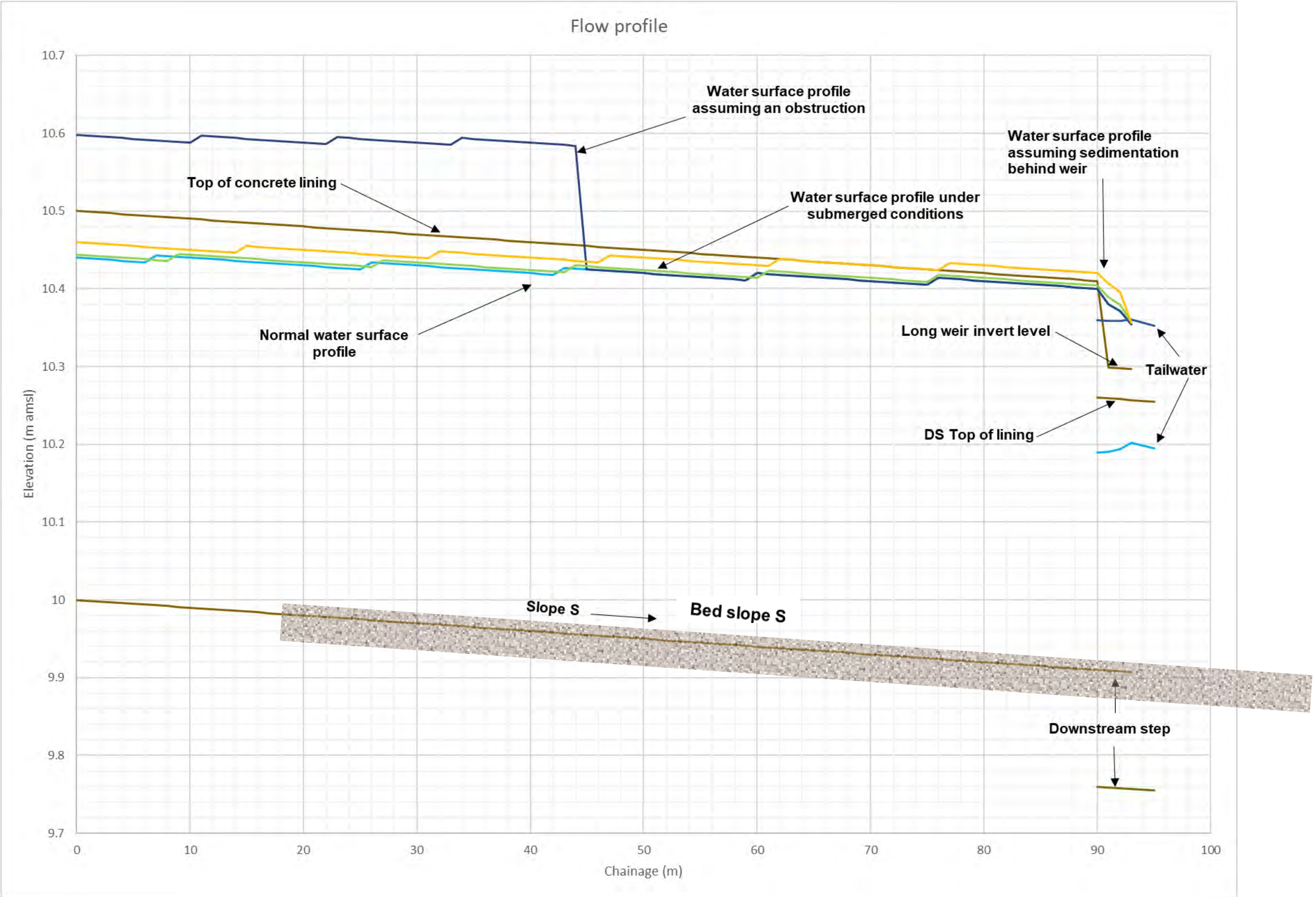

Figure 4.21 Calculated water surface profiles for various hydraulic conditions

4.4.5 Next steps of hydraulic modelling

The computation will be expanded to include other canal structures found at the scheme, including overnight dams, siphons, and rejects. Furthermore, the model can also be expanded to account for canal seepage (in situations of excessive seepage) and concrete condition, especially in cases where the integrity of the canal lining varies significantly from one section to the other.

For conducting hydraulic modelling and simulation of the water surface profiles along the irrigation canal, data is required for its geometry, the boundary conditions, the water discharge, the canal roughness, geometric description of the hydraulic structures along the canal course, such as gates, siphons, culverts, weirs, overnight dams. This information will be collected during the hydraulic and physical survey of the existing irrigation system at the scheme.

During the hydraulic survey, data will be measured and collected to allow for the calibration of the model. Data to be measured and collected includes: inflow into the scheme, flow at all the available measuring points along the main canal system, the offtake gate positions (i.e. closed, open, partially open) and the flow regimes at those gates, the effective heads at the offtake gates, the heads at the long weirs, the heads at the siphons, culverts and dam spillways the condition of the canal lining, and at least one water depth along each canal reach. During calibration, the Manning's coefficient "*n*", the discharge calibration factors and coefficients will be changed iteratively until the differences between simulated and observed values of water levels are within the allowable ranges. Samples of the canal water will also be taken for the purposes of grading the sediment contained in the flows.

4.5 Initial socio-hydrological conceptual modelling

4.5.1 Introduction

Socio-hydrology is a new science, therefore, in accordance with the recommendations by Troy et al. (2015) and Srinivasan et al. (2018), the development of the socio-hydrology model in this study will be benchmarked against socio-ecological systems (SES) theories.

The use of frameworks in socio-ecological systems (SES) has been found to aid transparency and comparability across models (Garcia et al., 2016). They are used to enable a satisfactory understanding of the system as a whole, given the number of diverse processes involved in them, and can aid the development of the dynamic hypothesis and the communication of the reasoning behind it (McGinnis and Ostrom, 2014; Garcia et al., 2016). Furthermore, they set a common language to structure research on SES and to guide towards their sustainable development (Binder et al., 2013). Framing involves deciding on which problems to focus on and which linkages to exclude or include, critical, as it affects what to model and the variables to be considered, which can influence the outcomes of the modelling process (Srinivasan, 2015).

Elshafei et al. (2014) uses a generic framework for socio-hydrology models applicable to agricultural catchments made up of six key components, namely catchment hydrology, population, economics, environment, socio-economic sensitivity and collective response, that combine to form the coupled system dynamics. Srinivasan et al. (2017) used a generic framework to replicate emergent phenomenon at multiple locations. Kuil et al. (2018) developed a coupled model framework that allows the exploration of smallholder farmers' perceptions regarding water availability, water allocation, and crop choice. His framework is based on cognitive theory [11]and bounded rationality theory[12]. Another approach is to embed the research into a stakeholder dialogue and let the definitions and questions emerge from this process (Srinivasan, 2015). Srinivasan et al. (2018) advocate for the involvement of an inclusive group of stakeholders who will live with the consequences of the policies that might be recommended based on the model.

Socio-hydrological modelers can develop their own framework (Elshafei et al., 2014). However, due to the large uncertainty in socio-hydrologic models, it is possible to create models that correspond to the interests of the modellers, stakeholders or policy makers, leading to the bias of model results (Melsen et al., 2018). The use of a generally accepted multitier nested frameworks helps to identify where the conceptual level research is located and how research undertaken at multiple conceptual levels using diverse methods complements research using other methods and other levels (Ostrom, 2007).

Binder et al. (2013) compared 10 established frameworks, explicitly designed to be used by a wider community of researchers and practitioners for analysing SES. According to Binder et al. (2013), only the Human-environment systems framework (HESF), the Management and Transition Framework (MTF) and the SES framework by Ostrom (2007, 2009) and collaborators (SESF), explicitly address the reciprocity between the social and the ecological systems, which is the focus of this study. The literature review therefore focuses on these 3 frameworks.

4.5.2 Literature review

Knieper et al. (2010) present the Management and Transition Framework (MTF). The main goal of this framework is to gain a better understanding of water governance and management regimes, as well as transition processes to more adaptive management, to enable comparative analyses of a wide range of diverse case studies; and to facilitate the development of simulation models based on empirical evidence (Kniepier et al., 2010; Binder et al., 2013). The MTF is based on common pool resource[13] theory, the Institutional Analysis and Development (IAD) Framework[14] and social psychology [15](Binder et al., 2013). The elements in the MTF are represented as classes, which together constitute the system. These classes are diverse, some represent elements from the structural context (e.g. ecosystem characteristics, institutions, technical infrastructure), and others describe processes (e.g. action situations, action arenas, management goals) or describe the state and non-state participants involved (e.g. actors, mental models, situated knowledge). Thus, the classes capture the factors that influence the state of the system. The MTF addresses different phases (e.g. policy formulation'', ''implementation'' and ''monitoring'') in governance and how these are connected.

The SES framework by Ostrom (2007, 2009) and collaborators (SESF), is built on the Institutional Analysis and Development (IAD) framework and the two are closely related (McGinnis and Ostrom, 2014). The framework is an extensive multitier hierarchy of variables that have proven to be relevant for explaining sustainable outcomes in the management of forestry, fishery, and water resources

[11] Cognitive theories focus on the idea that how and what people think, leads to the arousal of either healthy emotions and behaviours or disturbed emotions and behaviours (DiGuiseppe et al., 2016).

[12] Bounded rationality theory hypothesizes that humans, who are assumed to have limited cognitive abilities and imperfect information, adopt satisfying behaviour (Kuil et al. (2018).

[13] A common pool resource is a resource that benefits a group of people, but provides diminished benefits to everyone if each individual pursues their own self-interest.

[14] The IAD framework is typically used to aid policy analysis by highlighting the formal and informal rules in use.

[15] Social psychology is the scientific study of how people's thoughts, feelings, and behaviours are influenced by the actual, imagined, or implied presence of others.

(Binder et al., 2013). It has been broadly used as a diagnostic tool for the factors that contribute to the management of sustainable resources, in response to challenges presented in several case studies of human–environment interactions, and to study the conditions under which users of the resource develop rules for the sustainable management of the resource (Binder et al., 2013; Hernández-Flores, 2019). The SESF is based on theories such as collective choice[16], common-pool resources, and natural resource management (Binder et al., 2013). It was originally designed for application within the well-defined domain of common-pool resource management situations, in which a resource user extracts resource units from a resource system, and resource users provide for the maintenance of the resource system according to rules and procedures determined by an overarching governance system (McGinnis and Ostrom, 2014).

Human-environment systems (HES) are defined as the interaction of human systems with corresponding environmental or technological systems (Scholz and Binder, 2004). The Human-Environment System framework (HESF) was developed as a heuristic tool for structuring the investigation of human-environment interactions (Binder et al., 2013). It provides a set of operative concepts for an organised exploration of environmental problems related to human activities, as well as a methodological guide for investigating human-environmental structures and processes (Binder et al., 2013). It originated from environmental decision making and psychology (social sciences) and has its theoretical origins in systems science, decision theory, game theory, and sustainability science. It can be applied to any research area in which human-environmental interactions play a role, on any scale. The approach conceptualises a mutualism between human and environmental systems (Scholz and Binder, 2004).

The SESF will be used for this study as processes of extraction and maintenance of common pool resources systems are central to this framework. The framework is also compatible with a range of ecological and evolutionary theories as well as multiple social theories (McGinnis and Ostrom, 2014). Furthermore, according to Binder et al. (2013), Cumming (2014) and Hernández-Flores (2019), this framework treats the social and ecological systems in almost equal depth, is the most utilised framework, and has the best balance between empirical observation and theory.

4.5.3 Modelling approach

There are several modelling approaches that can be used for socio-hydrological modelling with different strengths and weaknesses (Troy et al., 2015; and Srinivasan, 2015). These approaches are categorised as either top-down, bottom-up, pattern-oriented or coupled approaches. Each of these approaches have their own advantages and disadvantages and are discussed in the paragraphs below. The coupled approaches, or coupled component models (CCM), are common when integrating social, economic and biophysical components (Kelly et al., 2013). They inherit the features of the component models that comprise them.

Top-down approaches focus on high-level system outlook and outcomes and are by design abstract and generalisable (Sivapalan and Bloschl, 2015; Srinivasan, 2015). These approaches search for correlations to determine system behaviour and therefore run the danger of predicting dynamics that are not observed in the real world (Srinivasan, 2015). They represent human systems as parametrised differential equations, which leads to difficulty when characterising human behaviour and are unable to determine base level processes as well as the impact of implementing policies and technologies (Srinivasan, 2015; Dziubanski et al, 2019; Blair and Buytaert, 2015). These approaches can only produce deterministic results (Sivapalan and Bloschl, 2015). Examples of top-down approaches include “toy” models and system dynamic (SD) models.

[16] Collective choice involves the aggregation of individual preferences to produce a social outcome.

Bottom-up modelling techniques involve the representation of system processes, thus require good knowledge of site-specific processes, in both a spatial and temporal sense, to develop system behaviour (Sivapalan and Bloschl, 2015). These approaches focus on the behaviour and decision-making of individual "agents" within a system (Blair and Buytaert, 2015). Examples include agent-based models (ABMs) and game theory.

In pattern-oriented approaches, multiple patterns are observed in the real system at different hierarchical levels and scales and are used systematically to optimise model complexity and to reduce uncertainty (Grimm et al, 2005). Grimm and Railsback (2012) define a pattern as anything beyond random variation. The use of observed patterns for model design links the model structure to the internal organisation of the real system (Grimm et al, 2005).

The characterising of human behaviour is central in common pool resource systems. Therefore, the use of ABMs will be required. However, to balance the data requirements of ABMs against the expected data on small canal schemes (SCS), a CCM approach will be followed. The components of the model will include a stylised model[17] and an ABM, and therefore can be considered a bottom-up approach.

4.5.4 Socio-hydrology base framework

4.5.4.1 Methodology

The start of socio-hydrologic models is with a specific research question (Garcia et al.; Grimm et al. (2005); Srinivasan et al. (2016); Ostrom (2007). The research question links the assessment of important variables and mechanisms to the question context rather than beginning with a prior understanding, and informs the inclusion of the elements and processes of the real system (Grimm, 2005; Garcia et al., 2015). This allows for the critical review of the model to focus on the acceptability of these choices relative to model goals, allows the flexibility and transparency needed to examine the acceptability of model assumptions while acknowledging the role of context and the potential for surprise and enables critical assessment of the range of applicability of identified processes through case and model comparison (Garcia et al., 2015).

In the present study, it is not feasible to embed the research project within a stakeholder process, particularly given the COVID-19 pandemic. The research questions were therefore determined by referencing literature. These will be verified and validated later following the observations made in the real system (during data collection) and expert consultation.

A question driven approach drives the process of system abstraction (Garcia et al., 2015). Garcia et al. (2015) demonstrated this process through the lens of forward and backward reasoning as seen in Figure 4.22. In a backward reasoning approach, the question is first used to identify indicators or the key outcome metrics; next, the analysis proceeds to identify the relevant processes and then the variables and their relationships (Garcia et al., 2015). In contrast, a forward-reasoning approach begins with the identification of variables and relationships and then proceeds toward outcomes (Garcia et al., 2015). Given that few researchers have expert knowledge of all domains involved in socio-hydrological modelling and data is sparse, Garcia et al. (2015) used the backward approach to conceptualise the socio-hydrological model and the same approach will be used here.

[17] Stylized models are a common type of pattern-oriented models, where relevant model results are matched to observed patterns of behaviour during the model calibration and validation stage.

Once the key outcome metrics have been determined, Garcia et al. (2015) used dynamic hypothesis to identify influential processes and variables, to explain the behaviour of the outcome metric over time.

This includes determining which variables change in response to forces outside the model scope (exogenous variables), which variables change endogenously (state variables) and which can be considered constants (parameters) (Garcia et al., 2015). The dynamic hypothesis in this context, is a data-driven working theory of how the dynamic behaviour of the system in question arose (Garcia et al., 2015).

The influential processes and variables will depend on the timespan of the model which in turn depends on the spatial scale of system behaviour that needs to be understood which in turn depends on the nature of the question (Garcia et al., 2017; Srinivasan et al., 2017). According to Srinivasan et al. (2017), in shorter time periods of about a year (e.g. a specific drought event), infrastructure, economic activity, and political structures can be held constant, though water availability and markets may change. Over a decade or two (e.g. the planning horizon for a water resources agency), infrastructure and politics would change and some incremental improvements in technology and market adjustments would occur, but it would be reasonable to assume that the structure of an economy or cultural beliefs are likely to remain unchanged. Over a hundred years (e.g. in making decisions over major infrastructure projects), all these factors along with hydro-climatic patterns are likely to change.

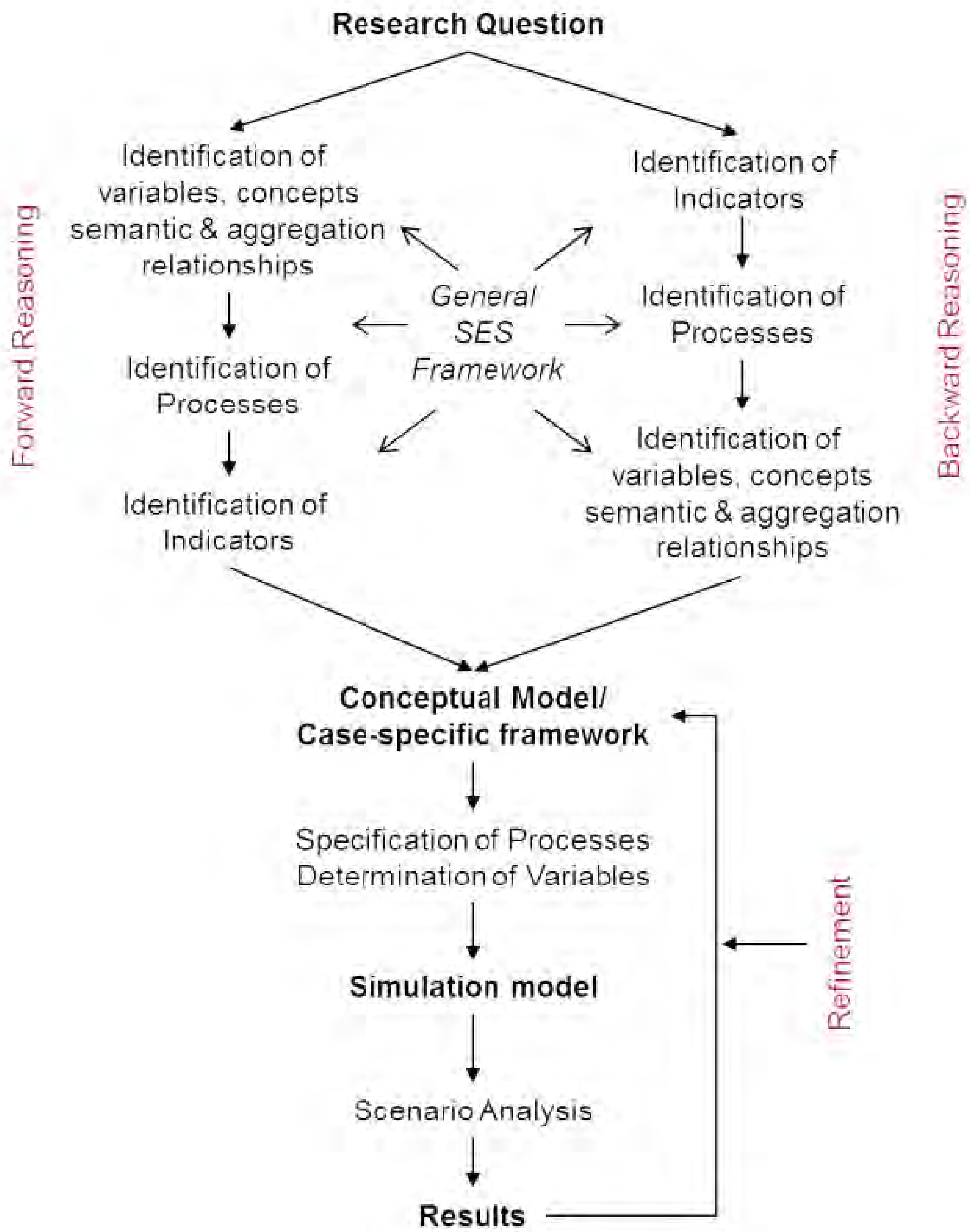

Figure 4.22 Modelling process with forward and backward reasoning for identification of relevant variables and relationships (Schlüter et al., 2014)

As indicated in Section 4.5.3, the characterising of human behaviour is central in common pool resource systems. Therefore, the use of agent-based models (ABMs) will be required. However, to balance the data requirements of ABMs against the available data on small canal schemes (SCS), a coupled component model (CCM) approach will be followed, including a pattern-oriented model (POM) and an ABM. This approach is common when integrating social, economic and biophysical components.

Observed patterns from the real system (collected during the data collection phase) will be used to guide model design. This is to ensure that the model design directly ties to the organisation of the real system (Grimm et al., 2005). Grimm et al. (2005) did this by asking questions such as: What observed patterns seem to characterise the system and its dynamics, and what variables and processes must be in the model so that these patterns could, in principle, emerge? This will then allow for the checking of the framework framing assumptions made and may help identify processes and variables that were not part of the initial conceptual model for inclusion. Thereafter, components of the model (or the sub models) will be systematically replaced with ABMs, determined by contrasting alternative decision models as done by Grimm et al. (2005). The acceptance of decision models will be based on how well they reproduce the observed patterns, particularly under extreme hydrologic variability (Joeng and Adamowski, 2016; Schulze et al., 2017). The data requirements for calibrating and validating the ABM model parameters will be obtained by employing game theory (Bouziotas and Ertsen, 2017). Bouziotas and Ertsen (2017) for example reviewed the key concepts in agent-based modelling for irrigation systems and coupled human-water systems in general to develop a proof-of-concept ABM based on the Irrigation Management Game (IMG) structure, a role-playing exercise in irrigation systems allowing the simulation of some dynamics encountered in real irrigation systems.

4.5.4.2 Research questions and key metrics

The research questions of major interest for the socio- hydrology model are as follows:

1. How can scheme user benefits be improved to encourage their participation in collective activities at the scheme?

To operationalise this research question, the outcome indicator is defined as the participation of scheme users in collective activities and the control variable is defined as the scheme user benefits. Scheme users in this context include scheme members and non-scheme members who obtain water resources from the scheme.

According to Muchara (2014), members in irrigation schemes can participate in collective activities through contributing labour, finance, decision making, information dissemination as well as regulation and control and monitoring. This can be represented as a socio-economic performance measure.

2. What impact do the water use decisions by the scheme users have on the availability of water at the scheme?

In this case the outcome indicator is the available water at the scheme and the control variable are the water user decisions. In this case, the outcome indicator is an ecological indicator (i.e. the available water) as well as a social indicator (i.e. satisfaction of the water user with the water received).

3. How well do the current irrigation scheduling rules meet the needs of the scheme users?

In this case the outcome indicator is the water delivery attributes (i.e. reliability, flexibility, equitability) and the control variable are the irrigation scheduling rules.

4. How can irrigation governance (i.e. political, social, economic and administrative systems) be strengthened for sustained water resource management?

The outcome indicator in this case is sustainable water resource management and the control variable is irrigation governance.

5. To what extent can the improvement of water delivery attributes (i.e. water equity, reliability and flexibility) to the scheme users improve crop productivity at the scheme?

Crop productivity in this case is the outcome variable and water delivery attributes are the control variable.

4.5.5 Smallholder canal scheme socio-hydrology model base framework

The SES framework by Ostrom (2007, 2009) and collaborators (SESF) is a nested conceptual map that partitions the attributes of a socio-ecological system into four broad categories, namely: (1) resource system (e.g. fishery, lake, grazing area), (2) resource units (e.g. fish, water, fodder), (3) actors or users of that system and (4) the governance system (see Figure 4.23) (McGinnis and Ostrom, 2014). These are referred to as the top four tier variables, and each of these has a series of second tier (and potentially higher tier) variables (Garcia e al., 2015). The actors (3) and the governance system (4) jointly affect and are indirectly affected by interactions and resulting outcomes achieved at a particular time and place (Ostrom, 2007).

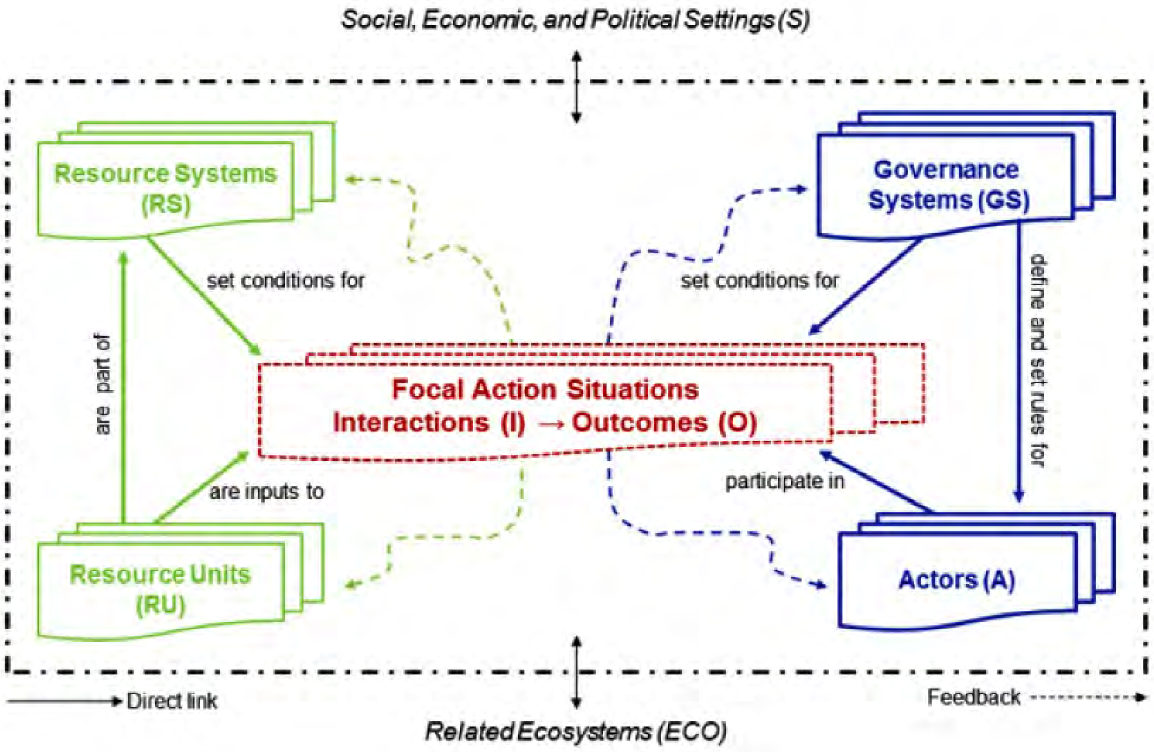

Figure 4.23 SES Framework with multiple first tier components
(McGinnis and Ostrom, 2014)

The action situations are where the inputs are transformed by actions of multiple actors into outcomes. The dashed arrows represent the feedback from the action situations to each of the top tier variables. The dotted dashed line surrounds the endogenous factors of the SES, however, there are exogeneous influences from ecological or socio-economic-political settings that can affect any component of the SES (McGinnis and Ostrom, 2014). Each of the eight broad variables illustrated in Figure 4.23, can be unpacked and further unpacked into multiple conceptual tiers (Ostrom, 2007). How far down one proceeds in the conceptual hierarchy depends on the policy question under investigation (Ostrom, 2007).

Table 1 in McGinnis and Ostrom (2014) lists the major second tier variables shown in empirical studies to impact diverse interactions and outcomes. They are an initial core of conceptual variables needed to identify a broad type of SES operating at a particular location in time and space (Ostrom, 2007). The variables in Table 1 by McGinnis and Ostrom (2014) were used to define the base framework for this study. This framework will be refined following data collection from the real system.

A smallholder canal scheme (SCS) at the highest tier consists of Social, economic and political settings (S) subsystem, a resource system (RS) subsystem, a resource unit (RU) of which water is sub concept, actors (A) subsystem including scheme members and non-scheme members, a governance system, interactions (I) amongst the actors, outcomes (O) subsystem including socio-economic and ecological performance measures and ecosystem (ECO) subsystem. Following a backward reasoning approach guided by the research questions and the literature review, the SESF was used to identify the case-specific variables, hypothesised to form the basis of the SCS socio-hydrologic model. Table 5.3 presents a summary of these variables. To make the framework more specific to SCS, some of the second level variables included in Table 1 by McGinnis and Ostrom (2014) were omitted and additional variables were identified for inclusion, the cells of these variables are shaded grey to ease identification.

Table 5.3 Case specific variables hypothesised to affect operation and management of smallholder canal schemes

Social, economic and political settings (S) Subsystem	
Second level variables	Third level variables
Economic development (S1)	S1a Economic sectors (S1a1: Formal and S1a2: Informal) S1b Employment per sector S1c Income per capita per sector S1d Inflation
Demographic trends (S2)	S2a Number of inhabitants S2b Population density S2c Demographic structure S2d Population growth rate S2e Migration trends S2f Settlement patterns
Political stability (S3)	S3a Regulatory quality S3b Control of corruption S3c Existence of political conflicts S3d Change of political leadership
Traditional Leadership	S3a Leadership quality S3b Control of corruption S3c Existence of conflicts
Government resource policies (S4)	S4a Governmental regulatory framework/ policy for the schemes
Market incentives (S5)	S5a Type of products S5b Influence of local markets S5c Access to markets S5d Demand for produce S5e Distance to market
Resource system (RS) Subsystem	
Second level variables	Third level variables
Sector(s) (RS1)	RS1a Water Sector RS1b Land/ property Sector
Clarity of system boundaries (RS2)	RS2a Manmade boundary RS2b Anthropogenic boundary RSa3 farm boundary
Size (RS3)	RS3a Size

Human constructed facilities (RS4)	RS4a Main Canal system RS4b Abstraction weir/ headworks RS4c Overnight dams RS4d Storm water infrastructure RS4e Furrows RSf Access Roads
Productivity of system (RS5)	RS5a Water reliability RS5b Water security RS5c Water flexibility RS5d Fairness of water distribution
Equilibrium properties (RS6)	RS6a Interactions between subsystems RS6b External impacts and subsystem responses
Storage characteristics (RS8)	RS8. Storage (memory) of the effects of disturbances
Location (RS9)	Location
Resource unit (RU) Subsystem	
Second level variables	Third level variables
Resource unit mobility (RU1)	RU1a The water resource is mobile
Growth or replacement rate (RU2)	RU2a Size of infrastructure RU2b Inflow into system RU2c Water uses in the system RU2d Losses from the system
Interaction amongst resource units (RU3)	RU3a Interaction within a system RU3b Interaction between systems
Resource value (RU4)	RU4a Market value RU4b Strategic value RU4c Human value
Number of units (RU5)	RU5a Total volume of water available
Spatial and temporal distribution (RU7)	RU7 Spatial and temporal distribution
Actors (A) Subsystem	
Second level variables	Third level variables
Relevant actors (A1)	A1a Scheme members (A1a1 participants and A1a2 nonparticipants) A1b Non scheme members (but users of the system) (A1b1 participants and A1b2 nonparticipants)
Socio-economic attributes of users (A2)	A2a Personal Attributes (A2a1 distance to the scheme, A2a2 Age, A2a3 Occupation of household head, A2a4 Access to credit, A2a5 Farm size, A2a6 Gender)
Benefits	Sense of ownership/responsibility for scheme Scheme longevity/ continuity Attainment of scheme water delivery objectives Agricultural productivity
History or past experiences (A3)	A3a History or past experiences

Location (A4)	A4 Location
Institutional Setting (A5)	A5a transparent A5b accountable A5c participatory A5d cooperative
Norms/social capital (A6)	A6a Social connectedness A6b Attitude towards corruption A6c Attitude towards free-riding scheme members
Knowledge of irrigation/mental models (A7)	A7a Full knowledge A7b Partial knowledge A7c No knowledge
Importance of resources (A8)	A8a Full dependence A8b Partial dependence A8c No dependence
Technologies available (A9)	A9 Technologies used
Governance system (GS) Subsystem	
Second level variables	Third level variables
Formal organisations (GS1)	GS1a Local government GS1b Water User Associations GS1c Farmer organisation GS1d Traditional leadership
Informal Organisations (GS2)	GS2a Informal organisation
Network structure (GS3)	GS3a Governance structure
Property-rights systems (GS4)	GS4a Land rights system GS4b Water rights system GS4c Property rights to infrastructure
Operational rules (GS5)	GS5a Scheme operational rules GS5b Scheme maintenance rules
Collective-choice rules (GS6)	GS6 Collective choice rules
Constitutional rules (GS7)	GS7a Constitutional rules
Monitoring and sanctioning processes (GS8)	GS8a Monitoring process GS8b Sanctioning process
Interactions (I) Subsystem	
Second level variables	Third level variables
Harvesting levels (I1)	Ia Scheme members (I1a1 participants and Ia2 nonparticipants) I1b Non scheme members (but users of the system) (Ib1 participants and Ib2 nonparticipants)
Information sharing (I2)	I2a Information/ know how sharing about resource use I2b Information on state of the resource
Conflicts (I4)	I4a Conflicts amongst users
Investment activities (I5)	Contribution to collective activities
Lobbying activities (I6)	I6a Water lobbying activities
Networking activities (I8)	I8a Internal networking I8b External networking

Monitoring activities (I9)	I9a Monitoring Activities
Evaluation activities (I10)	I10a Evaluation Activities
Outcomes (O) Subsystem	
Second level variables	Third level variables
Socio-economic performance measures (O1)	O1a Number of participants in collective activities (O1a1 scheme members and O1a2 Non scheme members) O1b User satisfaction with water received O1c Sustainable water resource management O1d Crop productivity
Ecological performance measures (O2)	O2a Water available to the users of the scheme O2b User water delivery attributes (O2b1 water reliability, O2b2 Water Equity and O1b3 water flexibility)
Ecosystems (ECO) Subsystem	
Second level variables	Third level variables
Climate patters (ECO1)	ECO1a Rainfall on the catchment ECO2 Evapotranspiration from catchment
Flows into and out of the focal the irrigation system (ECO3)	ECO3a storm water ECO3b Infrastructure overflows ECO3c Aquifers/ boreholes

The social, political and economic settings (S) subsystem describes the larger socio economic, political and ecological context in which the SCS is embedded (Delgado-Serrano, 2015). Third level variables were proposed for all second level variables in this subsystem for specificity, and need to be described at local and regional scale. Traditional leadership was added to the SESF variables, as past research suggests that it plays a significant role in land and water access at these schemes.

The resource system (RS) subsystem describes the environmental conditions where the resources are located or produced (Delgado-Serrano, 2015). Third level variables were included in this subsystem for specific reference to the SCS. These variables will be described at local or regional level and will be described using primary information from site.

The resource unit (RU) subsystem describes the natural resource units generated by the resource system. In the SCS this includes crops and water which are considered to be dynamic resources. The growth or replacement rate of these resources is a function of the dynamic processes.

The scheme users are the actors (A) that are considered to affect or be affected by the resource system. Some changes were made to this subsystem as indicated by the greyed cells. Actor benefits were included as this was considered a key component determining whether actors participate in collective activities. A5 in the original SESF is described as Leadership/ entrepreneurship (i.e. attitude towards leadership amongst users). This was changed to institution to account for the hypothesised leadership arrangements at the scheme.

The governance (GS) subsystem looks at the processes through which decisions on SCS management are made and enforced (Delgado-Serrano, 2015). Informal organisations are hypothesised to play a key role in this. GS2 was therefore changed from non-governmental organisation (NGO) to informal organisation. And GS1 was changed from Government Organisation to Formal Organisation to allow for the inclusion of NGOs.

The interactions (I) subsystem describes the internal and external resource influences. In SCS, it is hypothesised that these include contribution to collective activities, conflicts amongst users and water lobbying activities.

The outcome (O) subsystem describes the interaction amongst the variables. In this study, these are aligned to the research questions.

The ecosystems (ECO) subsystem describes the connection between the SCS and the surroundings. Only influences that are critical to the water availability on site were considered in this subsystem.

4.5.6 Data for socio-hydrological modelling

In order to undertake the socio-hydrological modelling, we need to specify the variables that co-determine changes in the state of another variable and organise them in process relationships.

Thereafter, the variables and processes will be defined using mathematical relationships and a simulation engine will be used to run the numerical model and simulate the changes in stocks (or state variables) and flows (or processes that influence change in stock levels) over time (Kelly et al., 2013), based on the primary data obtained from site. Based on the variables specified in Table 5.3, a detailed questionnaire was developed for obtaining both qualitative and quantitative data by means of structured interviews with farmer and scheme committee members. Most of the quantitative data are however not based on actual records as the time and other resources available for the project could not enable the collection of these data. The data are therefore estimates that are hopefully precise and adequately accurate to enable quantitative modelling.

The canal infrastructure is a key element as it is the interface between the human and natural system and is allowed for in the SESF as an autonomous agent (see the Resource system subsystem in Table 5.3). Detail on the hydraulics is therefore required. To achieve this, an appropriate hydraulic model of the canal system water balance will be developed and trained to behave like the real system.

5 DIAGNOSIS OF CURRENT STATE OF SCHEME INFRASTRUCTURE

5.1 Aim and structure of chapter

Aim of the chapter
The aim of this chapter is to inform about the current state of the canal and storage infrastructure at Raliphaswa, Mandiwana and Mamuhohi irrigation schemes based on field work done on 02 November 2020 and 19 November 2020. This includes:

- The locations of flow control structures and their state of functionality and maintenance.
- The functionality of the canals based on the existence of blockages by objects, vegetation, sediments, leakages and overflows, condition of canal lining and stability of canal surroundings (in cut/ infill banks)
- The existence and locations of illegal/ informal abstraction, and other uses (i.e. domestic).

Significant observations on the management, governance and institutional issues in the scheme were made during the field trips and they are therefore also included in this chapter.

Structure of the chapter
This chapter contains seven sections. Section 1 presents the aim and structure of the current chapter. Section 2 informs about the location and state of functionality of the flow control and measurement structures in the scheme while section 3 provides preliminary flow measurements taken during the field work. Sections 4 and 5 describe the functionality and the state of the canals and night storage dams respectively. Section 6 informs about the observed informal and illegal water abstractions and additional evidence of where this occurs. In Section 7, the observations made on management, governance and institutional issues are presented

5.2 Locations of flow control structures and their state of functionality and maintenance

Figure 5.1 shows the Raliphaswa, Mandiwana and Mamuhohi irrigation schemes including the main and secondary canal system. Raliphaswa irrigation scheme is mainly in quaternary catchment A80A while Mandiwana and Mamuhohi are in A80B. Raliphaswa weir is located in Mutshedzi River just before its confluence with Nzhelele River.

The Mutshedzi River inflow point into Raliphaswa weir is shown in Figure 5.2. Variations of water levels in the weir were observed during the field visits. During the field visit of 02 November 2020, it was observed that the water at Raliphaswa weir was low as compared with the observations made during the field visit of 18 June 2019 (Figure 5.3). The farmers had initially attributed this to limited rainfall as the area had not received significant rainfall since the beginning of the rainfall season in 2020 (which is expected to be the month of October). In the follow up visit of 19 November 2020, the water level in the weir had increased. The farmers reported that they decided to walk along Mutshedzi River towards Mutshedzi Dam as they started to suspect that illegal run-of-river abstractions by farmers upstream of Raliphaswa weir may also be contributing to reduced inflow of water into Raliphaswa weir. They found that farmers upstream of Raliphaswa weir had blocked Mutshedzi River to enable them to pump water from the river to their farms. Unblocking the river resulted in increase in water level within the weir.

The areas surrounding the crump weir gauging structure and sluice gate are vegetated (Figures 5.4 and 5.5). However, there is regular maintenance to remove debris and vegetation to unblock flow of water within the canal system. Every morning a representative of the farmers walks along the main canal to inspect blockages and illegal abstractions as part of regular maintenance of the irrigation schemes. Figure 5.6 shows removed debris from part of the main canal.

Figure 5.7 shows the first offtake structure at Mandiwana irrigation scheme during the field visit of 02 November 2020 revealing some inflow into Mandiwana irrigation scheme. During the field visit of 19 November 2020, the offtake structure was dry (Figure 5.8) and there was no inflow of water into Mandiwana.

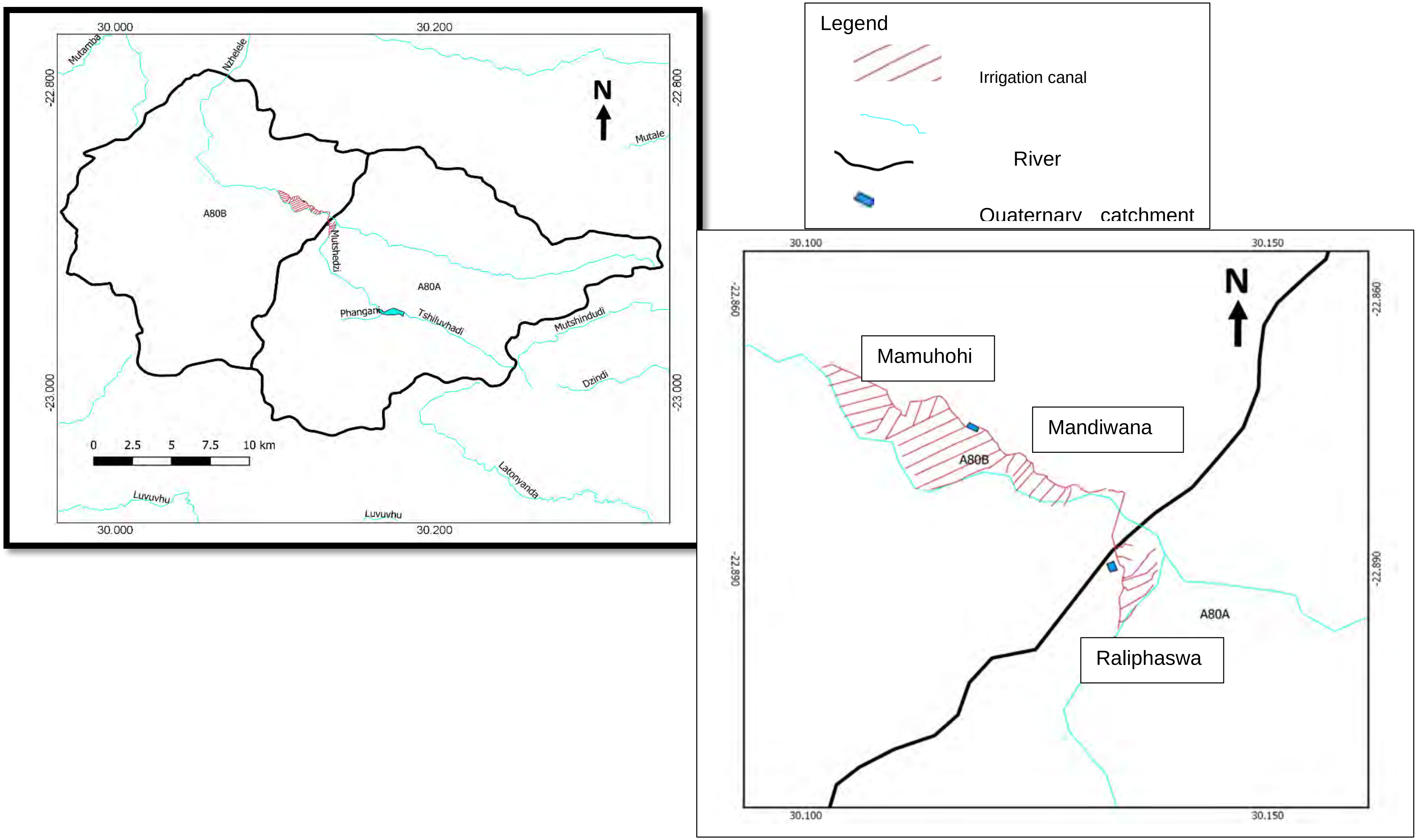

Figure 5.1: Location of Raliphaswa, Mandiwana and Mamuhohi irrigation schemes and canal system

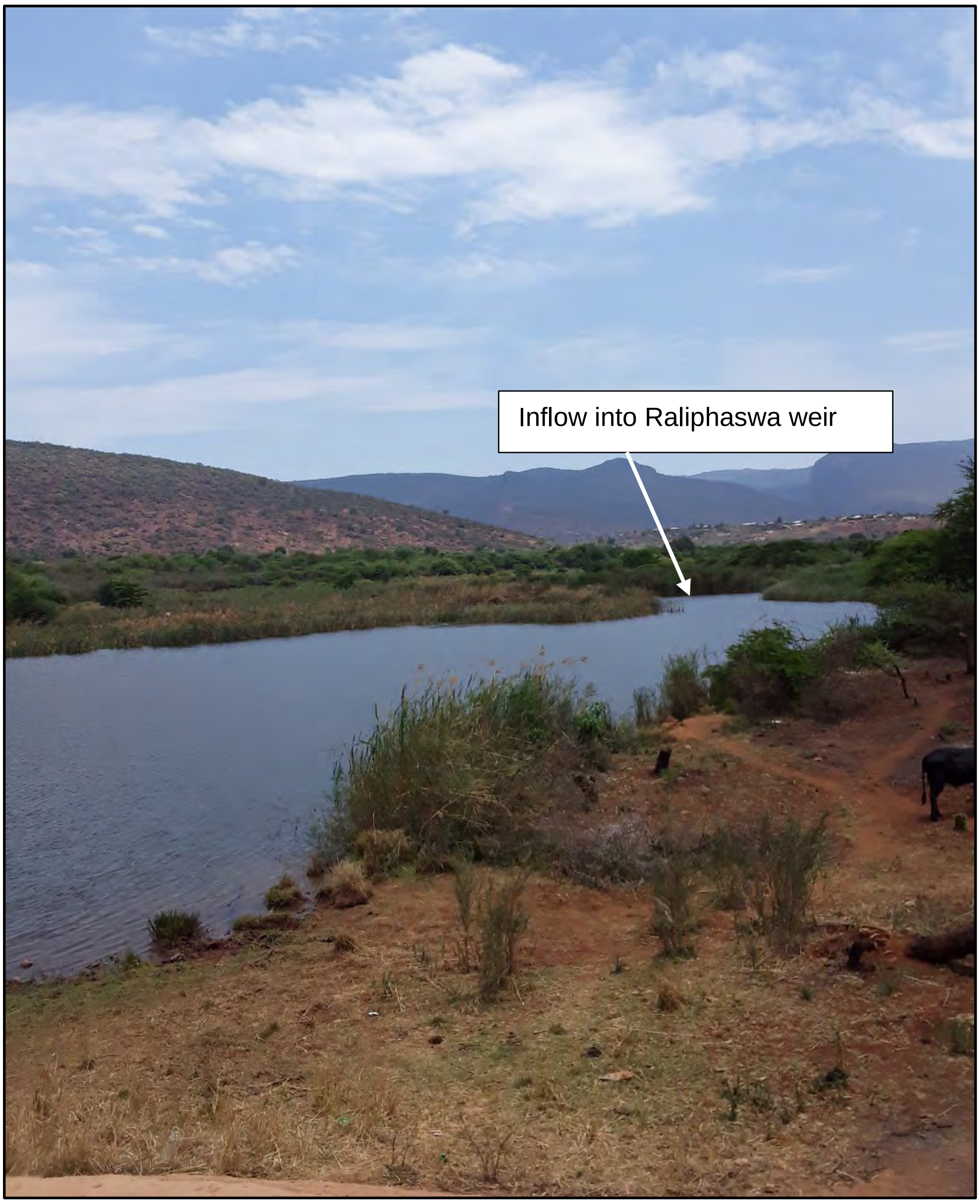

Figure 5.2: Inflow into Raliphaswa weir on Mutshedzi River

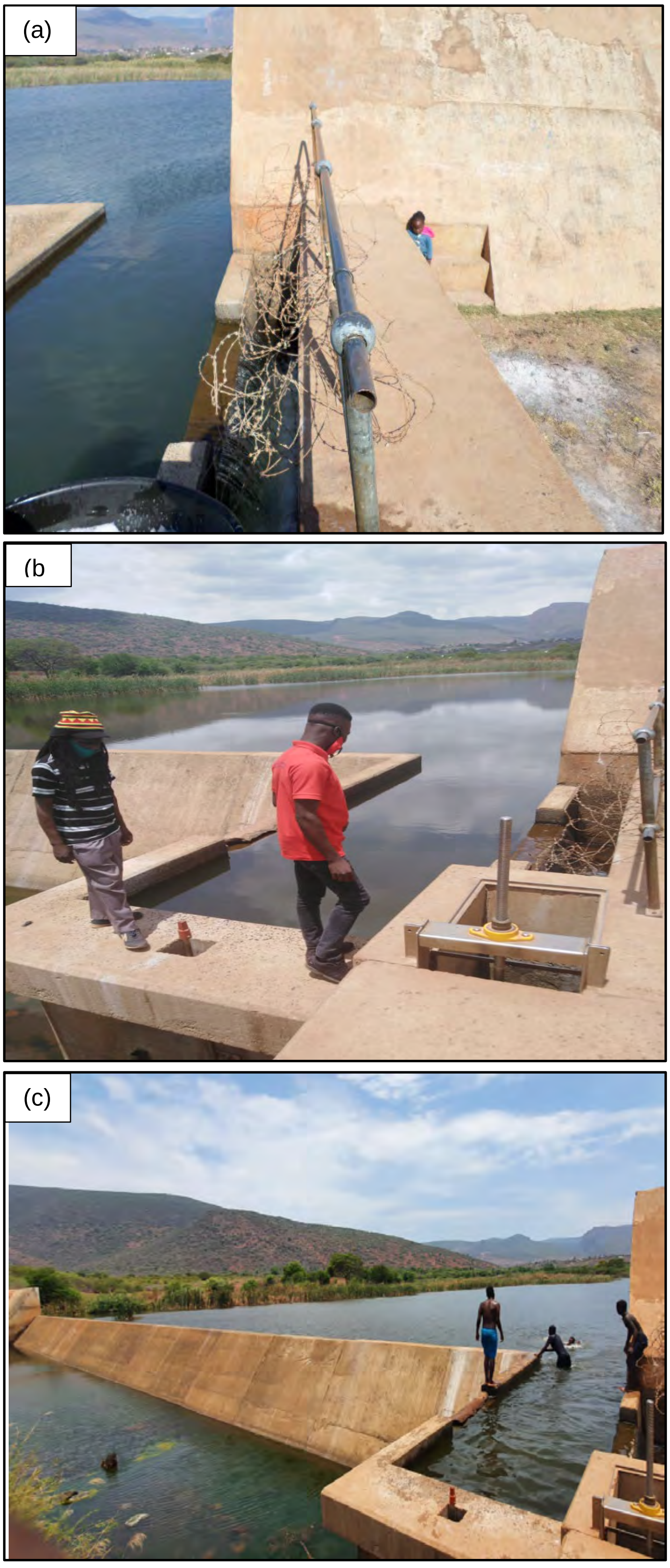

Figure 5.3: Raliphaswa weir on (a) 18 June 2019, (b) 02 November 2020 and (c) 19 November 2020

Figure 5.4: Intake pipe outlet and crump weir gauging structure on (a) 18 June 2019, (b) 02 November 2020 and (c) 19 November 2020

Figure 5.5: Sluice gate reject and reduction to scheme main channel on (a) 18 June 2019, (b) 02 November 2020 and (c) 19 November 2020

Figure 5.6: Removed debris in main canal at Raliphaswa

Figure 5.7: Offtake structure providing inflow into Mandiwana irrigation scheme on 02 November 2020

Figure 5.8: Offtake structure providing inflow into Mandiwana irrigation scheme on 19 November 2020

5.3 Velocity and flow measurements at selected points

Velocity and flow measurements were taken at selected points at Raliphaswa and Mandiwana irrigation schemes on 02 November 2020 using OTT MF-Pro flow meter. The OTT MF-Pro utilises the electromagnetic sensor to measure velocity and has a detachable discharge calculator handset capable of calculating discharge in open channels. It is capable of measuring velocity ranges of 0-6 m/s. The accuracy of the flow meter at 0-3 m/s and 0-5 m/s is ±2 % of measured value ±0.015 m/s and ±4 % of measured value ±0.015 m/s, respectively (OTT Hydromet, 2020). The one-point option of the 0.2/0.4/0.8 velocity measurement method was chosen. One-point measurement option measures the velocity at 0.4 x maximum depth of flow.

The measured approach height at the crump weir was 0.85 m while the original height as indicated on a staff gauge embedded at the site was 1.2 m (Table 5.1). This indicates reduction of depth of 0.35 m due to sediment deposits in the flow structure. The calculated flows at the crump weir and Parshall flume are 0.042 and 0.023 m^3/s, respectively (Table 5.1). Figures 5.9 and 5.10 indicate the site at the Parshall flume and Mandiwana take off structure where flow measurements were taken. The flow entering the offtake structure providing water to Mandiwana irrigation scheme was very low with a recorded flow velocity of 0.017 m/s.

Table 5.1 Velocity and flow measurements at selected points

Site	Shape; dimensions	Coordinates	Depth of flow (m)	Area (m^2)	Average velocity (m/s)	Flow (m^3/s)
Crump weir gauging structure	Rectangular; H=0.85 m, W=2 m	-22.896660, 30.133779	0.43	0.86	0.049	0.042
Canal next to Parshall flume before Raliphaswa scheme offtake	Trapezoidal; H= 0.5, Top width= 1.1 m; Bottom width=0.65	-22.894248, 30.134023	0.08	0.055	0.425	0.023
Small canal at Raliphaswa	-	-22.8912; 30.13436	-	-	0.451	-
Transit from Raliphaswa to Mandiwana	-	-22.8863; 30.13314	-	-	0.024	-
Inflow point at Mandiwana*	-	-22.8808; 30.12641	-	-	0.017	-

* where water was last observed


Figure 5.9: Flow measurement at Parshall flume in Raliphaswa irrigation scheme


Figure 5.10: Flow measurement at offtake structure in Mandiwana irrigation scheme

5.4 Functionality and state of maintenance of canals

The main canal at Raliphaswa irrigation scheme was mostly clear of debris and vegetation though there was evidence of sediments (Figure 5.11) and small rocks at the bottom of the canal (Figure 5.12). Though the small canals were also clear of debris, their surroundings were vegetated (see example in Figure 5.13) and one of the small canals has some sediments at the bottom (Figure 5.14). The canals at Raliphaswa and their surroundings looked stable.

Figure 5.11: Main canal just after sluice gate with sediment deposits

Figure 5.12: Small rocks at bottom of main canal at crossover bridge closer to entrance of Raliphaswa irrigation scheme

Figure 5.13: Vegetation around small canal at Raliphaswa

Figure 5.14: Small canal at Raliphaswa with some sediment deposits

The main canal at the inlet to the siphon has structural damage and part of it has vegetation overgrowth (Figure 5.15). Debris which is removed from the canal is disposed of on the canal banks. (Figure 5.16).There is also clearing of debris and removal of sediments from the canals at Mandiwana irrigation scheme (Figure 5.17 and 4.18). However, removed sediments are disposed of within the vicinity of the canal as shown in Figure 5.18. These sediments are likely to be transported back into the canal during periods of rainfall. The farmers indicated that they do not know what to do with the removed sediments as they have no means to transport them to other places. Parts of the main canal closer to the offtake had some structural cracks (Figure 5.19).

Figure 5.15: Main canal at inlet to underground pipe

Figure 5.16: Debris within vicinity inlet to underground pipe

Figure 5.17: Debris removed from canal at Mandiwana irrigation scheme

Figure 5.18: Sediments deposited within vicinity of canal

Figure 5.19: Structural damage to main canal at Mandiwana

The small canal transporting water to the farms just after the offtake structure at Mandiwana where water was last observed was clear but has some vegetation within its surroundings (Figure 5.10). The canals in the rest of the irrigation scheme were dry (Figures 5.20 and 5.21).

Figure 5.20: Small canal transporting water to farms just after offtake structure at Mandiwana

Figure 5.21: Dry canal close to offtake structure at Mandiwana (02 November 2020)


Figure 5.22: Dry canals at Mandiwana irrigation scheme with vegetation growth- 19 November 2020

The canal at the entrance of Mamuhohi irrigation scheme had deposits of dry leaves and plastics and a structural component of the small crossover bridge at the main canal to Mamuhohi night storage dam had collapsed (Figure 5.23). The main canal within Mamuhohi irrigation scheme downstream of the night storage dam was also dry and vegetation growth and sediments were clearly visible at the bottom of the canal (Figure 5.24).

Figure 5.23: Deposition in canal at entrance of Mamuhohi irrigation scheme and collapsed structural member of crossover bridge to night storage dam

Figure 5.24: Dry canals at entrance of Mamuhohi irrigation schemes

5.5 Diagnosis of current state of night storage dams

During field visits of 02 and 19 November 2020, a significant reduction of water level in Mamuhohi overnight storage dam (Figure 5.25) was observed as compared to the state on 18 June 2019. Part of the surface area of the dam was dry (Figures 5.26 and 5.27). The Extension Officer confirmed that Mamuhohi irrigation scheme had not received water by the time of the field visit. The Extension Officer informed that night storage dam receives more water when some of the farmers at Raliphaswa and Mandiwana opt not to plant during winter. During such periods, the dam gets full and water in the canals are also be used by nearby residents for purposes such as bathing and washing clothes.

Figure 5.25 Mamuhohi night storage dam on 18 June 2019

Figure 5.26 Mamuhohi night storage dam- 02 November 2020

Figure 5.27 Mamuhohi night storage dam- 19 November 2020

5.6 Existence and locations of illegal/ informal abstractions

Figure 5.28 shows the inflow point into the siphon that transports water from Raliphaswa to Mandiwana irrigation schemes. At this point, there is informal abstraction of water into farms are not part of the irrigation scheme. Farmers block the inflow point with rocks and insert pipes to siphon water to a storage reservoir (Figure 5.29) for irrigating their farms. This further reduces the volume of water that is transported to Mandiwana and Mamuhohi irrigation schemes. During field visit of 19 November 2020, the velocity of the water flowing into the inlet of Mandiwana underground pipe was too low to be measured using the OTT MF-Pro flow meter (Figure 5.28b). There were a number of farmers who were irrigating their crops at Raliphaswa irrigation scheme resulting to very low flows reaching the inlet.

Figure 5.28 Inflow point into Mandiwana siphon (a) 02 November 2020 and (b) 19 November 2020

Figure 5.29 Storage reservoir used to store informally abstracted water

The informal abstractions at transit point from Raliphaswa irrigation scheme affect the flow into Mandiwana and Mamuhohi irrigation schemes. During the field visit, the farms at Mandiwana and Mamuhohi irrigation schemes were not receiving water and most of their crops were dry or had stunted growth (Figures 5.30 and 5.31). Some of the farms at Mamuhohi irrigation scheme are lying fallow with no crops planted (Figure 5.33).

At Raliphaswa irrigation scheme, some secondary canals have been vandalised presumably to divert water to the adjacent plots (Figure 5.33) while canals get blocked by stones to also divert water to adjacent plots (Figure 5.34).

Figure 5.30 Butternuts drying due to lack of water at Mandiwana irrigation scheme

Figure 5.31 Maize drying due to lack of water at Mandiwana irrigation scheme

Figure 5.32 Fallow farms at Mamuhohi irrigation scheme

Figure 5.33 Broken canal to divert water to field (plot)

Figure 5.34 Stones used to block water from running through canal to other fields

5.7 Observations on management, governance and institutional issues

Although the formal questionnaire survey on management, governance and institutional issues is planned for December 2020, the field trips on 02 and 19 November 2020 included discussions with some farmers and Extension Officers that revealed significant management, governance and institutional issues in the schemes, and these are therefore presented in this Section. It is expected that more detailed and refined information based on a much larger sample of individuals will be obtained from the questionnaire survey.

The famers have internal institutional arrangements to govern the irrigation of crops within the schemes where they allocate themselves days when each group would water their crops. The discussions during the field trips revealed that shortage of water is creating conflicts among the farmers particularly those from Mandiwana and Mamuhohi irrigation schemes who are more severely impacted by the shortages (as Sections 3 to 6 inform). It was also revealed that farmers are not allowed to have boreholes in their plots although privately owned orchards can have them. The conflicts and challenges have taken various forms including the illegal/informal water abstractions described in Section 6. They have also taken other forms as described below.

5.7.1 Informal water abstraction upstream of Raliphaswa weir

Famers from areas upstream of Raliphaswa weir (that feeds the study schemes) block Mutshedzi River with stones and bags of sand and informally pump water to their irrigation fields. Farmers from Raliphaswa unblock the river to enable flow into Raliphaswa weir.

5.7.2 Farmers disregarding agreed upon irrigation arrangements

Some farmers deliberately do not follow the set irrigating schedules and divert water to their plots when it is not their turn to or for longer periods than agreed. The leading farmers assigned to oversee these arrangements do not have capacity to enforce them on all the farmers.

5.7.3 Vandalising of infrastructure

The main canal at Mandiwana scheme (Figure 5.35) has been vandalised presumably to enable or to increase flow to Mamuhohi irrigation scheme.

5.7.4 Blockage of main canals

The main canal in Raliphaswa gets blocked preventing flows to Mandiwana and Mamuhohi irrigation schemes.

5.7.5 Unregistered farming

Unregistered farmers secure small plots adjacent to the main fields onto which they divert water from the canals. The Extension Officers find it difficult to control these farmers because they are not registered by the Department of Agriculture. In rare cases, the registered and the unregistered farmers make arrangement to share irrigation water.

Figure 5.35 Example of vandalised dry main canal at Mandiwana irrigation scheme

6 HYDRAULIC SURVEY OF INFRASTRUCTURE AND QUESTIONNAIRE SURVEY

6.1 Aim and structure of chapter

Aim of the chapter
The main aim of this chapter is to inform about the detailed hydraulic survey and assessment of the condition of the irrigation infrastructure and to also provide information on the pilot questionnaire survey that was conducted in the Raliphaswa, Mandiwana and Mamuhohi irrigation schemes.

Structure of the chapter
This chapter contains three sections and three appendices. Section 1 presents the aim and structure of the current chapter. Section 2 informs about the detailed hydraulic survey and assessment and starts with a brief description of the UAV (drone) survey of the three schemes. Sections 3 describes the piloting of the questionnaire survey and provides the data and information obtained from this. The implications of the pilot survey on the intended full survey of all farmers in the three study schemes are summarised at the end of the Section. Appendices A and B provide data and information on the sizes of the irrigation infrastructure and its condition while Appendix C presents the questionnaire survey results conducted for three members of the scheme management committee. Appendix A is submitted as a separate document due to its large size.

6.2 Hydraulic survey and condition of infrastructure

6.2.1 Introduction

This section describes the features, the sizes, and the condition of the infrastructure of the selected smallholder irrigation schemes. Various methods were used to obtain this information including a UAV (drone) survey, a geometric survey as well as a hydraulic survey. The following sections present the findings made from these surveys.

6.2.2 Unmanned aerial vehicle (UAV) survey

A drone (UAV) survey of the scheme plots and infrastructure was conducted by Integrated Aerial Systems (IAS) on the 23rd of October 2020 between 08h00 and 16h00 Central African Time (CAT) to capture visual images of area of the smallholder irrigation schemes (SIS) and scheme infrastructure, to be used in the development of the scheme water balance. The survey was conducted using an RGB (red, green, blue) camera allowing for a ground sample distance of up to 3 cm per pixel. Overlying the surveys on a timeline enables the monitoring of differences in planting dates, tillage practices, cropping patterns, crop types, relative elevation difference, irrigated areas, illegal or unauthorised abstraction, infield water management and harvested yields from each plot. Inclusion of this information would allow for the modelling of the temporal variation of water demand at the scheme due to the different farmer practices. Furthermore, drone surveys done using an RGB camera allow for the capturing of the condition of the scheme infrastructure visually, including sedimentation patterns such as erosion and deposition along the banks of the canals. However due to budget constraints, only a single survey has been conducted.

The raw images and processed outputs from this survey include 3D mesh, point cloud, orthomosaic (GeoTiff) and Digital Surface Model (DSM). These outputs are compatible with all major GIS platforms including QGIS and ArcGIS. The processed outputs of the survey with an overlay of a schematic of the scheme infrastructure is illustrated in Figure 6.1.

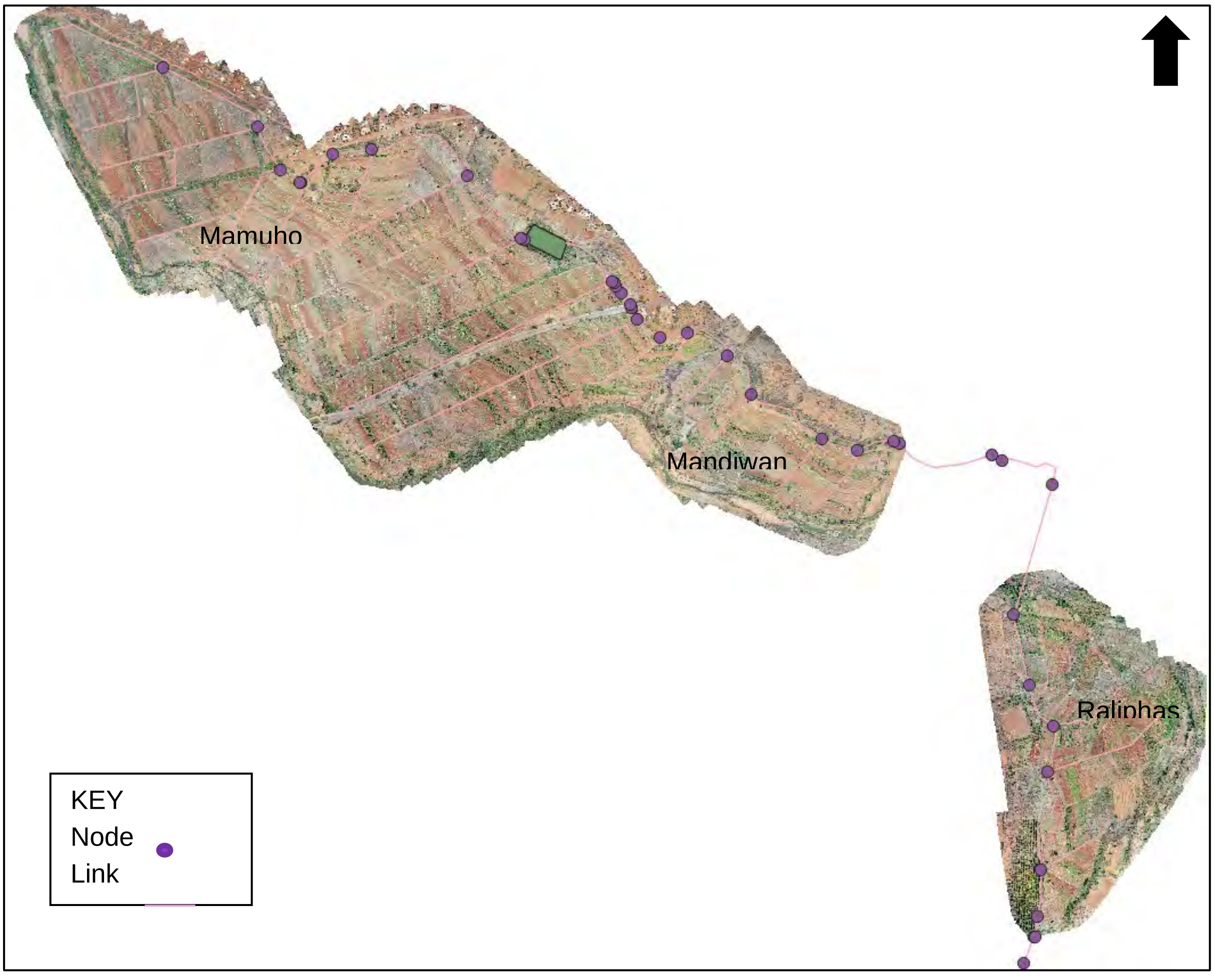

Figure 6.1: Raliphaswa, Mandiwana and Mamuhohi SIS orthomosiac

6.2.3 Mapping irrigation system hydraulic infrastructure network components

The hydraulic infrastructure network and drainage systems of the Raliphaswa, Mandiwana and Mamuhohi smallholder irrigation scheme, affecting the influxes and outfluxes of water in a given space and time, needs to be understood in order to enable the socio-hydrological modelling of the SIS. This requires the mapping of the flow routes across the scheme service area. The rest of this section describes the main features of the canal infrastructure and uses codes to identify the locations of the specific features of the infrastructure on the layouts presented on Figures 6.2, 6.3 and 6.4. The reader is advised to refer to these layouts while reading the detailed description of the infrastructure in this section.

The codes used to identify the various hydraulic features are based on the particular function of the structure including conveyance, water level control, measurement, division, diversion and safety; and the number of the structure starting from the most upstream point at the Raliphaswa SIS increasing towards the most downstream point at Mamuhohi SIS. In general, the nodes refer to points where structures of different functions meet and links refer to conveyance structures (whether canals, pipelines or furrows). Table 6.1 shows the codes used for the different structures.

Table 6.1: Codes applied in mapping hydraulic infrastructure of irrigation schemes

Structure	Code
Conveyance channel	C
Canal regulator -Water level control	CR
Informal canal regulator	ICR
Measurement	M
Division/Distribution	D
Unauthorised division/distribution	UD
Diversion	DW
Safety-disposal of excess water	SF
Storage	S
Siphon inlet	SI
Siphon outlet	SO
Conveyance pipe	CP
Furrow	F
Bridge	B
Energy dissipator	ED
Diversion storage	DS

The study SIS begins at the Raliphaswa Weir on the perennial Mutshedzi River, a tributary of the Nzhelele River, at 22˚ 53’ 51.27S and 30˚ 08’ 00.14’’E. The limited storage capacity of the weir is not utilised, and its essentially used to raise the natural water level of the river and divert water from the river to the intake canal by gravity. The weir’s other function is to enable diversion of irrigation water to the scheme and it is subsequently referred to as the diversion weir (DW) on Figure 6.2.

Water from the intake structure is conveyed through two pipelines. The first pipeline (referred to as conveyance pipe 1 (CP1)) conveys water to a crump weir at the Raliphaswa smallholder irrigation scheme and the second pipeline conveys water to a storage dam at Raliphaswa. The crump weir (referred to as measurement 1 (M1)) is used to monitor flow entering the Raliphaswa smallholder irrigation scheme and the storage dam has previously been used to supply the neighbouring Vhutuwa Nga Dzwebu SIS but is currently not in use.

Downstream of the crump weir, the canal section conveyance capacity reduces as the section transitions from a rectangular section to a parabolic cross section. A side sluice gate structure (or escape) (referred to as safety function 1 (SF1)) is constructed before the transition to ensure the safe disposal of excess water and, hence, prevent damage of the canal section further downstream. The section downstream of the crump weir up to the start of the parabolic canal section is referred to as the canal transition 1 (CT1).

The first parabolic canal conveyance section begins downstream of CT1 and is referred to as C1. C1 conveys water to a Parshall flume at Raliphaswa SIS referred to as measurement 2 (M2). Downstream of the Parshall Flume (M2), a parabolic canal section (C2) conveys water to a long weir control structure referred to as canal regulator 1 (CR1). CR1 regulates the water levels to the first farmer offtake referred to as distribution 1 (D1), minimising the variation in water level caused by any change in discharge. D1 consists of a manually operated check gate that functions as an orifice and delivers water from the main canal to the head of the secondary canals or concrete furrow referred to as furrow 1 (F1).

Downstream of D1, a parabolic canal section (C3) conveys the water to canal regulator 2 (CR2), distribution 2 (D2) and furrow 2 (F2). Downstream of F2, a parabolic canal section (C4) continues through a culvert (B1) to and unregistered distribution (UD1) with no regulating structure. Downstream of UD1, the canal (C5) passes two other bridges (B2 and B3) to another unregistered distribution (UD2). Downstream of UD2, the canal (C6) conveys water to a siphon inlet (SI1) located at the end of Raliphaswa SIS. At the siphon inlet (SI1) an informal low notch has been created on one side, serving to divide a pre-set share of the available water to downstream users (allegedly the orchards). This division structure shall be referred to as proportional division 1 (PD1). The inverted siphon (referred to as conveyance pipe 2 (CP2)) starting at SI1 then crosses the Nzhelele River to siphon outlet 1 (SO1) at the Mandiwana SIS.

At Mandiwana, the canal (C7) starts at siphon outlet 1 (SO1), conveys water across crossing (B4) to siphon inlet 2 (SI2). The siphon (referred to as conveyance pipe 3 (CP3)) conveys water across a natural stream to siphon outlet 2 (SO2). Canal 8 (C8) conveys flows from SO2 to siphon inlet 3 (SI3), at the junction of the Mandiwana SIS and the Vhutuwa Nga Dzwebu SIS. The siphon is referred to as conveyance pipe 4 (CP4). Canal 9 (C9) begins at siphon outlet 3 (SO3) and ends at canal regulator 3 (CR3), regulating flows into distribution 3 (D3) and furrow 3 (F3). Downstream of CR3, Canal 10 (C10) conveys water to CR4, regulating discharge to D4 and F4. C11 starts at CR4 passing B6, and continues CR5, regulating flows into D5 and F5. C12 then continues downstream of CR5 passing B7, up to CR6, D6 and F6. C13 starts at CR6, past B8 up to an informal canal regulator (ICR1) for distribution 7 (D7) and furrow 7 (F7). C14 starts at D7 and continues to CR7, regulating the flows into D8 and F8. C15 starts at CR7 and extends to CR8 and D9 and F9. C16 starts downstream of CR8 to SI4, the inlet of conveyance pipe 5 (CP5). The outlet of CP5 is SO4. C17 commences from SO4, beneath B9 to informal canal regulator (ICR2) for distribution 10 (D10) and F10. C18 starts at D10 to SI5, the inlet of CP6. C19 begins at SO5, the outlet of CP6 to CR9 for D11 and F11, the last Mandiwana offtake. C20 extends from CR9, past CP6 and ends at the Mamuhohi overnight storage dam 1 (S1).

Discharge exits the Mamuhohi overnight storage dam (S1) in one of three ways: when the dam is full, excess water overflows the spillway into the main canal (referred to as safety function (SF2)) or via distribution 12 (D12) and furrow F12, regulated by a gate valve linked to the water level in S1, or via diversion from S1 (referred to as diversion storage (DS)) to the main canal, also regulated by a gate valve linked to the water level in S1. Canal C21 starts at spillway SF2 and passes B10 up to CR10, regulating flows entering D13 and F13. A borehole (BH) was observed near the downstream end of D13 from where the users of this offtake supplement their water. From CR10, C22 continues to CR11, regulating flows into D14 and F14. Downstream of CR11, C23 continues past an energy dissipation structure (ED1) to SI6, the inlet of conveyance pipe 7 (CP7). Pipe CP7 ends at siphon outlet SO6.

The effective head at SO6 is regulated by CR12, which also regulates the flows into D15 and F15. Downstream of CR12, C24 continues to CR13, regulating the flows into D16 and F16. C25 begins downstream of CR13 and extends past B11 and B12, up to CR14 and D17 and F17. Between B11 and B12, there is a local water point used by local residents for domestic purposes, to be referred to as unregistered distribution 3 (UD3). Canal C26 commences from CR14, past seven drop energy dissipation structures (ED2 to ED8) up to CR15, D18 and F18. C27 starts at CR15 and passes 6 more drop structures (ED9 to ED13) before entering distribution 15 (D19) and furrow 15 (F19) to the Nzhelele River downstream.

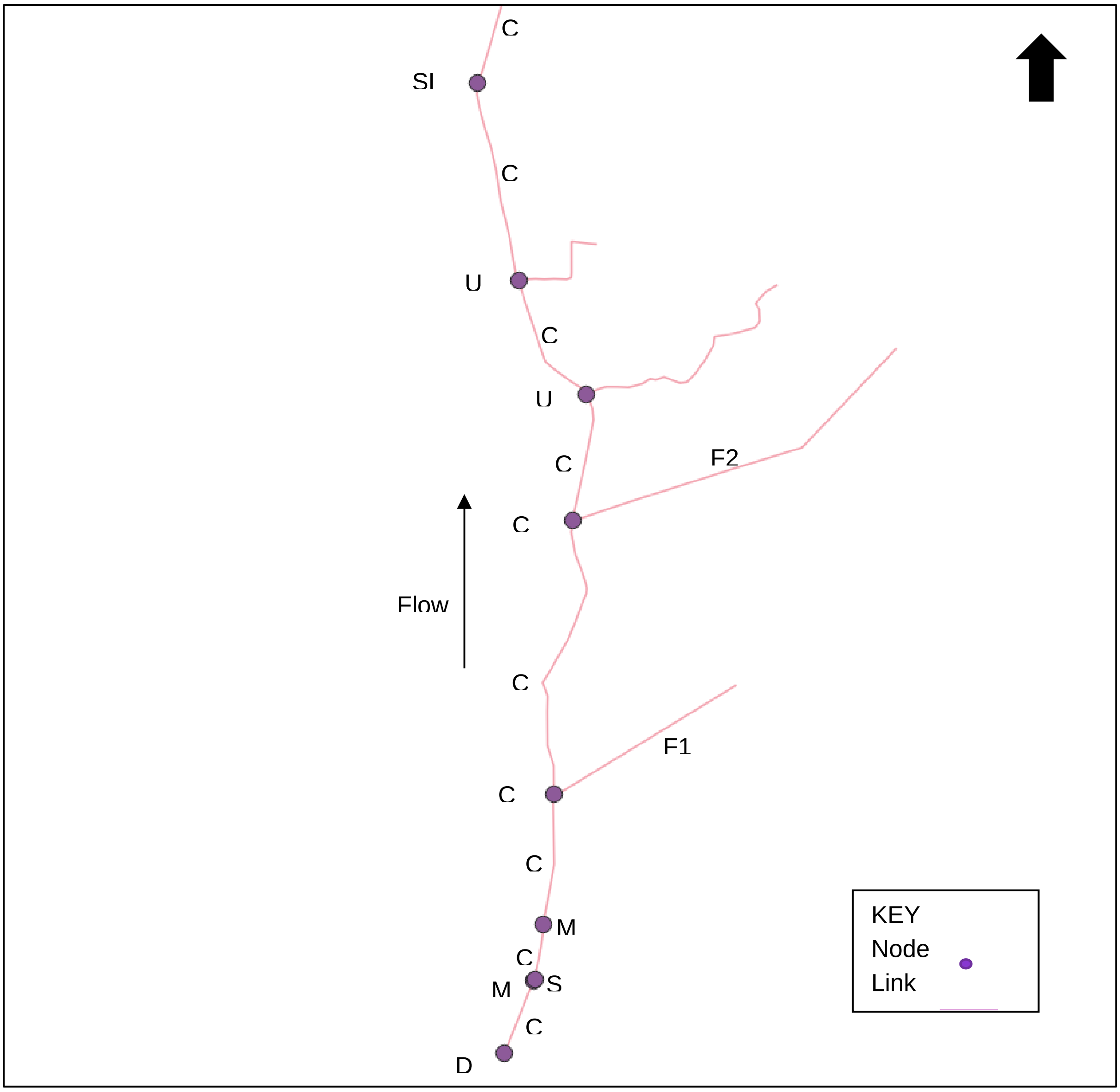

Figure 6.2: Coding of Raliphaswa scheme infrastructure

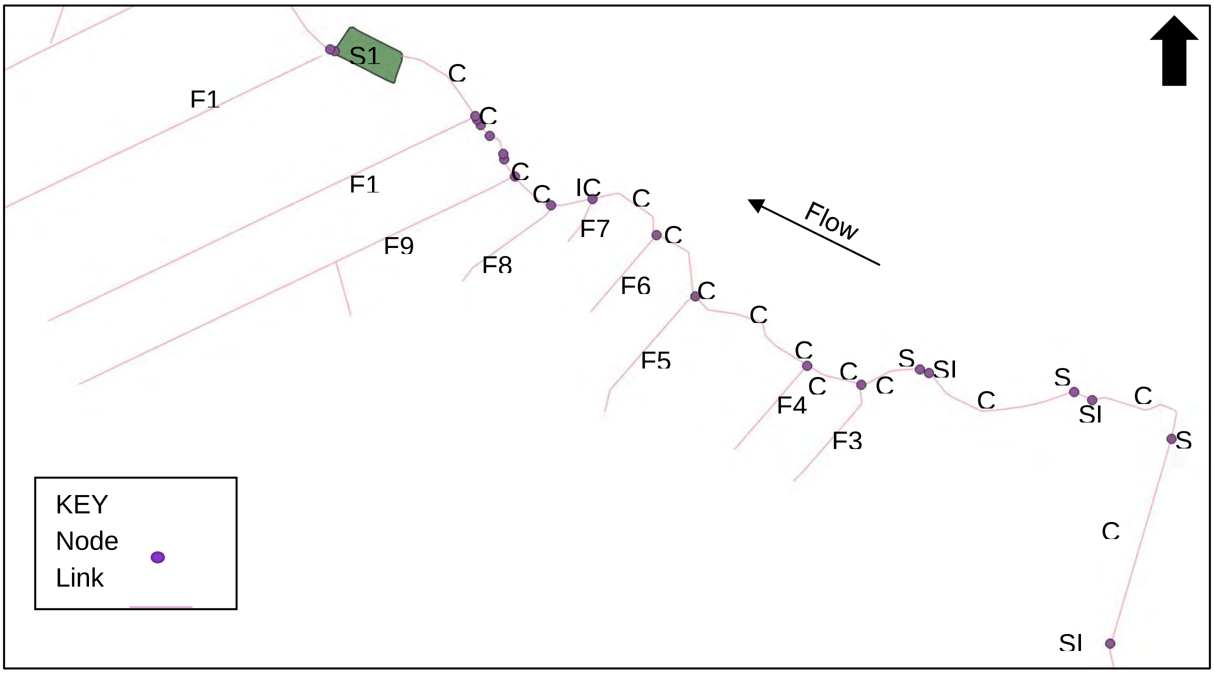

Figure 6.3: Coding of Mandiwana scheme infrastructure

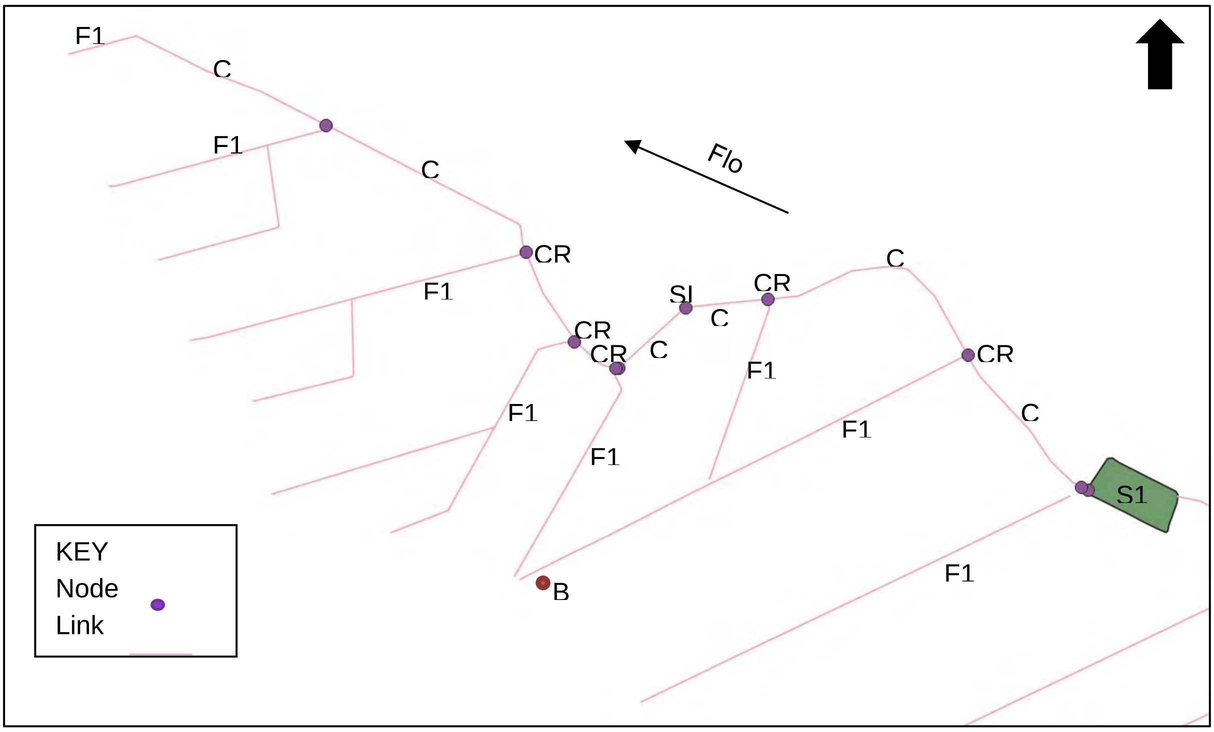

Figure 6.4: Coding of Mamuhohi scheme infrastructure

6.2.4 Surface condition assessment of infrastructure components

Hydraulic modelling and simulation of the water surface profiles along the irrigation system requires information for the calibration of the hydraulic roughness of the canal, usually quantified as the Manning's roughness coefficient "n".

The value of “n” in hydraulic computations is influenced by the following surface conditions:

- The initial finish of the surface;
- The deterioration of the surface with time;
- The effect (area reduction and change in effective roughness) of the deposition of sediments within the canal;
- Aquatic growth within the canal; and
- Other biological growth (DWS, 1980).

A detailed inspection of the canal infrastructure was therefore undertaken to assess the condition of the infrastructure and the canal roughness, to be factored in during hydraulic model calibration.

The site inspection was conducted between the 12th and 13th January 2021 between the start (the Raliphaswa diversion weir) and the last main canal segment (C27) at Mamuhohi. On the 12th of January 2021 the inspection commenced from the diversion weir (DW) up to SI4. The main canal is 5.8km in length, with three different sections as presented in Table 6.2. Access of canal sections C5 and C6 was not possible due to vegetation overgrowth. At Mandiwana, access was only possible from SI3, at the junction of the Mandiwana Smallholder Irrigation Scheme and the Vhutuwa Nga Dzwebu SIS.

Table 6.2: Canal infrastructure sections

Scheme	Start Chainage (m)	End Chainage (m)	Length (m)
Raliphaswa	0.00	1 742.80	1 742.80
Mandiwana	1 742.80	3 849.35	2 106.55
Mamuhohi	3 849.35	5 807.95	1 958.60

Appendix A, which is submitted separately due to document size limitations, presents the details of the surface conditions at 57 locations of the canal network and includes 54 photographs of these. The common surface conditions observed include aquatic growth, sediment deposition and damage of the canal regulating structures particularly in Mandiwana and Mamuhohi SIS.

6.2.5 Hydraulic survey of infrastructure components

Further to surface condition assessment, the calibration of hydraulic simulation models requires the following additional information: the physical characteristics of the canal and related structures and the water flow characteristics (i.e. water depth and velocity). This information was also collected during the site inspection conducted between the 12th and 13th January 2021.

The data collected included: inflow into the scheme, flow at all the available measuring points along the main canal system, the offtake gate positions (i.e. closed, open, partially open) and the flow regimes at those gates, the effective heads at the offtake, the effective heads at the conveyance pipelines, culverts and bridges, and at least one water depth along each canal reach. During calibration, the discharge calibration factors and coefficients are changed iteratively until the differences between simulated and observed values of water levels are within the allowable ranges.

The survey of the canal cross section and longitudinal slope was done using a total station survey equipment. Care was taken to ensure that at least one canal cross section and actual water surface elevation were taken for each canal reach. However, where there was another hydraulic structure serving a different function (i.e. diversion, distribution, measurement), the canal and water surface elevations were surveyed immediately upstream and downstream of the structure to accurately define the slope. The canal cross section was typically parabolic and along isolated sections of semi–circle shape. Consequently, only the depth and top width of the canal geometry and water surface elevation were surveyed to define the cross-sectional properties. The canal and flow depths were measured using staff gauges. Care was also taken to ensure that these properties are measured perpendicular to the direction of flow.

During calibration, it is desirable to have at least one good measurement of discharge that can be used to check the accuracy of the calibration. At the study SIS, there were two structures that served this function, the crump weir (M1) and the Parshall flume (M2). The crump weir on site operated under free flow conditions (i.e. the hydraulic jump observed downstream indicated that it functioned independently of the tailwater, see Figure 6.5). The water depth was therefore only measured upstream of the weir plate, approximately 4 × total energy head at the crump. However, sediment accumulation upstream of the crump made it difficult to measure the effective head at this weir relative to the crest of the crump weir.

Figure 6.5: Hydraulic jump downstream of crump weir at Raliphaswa SIS

The Parshall flume (M2), developed by Ralph Parshall in 1920, is a critical depth measuring device, which has the advantage of having a standard shape that can be used over a wide range of flows, with empirically determined discharge equations valid over the range. This structure measures the flow entering the Raliphaswa SIS. This flume was also operating under free flow conditions as indicated by a hydraulic jump in the throat section in Figure 6.6, and therefore only one depth measurement was taken upstream of the throat section (0.3 m).

Figure 6.6: Hydraulic jump downstream of Parshall flume.

The unsubmerged flow discharge equation of the Parshall flume is given by:

$$Q = Kh^u \quad (6.1)$$

Where Q is the flow rate (m^3/s), *K* is the dimensional free-flow coefficient given by the throat width, *u* is an exponent between 1.522 and 1.600 and *h* is the head (in meters) measured upstream of the throat section (James, 2012). The measured throat width of the Raliphaswa SIS Parshall flume structure is 0.305m. According to Herschy (1995), K = 0.6909 and u = 1.522 for a Parshall flume structure with these dimensions. Consequently, the flow entering Raliphaswa SIS in day 1 (the 12th of January 2021) of the site inspection was 111ℓ/s using equation 6.1.

Velocity readings taken using a velocity flow meter were also recorded for each surveyed section. The velocities were taken to obtain the mean vertical distribution of velocity, at 0.2, 0.4 and 0.8 × the total depth of flow, for the determination of the canal discharge. However, in some cases it was not possible to measure the velocity accurately as the meter was either too close to a boundary or was low on power. The recorded data will also be used to evaluate the accuracy of the simulated water surface profiles obtained during hydraulic modelling.

A summary of the collected data is presented in Appendix B. The findings indicate that most of the canal regulators in Mamuhohi are no longer functional. Only few distributors are fitted with functional gate valves and as a consequence they are either very cumbersome or difficult to operate. The infrastructure in place makes it very cumbersome or difficult to clean the siphon inlets from blockage. Furthermore, the measured velocities are low (<0.5 m/s) suggesting the maintenance requirements may be unduly high. This will be investigated further during the hydraulic modelling.

6.3 Questionnaire survey

6.3.1 Pilot questionnaire survey at Raliphaswa and Mandiwana irrigation schemes

6.3.1.1 Introduction

The piloting was originally scheduled for early December 2020 but was postponed as a result of the second COVID-19 wave that hit at that time. The piloting was then rescheduled for 25 and 26 February 2021 after the COVID-19 wave but could not take place due to devastating floods which destroyed access roads to Raliphaswa and Mamuhohi Villages. The extension officer helping the project team indicated that there was also no access to the farms as they were inundated with flood water. The piloting finally took place on 11 and 12 March 2021 at Raliphaswa community hall and Mandiwana Agricultural office, respectively.

The piloting was aimed at testing the questionnaire to determine the average time it will take to go through an entire set of questionnaires and find out if the respondents understand the questions. This was useful as it informed the need to restructure some of the questionnaires for ease of interpretation, determine the need to appoint research assistants to assist in administering the questionnaires, and train the students for the main questionnaire survey.

6.3.1.2 Administration of questionnaires

Twelve famers were interviewed during the pilot study. The constituted six from Raliphaswa and six from Mandiwana schemes. At Raliphaswa, the team was composed of 1 committee member and 5 farmers while at Mandiwana there were 2 committee members and 4 farmers. Figures 6.7 and 6.8 show the interviewers and farmers respectively at Raliphaswa. Figure 6.9 is a group photo of the farmers and project team members in Mandiwana while Figure 6.10 shows and interview session.

Prior to interviews, the extension officer Mr Muleka introduced UNIVEN research team to the farmers. Thereafter, Dr Mathaulula introduced UNIVEN team. The team was composed of one lecturer, three students and one intern. Before the administration of the questionnaires, Dr Mathaulula briefed the farmers about the project and the purpose of the workshop. The farmers were briefed on the purpose of the piloting survey before administration of the questionnaires. Also, research team was briefed on the issues that they should take note of during the interviews. These included, noting the time that administering each questionnaire will take, and finding out if the questions were clearly understood by both interviewers and interviewees.

During interviews, each research team member was assigned a farmer. The questionnaire consisted of six sections for the farmers and one section for the scheme committee members. The six sections were aimed at obtaining the following information: included section A: Farmers details; Section B: Farmers skills and assets; Section C: Land and crops grown, section D: Farmer water access and use, section E: Business and market access, and section G: Operation and maintenance. team. Section F was for the Scheme Committee aimed at obtaining information about the management structure, tasks and challenges.

During the interviews it was noted that it took at most three hours to administer all questionnaires per farmer. It was also found that a lot of the time was spent in translating English into Tshivenda, which is the common language spoken in the study area. It was therefore concluded that it will take 14 days to interview all 114 farmers in the three schemes (13 from Raliphaswa, 40 from Mandiwana and 61 from

Mamuhohi irrigation scheme). It was also decided to assign the task to four research assistants with each interviewing at least two famers per day.

Figure 6.7: Three students and intern during briefing on administration of questionnaire at Raliphaswa community hall

Figure 6.8: Farmers during briefing on administration of questionnaire at Raliphaswa community hall


Figure 6.9: Group photo of famers and UNIVEN research team during pilot questionnaire survey outside Mandiwana Agricultural office building


Figure 6.10: Research team members conducting interviews at Raliphaswa community hall

6.3.2 Main questionnaire survey

The main questionnaire survey was conducted over the months of July to October 2021 and managed to interview 56 of the 114 farmers in the three schemes. There were challenges in scheduling the interviews and in having the farmers available to undertake the long interviews. The survey data were compiled in spreadsheet format and are presented separately as Appendix C.

7 SMALLHOLDER CANAL SCHEME CONCEPTUAL SOCIO-HYDROLOGICAL MODELLING

7.1 Aim and structure of chapter

Aim of the chapter
The main aim of this chapter is to describe the formulation of the smallholder canal scheme conceptual socio-hydrologic model.

Structure of the chapter
This chapter contains three sections. Section 1 presents the aim and structure of the current chapter and section 2 informs about the formulation of the socio-hydrologic modelling framework. Section 3 describes the formulation of the process relationships of the conceptual socio-hydrologic model and these process relationships are then summarised into an influence diagram at the end of the section.

7.2 Conceptual socio-hydrologic modelling framework

7.2.1 Introduction

To conceptualise the socio-hydrologic model in this study, the combined backward and forward reasoning approach was adopted. To start off, the outcome indicator was identified, then a case specific model framework listing the variables of interest was developed based on Ostrom (2007, 2009) and collaborators.

7.2.2 Outcome indicator

An outcome indicator is a variable that needs to be measured in order to answer a specific question (Schluter et al., 2014). To identify the outcome indicator for this study, reference was made to the primary objective of SIS.

The main objective of SIS is to improve rural livelihoods through sustainable crop production for food security and poverty alleviation (Denison and Manona, 2007; Sinyolo et al., 2014; Moyo, 2016; Christian, 2017). This study focuses on the direct impact SIS have on the farmers or smallholders and their households, as the positive regional effects (i.e. regional livelihood improvement), are only realised when the farmers are efficient and successful (Christian, 2017).

Food security is enshrined in section 27 (b) of the South African Constitution Act 108 of 1996, which states that everyone has the right to have access to sufficient food and water. According to the Food and Agriculture Organization (FAO), food security is defined as a condition which exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. It exists in four interrelated dimensions, namely: availability, access, utilisation and stability (Christian, 2017). Only when a number of these dimensions are realised simultaneously does food security exist (Moyo, 2016). Due to the multidimensionality of food security, the key benefits of irrigation to food security include enhanced availability of food, increased opportunity to produce and retain food for home consumption, a reduced level of consumption shortfall, a reduced risk of crop failure and reduced seasonality effects of production (Moyo, 2016). Research in South Africa shows that food security primarily depends on total household income (Moyo, 2016).

Poverty is a lack of necessities such as food, clothing and shelter and it manifests through hunger, malnutrition, personal conflicts, high morbidity and mortality rates, high crime levels, low levels of education and loss of integrity but to name a few (Apam, 2012). Smallholder farming influences poverty through food price reduction and employment creation (Apam, 2012; Christian, 2017). An increase in crop productivity leads to an increase in staple and non-staple output which may result in lower prices for these foods and poverty reduction (Apam, 2012). The demand for labour in irrigation projects is typically for construction and ongoing maintenance of canals, and therefore increased farm output, as a result of irrigation, will stimulate demand for farm labour both within the main cropping season and across new cropping seasons (Apam, 2012).

According to Moyo (2016), the key direct pathways through which smallholder irrigation farming contributes to improved livelihoods comprise food production, income, employment, food security. The food production pathway comes about through key direct benefits from irrigation farming such as increased crop yields, increased crop areas, increased cropping intensity, increased crop diversification and opportunities for cropping throughout the year. The income pathway improves household welfare through increased income from crop production, increased family consumption of food, stabilisation of farm family income and reduced food prices. The employment pathway functions through increased on-farm employment opportunities, increased off-farm employment opportunities, stabilisation of employment opportunities and increased rural wage rates. Household food security pathway depends primarily on total household income required to afford bought-in food, and much less on household food production.

Based on the analysis of literature, socio-economic sustainability is the proposed indicator to measure the contribution of SIS to farmer livelihoods. Therefore, the socio-economic sustainability of the farmers was defined as the outcome indicator for this study. This is in alignment with the recommendations by Bjornlund et al. (2016) who indicated that it is critical that the business model for SIS be both financially and environmentally sustainable and socially equitable. Since the socio-economic sustainability of the farmers in a SIS is intrinsically linked due to their inherent interdependences, it will be concurrently assessed for each farmer.

7.2.3 Case specific socio-hydrologic modelling framework

In socio-hydrologic modelling, it is possible to create models that correspond to the interests of the modellers, stakeholders or policy makers, leading to the bias of model results and uncertainty (Melsen et al., 2018). In the study of socio-ecological systems (SES), this is overcome through the use of generic frameworks to aid transparency and comparability across models (Garcia et al., 2016). Furthermore, use of these frameworks enables a satisfactory understanding of the system as a whole, critical in developing sustainable SES (McGinnis and Ostrom, 2014).

Binder et al. (2013) compared ten established frameworks for analysing SES, explicitly designed to be used by a wider community of researchers and practitioners. According to Binder et al. (2013), out these established frameworks, only the SES framework (SESF) by Ostrom (2007, 2009) and collaborators addresses the reciprocal relationship between social and the ecological systems as well as the maintenance of common pool resource systems, such is the case at SCS. Therefore, for transparency and the wholistic understanding of the SCS, the SESF was adopted for socio-hydrologic modelling in this study.

The socio-ecological systems framework by Ostrom (2007, 2009) and collaborators (SESF) partitions the attributes of a socio-ecological systems (SES) into eight top tier variables, namely: social, economic and political settings (S) subsystem, a resource (RS) subsystem (e.g. fishery, lake, grazing area), a resource unit (RU) (e.g. fish, water, fodder), actors (A) or users of the system, a governance subsystem, interactions (I) amongst the actors, outcomes (O) subsystem including socio-economic and ecological performance measures and an ecosystem (ECO) subsystem. Each of these has a series of second tier (and potentially higher tier) variables (Ostrom, 2007; Garcia et al., 2016). The SESF is a generic framework for SES systems. In order to develop a case specific model framework for the smallholder canal schemes (SCS), the framework was compared against the variables and processes found to be influential to the socio-economic sustainability of the farmers in SCS according to literature (Meinzen-Dick, 2007; McGinnis and Ostrom, 2014; Delgado-Serrano, 2015; Garcia et al., 2016) and data collected from site. A discussion on the changes made to the generic framework is discussed in the following subsections.

7.2.4 Social, economic and political settings (s) subsystem

This subsystem describes the larger socio economic, political and ecological context in which the SES is embedded (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes six second level variables to describe this subsystem including economic development (S1), demographic trends (S2), political stability (S3), government resource policies (S4), market incentives (S5) and media organisation (S6). Each of these variables are discussed further below.

Economic development (S1) describes the economic situation and health of the area (Delgado-Serrano, 2015). This is particularly relevant for smallholder canal schemes (SCS) as they are located in areas with poor socio-economic conditions (i.e. former homelands). As a consequence, the per capita income of the community members wherein they are located is a key consideration for the farmer socio-economic sustainability. Furthermore, according to the background data, their economic participation is largely confined to the informal sector with a focus on primary agriculture (Magingxa and Kamara, 2003; Khoza et al, 2019). According to Thamaga-Chitja and Morojele (2014), most rural households in South Africa employ a mix of livelihoods strategies including salaries and wages contributing to household income followed by social grants, income from business and pension remittances. Nonfarm income comprises the most important livelihood source, with state pensions and salaries being the principal means of livelihood, these are of critical importance in sustaining agricultural activities by cross-subsidising initial capital investments, running costs, and labour (Olofsson, 2020). Therefore, income dispersion is also considered an important variable for explaining the economic development of SCS. For the purposes of this study, the employment of community members in other sectors is assumed to have a negligible influence on the outcome indicator. Therefore, three (per capita income, economic sector and income dispersion) out of the four proposed variables in the generic framework are considered relevant for explaining the socio-economic sustainability of smallholders.

Of the six proposed variables for explaining the demographic trends (S2) at SCS, only two variables are considered relevant for this study. The population growth rate was selected as this has a direct bearing on the market incentives for the smallholders and migration trends, particularly of youth, was selected as this is a key indicator of the long-term sustainability of the farming businesses. Myeni et al. (2019) attribute the migration of youth to competing livelihood opportunities and lifestyles.

The effect of political stability (S3) on farmer socio- economic sustainability was assumed to be negligible. SCS are highly regulated environments and therefore government water policies and commitment to reform (S4) was included as a second level variable. The related regulations include the smallholder irrigation policy, the National Water Policy, water rights and the National Water Act 36 of 1998.

Smallholder farmers are motivated by the certainty of market access, reduction in price uncertainty, better access to inputs and reduced input costs. Therefore, crop types, access to markets (based on the data analysis, this primarily includes local retailers, bakkie traders and hawkers), market volatility and water rights are key considerations. Market volatility was included as the agricultural produce market is open to world market influences following the deregulation of the sector after the publishing of the Berg report by the World Bank in 1981. The lack of clear and effective water rights systems creates problems for the management of irrigation water as it limits the value people assign to a resource, leading to decisions that adversely affect water use efficiency (Nieuwoudt and Backeberg, 2010; Fanadzo and Ncube, 2018). The security of water use rights implies that it can be monitored and enforced, which further implies that it can be measured (Nieuwoudt and Backeberg, 2010). Furthermore, users are willing to pay higher prices for secure and well-defined water rights, as it is expected to motivate smallholder farmers to use water more productively and invest in water-conserving technologies (Fanadzo and Ncube, 2018). As it stands, there are no market incentives for conservation of water, and therefore this variable was not included in the case specific framework.

The last second level variable in this subsystem is the media organisation (S6), which refers to the number, diversity and freedom of private and public media (Delgado-Serrano, 2015). This was assumed to have a negligible influence on the socio – economic sustainability of the farmers.

7.2.4.1 Resource system (RS) subsystem

The resource system (RS) subsystem describes the environmental conditions where the resources are located or produced (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes nine second level variables to describe this subsystem including sectors (RS1), system boundaries (RS2), size of resource system (RS3), infrastructure (RS4), resource productivity (RS5), equilibrium properties (RS6), predictability of supply (RS7), storage characteristics (RS8) and spatial and temporal distribution of resource (RS8).

The sector (RS1) refers to the biological production system of interest. In irrigation schemes, water is the resource of interest. The water system boundaries are influenced by natural boundaries, including water falling on the smallholder plots and flowing into the smallholder plots as storm water runoff, and anthropogenic boundary enabled by the diversion of water from the Mutshedzi River via an infrastructure system to augment water supply to the smallholder plots. These system boundaries determine the size of the resource available, a function of the hydrological processes in those catchments. The irrigation system infrastructure (including headworks structure, conveyance structure, regulating structures, safety and measurement structures) facilitate the management of this resource.

The resource productivity (RS5) refers to the quantity of crops that are produced through the expenditure of a unit water resource. It is a measure of sustainable production and consumption. The equilibrium properties refer to the influences affecting the equilibrium of the resource system. This includes biological and anthropological influences such as surface runoff, seepage, leakage, operational losses including spills/ overflows, evapotranspiration or crop water use, evaporation, withdrawals by upstream users and operational losses.

A search for the hydrological data was undertaken and is summarised in Section 4.3 of Chapter 4. It was found that daily rainfall data for station 0766324W is available for the period 1903/10/01 to 2014/02/10. Station 229303 from the SWAT database has daily data which include minimum and maximum temperature, rainfall, wind speed, relative humidity and solar radiation for the period 1979/01/01-2014/07/31. Mutshedzi rainfall and evaporation station (A8E004) has daily rainfall and evaporation data from 1991/07/01 to 2020/02/29. Streamflow data for the period 1991/12/03-2000/12/04 is available for station A8H011 downstream of Mutshedzi Dam obtained from South African Department of Water and Sanitation. The gauging station A8H001 at the outlet of A80B only has recorded water levels for the period 1932/10/04 to 194612/28. The periods of coverage indicate that the classical calibration and verification approach to the modelling may only be applicable over a period of 10 years when streamflow data is available. No measured flow data is available at the scheme.

The storage characteristics of the system refer to the natural or manmade storage volume affecting the system dynamics. The key storage affecting the resource system dynamics is the Mutshedzi Dam, with a capacity of 2.35 million m^3, located upstream of the scheme headworks. At the scheme, there is one functional overnight storage dam, supplying the Mamuhohi SIS.

7.2.4.2 Resource unit (RU) subsystem

The resource unit (RU) subsystem describes the natural resource units generated by the resource system (Delgado-Serrano, 2015). In the SCS, this refers to the crops produced. Ostrom (2007, 2009) proposes seven second level variables to describe this subsystem, including resource unit mobility (RU1), growth or replacement rate (RU2), interaction among resource units (RU3), resource value (RU4), number of units (RU5), distinctive characteristics (edited to crop types for this SES), spatial and temporal distribution (RU7) which was separated into two variables for the purposes of this study. For simplicity, it was assumed that the crops are independent of each other and therefore the interaction between resource units is assumed to be negligible. The resource unit mobility was also excluded in this study as the resource units of this study (i.e. crops) are static.

The crop growth rate is an important factor as it also determines the crop water requirements as well as the crop sensitivity to water deficiencies. The resource unit value was further subdivided into the market value of the resource produced, which determines the economic viability of the farming enterprises and the contribution of the resource units produced to the food security of each household. The number of units produced is also a key determinant of the socio-economic sustainability of the farmers. The crop type planted affects the profits made. The spatial and temporal distribution was separated into two variables as the data collected from site indicates that the crops grown are different in the winter and summer seasons, furthermore, the land allocation for the crops grown during these seasons also differs. Consequently, it is seen as more efficient to treat these variables separately rather than as combined.

7.2.4.3 Actors (A) subsystem

The scheme users are the actors (A) that are considered to affect or be affected by the resource system (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes nine second level variables to describe this subsystem, including the number of relevant actors (A1), the socio-economic attributes of the users (A2), history or past experiences of the users (A3), location (A4), leadership/ entrepreneurship (A5), norms and social capital (A6), knowledge of the SCS (A7), importance of resources to the actor (A8) and technologies available (A9).

In this study, the key scheme users that affect the resource system are the farmers or smallholders. However, based on findings made during the site visit, there are also a number of nonfarmers who use the water for domestic, livestock and business purposes.

Literature and data analysis suggests a number of socio-economic attributes as potentially influencing the socio-economic sustainability of the smallholders. The majority of farmers at the scheme are women, and according to literature, gender influences the support services that the farmers have access to. Farm size is a key factor in the number of crops produced and therefore the profits that can be made. Education level and training influences the agricultural practices (such as tillage, pest control, nutrient management etc). This is also influenced by the farmers experience. On farm income, off farm income and savings and investments influences the economic resilience of the farming enterprise. The age of the farmer typically determines whether the farmer has access to a grant or pension, which typically accounts for a large proportion of income for the farmers and this is also reflected at the scheme. Furthermore, age determines whether a farmer is of an economically active age which influences the farmers risk profile. Land tenure affects the farmers level of investment onto his/her land as well their farming expenses if the farmer is making a contribution towards the land. Other farming expenses include for services such as harvesting, transportation and labour for other farming activities. Support services are typically free and provided by the government. From the data analysis, support services at the SCS include the provision of seeds, agricultural extension services and marketing support services. The farming objective determines the orientation of farming activities and it is proposed to be a key factor influencing a number of decisions made by the farmers at the scheme. These include the percentage of crop produce sold to market, crop type selected, land use etc. Finally, the family size determines the household food requirements and required expenditure on food.

The socio-economic assets of the smallholders include implements and equipment, livestock which could offset the cost for fertiliser through the provision of organic manure and any other assets that can be transferred into cash or can be used as collateral for a loan such as a house.
Past or previous seasons ranks as a high consideration that the farmers make in how they manage water resources in the next or future season.

The location of resource system users is of critical importance in SCS with a hierarchical layout. Due to the lack of detailed information on the farmer locality, the description of the farmer locality will be limited to either Raliphaswa, Mandiwana or Mamuhohi scheme. The head-end farmers are therefore those based at the Raliphaswa scheme, and the tail-end farmers will be those based at the Mamuhohi scheme.

Leadership refers to the existence of and attitude towards leadership by the scheme users. At the scheme there are generally two forms of leadership that seem to have an influence on the system: the scheme committee and traditional leadership. Research suggests that the farmers attitude towards the scheme committee is dynamic and usually perception based. Meanwhile traditional leadership is generally continuously respected.

The norms or social capital refer to the levels of social and institutional interaction amongst users including reciprocity and trust. At the scheme this is identified through farmer collaboration and scheme mutualism. Awareness of activities undertaken by other farmers (particularly neighbouring farmers) is also proposed as a key driver of the norms that take place at the scheme.

The knowledge among smallholders of the SCS system, potential and real disturbances and their possible effects were grouped into indigenous knowledge and scientific knowledge. It is proposed that indigenous knowledge refers to knowledge mainly gained from experience whilst scientific knowledge is mainly obtained from higher level education and training. It is assumed that the farmers obtain water from either rainfall, or the diversions provided by the irrigation canal system and therefore have no alternate water resources. Furthermore, that furrows are the only system available for the users to access irrigation water from the canal system. Therefore, the importance of the resource (A8) was excluded from the case specific model framework.

7.2.4.4 Interactions (I) subsystem

The interactions (I) subsystem describes the internal and external resource influences (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes ten second level variables to describe this subsystem, including harvesting levels (I1), information sharing (I2), deliberation processes (I3), conflicts (I4), investment activities (I5), lobbying activities (I6), self-organising activities (I7), networking activities (I8), monitoring activities (I9) and evaluation activities (I10).

Harvesting levels refers to the quantity of resources harvested by the different users. To make it more case specific, this description was changed to water withdrawn by users. This variable was further divided into water withdrawn by the scheme farmers, water withdrawn by nonfarmers (i.e. for domestic/ commercial purposes) and water withdrawn by farmers who are not part of the scheme. The last two are referred to as free riding activities as there are no costs or expenses associated with them.

Information sharing is a key part of irrigation scheme management as users need to have information about the allocation of water, the scheduling of supply, and about measurements of deliveries (Renault et al., 2007). However, this type of information is generally not made available at the scheme. Consequently, this variable was excluded from the case specific framework. Information is generally shared through the scheme committee meetings included as part of the deliberation processes.

The common cause of conflict at the scheme is associated with water resource allocation, typically between head-end and tail- end farmers.

Lobbying activities refer to the internal and external influence capacity of the SCS users. This has been divided into traditional leadership, neighbouring farmers and informal water institutions such as farmer groups outside the scheme committee. The data analysis suggest that these three groupings may have an influence on how the SCS are managed and the rules being adopted by the users.

The data collected suggests that some internal networking and partnership activities do happen at the scheme. This includes farmers partnering to exchange workers, share excess water, helping each other with farm work when overwhelmed, advising each other, sharing of plots not in use. Lastly, it is proposed that monitoring activities are primarily done by the scheme committee although the farmers do report observations that are not aligned with the scheme rules.

7.2.4.5 Governance system (GS) subsystem

The governance (GS) subsystem looks at the processes through which decisions on SCS management are made and enforced (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes eight second level variables to describe this subsystem, including government organisations (GS1), nongovernment organisations (GS2), organisation network structure (GS3), property rights system (GS4), operational rules (GS5), collective choice rules (GS6), constitutional rules (GS7) and monitoring and sanctioning processes (GS8).

The government organisations (GS1) proposed to be influencing the SCS include the Department of Land Reform and Rural Development (DALRRD), the Department of Water and Sanitation (DWS), the Water User Association (WUA) and the Agricultural Research Council (ARC). The proposed nongovernment organisations include traditional leadership and the scheme committee. The social network and the irrigation governance networks are the key network structures at local level. The social network structure including informal farmer groups drive the informal rules at the scheme and irrigation governance network, primarily including the scheme committee, traditional leadership and the provincial DALRRD, derive the formal rules and regulations at the scheme.

Property rights and their relation to water resource management (GS4) was changed to water rights to be more case specific. The key water rights holders impacting on the socio-economic sustainability of the farmers are the water right holders upstream of the SCS diversion point on the Mutshedzi River. Based on these users' water rights, they will have first preference to the water made available on the Mutshedzi River. Furthermore, the socio-economic sustainability of the farmers at the scheme will be affected by the water rights the SCS has.

The operational rules define who, how, when, and why each user has access to the water supplied via the canal irrigation system. This includes the scheme operating protocol, which according to the scheme committee members, is based on a rotational leading turn schedule that does not vary with time. The maintenance of the canal including the removing of sedimentation, clearing of vegetation and repair of mechanical parts is instructed by the scheme committee members. The data analysis suggests that these maintenance activities are undertaken seasonally. There are no rules around conflict resolution besides that the scheme committee is responsible for resolving these. According to the data collected, this usually involves meetings with the parties in conflict and the issuing of fines.

Scheme users participate in collective activities through contributing labour, finance, decision making, information dissemination as well as regulation and control to encourage a sense of ownership and responsibility (Muchara et al., 2014). Collective choice rules therefore are the rules defined or determined by the actors or famers themselves. In SCS this typically includes cropping patterns, planting dates, participation in collective activities, nutrient and land management.

The legal framework defining the management of water resources in the country is the National Water Act 36 of 1998. The scheme committee is wholly responsible for the monitoring of use of the water resource and the main sanctioning process is through fines.

7.2.4.6 Outcomes (O) subsystem

The outcome (O) subsystem describes the interaction amongst the variables (Delgado-Serrano, 2015). Ostrom (2007, 2009) proposes three second level variables to describe this subsystem, including socio economic performance measures (O1), ecological performance measures (O2) and externalities to other SES (O3).

The socio-economic performance measure describes the evolution and impacts of socio-economic concepts. According to Skvarciany et al. (2020), socio-economic sustainability can be understood as the ability to ensure economic growth without undermining humans' interests and to meet their needs without harming nature. Based on this definition, socio-economic sustainability can be operationalised with indicators that relate both ecological and socio-economic performance measures.

The primary objective of SIS is to improve rural livelihoods. Livelihoods comprise capabilities, (natural, social, human, physical and financial) assets and activities that can be accessed and controlled for a means of making a living. According to the sustainable livelihoods' framework, Human capital represents the skills, knowledge, ability to labour and good health that together enable people to pursue different livelihood strategies and achieve their livelihood objectives. Social capital refers to the social resources upon which people draw in pursuit of their livelihood objectives. Physical capital refers to the basic infrastructure and machinery needed to support livelihood strategies. Financial capital denotes the financial resources that people use to achieve their livelihood objectives. And natural capital refers to the natural resource stocks from which resource flows and services useful for livelihoods are derived. For the purposes of this study, the only assets that are endogenous to the model scope are financial (i.e. savings/ net profits and crop yields) and natural assets (i.e. water supply efficiency). The rest of the assets are considered as either constants or exogeneous to the model scope.

Smallholders are by their nature vulnerable to extreme weather events. According to Apam (2012), vulnerability refers to the level of exposure a smallholder has to external shocks and stresses and their ability to cope with the damages and losses resulting from these external factors. According to Moyo (2016) the key ecological irrigation scheme benefits that bring about reduced vulnerability are the provision of adequate level of service. Therefore, the satisfaction with the level of service, particularly in regard to the most vulnerable farmers (i.e. Mamuhohi farmers) is proposed as the ecological performance measure. For the purposes of this study, the effects of other extreme events such as floods and hail will not be considered.

The continued support of the SIS to farmer livelihoods depends on the sustainability of the scheme. The failure of many schemes however is linked to the low participation of farmers in maintenance and operation collective activities (Mutambara et al., 2016). Muchara et al. (2014), Sithole et al. (2014), Totin et al. (2014) and Lopus et al. (2017), link the degree of participation by farmers and scheme longevity to the level at which water delivery objectives are met. Given the inherent link between the scheme and the socio-economic sustainability of the farmers, the adequacy of user participation in collective activities was also proposed as an additional socio-economic performance measure.

No non desirable effects of the SCS will be considered in this study.

7.2.4.7 Ecosystem (ECO) subsystem

The ecosystems (ECO) subsystem describes the connection between the SCS and the surroundings (Delgado-Serrano, 2015). This subsystem includes three second-level variables: climate patterns (ECO1), pollution patterns (ECO2) and flows into and out of the focal SCS (ECO3). For the purposes of this study, only the upstream impact on the flows into the SCS will be considered. These will be particularly with regards to the increase in demand expected at the Mutshedzi dam with increase in population growth. The impact of climate change will not be considered in this study.

The case specific SCS model framework to be used in developing the conceptual model is presented in 7.1. The table also includes additional categories to further describe the variables, including the variable analysis scale (i.e. local, regional, national, international) and the variable type (i.e. exogeneous, state or constant).

Table 7.1: Case specific SES Framework, modified for smallholder canal schemes

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
Social, economic and political settings (S) subsystem	Economic development (S1)	Per capita income	Local	Exogeneous
		Economic sector	Regional	Constant
		Income dispersion	Local	Constant
	Demographic trends (S2)	Population growth rate	Local	Exogeneous
		Migration trends	Regional, Local	Exogeneous
	Government water policies and commitment to reform (S4)	Related regulations	National, Regional	Constant
	Market incentives (S5)	Access to markets	Local	Constant
		Market volatility	National, Regional	Exogeneous
		Crop type	Local	Constant
		Water market/ rights	Regional	Exogeneous
Resource system (RS) subsystem	Sector(s) (RS1)	Water	Regional	Exogeneous
	System boundaries (RS2)	Natural/ catchment boundary	Local	Constant
		Anthropogenic boundary	Regional	Constant
	Size of resource system (RS3)	Size of catchment/ watershed boundary	Local	Constant
		Size of the Mutshedzi river catchment boundary	Regional	Constant
	Infrastructure (RS4)	Headwork physical characteristics	Local	Constant
		Conveyance structure characteristics		Constant
		Regulating structure characteristics		Constant
		Measurement structure characteristics		Constant
		Safety structure characteristics		Constant

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
		Energy dissipation structure characteristics		Constant
	Resource productivity (RS5)	Resource productivity	Local	State
	Equilibrium properties (RS6)	Evaporation	Local	State
		Seepage		Constant
		Leakage		Constant
		Surface runoff		State
		Withdrawals		State
		Operational losses		State
	Predictability of supply (RS7)	Data availability	Local, Regional	Exogeneous
	Storage characteristics (RS8)	Mutshedzi Dam	Local	State
		Mamuhohi Overnight Storage Dam	Local	State
Resource Unit (RU) Subsystem	Growth or replacement rate (RU2)	Crop growth rate	Local	State
	Resource value (RU4)	Market value	Local	Exogeneous
		Offset/ reduction of household expenditure on food	Local	State
	Number of units (RU5)	Amount/ volume/ tonnage of resource	Local	State
	Crop type (RU6)		Local	State
	Temporal distribution (RU7)	Winter season	Local, Regional	State
		Summer season	Local, Regional	State
	Spatial distribution (RU8)	Land allocation/ distribution	Local	State
Actors (A) Subsystem	Number of Relevant actors (A1)	Number of Farmers	Local	Constant
		Number of non-farmers	Local	Constant

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
	Socio-economic attributes of users (A2)	Educational level	Local	Constant
		Training	Local	Constant
		Income from farming	Local	State
		Farm size	Local	Constant
		Off farm income	Local	Exogeneous
		Farming objective	Local	Constant
		Age	Local	Exogeneous
		Savings	Local	State
		Family size	Local	State
		Farming experience	Local	Exogeneous
		Gender	Local	Constant
		Land tenure	Local	Constant
		Cost of services	Local	Constant
		Support services	Local	Exogeneous
		Labour	Local	Constant
		Ownership/ access to implements and equipment	Local	Constant
		Livestock ownership	Local	Constant
		Other assets	Local	Constant
	History or past experiences (A3)	Past/ previous seasons	Local, Regional	State
	Location (A4)	Raliphaswa (head - enders)	Local	Constant
		Mandiwana (middle)	Local	Constant
		Mamuhohi (tail- enders)	Local	Constant
Actors (A) Subsystem	Leadership (A5)	Traditional leadership	Local	Constant
		Scheme committee	Local	State
	Norms/social capital (A6)	Farmer collaboration	Local	Constant
		Identification as part of the schemes/ collective well being	Local	Constant

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
		Awareness and influence amongst farmers	Local	Constant
	Knowledge of SCS/mental models (A7)	Indigenous knowledge of farming	Local	Constant
		Scientific knowledge of farming	Local	Constant
	Technologies available (A9)	Furrows	Local	Constant
Interactions (I) Subsystem	Water withdrawn by users (I1)	Water withdrawn/ abstracted from scheme by farmer	Local	State
		Water withdrawn/ abstracted by nonfarmers (i.e. for domestic/ commercial purposes)	Local	Constant
		Theft/ illegal/ unauthorised water abstracted by farmers who are not part of the scheme	Local	State
	Deliberation processes (I3)	Scheme committee meetings	Local	State
	Conflicts among users (I4)	Resource allocation conflicts	Local	State
	Lobbying activities (I6)	Traditional authority/ leadership	Local	Exogeneous
		Neighbouring farmers	Local	State
		Informal water institutions	Local	Exogeneous
	Networking activities (I8)	Internal networking	Local	Constant
	Monitoring activities (I9)	Policing	Local	State
		Inspections	Local	State
Governance (GS) Subsystem	Government organisations (GS1)	Department of Agriculture, Land Reform and Rural Development	Regional, Local	Constant
		Department of Water and Sanitation	Regional	Constant
		Agricultural Research Council	Regional	Constant
		Water User Association	Regional	Constant
	Nongovernment organizations (NGOs) GS2	Traditional leadership	Local	Constant
		Scheme Committee	Local	Constant
	Network structure (GS3)	Social network	Local	Constant

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
		Irrigation Governance network	Regional	Constant
	Water-rights systems (GS4)	Prior appropriation	Regional	Exogeneous
		Property rights to water	Local	Constant
	Operational rules (GS5)	Operational rules/ operating protocol	Local	State
		Canal repairs (i.e. gates, concrete)	Local	State
		Removing sedimentation from the canal	Local	State
		Clearing of vegetation in and around canal	Local	State
		Conflict resolution	Local	Constant
Governance (GS) Subsystem	Collective-choice rules (GS6)	Nutrient management	Local	State
		Crops planted/ cropping patterns	Local	State
		Planting dates	Local	State
		Participation in collective activities	Local	State
		Land management/ tillage	Local	State
	Constitutional rules (GS7)	National Water Act	National	Constant
	Monitoring and sanctioning processes (GS8)	Fine	Local	State
		Monitoring of water delivery	Local	State
Outcomes (O) Subsystem	Socio-economic performance measures (O1)	Water supply efficiency	Local	State
		Crop yields	Local	State
		Savings/ net profit	Local	State
		Adequacy of user participation in collective activities	Local	State

Top tier variable	Second level variable	Third level variables	Analysis Scale	Variable Type
	Ecological performance measures (O2)	Satisfaction of farmer expectations	Local	State
Ecosystems (ECO)	Flows into and out of the scheme (ECO3)		Regional	Exogeneous

7.3 Conceptual socio-hydrologic modelling process relationships

As explained in Section 7.2, the outcome indicator identified in this study is the socio-economic sustainability of the smallholders or farmers. Section 7.2.3 informs that socio-economic sustainability can be operationalised using indicators relating to socio-economic and ecological performance measures. This section describes the processes that explain the changes in the state variables that are in the domain of the outcome indicator (i.e. socio-economic and ecological performance measures), based on the Model Framework described in Section 7.2.

Process relationships are dynamic hypothesis, represented as mathematical directed relation types, wherein the influencing variables are located in the domain and the influenced variables are in the codomain of the relation types. For example, if variable A and B influence variable C, the relation type can be represented as follows:

$$(A, B) \rightarrow C$$

The influencing variables are on the left-hand side (the domain) and the influenced variables are on the right-hand side (the codomain). These process relationships will be developed from the highest level of aggregation in the domain of the outcome indicator, down until changes in all relevant state variables have been explained (Schluter et al., 2014). Aggregation relationships are a special form of relation types, used to define how variables that are measured at different levels or scales are aggregated. These relationships are denoted as (codomain) ← (domain).

Where the notation *concept. variable* is used, the variable after the full stop is attributed to the concept named before the full stop (Schluter et al., 2014). For example, *operation of offtakes. planned, operation of offtakes. unplanned* indicates that the operation of offtakes have a planned and unplanned scenario.

7.3.1 Process relationships

Studies by Muchara et al. (2014) and Lopus et al. (2017) show that the quality of water delivery drives farmer's satisfaction, which influences their participation in collective water management, and in turn, affects the schemes sustainability.

Therefore, the satisfaction of farmer expectations at an irrigation scheme is linked to the quality of water delivery, hypothesised to be a function of the scheme operation and maintenance requirement and the actual operation and maintenance, represented as follows:
farmer. satisfaction ← (scheme. operation and maintenance requirement, scheme. actual operation and maintenance)

The variables in the domain of the ecological performance measure are therefore *scheme. operation and maintenance requirement* and the *scheme. actual operation and maintenance*. The process relationships used to describe the changes in these variables are described below.

7.3.1.1 Scheme operations and maintenance requirements

The integration of the perturbation domain, sensitivity domain and agreed level of service by the users of the scheme determines the operation and maintenance (O and M) requirement, categorised by the observation, measurement and regulation requirement (Renault et al., 2007).

The proposed relation type for scheme operations and maintenance requirement is therefore as follows:

(farmer. agreed level of service, location. perturbation domain, location. sensitivity domain) → scheme. O & M requirement

The *farmer .agreed level of service* is hypothesised as defined by three time-related aspects that are important for farmers, these include allocation of water for the season or year; irrigation delivery schedule and actual water delivery. (farmer. allocation of water, farmer. irrigation delivery schedule, location. water delivery rate) → farmer. agreed level of service

The variables hypothesised to be influencing the agreed level of service are illustrated in Figure 7.1 and are discussed below.

Typically, water rights or licensed allocation would also be included in the domain of the *farmer. agreed level of service*, however, it was established during data collection that none of the smallholders have an individual water right or a licensed allocation.

In terms of *farmer. allocation of water* for the season or the year, the service usually includes not only the volume of water to be delivered but also the flexibility in negotiating variations around the agreed value (Renault et al., 2007). This aspect is important for example, in adjusting the cropping pattern to whatever water is allocated, or conversely, in securing additional water supply to cover a change in the cropping pattern. According to Renault et al. (2007), this aspect can be specified by two variables: target (i.e. volume) and tolerance (allowed fluctuation of the target).

The relation type for *farmer. allocation of water* can therefore be represented as:
(farmer. allocated volume, location. allowable tolerance in volume) → farmer. allocation of water

The allocated volume per farmer is a function of the resource system capacity and the number of relevant users (i.e. farmers and nonfarmers) sharing the water resource. Surface water for each farmer is made available in the form of either rainfall directly on the plots, storm water conveyed onto the plots or deliveries from the canal system, supplied by the Mutshedzi River or the overnight storage dams. According to the site visit, the only functional overnight storage dam supplies the Mamuhohi Scheme. Water provided through the canal system is affected by seepage, leakage, evaporation and operational losses. Furthermore, the water available from the canal system is unavailable once it has been appropriated to a user (Ostrom, 1993).

The proposed relation type describing the allocated volume is therefore as follows:
(farmer. rainfall on the plot, farmer. storm water runoff onto the plot, location. expected instantaneous flow) → farmer. allocated volume

Where:
(farmer. plot area, rainfall) → farmer. rainfall on the plot
(farmer. catchment, rainfall) → farmer. storm water runoff onto the plot

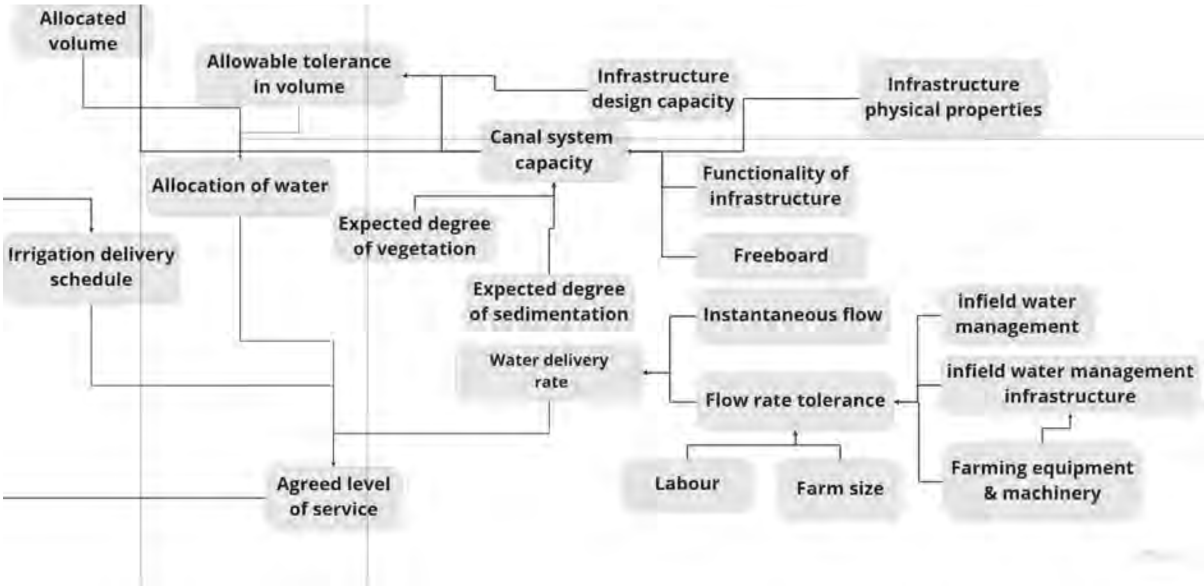

Figure 7.1: Variables influencing the agreed level of service

The expected instantaneous flow (or discharge) is assumed to be a function of the main canal system water balance, including all the inputs and outputs as follows:

(Expected diversions from Mutshedzi River, Mamuhohi. releases from overnight storage dam, losses. Seepage, losses. Leakage, losses. Evaporation, losses. Operational, expected canal system capacity, farmer. expected appropriated volume, nonfarmers. appropriated volume, location. number of farmers, location. number of nonfarmers) → location. expected instantaneous flow

The appropriated volume from the canal system to the nonfarmers is assumed to be constant for the purposes of this study.

The changes in the diversions from the Mutshedzi River are affected by the Mutshedzi River catchment hydrology, the river intake structure and the operation and maintenance of the river intake structure. The Mutshedzi River catchment hydrology will be discussed further in the catchment hydrology section of the study.

The proposed functional relationship is as follows:
(Predications based on the catchment hydrology, capacity of river intake structure, expected operation of river intake structure, expected vegetation at river intake structure, expected sedimentation at river intake structure) → expected diversions from Mutshedzi River

Releases from the overnight dam are based on the dam water balance as follows:
(location. expected instantaneous flow, Mamuhohi Overnight dam inflows. storm water, Mamuhohi Overnight dam inflows. rainfall, Mamuhohi overnight dam storage, Mamuhohi overnight dam Losses. seepage, Mamuhohi overnight dam Losses. evaporation, Mamuhohi overnight dam outlet expected operation, Mamuhohi overnight dam overflows) → Mamuhohi overnight dam. releases

During the site visit, it was observed that the sediment concentration of the flows that enter the Mamuhohi Overnight Dam were quite low. Therefore, sedimentation was assumed to not be affecting the overnight dam storage characteristics and these will be assumed to be constant in the model simulation.

The expected appropriated volume is assumed to be dependent on the expected instantaneous flow at an offtake, the regulating properties of the offtake, the offtake operating period, the number of farmers served at the offtake and the distribution losses.

The proposed relation type is as follows:
(location. expected instantaneous flow, expected operation of offtakes, scheme offtake. regulating structure physical properties, scheme offtake. number of farmers, scheme furrow. distribution losses) → farmer. expected appropriated volume

The variables hypothesised to be influencing the agreed level of service are illustrated in 7.2 and are discussed below.

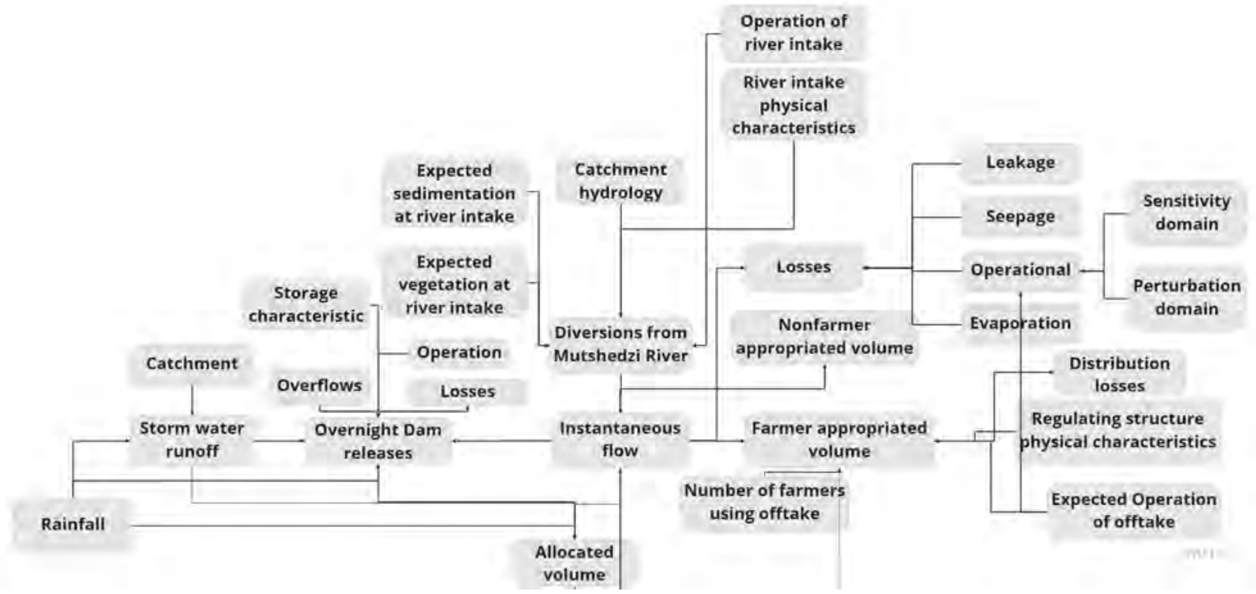

Figure 7.2: Variables influencing allocated volume

It is assumed that the allowable tolerance in volume change is limited by the difference between the infrastructure design capacity and the infrastructure total capacity, given by the freeboard capacity. The freeboard capacity is expected to change throughout the system depending on the physical characteristics of the infrastructure, the condition of the lining material, and the expected degree of sedimentation and vegetation. For the purposes of this study, focus shall be on the accumulation of sediment only on the inlet side of regulating structures and the river intake structure.

The proposed relation type for the allowable tolerance is therefore:
(location. infrastructure design capacity, location. infrastructure capacity) → location. Allowable tolerance

The irrigation delivery schedule will differ for each farmer based on their location. A similar relationship to the allocation of water can be developed for the irrigation delivery schedule, as recommended by Renault et al. (2007).

(location. water availability frequency, farmer. allowed tolerance in water availability frequency) → farmer. irrigation delivery schedule

The quality of service for the irrigation delivery schedule aspect is specified by the frequency with which water will be made available, e.g. every week, fortnight or month, as well as the flexibility in modifying the schedule to match unexpected changes (Renault et al., 2007). This aspect is important for ensuring that the water supply will prevent moisture deficit at field level, and also for the organisation of the human resources and equipment at farm level (Renault et al., 2007). The water availability frequency is determined by the availability of the water, the location of the farmer within the scheme, and the operation of the offtakes.

The proposed functional relationship is as follows:
(farmer. location, location. expected operation of offtakes, location. expected instantaneous flow) → farmer. water availability frequency

The *farmer. allowed tolerance in the frequency of water availability* depends on the water needs of the crop and the capacity of the root zone to store water, which changes throughout the life of the crop (Pereira et al., 1996).
(farmer. crop type, farmer. planting calendars, location. soil type, climate) → farmer. allowed tolerance in water availability frequency

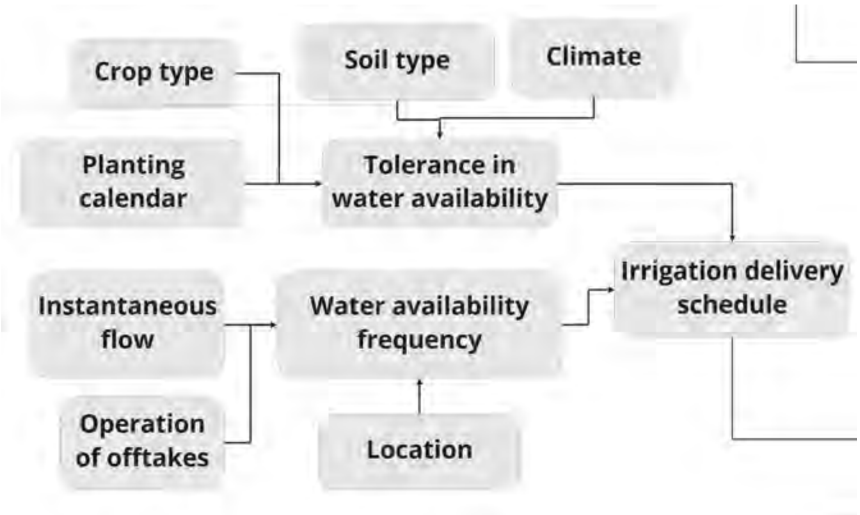

Figure 7.3: Variables influencing irrigation delivery schedule

The proposed water delivery rate relation type is similar to that of the *irrigation delivery schedule* and the *allocation of water* as follows:
(location. expected instantaneous flow, farmer. flow rate tolerance) → location. water delivery rate

The expected canal system capacity is a function of the expected sedimentation and vegetation as follows:
(infrastructure physical characteristics, location. expected sedimentation, location. expected vegetation, functionality of infrastructure components, freeboard) → location. expected canal system capacity

The tolerance in flow rate is affected by the resources (i.e. human and equipment) that the farmer has access to. Therefore, it is proposed to be a function of the farmer's socio-economic attributes. The proposed relation type is as follows:
(farmer. water management practices, farmer. water management infrastructure, farmer. Labour, farmer. Farm size, farmer. Farming equipment) →farmer. flow rate tolerance

The sensitivity of structures determines their impact on transient flows that enter the canal system (Renault et al., 2007). The sensitivity domain is characterised by the physical properties of the conveyance and distribution system and is therefore constant for an existing infrastructure system. The proposed relation type is therefore as follows:

(location. conveyance structure physical characteristics, location. regulating structure physical characteristics, location. offtake structure physical characteristics, location. informal division structure physical properties, location. informal regulating structure physical properties, location. expected degree of sedimentation, location. expected degree of vegetation) → location. sensitivity domain

Renault et al. (2007) defines a perturbation as a significant change in ongoing discharge. These changes may arise from planned (i.e. during the implementation of an agreed water delivery schedule) or unplanned change (i.e. deviation from expected operating rules, placement of unauthorised objects such as rocks, unauthorised abstraction etc). The perturbation domain refers to the frequency and magnitude of perturbation events such as these occurring in a subsystem. Computation of the perturbation enables the evaluation of the stability of the service with respect to the demands.
(location. instantaneous flow, location. number of regulating structures, location. operation of offtakes, location. number of informal division structures, location. number of informal regulating structures, location. rainfall) → location. perturbation domain

These functional relations assume that decisions regarding the following variables would have been predetermined in consultation with the farmers at the scheme, as these inform the level of service that the farmers can expect to receive, and therefore the scheme operation and maintenance requirements, which have a cost implication to the farmers:

- losses;
- expected operation of river intake structure;
- expected vegetation at river intake structure;
- expected sedimentation at river intake structure;
- Mamuhohi overnight dam outlet expected operation;
- expected operation of offtakes;
- location. expected sedimentation;
- location. expected vegetation;
- farmer. crop type; and
- farmer. planting calendars.

The expected sedimentation and vegetation at various locations and operation requirements, define the farmer operations and maintenance performance targets or collective activities. The losses will be determined through baseline modelling, based on the assumptions made. Therefore, these variables would be constants in the model simulations, however, can be changed at the beginning of each simulation as desired and agreed with the farmers, as any change to these variables impacts on the achievable level of service. These influences on the operation and maintenance requirements are summarised in 7.4.

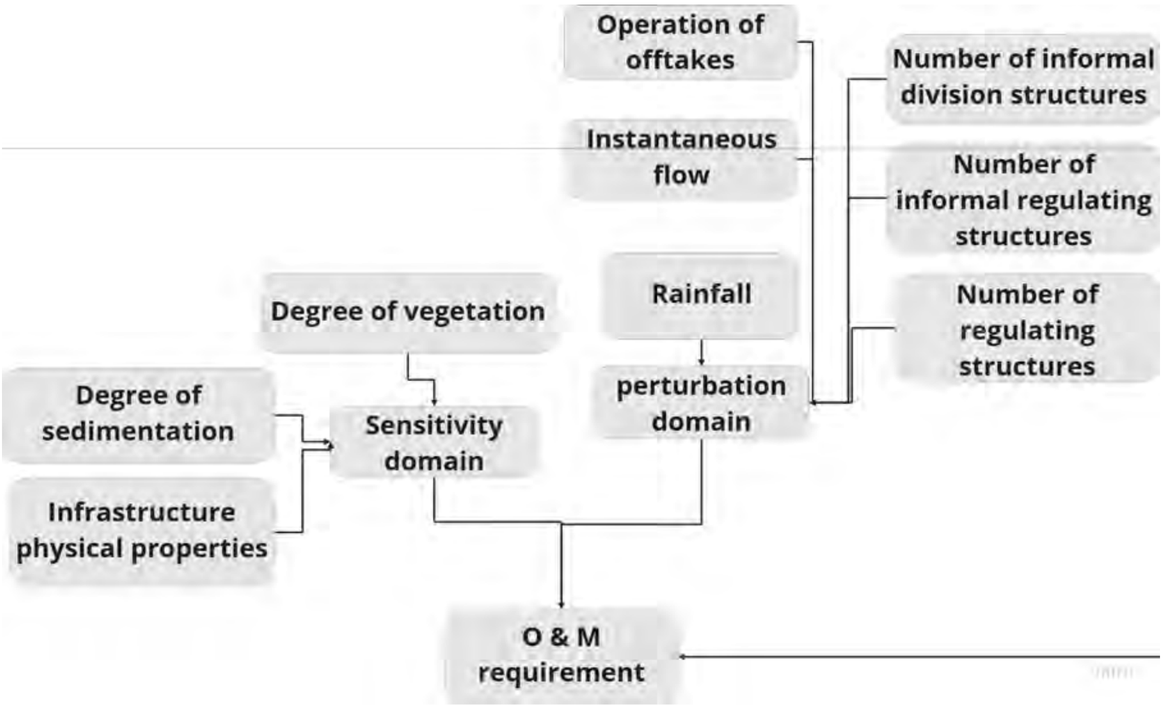

Figure 7.4: Variables influencing operation and maintenance requirements

7.3.1.2 *Actual operation and maintenance*

The constraints affecting the difference between the *scheme. operation and maintenance requirement* and the *scheme .actual operation and maintenance* and therefore the farmer satisfaction of expectation (*farmer. satisfaction*) are vast. For the purposes of this study, these are assumed to be limited to:

- the degree of sedimentation and vegetation;
- the variability of scheme inflow from the *expected diversions from Mutshedzi River*;
- climatic variability affecting the crop water requirements; and
- deviation from the expected operating of the river intake structures or offtakes leading to over or under appropriation; and

The proposed relation type for the actual scheme operations and maintenance is therefore as follows: (scheme. maintenance number of participants, scheme offtake/ river intake. operation) → scheme. actual O & M

The failure of infrastructure components (i.e. dam breach or canal failure) has not been included. The proposed process relationships for these variables are discussed further below.

Similar to the expected *diversions from Mutshedzi River* relation type, the proposed relation type for the variability in diversions from Mutshedzi River is as follows*:*
(Mutshedzi River flows, capacity of river intake structure, operation of river intake structure, vegetation at river intake structure, sedimentation at river intake structure) →variability in diversions from Mutshedzi River

The degree of sedimentation and vegetation and the operation of the river intake structure and farmer offtake structures are influenced by the number and intensity of farmers who participate in maintenance collective activities (Muchara, 2014).

Routine maintenance in this study refers to the removal of sedimentation and vegetation. Faulty cleaning and sediment accumulation in the canals leads to an increase in canal roughness and a reduction of the canal capacity, which increases the risk of operational losses. Continual use of irrigation systems requires farmers to routinely maintain the infrastructure, which involves collective action by plot holders. If too few farmers contribute towards this maintenance, then the capacity of the infrastructure to deliver water is reduced thereby increasing the risk of water shortage for farming (Yu et al., 2015 and Totin et al., 2014). Yu et al. (2015) refers to the point at which water shortage starts as the maintenance threshold, which is a function of the biophysical and natural environment.

The number and intensity of farmer participation in the control of sediment and vegetation is influenced by the farmer socio-economic attributes, institutional setting, the incentive system and the wider socio-economic context (i.e. market access, market volatility). Olson (1965) showed that successful participation of members in group activities depends on the expected benefits and costs.

The following relation type is therefore proposed for determining the number of participants in maintenance collective activities:
(farmer. satisfaction, farmer. socio-economic attributes, farmer. cost of participation in maintenance, farmer. expected benefits of participation in maintenance, farmer. benefits of nonparticipation in maintenance, scheme. rule enforcement efficacy, farmer. scheme mutualism, farmer. farming objective) → scheme. maintenance number of participants

The variables *farmer. expected benefits of participation in maintenance* and *farmer. benefits of nonparticipation in maintenance,* can be determined through scenario modelling. These inform the farmer incentives and disincentives respectively for participating in collective maintenance activities.

The assumed farmer socio-economic attributes influencing the level of participation of an individual farmer in maintenance are the farmer's age, health, gender, labour availability, equipment availability, off farm income, family size, crop yield and farm profitability.
(farmer. age, farmer. health, farmer. gender, farmer. labour, farmer. off farm income, farmer. equipment, farmer. family size, farmer. profitability, farmer. distance to canal) → farmer. socio-economic attributes

The profitability of each smallholder is a function of the agricultural income and their expenditure on agriculture represented as follows:
(farmer. income, farmer. expenditure) → farmer. profitability
The above relations can be expanded as follows:
(market volatility, farmer. market access, farmer. crop yield, farmer. crop percentage sold, farmer. labour costs, farmer. transportation costs, farmer. harvesting costs, farmer. other input costs, farmer. land fees, farmer. scheme fines, farmer. scheme membership fees) → farmer. profitability

According to the data analysis, three forms of land control are prevalent at the scheme, permission to occupy (PTO), ownership and leasehold. The land-related fees will therefore vary depending on each farmer's form of land control. Furthermore, the smallholders have three main markets with different benefits: bakkie traders, hawkers and local retailers. Therefore:
(market access. bakkie traders, market access. local retailers, market access. hawkers → farmer. market access

Studies by Fanadzo et al. (2009) and Moswetsi et al. (2017) suggest that the crop yields are a result of agronomic management practices. These include tillage practices, nutrient (fertiliser) management, soil characteristics, infield water (irrigation and rainfall) management, cultivar choice, planting dates, planting densities, plant protection as well as the interaction among these factors. The variables that influence smallholder crop yield are summarised into functional relationship as follows:
(location. adequacy of nutrients in soil, farmer. water supply efficiency) → farmer. crop yield

Repeated low crop yields lead to low levels of income and prevent farmers from purchasing labour, fertilisers or high yielding crop varieties that may otherwise help them to stabilise crop production (Pande and Sivapalan, 2017).

The target in the operation of smallholder canal schemes (SCS) is to deliver a certain volume of water at a flow rate that matches the needs of the user (Plusquellec et al., 1994). According to Pereira et al. (1996), the timing for irrigation and how much water to apply depends on the water needs of the crop, the availability of water to irrigate and the capacity of the root zone to store water, which changes throughout the life of the crop. The major factor amongst these being the crop water needs (Pereira et al., 1996, Brouwer and Prins, 1989). Brouwer and Prins (1989) define the water need of the crop as the crop water need minus the effective rainfall, usually expressed in millimetres per day or millimetres per month. Water supply efficiency is hypothesised to be a function of farmer water requirements (including crop water requirements and constraints posed by physical and socio-economic factors) and the actual water delivered.
(farmer. water requirements, farmer. water delivered) → farmer. water supply efficiency
A *farmer. water supply efficiency* significantly greater than 1 implies excessive irrigation, resulting in a reduction in crop yield.

The crop water need is the primary driver of *farmer. water requirements*. The crop water need or evapotranspiration is obtained as product of the crop area, the reference evapotranspiration and the crop coefficient. The crop coefficient is a function of the crop variety, growth stage and climate (i.e. temperature, rainfall, solar radiation, relative humidity, and wind speed) (Renault et al., 2007). However, *farmer. water requirements* are further complicated by differences in irrigation techniques, labour requirements, economic returns, vulnerability to service failures, bargaining power, status and gender divisions (Renault et al., 2007).
(crop. type, crop. growth stage, farmer. plot size, climate, famer. tillage practices, farmer. cropping pattern, farmer. socio-economic attributes) → farmer. water requirements

The water delivered to each smallholder is a function of the volume delivered at each offtake, the number of farmers served by the offtake and the distribution losses, similar to the expected appropriated volume:
(location. instantaneous flow, scheme offtake. operation, scheme offtake. regulating structure physical properties, scheme offtake. number of farmers, scheme furrow. distribution losses) → farmer. water delivered

Error Figure 7.5 illustrates the factors assumed to be influencing the water delivered to the farmers.

The instantaneous flow is similar to the expected instantaneous flow, and is a function of the water inputs and outputs from the main canal system as follows:
(diversions from Mutshedzi River, Mamuhohi. releases from overnight storage dam, losses. Seepage, losses. Leakage, losses. Evaporation, losses. Operational, canal system capacity, farmer. water delivered, nonfarmers. appropriated volume, location. number of farmers, location. number of nonfarmers) → location. instantaneous flow

The canal system capacity determines the maximum water that can be supplied, losses from the system, based on the interconnectivity of the system weak points, bottlenecks and/or areas of deficiencies. The proposed relation type for the canal system capacity is similar to the expected canal system capacity, as follows:
(infrastructure physical characteristics, location. degree of sedimentation, location. degree of vegetation, functionality of infrastructure components, freeboard) → location. canal system capacity

From the site visit, unauthorised withdrawals are an important source of loss from the system. It is proposed that the level of these withdrawals is related to the effectiveness of the scheme committee to enforce rules and regulations and the consequences of complying and not complying to the operation and maintenance (O& M) requirements as follows:
(scheme. O&M requirements, farmer. cost of participation in regulation, farmer. benefit of participation in regulation, farmer. benefit of nonparticipation, scheme. rule enforcement efficacy) → scheme offtake. operation

Operational losses from a canal system are caused by the incorrect setting of gates, lack of gate adjustment over time etc. They are affected by the canal system operating protocol, infrastructure lag time, perturbations and degree of sedimentation and vegetation.
(scheme offtake. operation, location. sensitivity domain, location. perturbation domain) → losses. operational

It is hypothesised that the crop percentage sold is function of the farming objective or orientation (i.e. subsistence or commercial), the family size determining food security requirements and the farmer's off farm income as follows:
(farmer. farming objective, farmer. family size, farmer. off farm income) → farmer. crop percentage sold

It is assumed that the percentage crop that is not sold or failed, is consumed at household level.
Higher yields mean greater nutrient uptake by crops since nutrient uptake is roughly proportional to crop yield (Fanadzo et al. (2009). Therefore, the nutrients in the soil and the crop yield are assumed to be co – dependant. Furthermore, excessive irrigation stimulates excessive vegetative growth, impairs the quality of produce and leaches out nutrients from soil (Whitemore, 2000, Annandale et al., 2011).

These nutrients need to be replenished:
(location. crop yield, location. nutrient replenishment, farmer. water supply efficiency) → location. adequacy of nutrients in soil

Members participate in collective activities through contributing labour, finance, decision making, information dissemination as well as regulation and control to encourage a sense of ownership and responsibility (Muchara et al., 2014). The cost of participation in maintenance is therefore labour, financial and/or time. The proposed relation type is therefore as follows:
(farmer. maintenance equipment, farmer. labour costs, farmer. financial contribution, farmer. maintenance time, farmer. maintenance frequency) → farmer. cost of participation in maintenance

The allocated water volume, delivery schedule and the water delivery rate are proposed to be the direct benefits received by the farmers as a consequence of participation in operation and maintenance activities, based on the agreed level of service. A similar relationship can be derived for the benefits of nonparticipation in collective activities (assuming a high degree of sedimentation and vegetation and no operation of the offtake structure) as defined below:
(allocation of water, location. water delivery rate, location. irrigation delivery schedule) → farmer. benefits of participation/ farmer. benefits of nonparticipation

According to Muchara (2014), farmer behaviour at the schemes is to a large degree influenced by formal and informal institutions present at the scheme. These institutions define the rules that guard water extraction and enforce order in the maintenance of scheme resources for sustainable use (Akuriba et al., 2018). They structure social interaction by constraining and enabling actors' behaviour (Helmke and Levitsky, 2004). Institutions therefore play a very important role for cooperative behaviour and can

create incentives that motivate or demotivate individual farmers to contribute to the collective maintenance of irrigation infrastructure (Totin et al., 2014). Farmers pursuing individual goals instead of collective goals challenge institutions and erode organisations of irrigator communities (van Averbeke et al., 2011, Fanadzo and Ncube, 2018). The efficacy of rule enforcement is therefore assumed to be influenced by the monitoring effectiveness of the scheme committee, the sanctioning effectiveness, the farmers farming objective and scheme mutualism:
(scheme. water monitoring effectiveness, scheme. sanctioning effectiveness) → scheme. rule enforcement efficacy

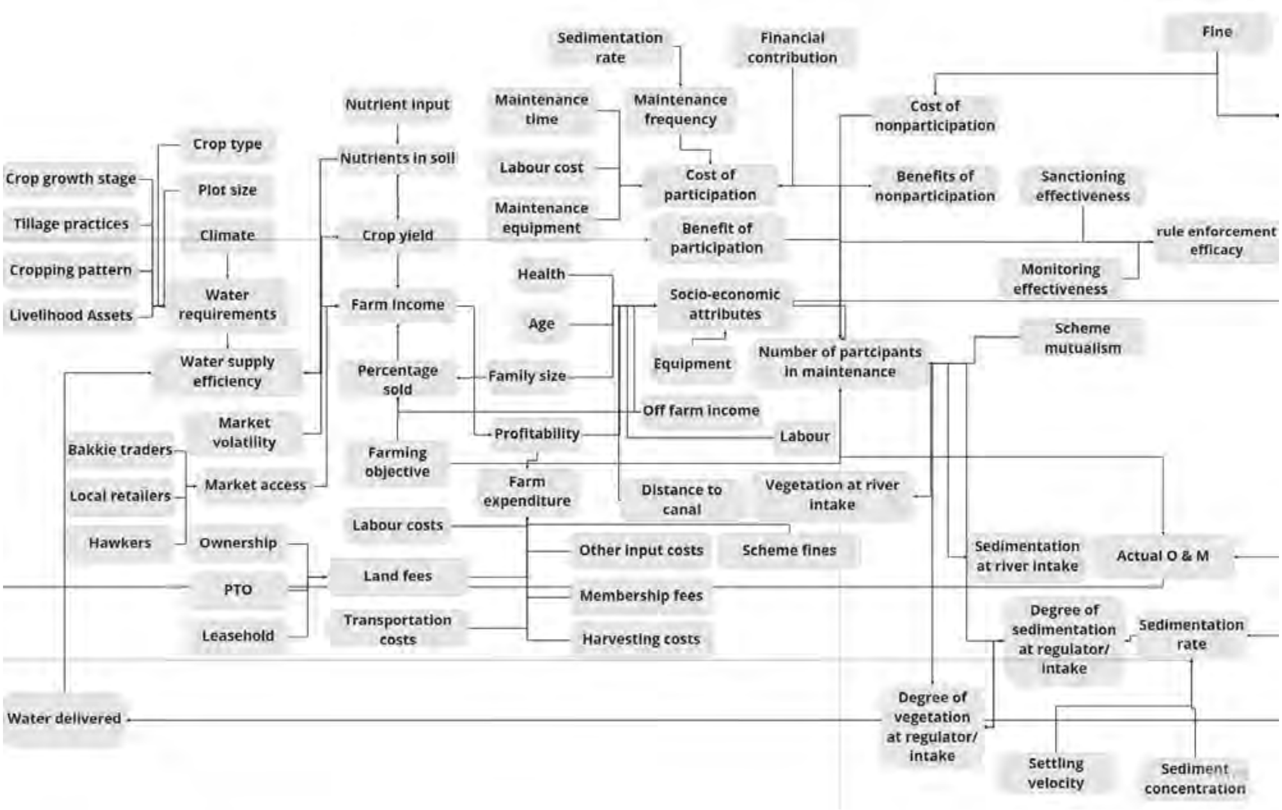

Figure 7.5: Variables influencing water delivered

Similarly to the relation types used to determine the number of participants in maintenance collective activities, variables assumed to be influencing the number of participants in regulation collective activities are socio-economic attributes, institutional setting and the expected benefits and costs:
(farmer. satisfaction, farmer. socio-economic attributes, farmer. cost of participation in regulation, farmer. cost of nonparticipation in regulation, farmer. expected benefits of participation in regulation, farmer. benefits of nonparticipation in regulation, scheme. rule enforcement efficacy) → farmer. number participating in regulation

In this case, nonparticipation in regulation, could mean that the farmers at any specific offtake, keep their offtake open at all times.

Similarly, the *farmer. expected benefits of participation* in regulation and *farmer. benefits of nonparticipation in regulation*, can be determined through scenario modelling. The farmer cost of participation in regulation relation is assumed to be similar to the farmer cost of maintenance as follows:
(farmer. regulation equipment, farmer. labour costs, farmer. financial contribution, farmer. regulation time, farmer. regulation frequency) →farmer. cost of participation in regulation
Similar to the operation of each offtake, the operation of the river intake can be written as follows:

(expected diversions from Mutshedzi River, farmer. cost of participation in regulating intake structure, farmer. benefit of participation in regulating intake structure, farmer. benefit of nonparticipation in regulating river intake, scheme. rule enforcement efficacy) → river intake. Operation

Error! Figure 7.6 illustrates the variables influencing the operation of the river intake.

The *farmer. cost of participation in regulating intake structure* is the same as *farmer. cost of participation in regulation*, only difference being that in the former, the cost is associated just with the river intake structure. The variables *farmer. benefit of participation in regulating intake structure* and *farmer. benefit of nonparticipation in regulating river intake* can also be obtained through scenario modelling.

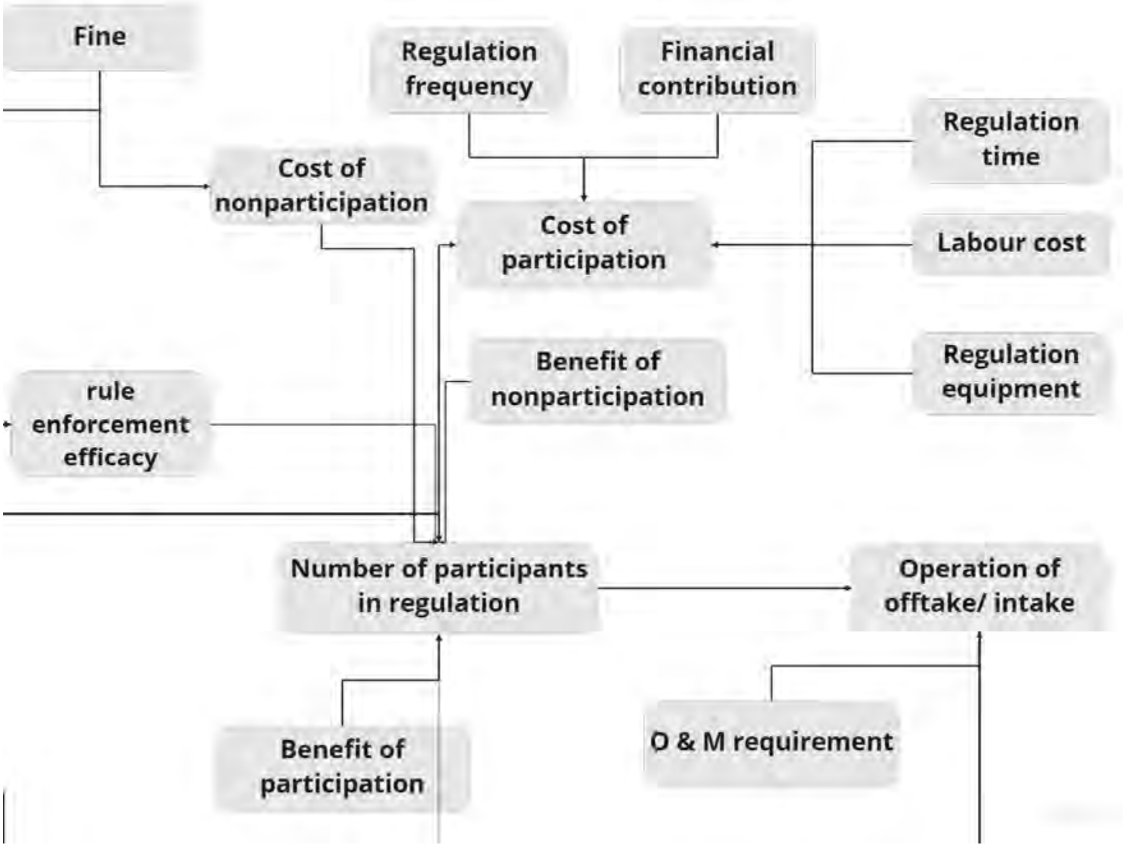

Figure 7.6: Variables influencing operation of offtake or river intake

Fine sediments settle on the beds of the smaller canals in many runoff river irrigation schemes. Sedimentation affects the operation of schemes by reducing discharge capacities and raising water levels (Renault et al., 2007). Consequently, sedimentation is a key determinant of canal system capacity and has to be removed periodically to maintain irrigation supplies.

The proposed relation types to explain sedimentation are as follows:
(location. operation of offtakes, location. instantaneous flow, sediment. settling velocity range, sediment. concentration) → location. sedimentation rate
(scheme. maintenance number of participants, location. sedimentation rate) → location. degree of sedimentation

Similarly, the degree of sedimentation at the river intake is determined as follows:

(scheme. maintenance number of participants, river intake. operation, sediment. settling velocity range, sediment. concentration, intake structure characteristics, variability in diversions from Mutshedzi River) → river intake. degree of sedimentation

Vegetation increases the overall flow resistance and reduces the shear stress applied to the bed, resulting in reduced capacity of bed-load transport and increased propensity for trapping, deposition, and stabilisation of sediment (Renault et al., 2007). Therefore, there is also a co-dependency between sedimentation and vegetation.

Location. degree of sedimentation ↔ location. degree of vegetation

River intake. degree of sedimentation ↔ river intake. degree of vegetation

7.3.2 Conceptual modelling influence diagram

The resulting processes explaining the changes in the state variables are illustrated in Figure 7.7. The exogeneous variables and constants impacting these state variables are illustrated in Figures 7.1 to Figure 7.6. The model structure will be refined further during data analysis should the results indicate that the relationships are not as currently hypothesised.

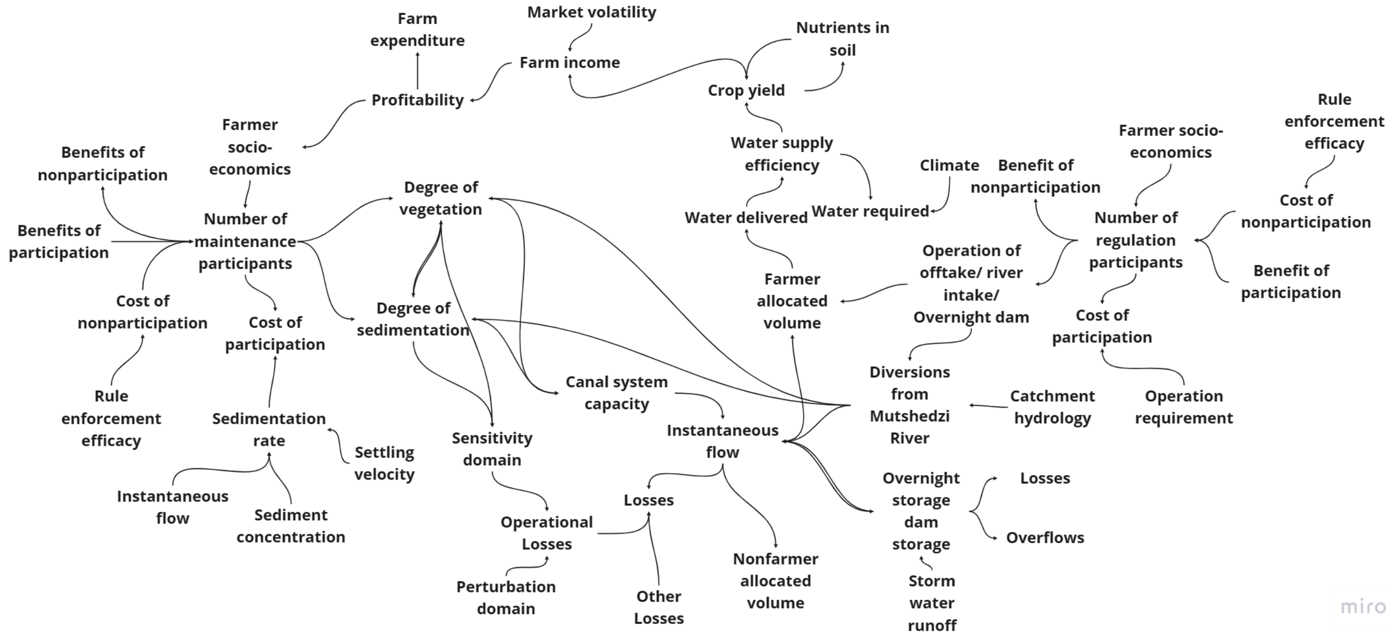

Figure 7.7: Influence diagram based on defined relations (second stage variable text in red)

The model setup aims to strike a balance between the level of service expected by the farmers and their involvement in collective activities (i.e. operation and maintenance), which has an associated cost. This is aligned with the recommendations of Ostrom (1993), stating that the rules affecting appropriation and provision be modelled as a bargaining problem.

In the model, the farmer. satisfaction is hypothesised to be a function of the scheme. operation and maintenance requirement and the scheme. actual operation and maintenance activities taking place at the scheme. The scheme. operation and maintenance requirement is informed by the farmer. agreed level of service, location. perturbation domain and location. sensitivity domain, defined by farmer. water requirements, the operation and maintenance targets and the climate. The operation and maintenance targets are defined by the location. expected degree of sedimentation, location. expected degree of vegetation and the farmer operation requirements (scheme offtake. operation, river intake. operation, overnight dam. operation etc). These prescribe the operation and maintenance collective activities expected from the farmers (ie. the cost of involvement in collective activities) and the quality of water delivery expected by the farmer (i.e. the benefits of involvement in collective activities).

In order to ensure that the quality of water delivery expected by the farmers is realistic for forecasting purposes, the water quality expected by the farmers' first needs to be determined based on realistic operation and maintenance targets determined in consultation with the scheme farmers. These, together with the scheme catchment hydrology, which determines the capacity of the resource system, the user population (farmers and nonfarmers), the farmer socioeconomics and the infrastructure physical characteristics will then be used to determine the farmer. agreed level of service.

The *scheme. actual operation and maintenance* activities are hypothesised to be influenced by the variability of the catchment hydrology, changes in the climate and the involvement and behaviour of the farmers towards collective activities. At scheme level, only the involvement and behaviour of the farmers can be influenced as the climate and catchment hydrology are assumed to be exogeneous variables.

The involvement and behaviour of the farmers in scheme collective activities is hypothesised to be influenced by the farmer's socio-economic attributes, the farmers satisfaction with the level of service in the previous period, the institutional setting, the incentive system and wider socio-economic factors (i.e. market volatility, market access). The incentive system depends on the expected benefits (i.e. water supply efficiency) which can be determined for participating and nonparticipating farmers through scenario modelling, and the cost of participating, dependent on the intensity of participation required, or the cost of nonparticipation dependent on the rule enforcement efficacy of the scheme committee.

The institution setting is determined by the scheme committee which defines the operating and maintenance protocol (i.e. *scheme offtake. operation*) informed by the *farmer. agreed level of service* and the *scheme. rule enforcement efficacy* limiting unauthorised withdrawals and operational losses, caused by the nonadherence of farmers to the set operating protocol and maintenance targets (i.e. expected degree of sedimentation and vegetation) respectively.

The envisioned modelling process therefore has two stages as illustrated in Figure 7.7. In the first stage the *farmer .agreed level of service* is determined and the benefits of participation and nonparticipation (i.e. the expected quality of water delivery) are evaluated, excluding the behavioural and institutional factors, and solely based on assumed operational and maintenance targets. In the second stage, behavioural and institutional factors (i.e. number of maintenance participants, number of regulation participants) are included in the calibrated model produced in the first stage, and the model can then be used as a forecasting tool to assess whether the quality of water delivery after each model run meets the *farmer. satisfaction* and how the scheme sustainability is affected.

8 OPPORTUNITIES TO IMPROVE SMALLHOLDER CANAL SCHEMES SUSTAINABILITY AND APPLICABILITY OF SOCIO-HYDROLOGIC MODELLING

8.1 Aim and structure of chapter

Aim of the chapter
The main aim of this chapter is to describe the process taken to seek opportunities to improve smallholder canal schemes sustainability and the applicability of socio – hydrologic modelling for this. The opportunities for improving governance for improved scheme performance are also presented in this Section.

Structure of the chapter
This chapter contains six sections. Section 1 presents the aim and structure of the current chapter while section 2 informs about the search for quantitative socio-hydrologic relationships for the implementation of the socio-hydrologic conceptual model described in Chapter 7 and how the modelling was modified after it was found that realistic quantitative socio-hydrologic relationships could not be obtained from the field survey data. Section 3 describes the hydrologic analysis for determining the expected water supply inflows into the study schemes while Section 4 presents the hydraulic analysis of scheme water supply to determine water distribution for three scenarios that align to varying states of scheme governance and management. The crafting of the scenarios and the hydraulic modelling was conducted in a manner that enabled the search for opportunities to improve scheme performance and sustainability. In Section 5, the impact of the improvements proposed in the scenarios on crop water availability on the farms is presented. Finally in section 6, the existing state of governance in the schemes and the opportunities proposed for improving this are described.

8.2 Searching for quantitative socio-hydrologic relationships

8.2.1 Introduction

The socio-hydrologic conceptual modelling formulated in Chapter 7 required several quantitative causal relationships that span across social, governance, hydraulic and hydrologic aspects. These relationships needed to be mainly based on the data obtained from the field survey (Chapter 6), the intuitive understanding of the expected inter-relationships among the variables, and from socio-hydrologic and related literature. The data and other information were obtained from field survey interviews and not actual records and the quantitative ones are therefore effectively approximated estimates are referred to as reported and not measured. Due to various constraints and situations in field data collection, there were considerable gaps in data and assessment of data consistency led to exclusion of some of the collected. The attempt to formulate quantitative socio-hydrologic relationships from these data was therefore substantially constrained. In particular, the data on actual water supply levels to individual farmers was found to be inconsistent and not suitable for quantitative modelling.

The modelling attempts took on statistical approaches using Multiple Linear Regression and Path Analysis and conceptual modelling calibrated using a genetic algorithm optimiser. It was tried on the relationships for which data that were considered amenable to quantitative modelling as opposed to more subjective data obtained from ranking on defined scales. Since the variables involved have highly varied dimensions and numerical values, the data were first normalised by dividing each data values with the average value of the respective data type. The normalised modelled output data were then obtained by scaling back by multiplication with the corresponding average value. Out of the three, the conceptual modelling obtained better performance the modelling of crop yield, annual income and annual expenses is described. The implications of the quantitative modelling on the socio-hydrologic modelling of the SIS schemes concludes this section.

8.2.2 Modelling crop yield

Crop yields were reported for summer and for winter separately and were considered to depend on the level of training of the farmer, the labour available, the plot size, the level of fertiliser application and the types of crops grown. Based on the understanding of how each of these variables could impact on the yield, and the form in which data were recorded, the model described in equation 8.1 was formulated.

$$y = \frac{C(x_1 - m_1)^{e_1}(x_2 - m_2)^{e_2}(x_3 - m_3)^{e_3}(x_4 - m_4)^{e_4}}{\times} \atop (w_5x_5 + wx_6 + wx_7 + w_8x_8 + w_9x_9)^{e_{59}} \left(\frac{s_{10}}{x_{10}}\right)^{e_{10}} \quad (8.1)$$

Where y is the crop yield, x_1 is the overall farmer training score, x_2 is the total labour in winter (sum of casual, family and permanent labour), x_3 is the size of plot, x_4 is the fertiliser use in summer, x_5, x_6, x_7, x_8, and x_9 are the areal proportions of maize, potatoes, beans, butternut and other crops(sweet potatoes, nuts, sugarcane, cabbage, onions, tomatoes, spinach) grown respectively, and x_{10} is an indicator of the distance from the Raliphaswa weir to the farm lumped to sub-scheme level.

The modelling recognises that the crop yield may not relate in simple direct proportion to the variables considered to impact on it by allowing for non-zero central tendency using parameters m_1, m_2, m_3 and m_4 and exponents e_1, e_2, e_3, e_4, e_{59} and e_{10}. In addition, the modelling allows for variable proportions of contributions of different crops to yield using the weighting factors w_5, w_6, w_7, w_8 and w_9 that sum up to unity (1.0). Increasing distance from the Raliphaswa weir is considered to disadvantage crop yield as the common problem of lower water supply levels for downstream farmers was reported in the field survey and was verified in the hydraulic analysis of the SIS. Farms in Raliphaswa, Mandiwana and Mamuhohi were assigned distances of 1, 2 and 3 respectively.

There were many gaps in the data and very few of the individual farmers' data were complete (contained all variables x_i, (i=1 to 10)) and a method to enable the use of the incomplete data was required. For the multiplicative components (relating to x_1, x_2, x_3, x_4, and x_{10}), missing data led to the assignment of the neutral value of unity (1.0) for the respective sub-model (e.g. $(x_1\text{-}m_1)^{e1}$ = 1 if x_1 is missing). Given the short length of data, all the data available were used for calibrating (fitting) the model and no verification was carried out. The calibration applied the genetic algorithm optimiser embedded in MS Excel (solver) aimed at minimising the sum of the absolute differences between the modelled and the reported crop yields. Several calibration runs were conducted by varying the parameter search ranges and the parameter values obtained from two of these are presented in Tables 3.1 and 3.2 respectively for summer and winter.

For summer, multiple runs included those on Table 8.1 revealed that x_2 (total labour in winter), x_3 (size of plot), and x_4 (fertiliser use in summer) did not impact on crop yield as their corresponding exponents were negligible and the simplified model defined by equation 8.2 could be applied. In this model, crop yield in summer depends on the level of farmer training, the mix of crops grown and how far downstream from the weir the farm is located.

$$y = C(x_1 - m_1)^{e_1}(w_5x_5 + w_6x_6 + w_8x_8 + w_9x_9)^{e_{59}} \left(\frac{s_{10}}{x_{10}}\right)^{e_{10}} \quad (8.2)$$

Table 8.1 Calibrated parameter values for crop yield modelling in summer

Parameter	Run 1			Run 2		
	Search range limits			Search range limits		
	Lower	Upper	Calibrated value	Lower	Upper	Calibrated value
C	0	2	0.751	0	3	0.920
e_1	0	2	0.405	0	3	0.187
e_2 *	0	2	0.014	0	3	0.041
e_3	0	1	0.000	0	1	0.000
e_4	0	3	0.044	0	3	0.027
e_{59}	0	2	1.161	0	3	1.693
e_{10}	0.5	1.5	0.759	0.5	1.5	0.704
w_5	0	1	0.171	0	1	0.195
w_6	0	1	0.457	0	1	0.369
w_7	0	1	0.056	0	1	0.082
w_8	0	1	0.192	0	1	0.211
w_9	0	1	0.124	0	1	0.143
m_1	-5	5	-0.396	-5	5	-0.019
m_2	-5	5	0.242	-5	5	0.209
m_3	0	1	0.901	0	1	0.859
m_4	-5	5	-4.761	-5	5	-0.846
s_{10}	0	3	1.164	0	3	0.963

e_2 * Parameters shaded in grey are considered redundant

The modelling performance is illustrated in the comparison between modelled and reported summer crop yield on Figure 8.1. It reveals large scatter for the complete range of yields and the failure to model yields beyond 2000 kg.

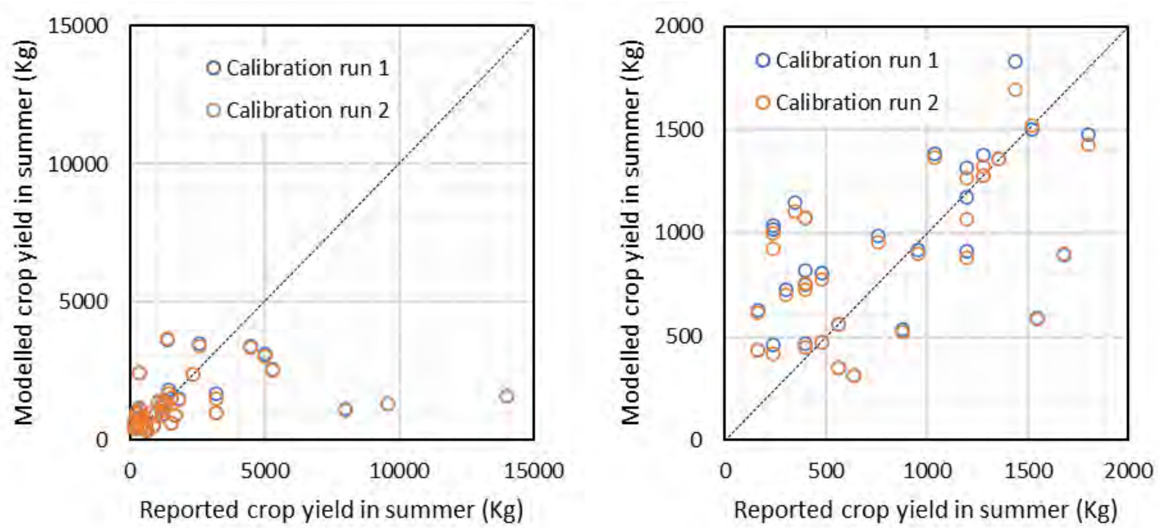

Figure 8.1 Calibrated parameter values for crop yield modelling in summer

Table 8.2 Calibrated parameter values for crop yield modelling in winter

Parameter	Calibration run 1			Calibration run 2		
	Search range limits		Calibrated value	Search range limits		Calibrated value
	Lower	Upper		Lower	Upper	
C	0	3	0.793	0	4	0.847
e_1 *	0	3	0.049	0	4	0.290
e_2 **	0	3	0.013	0	4	0.028
e_3	0	3	0.000	0	4	0.015
e_4	0	3	1.227	0	4	1.381
e_{59}	0	3	1.931	0	4	2.035
e_{10}	0	3	0.559	0	4	0.700
w_5	0	1	0.269	0	1	0.223
w_6	0	1	0.252	0	1	0.256
w_7	0	1	0.244	0	1	0.238
w_8	0	1	0.126	0	1	0.202
w_9	0	1	0.110	0	1	0.081
m_1	-5	5	0.020	-5	5	-0.271
m_2	-5	5	-2.727	-5	5	-4.220
m_3	0	1	0.782	0	1	0.532
m_4	-5	5	-0.050	-5	5	-0.102
s_{10}	0.5	1.5	0.554	0.1	3	0.388

***e_1* *** Parameters shaded in green are significant in one run but not the other

e_2 ** Parameters shaded in grey are considered redundant

For winter, Table 8.2 reveals that fertiliser usage impacts on crop yield since exponent ***e_4*** takes on significant values unlike in winter (Table 8.1). Parameters ***e_1*** and ***m_1*** related to farming training were significant in some runs (e.g. run 1) but not in others (e.g. run 2). The simplified model for winter crop yield could take the form of equation 8.3.

$$y = C(x_1 - m_1)^{e_1}(x_4 - m_4)^{e_4}(w_5x_5 + w_6x_6 + w_8x_8 + w_9x_9)^{e_{59}} \left(\frac{s_{10}}{x_{10}}\right)^{e_{10}} \quad (8.3)$$

Figure 8.2 shows a comparison between the modelled and the reported winter crop yield revealing, as for summer, a wide scatter and under-estimation of many of the crop yields exceeding 2000 kg.

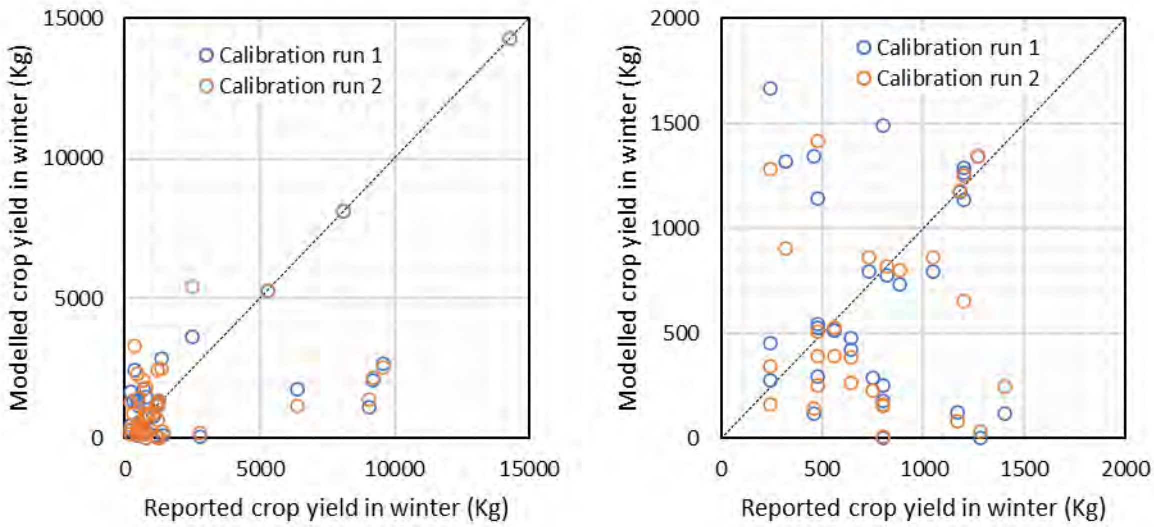

Figure 8.2 Comparison of modelled and report crop yield in winter

8.2.3 Modelling annual income

The annual income received by an individual farmer from agricultural production was considered to depend on the size of household, the size of labour, the size of the plot, the annual fertiliser use, the annual produce, and the farmer's marketing skills. The model for the annual income therefore took the form:

$$y = C\prod_{i=1}^{6}(x_i - m_i)^{e_i} \quad (8.4)$$

Where y is the annual income received from agricultural production, x_1 is the number of household members, x_2 is the number of individuals available for labour, x_3 is the size of the plot, x_4 is the annual fertiliser use, x_5 is the annual produce, and x_6 is the marketing skills score.

The parameter values of two calibration runs of this model presented on Table 8.3 indicate that household, labour, and plot size do not relate significantly to annual income as their respective exponents e_1, e_2 and e_3 were close to zero. A simplified model of annual income based on fertiliser use, annual production and marketing skills is thus:

$$y = C\prod_{i=4}^{6}(x_i - m_i)^{e_i} \quad (8.5)$$

It is however noted that fertiliser usage could probably be excluded from the model as it is expected to more directly relate to annual produce which is also a variable of the model.

Table 8.3 Calibrated parameter values for annual income modelling

Parameter	Calibration Run 1			Calibration Run 2		
	Lower limit	Upper limit	Value	Lower limit	Upper limit	Value
C	0	1.5	0.231	0.4	1.5	0.688
e_1	0	1.5	0.002	0	1.5	0.000
e_2	0	1.5	0.000	0	1.5	0.000
e_3	0	1.5	0.000	0	1.5	0.000
e_4	0	1.5	0.999	0	1.5	0.495
e_5	0	1.5	0.309	0	1.5	0.465
e_6	0	1.5	0.377	0	1.5	0.000
m_1	-5	5.	-2.349	-5	5	-4.061
m_2	-5	5.	-3.951	-5	5	-1.725
m_3	-0.2	0.2	-0.200	-0.4	0.4	-0.110

m_4	-5	5	-0.536	-5	5	0.046
m_5	-5	5	0.036	-5	5	0.021
m_6	-5	5	-2.334	-5	5	-0.092

e₁ ** Parameters shaded in grey are considered redundant

e₆ * Parameters shaded in green are significant in one run but not the other

The annual income modelling performance shown on Figure 8.3 reveals large scatter and large under-estimation of annual incomes exceeding R 10 000.

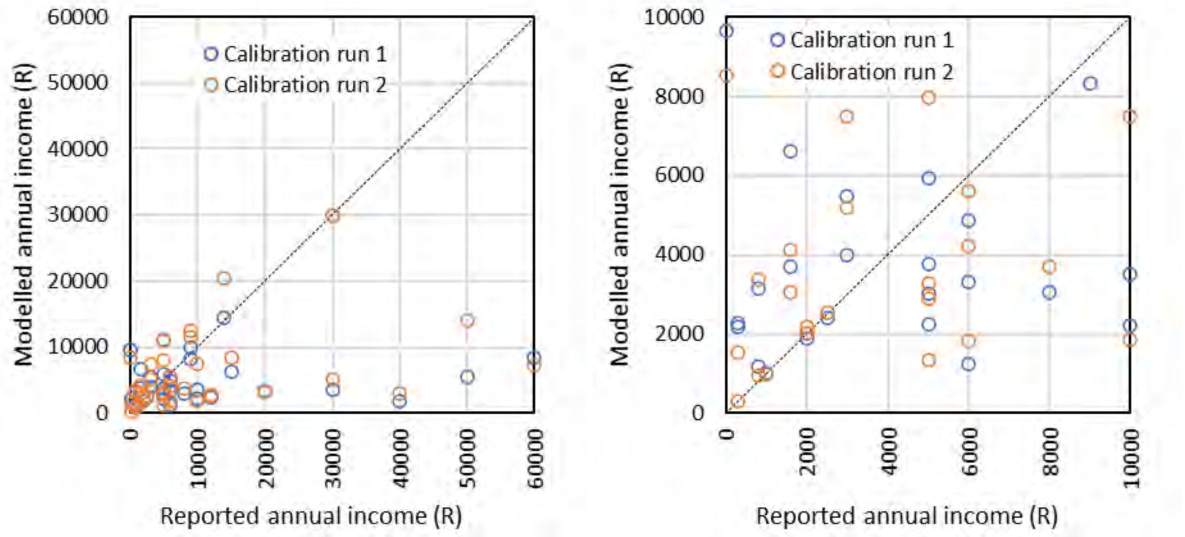

Figure 8.3 Comparison of modelled and report annual income

8.2.4 Modelling annual expenditure

The annual farming expenditure was assumed to depend on household size, labour size, plot size, annual fertiliser use, annual produce, and the farmer's marketing skills. These variables were however considered to mainly impact on expenditure additively and not multiplicatively as for annual income. High marketing skills were expected to reduce expenses in marketing and selling produce and were modelled as subtractive. For this additive modelling scaling parameters (s_i) therefore replaced the exponential parameters included in the previous models (equations 8.1 to 8.5). The model for annual expenditure took the form:

$$y = \sum_{i=1}^{5} s_i(x_i - m_i) - s_6(x_6 - m_6) \qquad (8.6)$$

Where y is the annual income received from agricultural production, x_1 is the number of household members, x_2 is the number of individuals available for labour, x_3 is the size of the plot, x_4 is the annual fertiliser use, x_5 is the annual produce, and x_6 is the marketing skills score.

Parameter values from multiple calibration runs including the two shown on Table 8.4 indicated that only the size of plot and the annual fertiliser usage significantly impacted on the reported annual expenditure. This led to the simpler model defined by equation 8.7.

$$y = s_3(x_3 - m_3) + s_4(x_4 - m_4) \qquad (8.7)$$

The modelling performance and features illustrated graphically on Figure 8.4 are similar to those of annual income modelling; large scatter, meaning low predictive ability, and gross under-estimation of annual expenses higher than R 5000. Figure 8.4 also reveals the general over-estimation of annual expenditure for expenses below R 5000.

Although the value of the calibrated scaling parameters s_i (in Table 8.4) have been used to inform which of the independent variables are significant, an alternative approach involves determining the values of the six additive components of the model (equation 8.6) and their variation for the all the modelling data points (56 farmers). A graphical illustration of this approach presented on Figure 8.5 shows that additive components for labour size and plot size are significant and vary substantially for different farmers.

These two variables could therefore be retained in the original model. Figure 8.5 reveals very low values for the modelling sub-components for household size and marketing skills and these variables could therefore be excluded from the model. This approach could also be applied for the models for crop yield and housing income.

Table 8.4 Calibrated parameter values for annual expenditure modelling

Parameter	Search range limits		Value from calibration	
	Lower limit	Upper limit	Run 1	Run 2
s_1	0	5	0.000	0.003
s_2	0	5	0.061	0.043
s_3	0	5	0.414	0.173
s_4	0	5	0.172	0.106
s_5	0	5	0.047	0.079
s_6	0	3	0.066	0.008
m_1	-5	5	-4.776	-2.446
m_2	-5	5	0.060	-1.131
m_3	-5	5	0.230	-1.449
m_4	-5	5	0.525	-1.533
m_5	-5	5	-0.115	0.074
m_6	-10 (Run 1), -5(Run 2)	5	5.000	0.359

s_1 ** Parameters shaded in grey are considered redundant

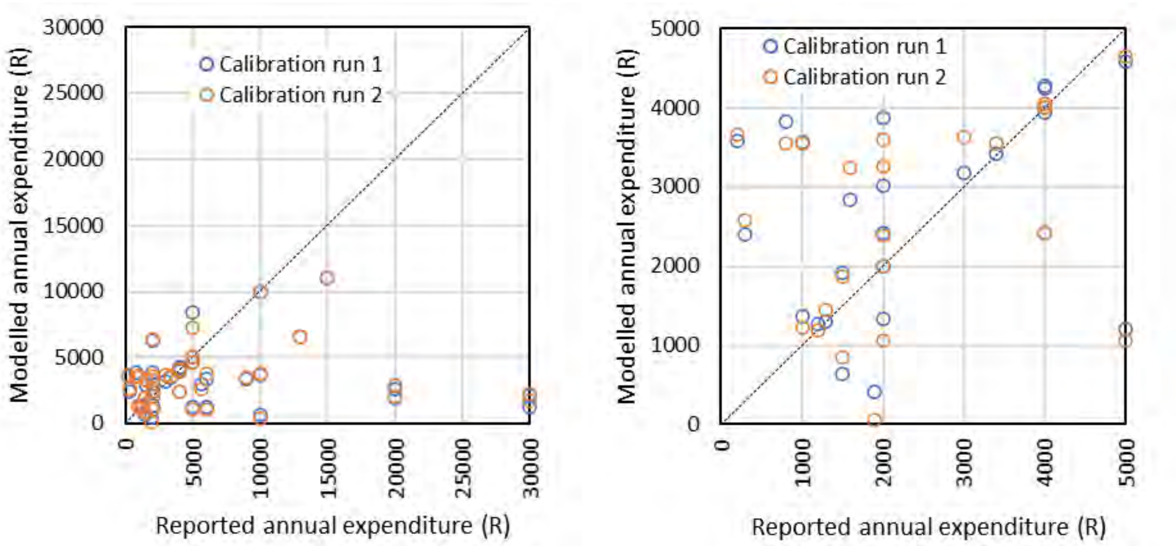

Figure 8.4 Comparison of modelled and report annual expenditure

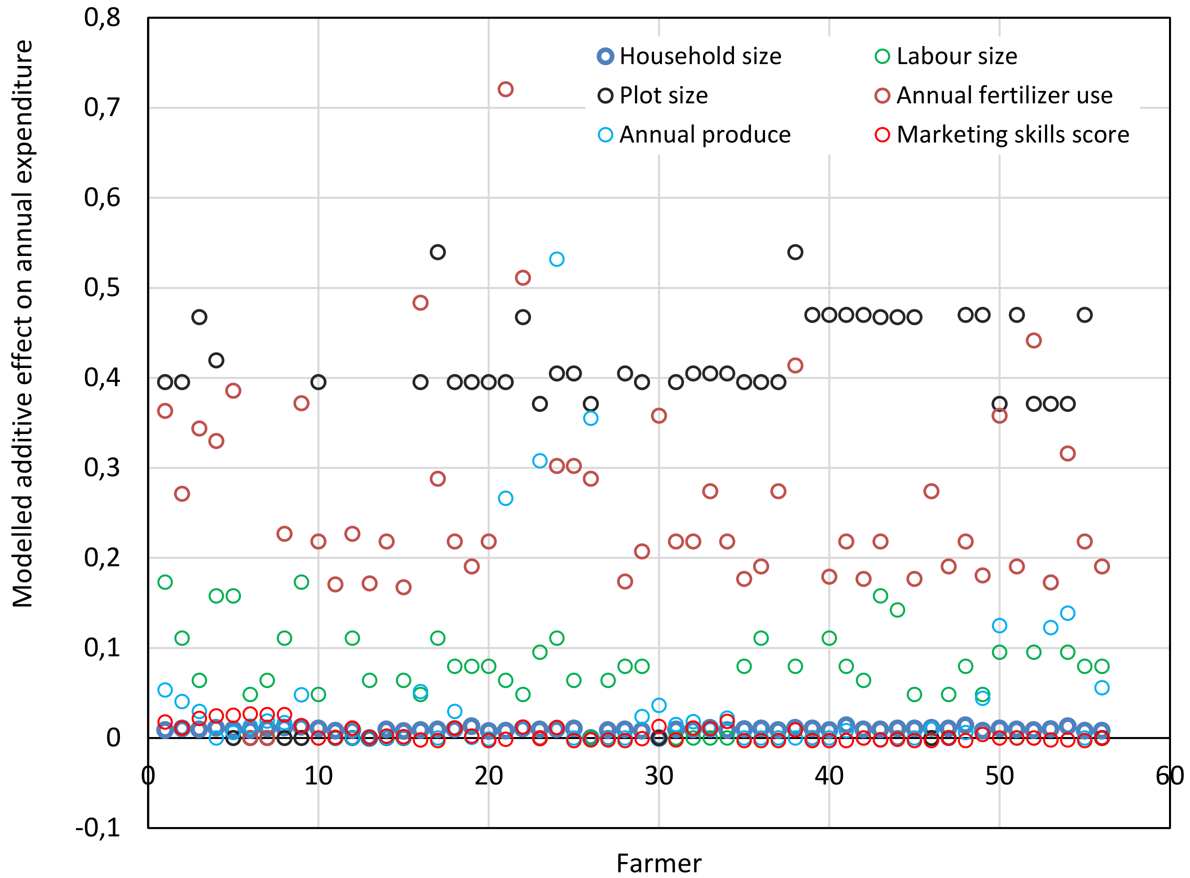

Figure 8.5 Variation of modelled additive effects of variables on annual expenditure

8.2.5 Updating socio-hydrologic modelling approach

The attempt to obtain realistic socio-hydrologic relationships from the field survey data was not successful as the comparison of modelled and reported field data on Figures 8.1 to 8.4 shows. The models described in sections 8.2.2 to 8.2.4 were themselves the most successful out of many others that were attempted. Given this result, the conceptual socio-hydrologic modelling approach proposed in Chapter 7 could therefore not be implemented in that form as the quantitative causal relationships required for the approach were not obtainable.

Since the social (or human) aspects relating to governance and management impact on the operation, maintenance and adequacy of infrastructure of the scheme, these could be used as a surrogate for the social (human) aspects. it was therefore decided to incorporate the social aspects into the analysis by undertaking scenarios of hydrologic/hydraulic modelling that correspond to various levels of adequacy of operation, maintenance and infrastructure of the study schemes. Three scenarios, one corresponding to the current state, another one involving moderate improvements, and a scenario with comprehensive improvements of operation, maintenance and SIS infrastructure were formulated to affect the indirect inclusion of social factors into the quantitative hydrologic and hydraulic modelling.

8.3 Determining expected inflows into study schemes

Just as for other water resource systems, natural hydrologic variability that includes periods of low, normal, and high rainfalls at various time scales impact the study SIS. The available inflows into the schemes needs to be expressed statistically and not as a single long-term average. The hydrologic data available in and around the catchment (Figure 8.6) in which the schemes are located have been described in detail in Section 4.3 of Chapter 4. These data were applied to determine the expected flows into the scheme.

The Department of Water and Sanitation (DWS) provided monthly water balance for Mutshedzi dam from September 1996 to January 2022 and this provided the total water release from the dam. These consisted both controlled and uncontrolled flows through the spillway.

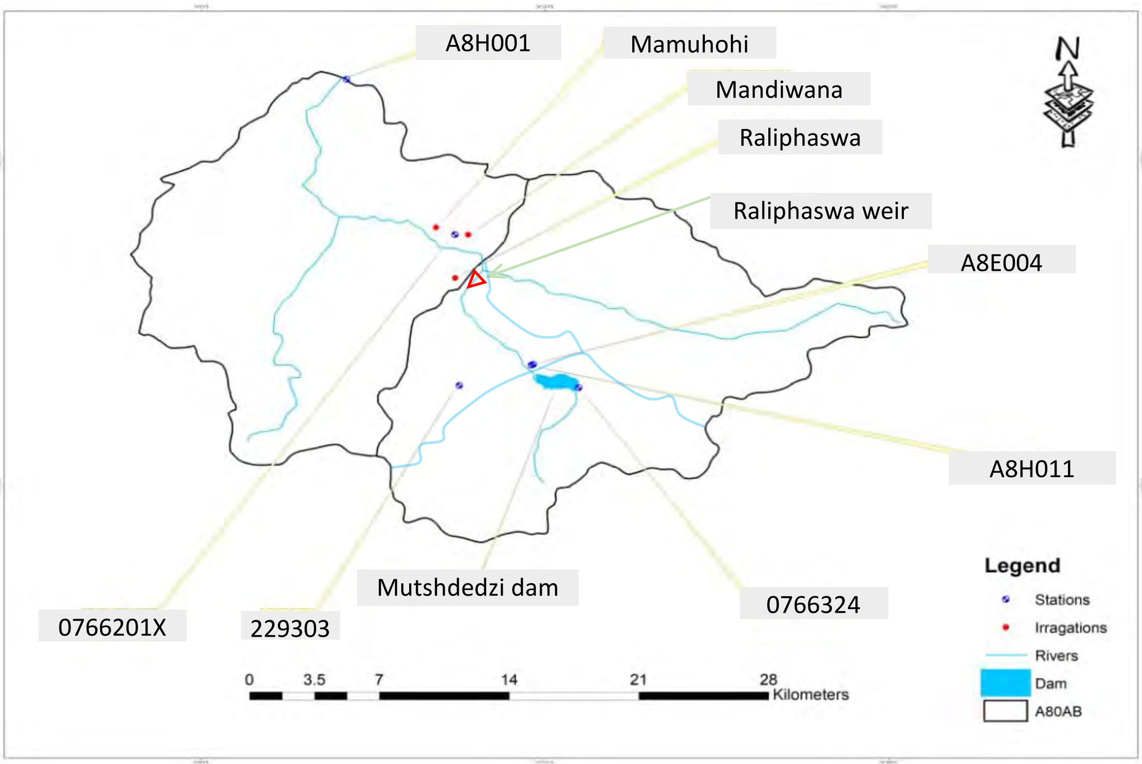

Figure 8.6: Catchment of study area including main storage features and hydrometric stations

In order to determine the inflows into the Raliphaswa weir, the incremental flows from the sub-catchment from the dam to the weir needed to be added with a consideration of the irrigation water demand within the sub-catchment. The incremental flows were obtained from the naturalised monthly flows obtained in the WR2012 study (Bailey and Pitman, 20??) while the monthly crop water requirements were obtained by Hargreaves method (???) assuming the dominant maize crop and an irrigation area of 171 ha. Figure 8.7 shows the releases from Mutshedzi dam, the incremental flows, and the estimated irrigation water supply in the incremental area. Although the irrigation water supplies might seem negligible, their impact could be very significant during prolonged dry periods. The three time series on Figure 8.7 provide the expected inflow time at Raliphaswa weir shown on Figure 8.8.

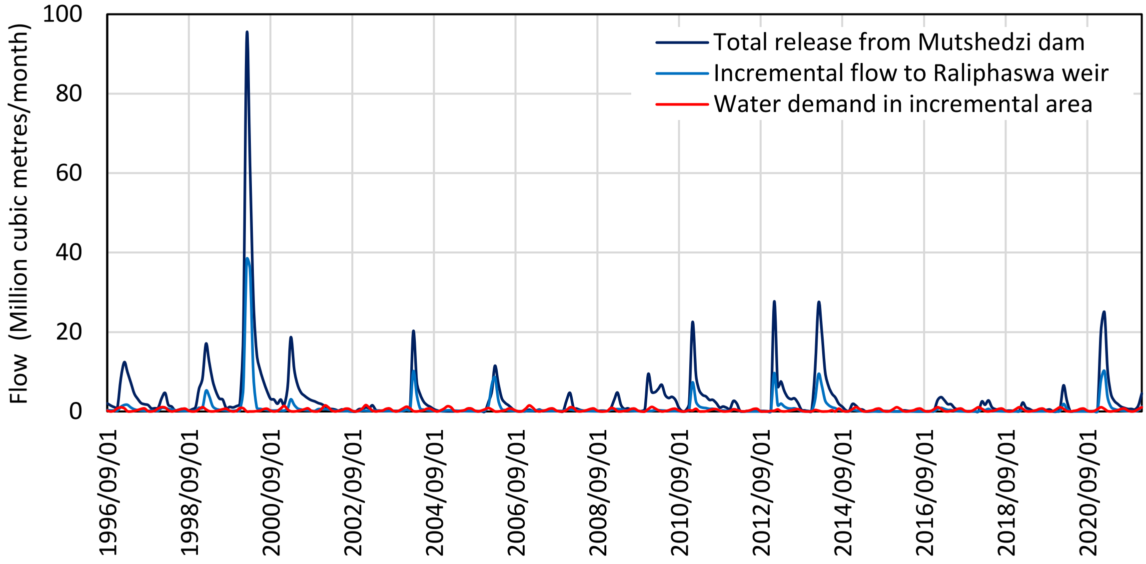

Figure 8.7 Release from Mutshedzi dam, incremental flows and irrigation water demand in incremental area

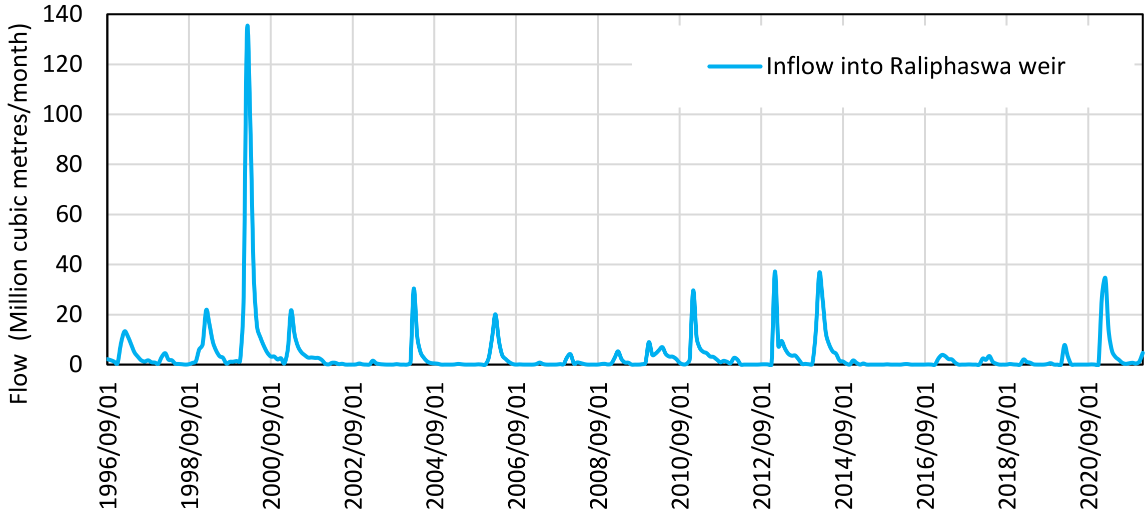

Figure 8.8 Expected inflows into Raliphaswa weir

The inflows into Raliphaswa weir are partitioned into overflows into the scheme itself and overflows back to the river on the downstream side of the weir as illustrated on Figure 8.9. The overflow rate into the scheme depends on the inflow into the weir and the hydraulic characteristics of the weir structure. By hydraulic analysis of the structure, the variation of overflow rates into the scheme as a function of the inflow into the weir illustrated on Figure 8.10 was obtained.

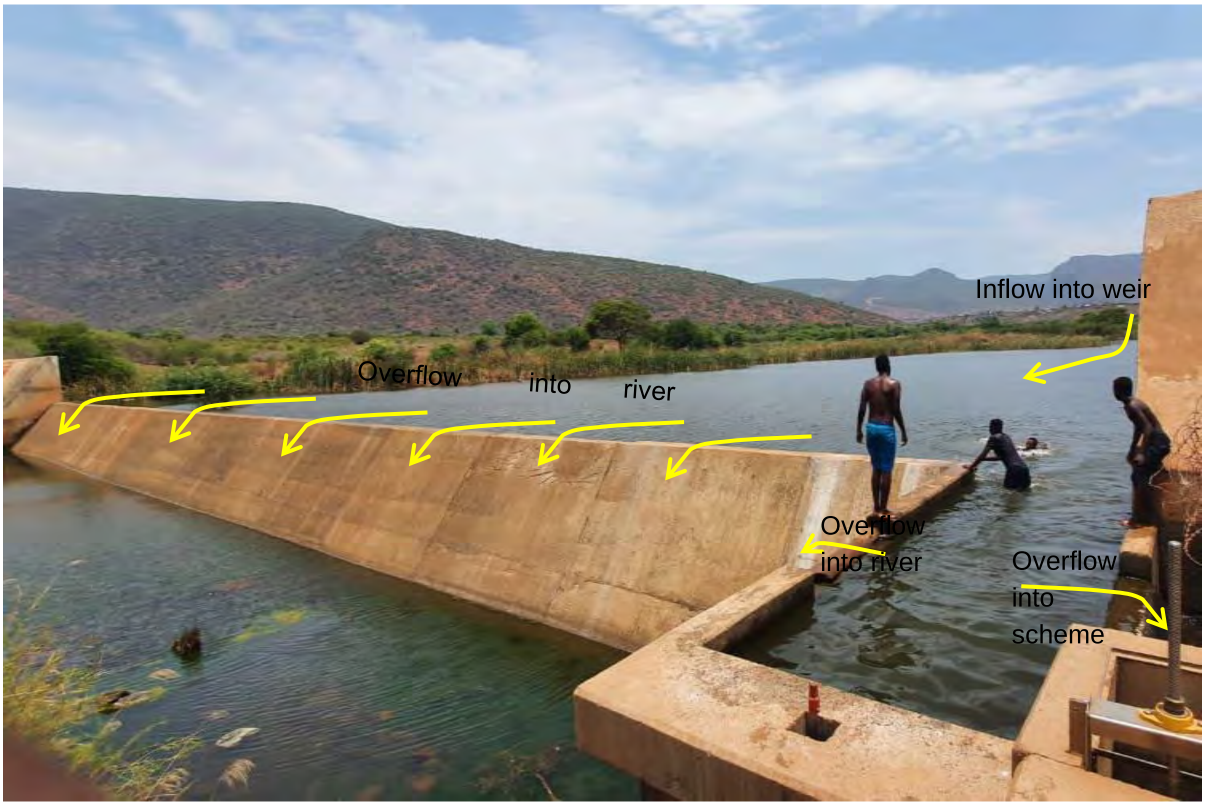

Figure 8.9 Illustration of inflows and outflows from Raliphaswa weir

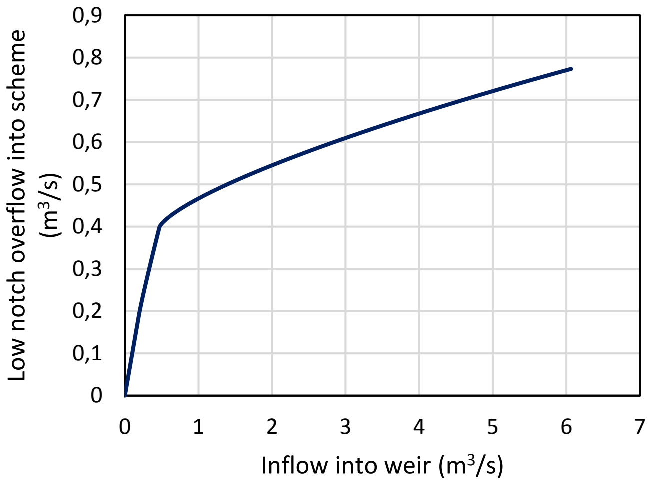

Figure 8.10 The dependence of inflow into scheme on Raliphaswa weir inflows

Hydraulic analysis of the conveyance conduit from the overflow weir into the scheme at the weir into the first offtake to the farmers at control structure CR 1 (Figure 6.2, Chapter 6) informed that that the capacity of the long-weir control structure had the least capacity of 0.186 m3/s. Beyond this flow rate, the long weir overtops and the excess water spills to the natural stream channel. The actual flow rate available to the farmers in the schemes cannot therefore exceed this capacity. This capacity was consequently set as the upper limit of water availability for all overflows at the weir (based on Figure 8.10) exceeding this capacity. If the overflows at the weir were lower, these flow rates these were considered to be available at the first flow control structure (long weir CR1) for the Raliphaswa SIS. By applying these considerations and the expected inflows into the weir (Figure 8.8), the time series of expected water availability to the three schemes shown on Figure 8.11 was obtained. Figure 8.12

shows a flow-duration curve of this time series revealing that the peak flow rate of 0.186 m^3/s would be expected 63% of the time while not flows are expected 26% of the time.

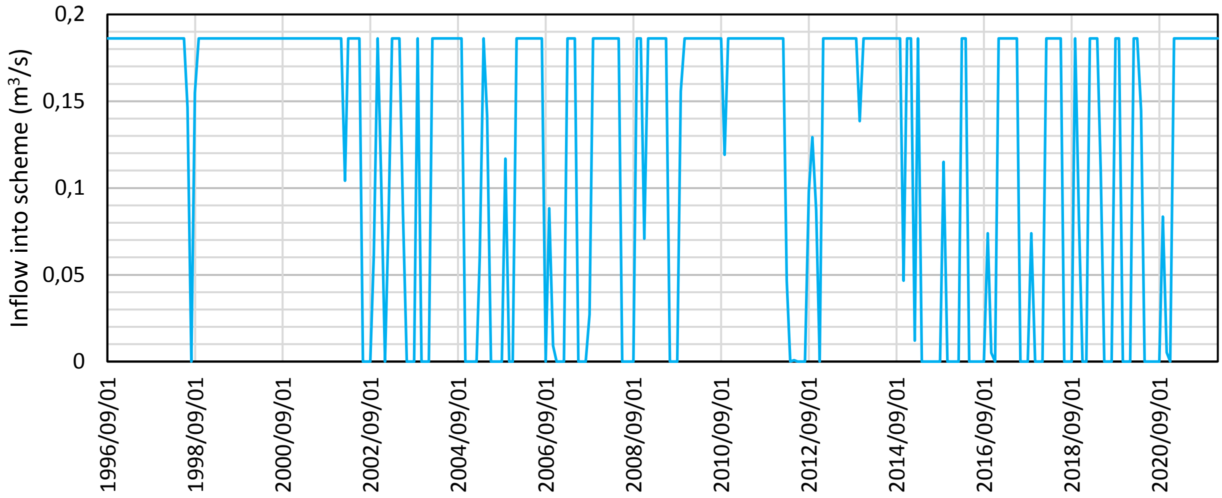

Figure 8.11 Expected water availability based on historic monthly water balance

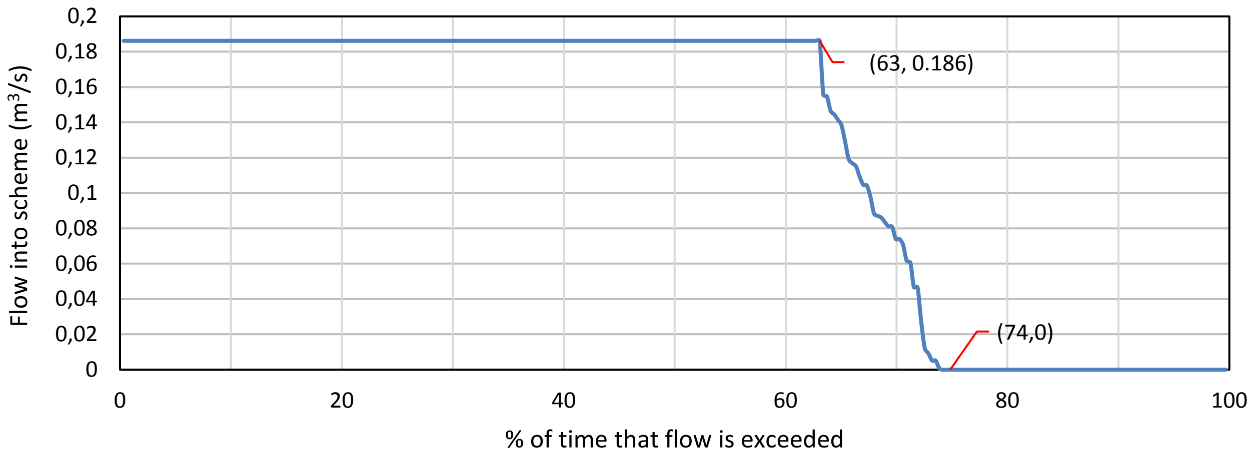

Figure 8.12 Flow-duration curve of expected water availability for study schemes

8.4 Hydraulic modelling of existing and improved conditions of infrastructure, maintenance and operation

8.4.1 Introduction

After the unsuccessful attempt to obtain quantitative socio-hydrologic relationships using the field data, it was stated in Section 8.2.5 that hydraulic modelling of scenarios that correspond to three probable states of governance and management would be undertaken. The three states would be reflected in the assumed but realistic states of scheme infrastructure, its maintenance, and its operation. This Section describes the hydraulic modelling of these scenarios after informing how the hydraulic model was calibrated and how the actual water supply to the farms was modelled. The scenario analysis is also serves to determine the opportunities for improving the performance and sustainability of the system. The scenarios studied therefore reflect a) the current state, b) a moderately improved state, and c) a comprehensively improved state. For each scenario, two flow rate were used to align with the expected range of water supply as determined in Section 8.3: 186 ℓ/s; the canal capacity expected to occur 63% of the time, and 93 ℓ/s which is 50% of that capacity.

8.4.2 Hydraulic model calibration

The steady gradually varied flow method as described in Section 4.4 of Chapter 4 was used for the determination of the water surface flow profile for model calibration. The existing canal infrastructure and the hydraulic survey and measurements used for the calibration are described in Section 6.2 of Chapter 6.

The modelling was carried out on spreadsheet and computational modules were developed for the following, for a range of inflows up to the capacity of the canal infrastructure:

a. The flow control structures (i.e. the weir intake, long weir structures, flow measuring structures etc); and
b. The gradually varied flow profile between the control structures.

Depending on the starting inflow at the Raliphaswa weir, the water surface profile was developed incrementally and iteratively along the length of the canal, under different initial and boundary conditions (i.e. submerged and unsubmerged downstream controls). The computations proceeded from the most upstream point (the Raliphaswa Weir on the Mutshedzi River) to the last offtake at the Mamuhohi SIS, and therefore covered the entire length of the schemes' main canal. For simplicity, the outflow rates from the Mamuhohi overnight dam were assumed equal to the inflow rates into the dam that occurred in the previous night. These simplifications were considered reasonable in establishing the daily flow distribution at the scheme.

A flow of 111 ℓ/s was measured to be entering the Raliphaswa SIS at the Parshall flume during the hydraulic survey. The hydraulic survey also measured the gate positions and degree of sedimentation of the canals. During calibration, the Manning's coefficient (n) and the spillway and pipe discharge coefficients (C_d) were changed iteratively until the differences between simulated and observed water depths were considered to be minimised. The calibrated values of these coefficients are shown in Table 8.5 and were then used in all the hydraulic simulations for scenario analysis. An assessment of the quality of the calibration based on a comparison of the measured and modelled water depths at the existing long weir structures.is illustrated in Figure 8.13 The modelled water levels are reasonably close to the measured values indicating that the calibrated hydraulic coefficients (Table 8.5) have been appropriately specified.

Table 8.5 Calibrated hydraulic modelling parameters for canal infrastructure

Description	Scheme	Chainage (m)	Invert Level (masl)	Simulated Water Elevation (m (masl)	Manning's n	Discharge coefficient Cd
Scheme weir	Raliphaswa	0	756.62	756.83		0.327
Start of canal	Raliphaswa	100.58	755.56	755.90	0.016	
CH50	Raliphaswa	150.58	755.49	755.81	0.016	
CR1	Raliphaswa	330.58	755.03	755.60		0.230
CR2	Raliphaswa	699.55	753.24	753.67	0.015	0.137
UD1	Raliphaswa	865.78	753.15	753.58	0.017	0.417
UD2	Raliphaswa	1039.27	753.15	753.58		0.337
SI1	Raliphaswa	1292.49	752.75	753.03	0.016	
CR3	Mandiwana	2558.68	748.81	749.19		0.215
CR4	Mandiwana	2682.16	748.75	749.09	0.015	0.530
CR5	Mandiwana	2983.01	748.59	748.96	0.015	0.310

Description	Scheme	Chainage (m)	Invert Level (masl)	Simulated Water Elevation (m (masl)	Manning's n	Discharge coefficient Cd
CR6	Mandiwana	3158.39	748.35	748.71	0.015	0.530
ICR1	Mandiwana	3342.31	748.21	748.45	0.015	
CR7	Mandiwana	3432.36	748.12	748.44	0.015	0.400
CR8	Mandiwana	3537.09	747.93	748.37	0.015	0.400
CR9	Mandiwana	3699.71	747.91	748.27	0.015	0.400
CR10	Mamuhohi	298.09	744.6	744.96		0.373
CR11	Mamuhohi	700.49	744.08	744.33	0.015	0.378
CR12	Mamuhohi	850.49	737.81	737.94		0.327
CR13	Mamuhohi	934.06	736.77	737.02	0.015	0.335
CR14	Mamuhohi	1099.67	736.54	736.71	0.015	0.332
CR15	Mamuhohi	1099.67	729.4	729.66		0.455

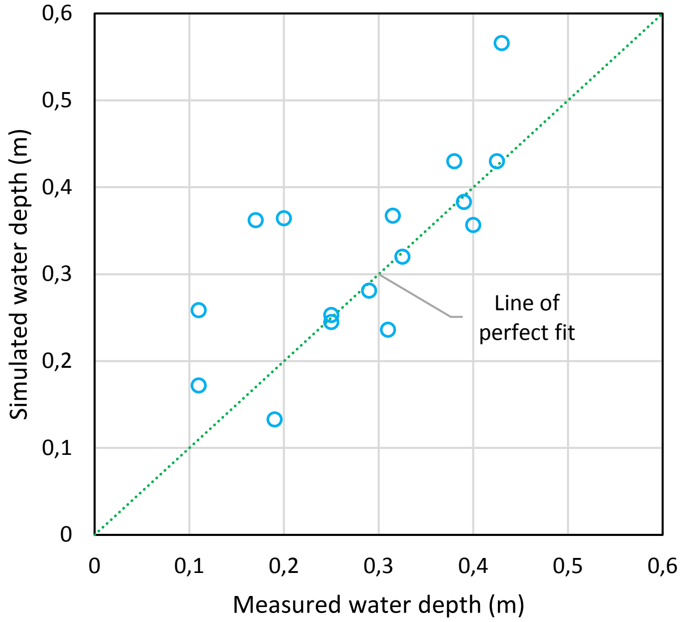

Figure 8.13 Comparison of measured and modelled water depths in calibration

8.4.3 Modelling of water supply to farms

Based on the simulated water surface profile, the flow volumes diverted into each of the furrows were determined using the submerged or unsubmerged inlet control relationships and the simulated heads at the offtakes supplying the furrows. These flow volumes were then subtracted from the volumes continuing further downstream. Water losses from the main canal system were assumed to include operational losses, evaporation and seepage and operational losses were considered the only variable amongst these. Operational losses were considered to be the incoming flow rate in excess of the flow capacity of the related control structure.

The canal capacity was estimated based on the flow capacity of the first long weir structure, canal regulator 1 (CR 1 – Figure 8.2 and Appendix A), at Raliphaswa SIS, determined based on the available head difference between the spillway invert level, the canal top of concrete level and the calibrated spillway discharge coefficient (C_d). Above this head, it was assumed water overflows the canal and is no longer available in the main canal. The available head at CR 1 was measured to be 100 mm, and based on this, the flow capacity of the structure was determined as 186.86 ℓ/s.

8.4.4 Current state scenario

The purpose of this scenario was to evaluate the water distribution at the schemes for the current state of maintenance, operation and governance. The infrastructure condition was assumed to in the current state, including the information on state variables provided on Table 8.6 and the damage observed on the canal regulating structures, particularly in Mandiwana and Mamuhohi SIS as described in Section 6.2 of Chapter 6.

Table 8.6. Measured and estimated state variables during hydraulic survey

Structure *	Chainage (m)	Invert Level (masl)	Top of concrete (masl)	Measured Offtake head (m)	Degree that offtakes 1, 2 and 3 are open			Sediment (% of weir height)
					1	2	3	
Scheme weir,	0	756.62	756.88		-			
Start of canal	100.58	755.56	756.02		-			
CH50	150.58	755.49	756.01		-			
Parshall Flume	166.67	755.43	755.9		-			
CR1	330.58	755.03	755.63	0.34	1			80
CR2	699.55	753.24	753.67		1			0
UD1	865.78	753.15	753.58		-			
UD2	1039.27	753.15	753.58	-	-			
SI1	1292.49	752.75	753.3	-	-			
CR3	2558.68	748.81	749.25	0.31	1			80
CR4	2682.16	748.75	749.173	0.305	0.5			30
CR5	2983.01	748.59	748.96	0.27	0.01			20
CR6	3158.39	748.35	748.78	0.355	0.0001			0
ICR1	3342.31	748.21	748.67	0.15	0.1			
CR7	3432.36	748.12	748.56	0.13	1			0
CR8	3537.09	747.93	748.45	0.25	0.5			0
CR9	3699.71	747.91	748.35	0.36	0.05	0.8		0
Furrow below dam					0.005	0.005	1	
CR10	298.09	744.6	745.05	0.285	0.1			0
CR11	700.49	744.08	744.4	0.3	0.25			90
CR12	850.49	737.81	738.15	0.27	0.6			20
CR13	934.06	736.77	737.1	0.29	0.2			0
CR14	1099.67	736.54	736.85	0.175	0.35			0
CR15	1099.67	729.4	729.71	0.175	1			0

Note: UD – unregistered distributor, CR – canal regulator, SI – siphon inlet, ICR – informal canal regulator

* Section 6.2 of Chapter 6 provides details on the locations of the structures

For this scenario, it was assumed that all the offtakes at Raliphaswa and Mandiwana SIS are open between 06:00 – 16:00, and closed between 16:00 – 06:00 the next day, to allow for the filling of the Mamuhohi SIS overnight dam. All the long weirs were assumed to be 90% sedimented, as a consequence of poor maintenance. The rock weirs and the unauthorised diversions were kept unchanged as for the existing system.

Figure 8.14 illustrates the flow rate variation and the daily volumes of water supplied along the main canal for a 186 ℓ/s inflow into the scheme at the first canal regulator (CR 1). As can be seen, the main canal flow rate drops significantly between CR 1 and CR 2. Furthermore, only half of the Mandiwana SIS scheme is supplied, as there is no flow available downstream of CR 6.

Between 16:00 – 06:00 the next day, it is assumed that all the offtakes to Raliphaswa and Mandiwana SIS are closed, in order to allow water to fill the Mamuhohi SIS overnight dam, to supply the Mamuhohi SIS the following day. Figure 8.14 illustrates the flow variation along the main canal in this scenario. As can be seen, there is a significant drop in flow rate between CR 1 and CR 9 (the end of Mandiwana SIS), the flow rate reduces from 186 ℓ/s to 40 ℓ/s due to operational losses at CR 2. As a consequence, water is only available to supply a portion of the Mamuhohi SIS.

The findings for a flow rate of 93ℓ/s into the scheme shown on Figure 8.15 reveal similar behaviour as for the higher inflow rate of 186 ℓ/s.

These findings confirm that under this scenario, water distribution along the main canal system is not equitable and that the blocking of the canals using rock weirs by unregistered farmers leads to significant operational losses. It is likely that these factors result in downstream farmers vandalising the upstream irrigation infrastructure in order to disturb the control relationship of regulating structures and enable increased flow rate to the downstream main canal sections, as well as the nonadherence of farmers to the irrigation schedules.

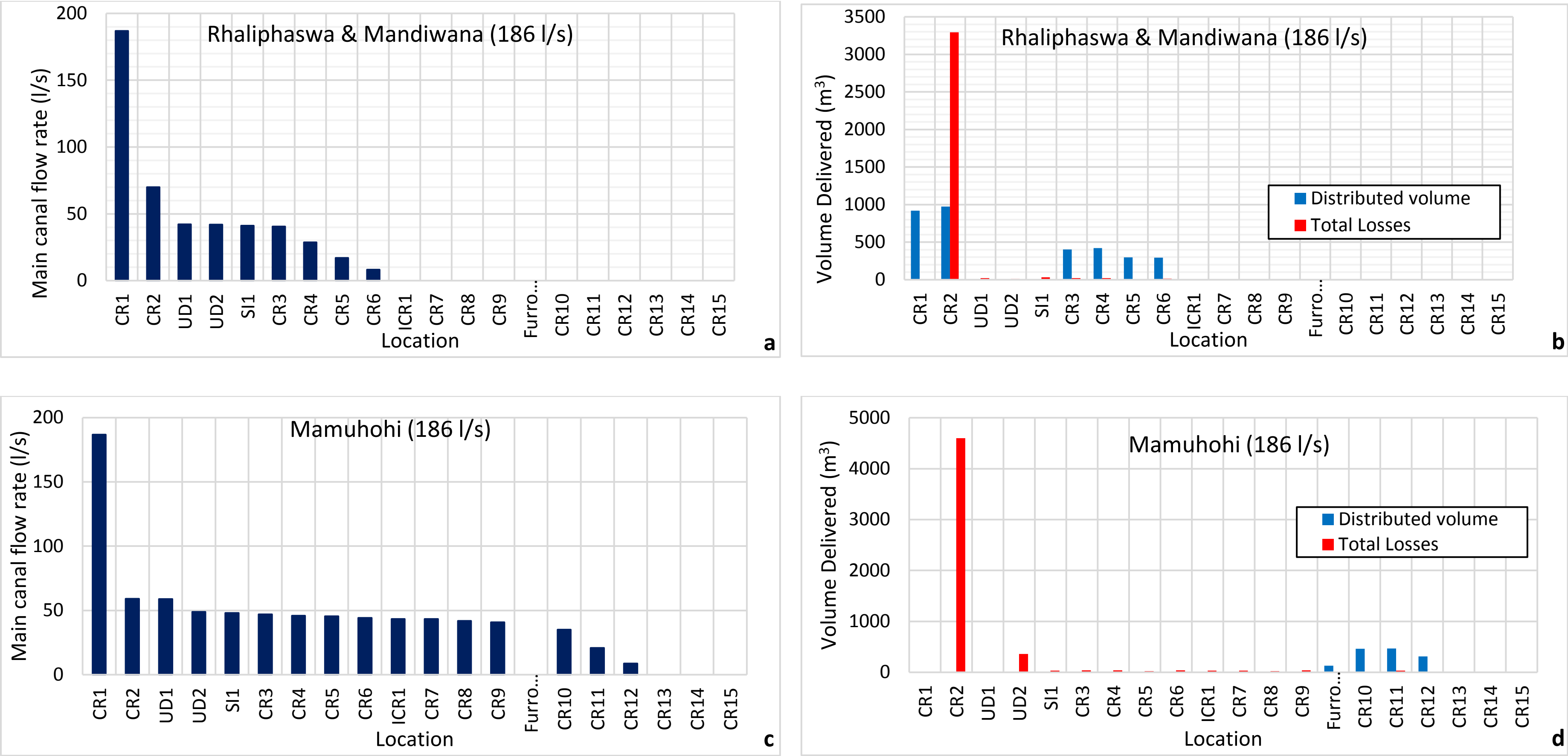

Figure 8.14 Simulated flow rate and volume distribution for 186 ℓ/s inflow for existing scenario

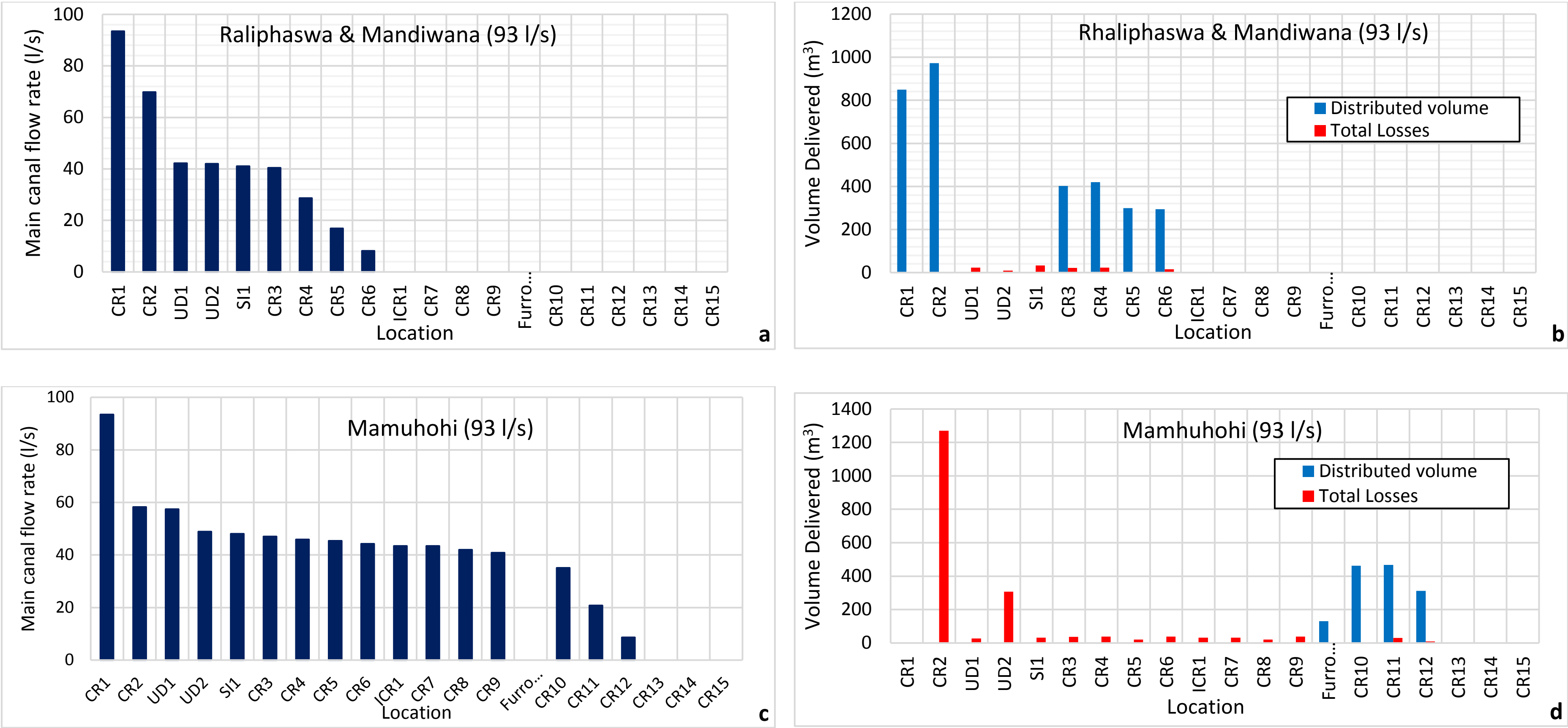

Figure 8.15 Simulated flow rate and volume distribution for 93 ℓ/s inflow for existing scenario

8.4.5 Moderate improvements scenario

The purpose of this scenario was to evaluate the consequence of moderate improvement in governance, operation and maintenance as well as the infrastructure condition. It was assumed that the unregistered farmers could be prevented from accessing the water in the canal system and the rock weirs would be removed through the improvement of governance. The rotation schedule was changed to assign water supply in direct proportion to the areas of each scheme. Consequently, the Raliphaswa SIS would be supplied between 05:00 – 07:00; Mandiwana SIS between 07:00 – 17:00 and the Mamuhohi overnight dam between 17:00 and 05:00 the next day. To minimise leakage losses from the main canal, gates were assumed to be installed at the offtakes with no gates and that the vandalised structures would be rehabilitated back to their initial design. Sedimentation levels were assumed to be at 50% due to an improved maintenance effort. The flow rates and daily volumes from hydraulic analysis with these modifications are presented in Figures 8.4 and 8.5 for inflows of 186 and 93 ℓ/s respectively.

As observed on the two figures, these improvements would lead to an improved water distribution between the schemes. However, it can be seen that there would still be significant water losses at CR 2, CR 3 and CR 5. Under the low flow condition of 93 ℓ/s, these losses would particularly lead to water shortages at the Mamuhohi SIS. Such water shortages are likely to encourage the vandalism of the upstream canal regulating structures by the downstream farmers. Furthermore, the removal of the unregistered farmers from the scheme is unlikely to be sustainable, as it does not address water provision for these farmers who are also dependent on this water resource. This may increase conflict between the registered and unregistered farmers and lead to the recurrence of unregistered offtakes in the form of rock weirs or other diversions.

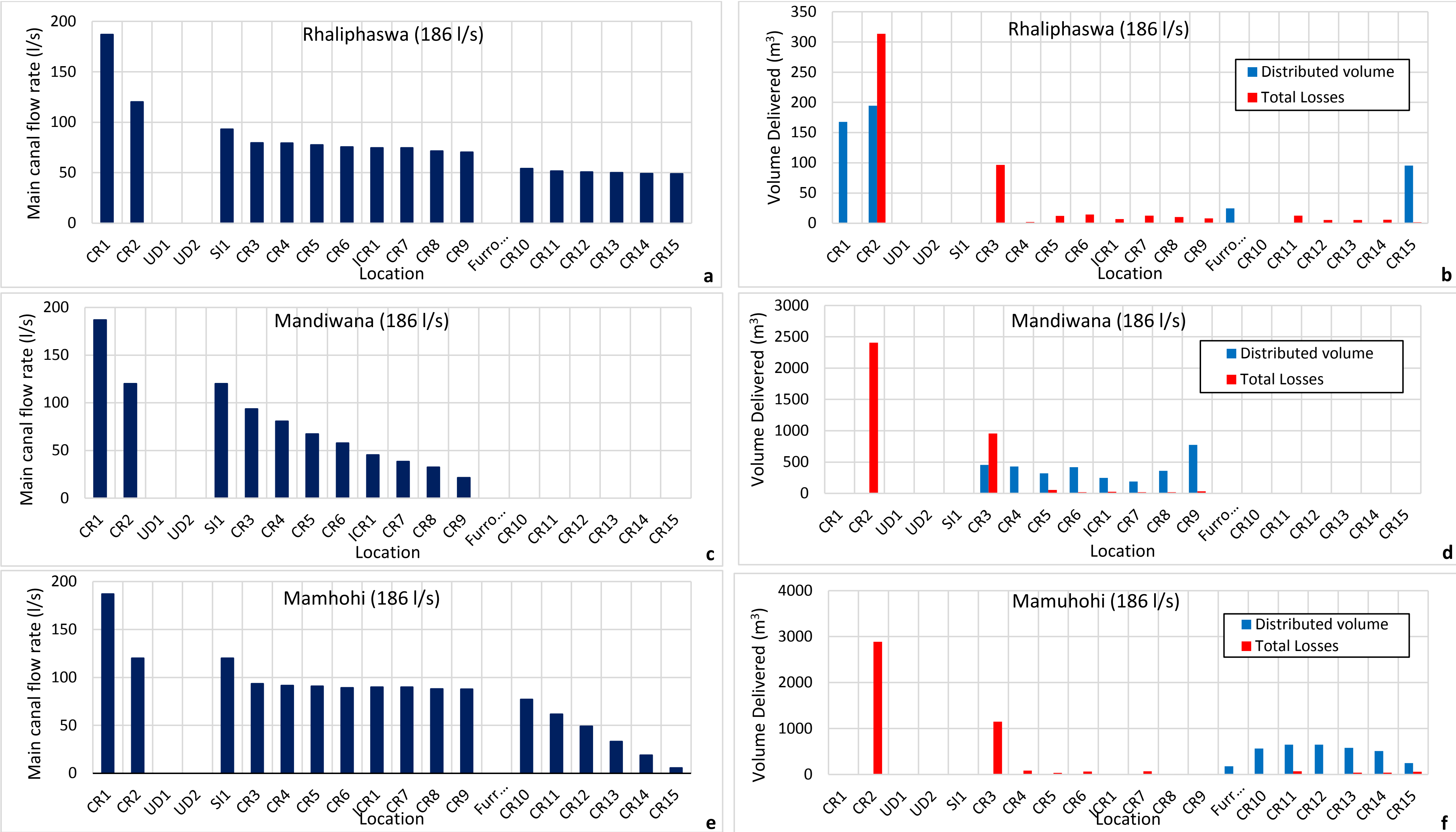

Figure 8.16 Simulated flow rate and volume distribution for 186 ℓ/s inflow for moderately improved scenario

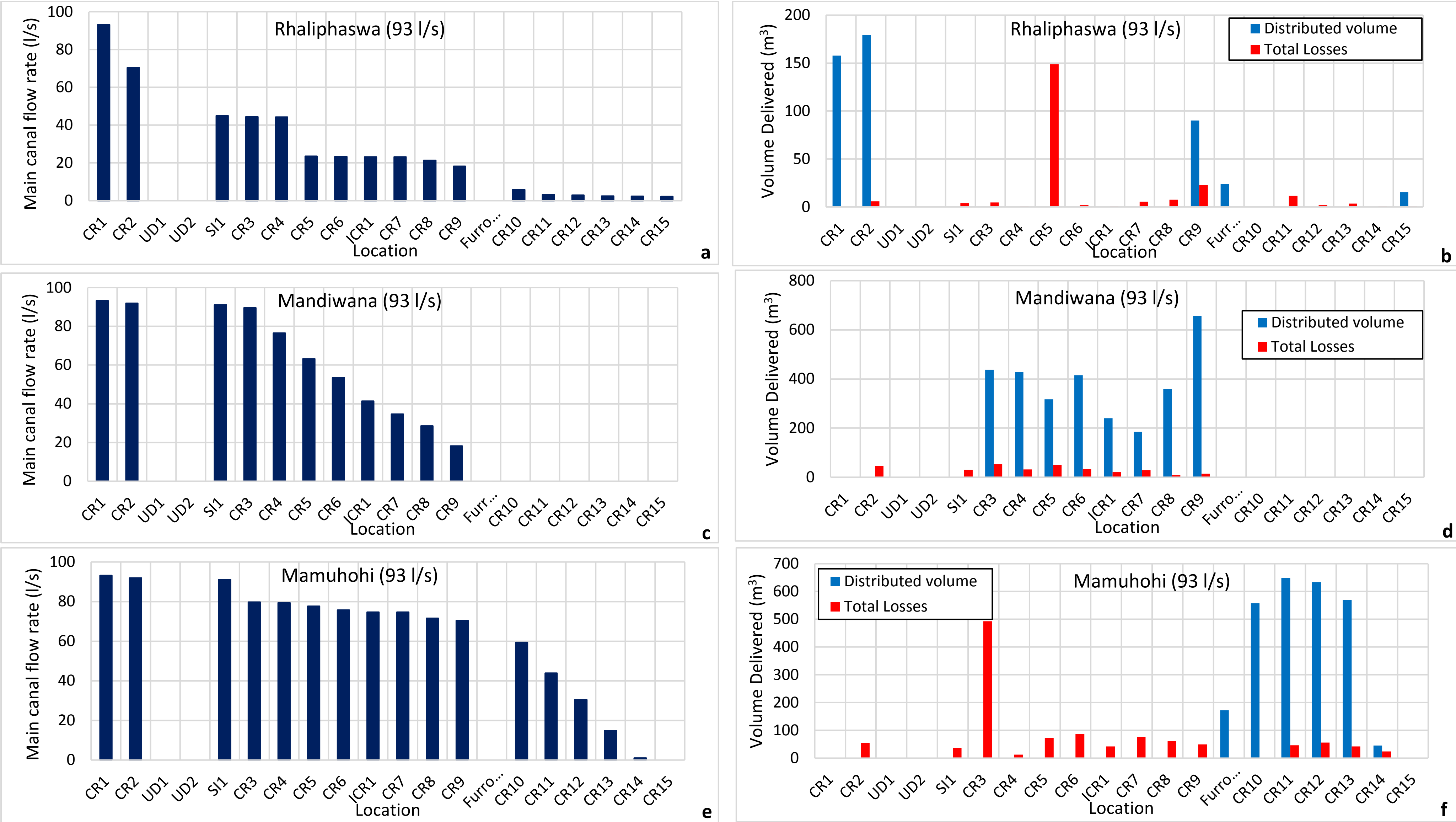

Figure 8.17 Simulated flow rate and volume distribution for 93 ℓ/s inflow for moderately improved scenario

8.4.6 Comprehensive improvements scenario

In this scenario, an attempt was made to further improve water supply to the three schemes by reducing operational water losses and promoting an equitable distribution of water, particularly under low flow conditions. The proposed improvements were obtained from an iterative process using the calibrated hydraulic model of the SIS and variations of these changes could be made. In addition to the changes proposed for the moderate improvement scenario, new formal canal regulating structures and improvements to several of the existing ones are proposed. The improvements to existing structures consist of changes in selected hydraulic features of long weirs illustrated on Figure 8.18. Two new long weir structures replace the informal rock weirs currently used by unregistered farmers at Raliphaswa SIS. These are referred to as NLW 1 and NLW2 on Table 8.7 that provides the details of the improvements and on Figure 8.19 that shows the locations of these changes. An additional long weir structure is also proposed for the Mandiwana SIS to replace an informal control structure and is referred to as NLW3 on Table 8.7 and Figure 8.20. Improvements to management and governance that lead to optimal operation and maintenance of infrastructure are assumed and sediment accumulation and other impediments to water flow are assumed to be negligible.

For the high inflow rate of 186 ℓ/s, it was found, through hydraulic simulations, that having separate periods of water supply for Raliphaswa SIS and Mandiwana SIS would result in one of these schemes having to be supplied with water through the evening and early night to 21:30. This would be impractical considering visibility and security concerns and was therefore not adopted. It was therefore decided that for this high flow condition, both Raliphaswa SIS and Mandiwana SIS would be supplied simultaneously from 05:30 to 18:00. Thereafter, from 18:00 – 05:30 the next day, water is allowed to fill the Mamuhohi Overnight dam for use in the next day. Between the Raliphaswa SIS and the Mandiwana SIS, Mandiwana SIS has the lower distribution capacity (to the farms) per unit area, and would therefore require a longer irrigation period. Through the provision of additional offtakes at the Mandiwana SIS, this period could be reduced and separate water supply periods for Raliphaswa and Mandiwana could probably be scheduled.

Figure 8.18 Hydraulic features of long weir and offtake structures

For equitable water delivery under low flow conditions, representative flow rate of 93 ℓ/s, which would be expected to be exceeded about 67% of the time (Figure 8.12) was assumed. After several iterative simulations, the following operational schedule that delineates the water supply into 3 sections of the SIS over 24 hours as follows was obtained:

- From 5:30 to 11:00, supply Raliphaswa SIS and the first 2 offtakes of the Mandiwana SIS (CR3 and CR4).
- Between 11:00 and 18:00, supply the rest of the Mandiwana SIS.
- From 18:00 to 05:30 the next day, supply water to the Mamuhohi Overnight dam for use in the next day.

Figures 8.22 and 8.23 show the distributions of the flow rates and daily supply volumes for the inflow rates of 186 and 93 ℓ/s respectively. It is observed from the two Figures that in this comprehensive improvements' scenario, the total water losses are kept below 100 m^3/ day during all rotation schedules and consequently, more water is available for the farmers. Since different rotation schedules are required under the low flow and high flow conditions, flow monitoring would be required to ensure that the appropriate rotation schedule is being applied. Therefore, the gauging structures at the scheme (i.e. the crump weir and Parshall flume) would need to be equipped with appropriate flow monitoring instrumentation.

Figure 8.23 reveals that for low inflow conditions (such as 93 ℓ/s), water shortages would still be experienced most at the lower end of the scheme (Mandiwana), as the long weir regulating structures used at the schemes have low sensitivity to changes in flow rates. However, as Figure 8.12 reveals, these inflows would only be expected to occur about 33% of the time.

Table 8.7 Infrastructure alterations for the comprehensive improvements' scenario

Structure	Scheme	Chainage (m)	Invert Level (masl)	Top of concrete (masl)	Spillway level (masl)	Side weir length (m)	Offtake diameter (m)	Offtake Level (masl)	Alterations to existing long weir structures				
									∆Top of Concrete level (m)	∆Spillway level (m)	∆Offtake diameter (m)	∆Side weir length (m)	∆Offtake invert level (m)
CR1	Raliphaswa	330.58	755.03	755.63	755.53	6.9	0.16	755.25	-	-	-0.05	-	-
CR2	Raliphaswa	699.55	753.24	753.67	753.56	6.9	0.16	753.26	0.12	0.07	-0.05	-	0.1
NLW1*	Raliphaswa	865.78	753.15	753.58	753.45	12	0.11	753.26	-	-	-	-	-
NLW2*	Raliphaswa	1039.27	752.97	753.39	753.27	12	0.11	753.12	-	-	-	-	-
CR3	Mandiwana	2558.68	748.81	749.25	749.14	4.5	0.11	748.886	-	-	-	3.5	-
CR4	Mandiwana	2682.16	748.75	749.173	749.06	7.5	0.11	748.784	-	-0.01	-	3	-
CR5	Mandiwana	2983.01	748.59	748.96	748.87	5.5	0.11	748.689	-	-	-	1	-
CR6	Mandiwana	3158.39	748.35	748.78	748.64	5.66	0.11	748.354	-	-	-	1.3	-
NLW3*	Mandiwana	3342.31	748.21	748.67	748.56	5.5	0.11	748.297	-	-	-	-	-
CR7	Mandiwana	3432.36	748.12	748.56	748.44	4.75	0.11	748.329	-	-	-	0.25	-
CR8	Mandiwana	3537.09	747.93	748.45	748.35	4.25	0.11	748.111	-	-	-	-	-
CR9	Mandiwana	3699.71	747.91	748.35	748.26	4.7	0.11	747.916	-	-	-	-	-
CR10	Mamuhohi	298.09	744.6	745.05	744.95	4.8	0.11	744.613	-	-	-	-	-
CR11	Mamuhohi	700.49	744.08	744.4	744.32	4.96	0.11	744.061	-	-	-	-	0.05
CR12	Mamuhohi	850.49	737.81	738.15	738.08	4.51	0.11	737.743	-	-	-	-	0.1
CR13	Mamuhohi	934.06	736.77	737.1	737.03	4.95	0.11	736.656	-	-	-	-	-
CR14	Mamuhohi	1099.67	736.54	736.85	736.78	4.75	0.11	736.469	-	-	-	-	-
CR15	Mamuhohi	1099.67	729.4	729.71	729.61	3.47	0.11	729.27	-	-	-	-	-

* **NLW1**, **NLW2** and **NLW3** are proposed new long weir structures.

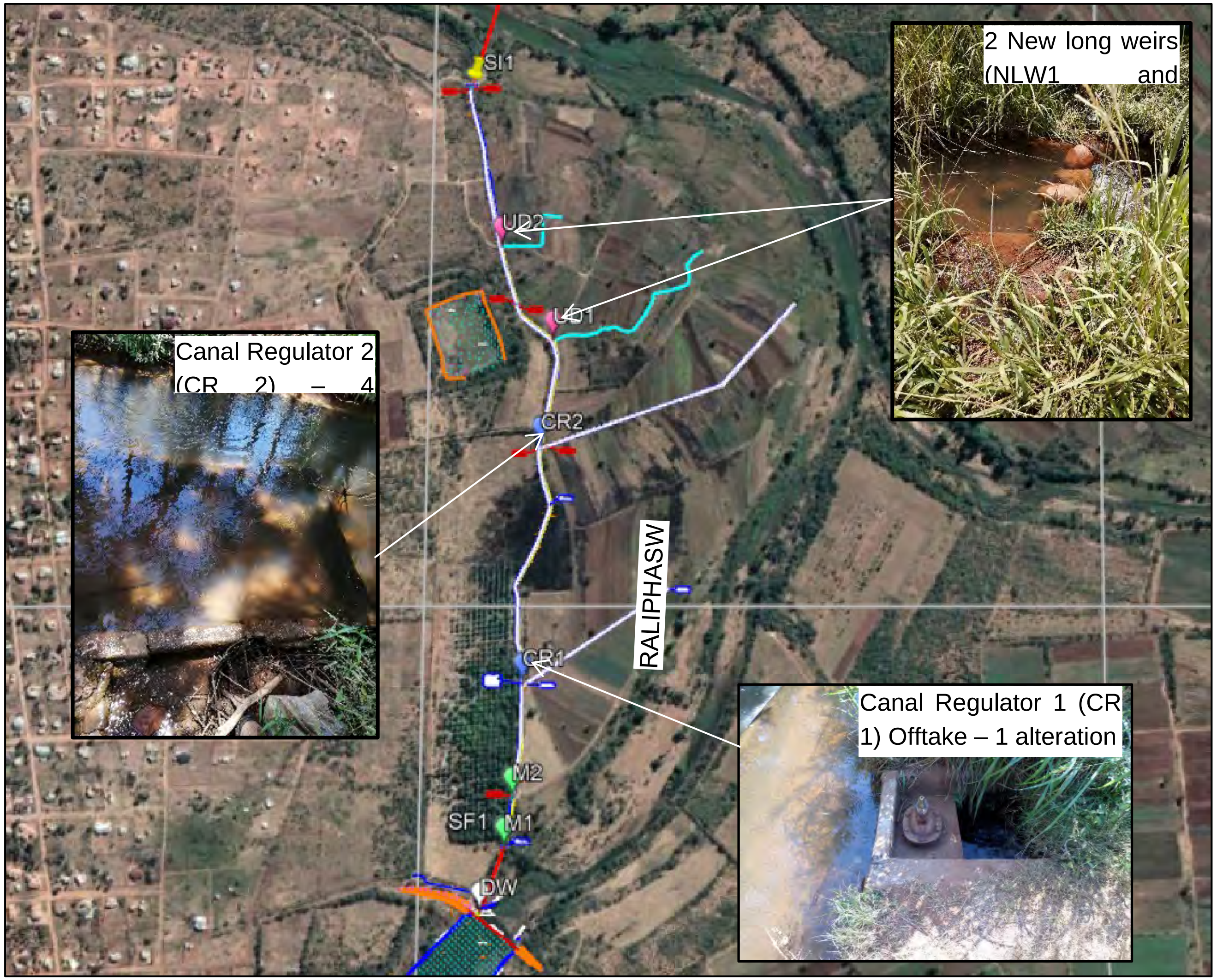

Figure 8.19 Alterations to canal regulation in Raliphaswa for comprehensive improvements scenario

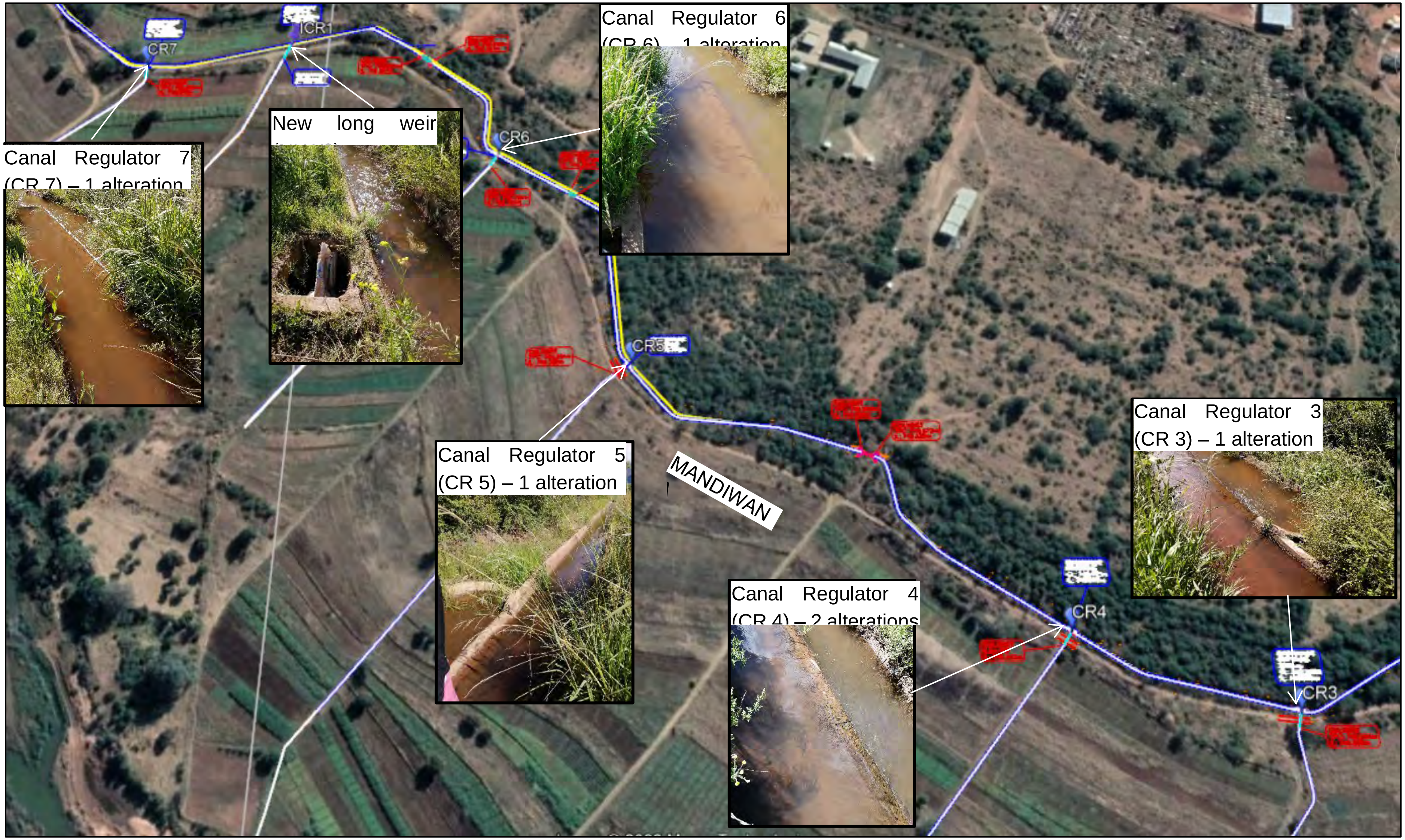

Figure 8.20 Alterations to canal regulation in Mandiwana for comprehensive improvements scenario

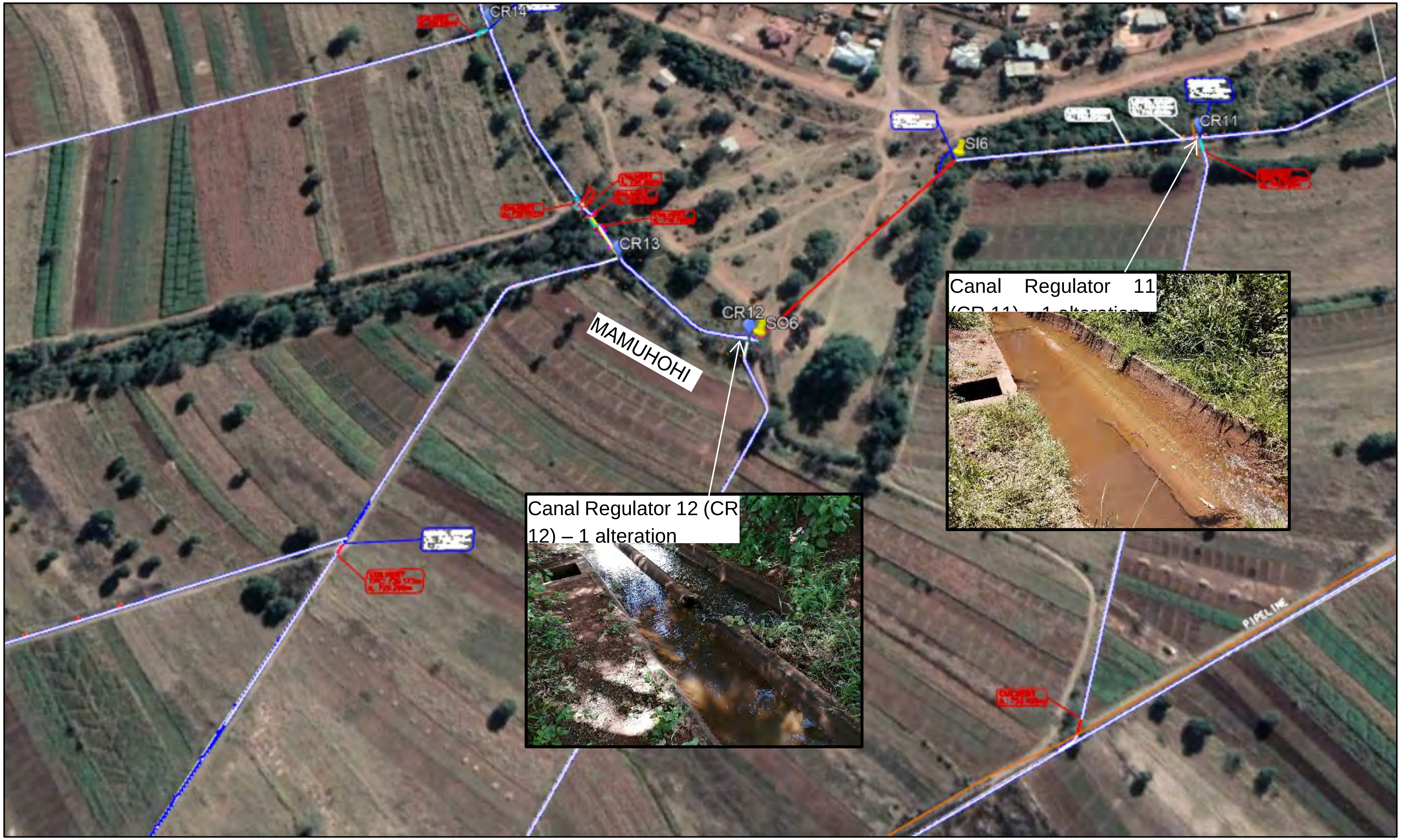

Figure 8.21 Alterations to canal regulation in Mamuhohi for comprehensive improvements scenario

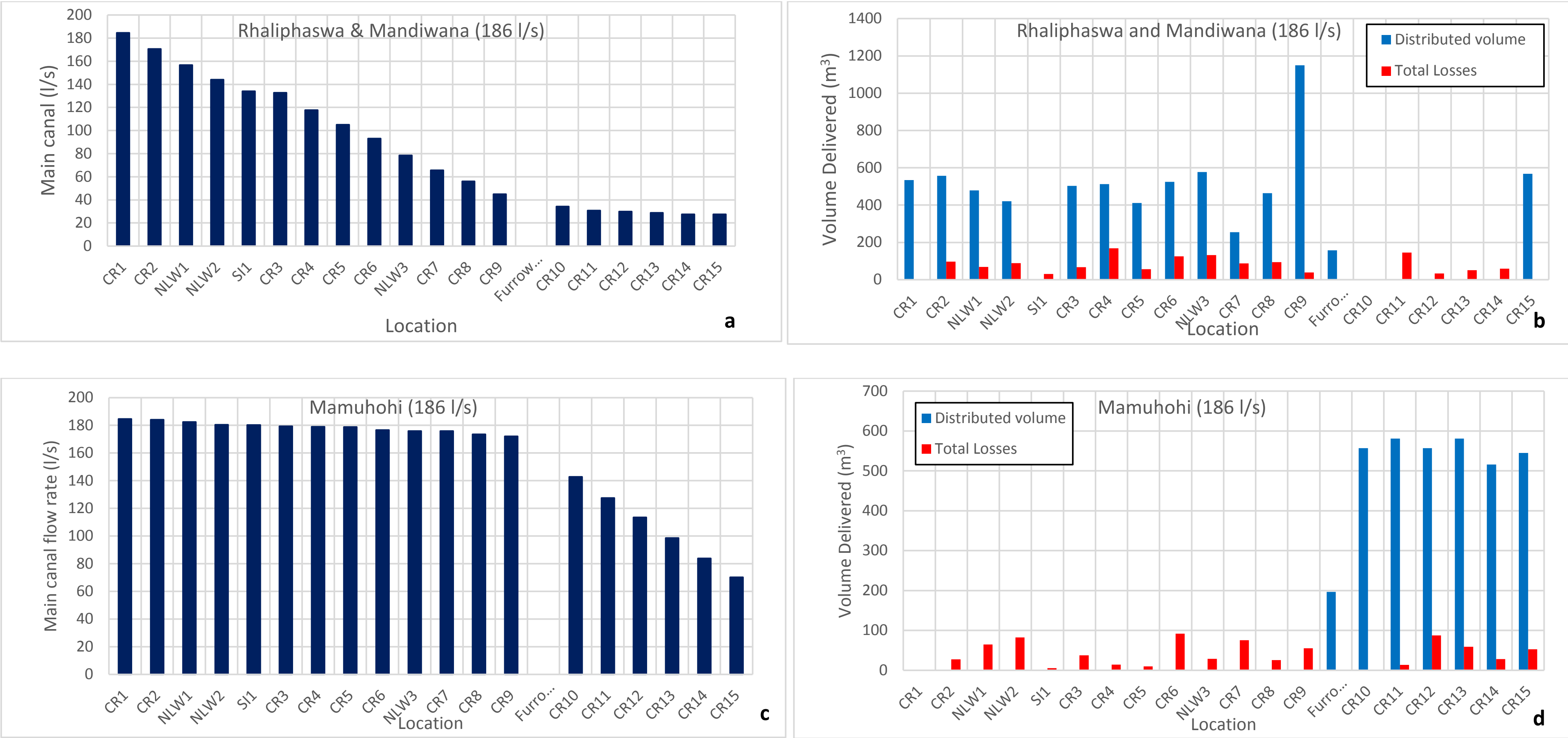

Figure 8.22 Simulated flow rate and volume distribution for 186 ℓ/s inflow for comprehensively improved scenario

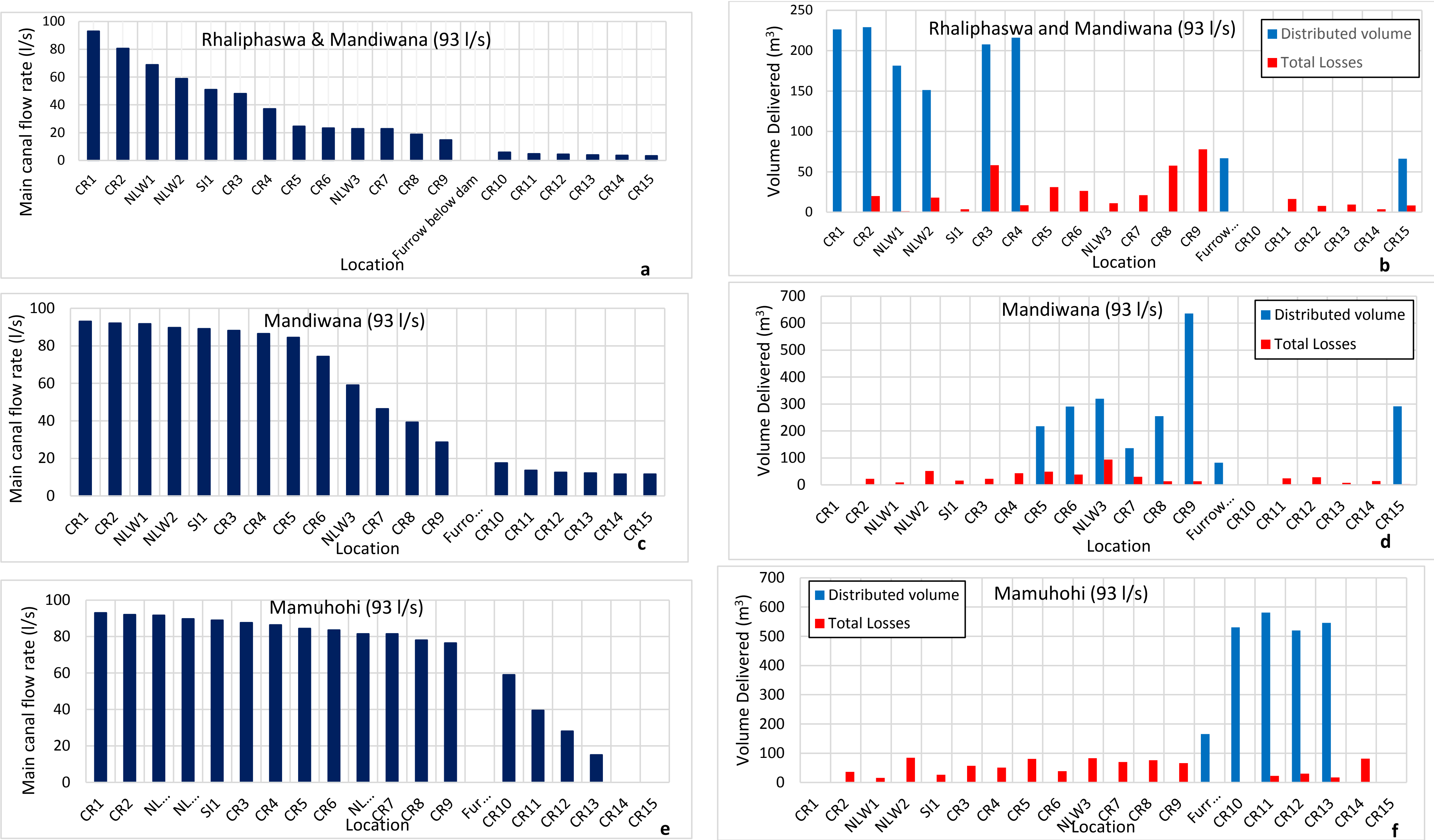

Figure 8.23 Simulated flow rate and volume distribution for 93 ℓ/s inflow for comprehensively improved scenario

8.4.7 Comparative water distribution of three scenarios

For the three scenarios examined in Sections 8.4.4 to 8.4.7, Table 8.8 presents a comparison of the volumes of water available, the volumes actually delivered and those lost, and the daily depths of water available on the farms. Figure 8.24 compares the daily depths of supply and the % water losses obtained from the three scenarios.

For the current state scenario, Table 8.8 and Figure 8.24 reveal that for both high and low inflow rates, the depth of supply (volume per unit area) is 5 to 6 times higher for Raliphaswa than for Mandiwana and Mamuhohi. For Raliphaswa, the high inflow condition for the current state results in a much higher water loss (mainly through spillage over the top of concrete) of 176% as compared with 2% for the low inflow state. The losses for both states of inflow are negligible in Mandiwana while high and low inflows lead to losses of 79% and 58% respectively for Mamuhohi.

For the moderate improvement scenario, Table 8.8 and Figure 8.24 inform that the losses in Raliphaswa and Mamuhohi could be reduced by rehabilitating the infrastructure, changing the rotation schedule, increasing the maintenance frequency of the main canal and ensuring that there is no illegal abstraction of water taking place by the unregistered farmers. This would increase the water loss in Mandiwana considerably to 53% for high inflows while also leading to considerable increases in water delivery to Mandiwana and Mamuhohi. However, water delivery at Raliphaswa SIS would reduce by 82% and water accessibility for the Raliphaswa SIS farmers would be reduced to two hours based on the proportionate areas of each scheme applied for the moderate improvement scenario. The Raliphaswa SIS farmers would be worst affected and the water delivery would remain unequitable. It is surmised that the Raliphaswa SIS farmers would most likely not accept this and would most likely not agree to such a water allocation schedule. Furthermore, this scenario would not include water provision for the unregistered farmers and it is therefore unlikely to be sustainable.

In the comprehensive improvement scenario, pragmatic opportunities to reduce operational water losses to improve the water efficiency of the canal system were iteratively searched for and identified. It is observed from Table 8.8 and Figure 8.24 that the alterations proposed in this scenario would result in low water losses ranging from 8 to 22% for the three schemes and the two inflow rates. These alterations consequently lead to much higher water delivery to the three schemes especially at the high flow rate which is expected 63% percentage of the time as seen on Figure 8.12. The volumes delivered are however not equitable as Raliphaswa would receive much higher depth of water than Mandiwana and Mamuhohi. For the low flow condition of this scenario, the water supply is much more equitable for the three schemes ranging from 3.69 to 3.91 mm/day. Furthermore, new structures are proposed to enable the formalisation of the unregistered farmers, to ensure that they form part of the schemes. This scenario is therefore much more likely to be sustainable and probably easier to govern and manage as the overall water supply and equitability of that supply are much better than the current or the moderately improved scenario.

Table 8.8 Volumes of water available, delivered and lost from simulation of scenarios.

Scenario	Scheme	Area (ha)	Period of water supply	Total volume available (m^3/day)	Total volume delivered (m^3/day)	Total volume lost (m^3/day)	Total depth delivered (mm/day)	% of water loss *
Current state (186 ℓ/s)	Raliphaswa	15	06:00 – 16:00	6 727	1 892	3 325	12.61	176
	Mandiwana	67			1 415	95	2.11	7
	Mamuhohi	77	16:00 – 06:00	9 418	1 981	7 437	2.57	79
Current state (93 ℓ/s)	Raliphaswa	15	06:00 – 16:00	3 365	1 822	32	12.15	2
	Mandiwana	67			1 415	95	2.11	7
	Mamuhohi	77	16:00 – 06:00	4 711	1 980	2 731	2.57	58
Moderate improvement (186 ℓ/s)	Raliphaswa	15	05:00 – 07:00	1 347	362	314	2.41	46
	Mandiwana	67	07:00 – 17:00	6 733	3 190	3 543	4.76	53
	Mamuhohi	77	17:00 – 05:00	8 079	3 555	4 524	4.62	56
Moderate improvement (93 ℓ/s)	Raliphaswa	15	05:00 – 07:00	671	337	6	2.25	2
	Mandiwana	67	07:00 – 17:00	3 354	3 039	315	4.54	9
	Mamuhohi	77	17:00 – 05:00	4 025	2 871	1 154	3.73	29
Comprehensive improvement (186 ℓ/s)	Raliphaswa	15	05:30 – 18:00	8 310	1 991	253	13.27	11
	Mandiwana	67			4 397	802	6.56	15
	Mamuhohi	77	18:00 – 05:30	7 645	6 884	762	8.94	10
Comprehensive improvement (93 ℓ/s)	Raliphaswa	31.75	05:30 – 11:00	1 842	1 212	109	3.82	8
	Mandiwana	50.25	11:00 – 18:00	2 344	1 854	403	3.69	18
	Mamuhohi	77	18:00 – 05:30	3 851	3 013	838	3.91	22

* % of water loss = volume lost/volume delivered

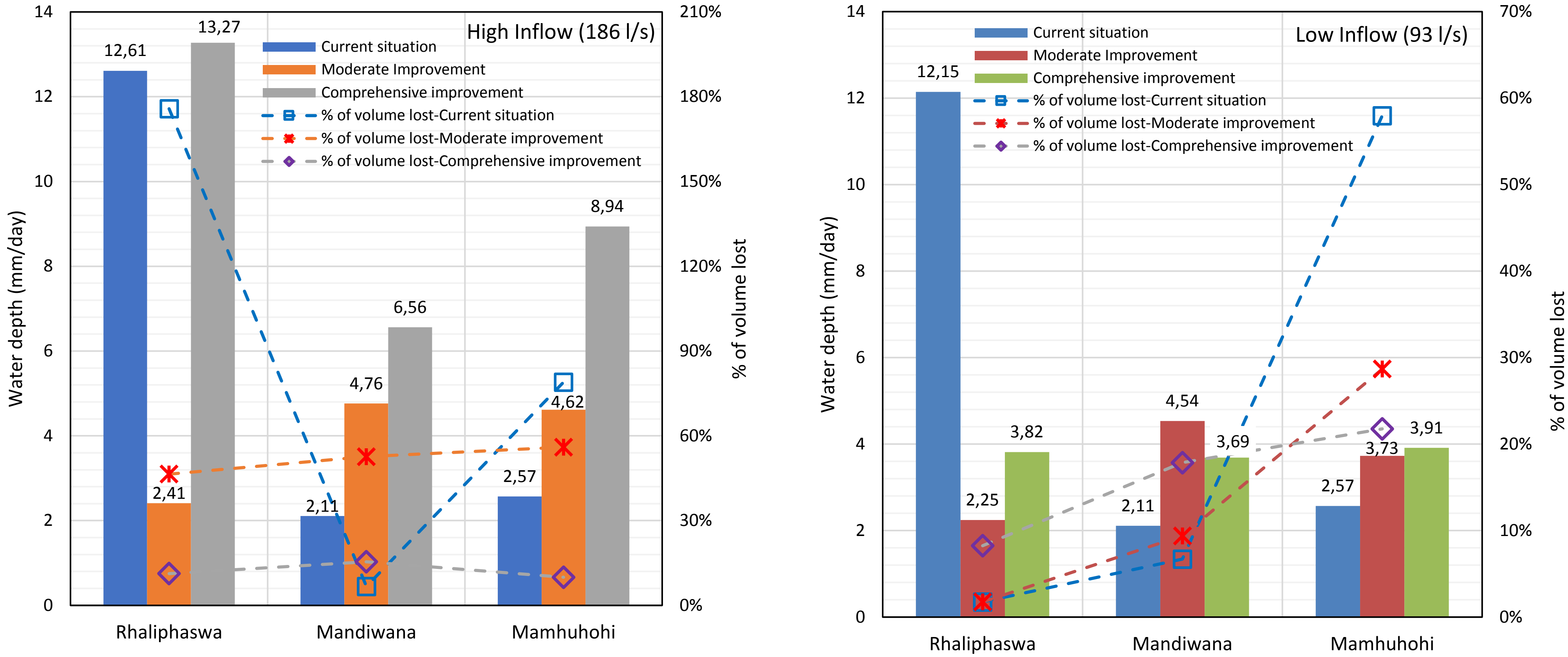

Figure 8.24 Comparison of daily depths of water available and percentages of water losses from hydraulic simulation of scenarios.

8.5 Impacts of improving conditions of infrastructure, maintenance and operation on crop water availability

This section aims to assess the impact of the improvements considered in the three scenarios analysed in Section 8.4 on crop water availability on the farms. Representative crop water requirements based on maize; the dominant crop grown in the study schemes are determined using Hargreaves method (Hargreaves and Samani, 1982). Daily data available at SWAT station 229303 (Figure 8.6) are used for this from September 1996 to June 2014; the last month in which the daily data is available. Monthly irrigation water requirements are then determined as the crop requirement in excess of the monthly rainfalls obtained from station 229203 over the same period. For July 2014 to January 2022, the average monthly water requirements obtained in from September 1996 to June 2014 are assumed as the variation of water requirements is found to be distinctly seasonal without large variations across years. These monthly crop requirements are then compared with the monthly water supplies that would be provided from the three scenarios over the period of analysis. These monthly water supplies have been specified as daily depths on Table 8.8 for the various scenarios for flow rates of 186 and 93 ℓ/s. Using the time series of expected water inflows into the scheme from September 1996 to January 2022 (Figure 8.11), and the daily depths of supply at 186 and 93 ℓ/s (from Table 8.8), a time series of monthly depths of supply at the farm level are computed for all the scenarios. For the estimation of the depth of supply at any flow rate, linear interpolation using the depths at 186ℓ/s, 93 ℓ/s (from Table 8.8) and 0 ℓ/s (where the depth of supply is 0 mm/day) is applied. The flow-duration curve of the expected inflows (Figure 8.12) informs that interpolation would be required for only the flows in the 63 - 74% exceedance range which is a small proportion (11%) of the inflow data. Since the field survey informed that land usage in the schemes is considerably lower than 100%, two levels of land usage; 100% and 50% were used in the assessment of the impact of the improvements proposed in the scenarios.

The average monthly water deficits for the various scenarios and schemes are shown on Tables 6.1 and 6.1 and compared graphically on Figures 8.25 and 8.26 for 100% and 50% land usage respectively. It is found that the differences in deficit for the three scenarios are considerably less distinct than those of water supply depths compared on Figure 8.24. This is considered to result from the modulating effect of rainfall and an indication that the crop water requirements are large in relation to the range of irrigation water supplies by the three scenarios. The existing scenario reveals much higher deficits for Mandiwana and Mamuhohi in comparison to Raliphaswa. The moderately improved scenario on the other hand disadvantages Raliphaswa slightly although the actual water depths of irrigation supply are much lower than for the other two schemes (Figure 8.24). In comparison to the deficits for the existing scenario, the moderately improved scenario gives much higher deficits and the farmers in Raliphaswa are therefore not likely to agree to such changes. The comprehensive scenario obtains lower deficits for all three schemes and could although it favours Raliphaswa more than the two other schemes.

Table 8.9 Average monthly crop water deficits for various scenarios at 100% land usage

Scenario	Scheme	September	October	November	December	January	February	March	April	May	June	July	August
Existing	Raliphaswa	1.65	0.00	1.00	4.90	11.26	3.90	0.00	0.00	0.38	1.96	6.41	7.87
	Mandiwana	2.51	0.00	1.38	8.98	17.57	11.25	0.88	0.00	0.72	4.44	10.48	12.35
	Mamuhohi	2.30	0.00	1.27	8.74	17.25	10.88	0.64	0.00	0.47	4.13	10.27	12.15
Moderate Improvement	Raliphaswa	2.38	0.00	1.31	8.83	17.36	11.02	0.71	0.00	0.55	4.25	10.35	12.22
	Mandiwana	1.73	0.00	1.06	7.71	15.78	9.18	0.13	0.00	0.38	2.68	9.31	11.19
	Mamuhohi	1.74	0.00	1.08	7.79	15.87	9.33	0.19	0.00	0.38	2.79	9.39	11.25
Comprehensive improvement	Raliphaswa	1.74	0.00	1.07	5.07	10.90	4.31	0.07	0.00	0.38	2.00	6.48	7.69
	Mandiwana	1.74	0.00	1.08	6.99	14.67	8.01	0.08	0.00	0.38	2.04	8.57	10.40
	Mamuhohi	1.74	0.00	1.07	6.14	13.28	6.41	0.07	0.00	0.38	1.99	7.57	9.35

Table 8.10 Average monthly crop water deficits for various scenarios at 50% land usage

Scenario	Scheme	September	October	November	December	January	February	March	April	May	June	July	August
Existing	Raliphaswa	1.62	0.00	0.92	4.47	7.32	2.47	0.00	0.00	0.37	1.96	6.34	7.56
	Mandiwana	1.74	0.00	1.06	7.95	16.13	9.57	0.23	0.00	0.38	3.02	9.55	11.43
	Mamuhohi	1.72	0.00	1.05	7.52	15.54	8.87	0.06	0.00	0.38	2.45	9.14	11.02
Moderate Improvement	Raliphaswa	1.73	0.00	1.06	7.68	15.74	9.14	0.13	0.00	0.38	2.65	9.29	11.16
	Mandiwana	1.68	0.00	1.02	5.77	12.95	5.66	0.00	0.00	0.38	1.96	7.26	9.09
	Mamuhohi	1.70	0.00	1.04	5.92	13.11	5.95	0.00	0.00	0.38	1.96	7.39	9.22
Comprehensive improvement	Raliphaswa	1.70	0.00	1.03	4.64	7.22	3.38	0.00	0.00	0.38	1.96	6.34	7.56
	Mandiwana	1.70	0.00	1.04	4.98	10.98	4.07	0.00	0.00	0.38	1.96	6.43	7.72
	Mamuhohi	1.69	0.00	1.03	4.67	8.60	3.44	0.00	0.00	0.38	1.96	6.34	7.56

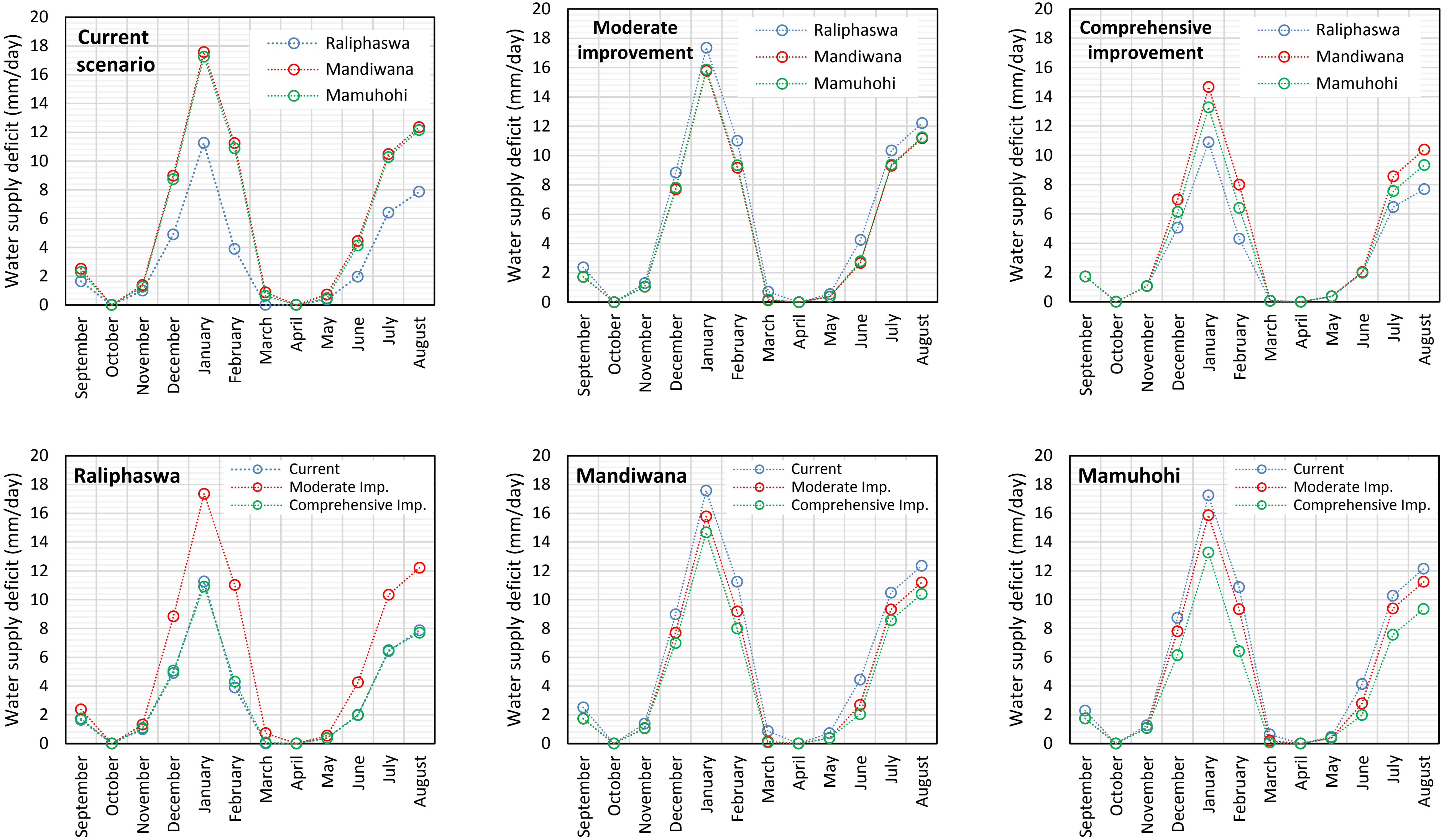

Figure 8.25 Average monthly crop water deficits for various scenarios at 100% land usage

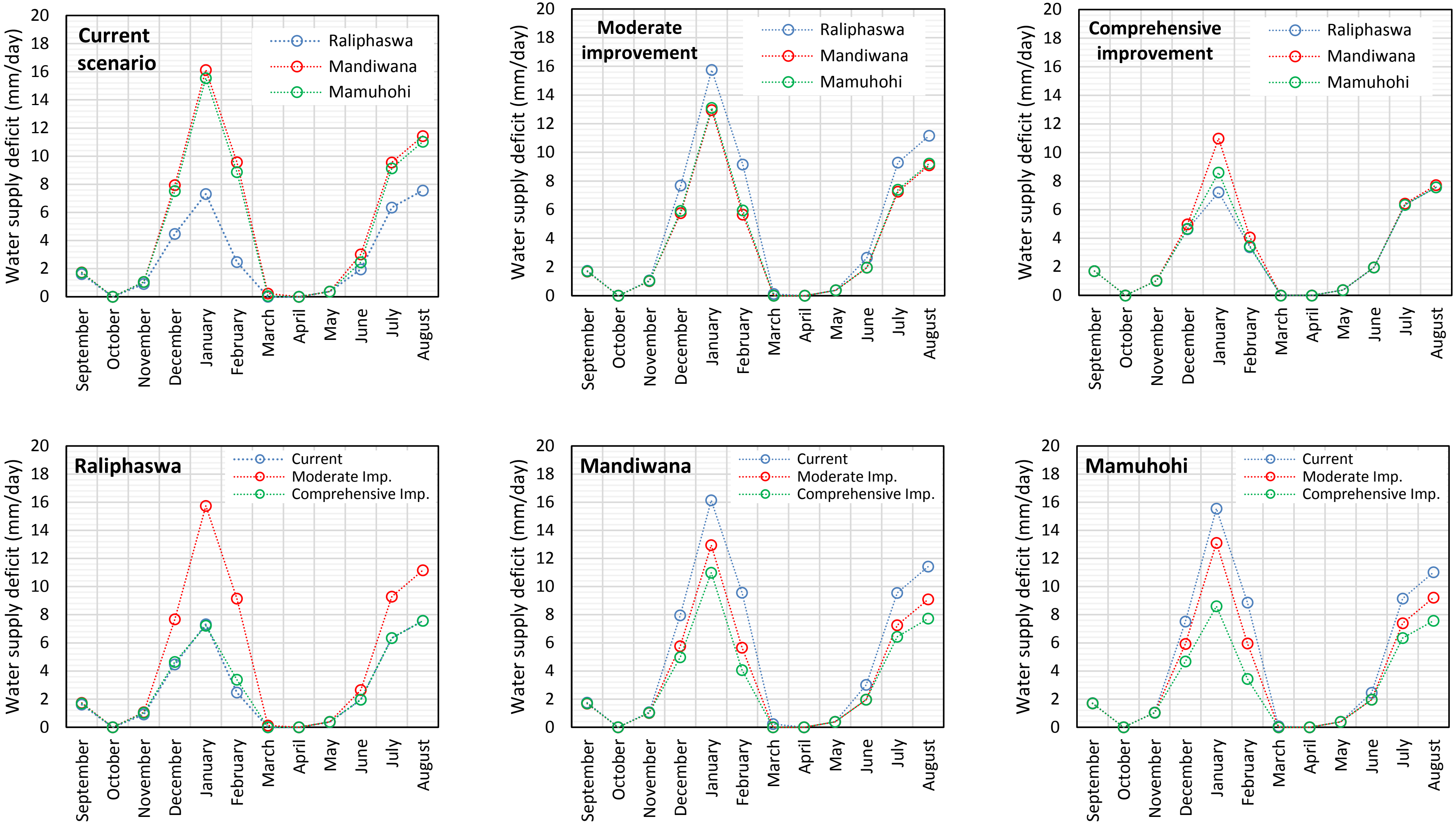

Figure 8.26 Average monthly crop water deficits for various scenarios at 50% land usage

8.6 Evaluation of water governance systems for improved scheme operation

8.6.1 Existing water governance in study schemes

Data from the questionnaire survey were used to find out how governance is undertaken in the schemes and the institutions involved in this. The water governance institutions identified and their roles in the study schemes are presented in Figures 8.27 and 8.28. It was found that there are various governance institutions and structures in the schemes. These included Scheme committee, Water Users Association (WUA), Informal water institutions, Department of Water Affairs, Cooperatives, Government Water Schemes (GWS), Irrigation Board (IB) and the traditional leadership. Figure 8.27 presents the proportion of respondents who recognised the respective institutions/structures while Figure 8.28 includes some of the expressions from respondents relating to the roles of the respective institutions/structures.

The Scheme Committee is revealed as the main water governance (recognised by 84% of the respondents) structure, while traditional leadership and informal water institutions (gatherings of farmers) also have significant recognition and roles.

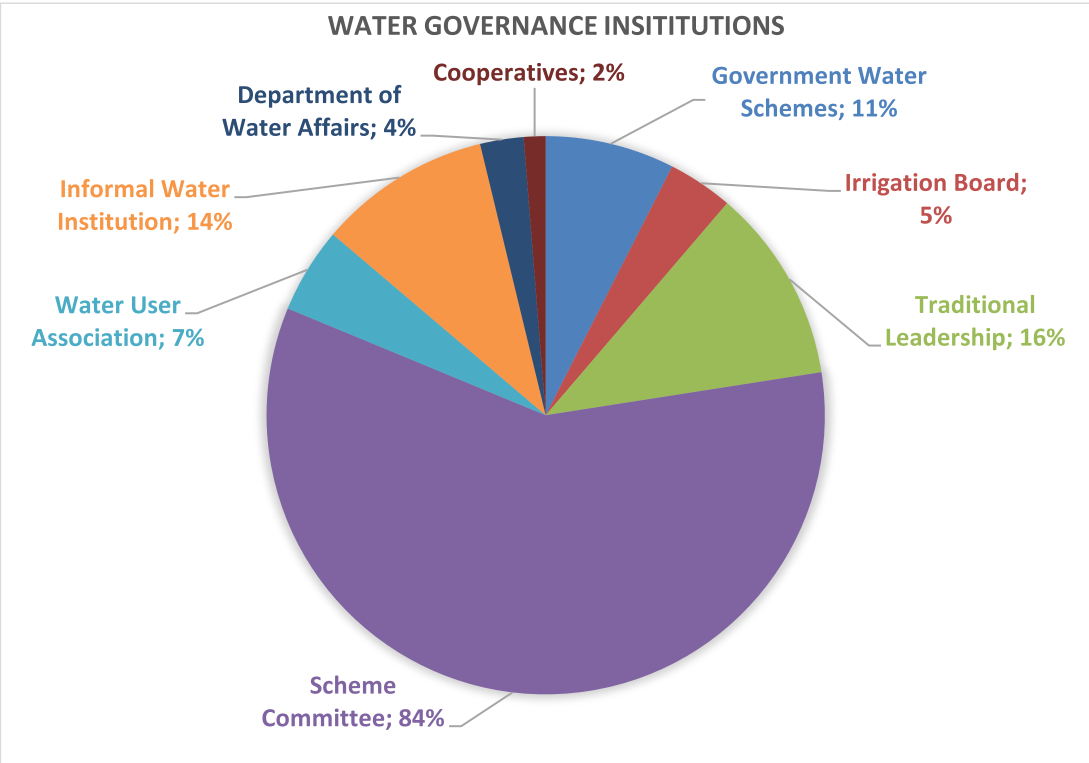

Figure 8.27 Recognition of water governance institutions in selected study schemes

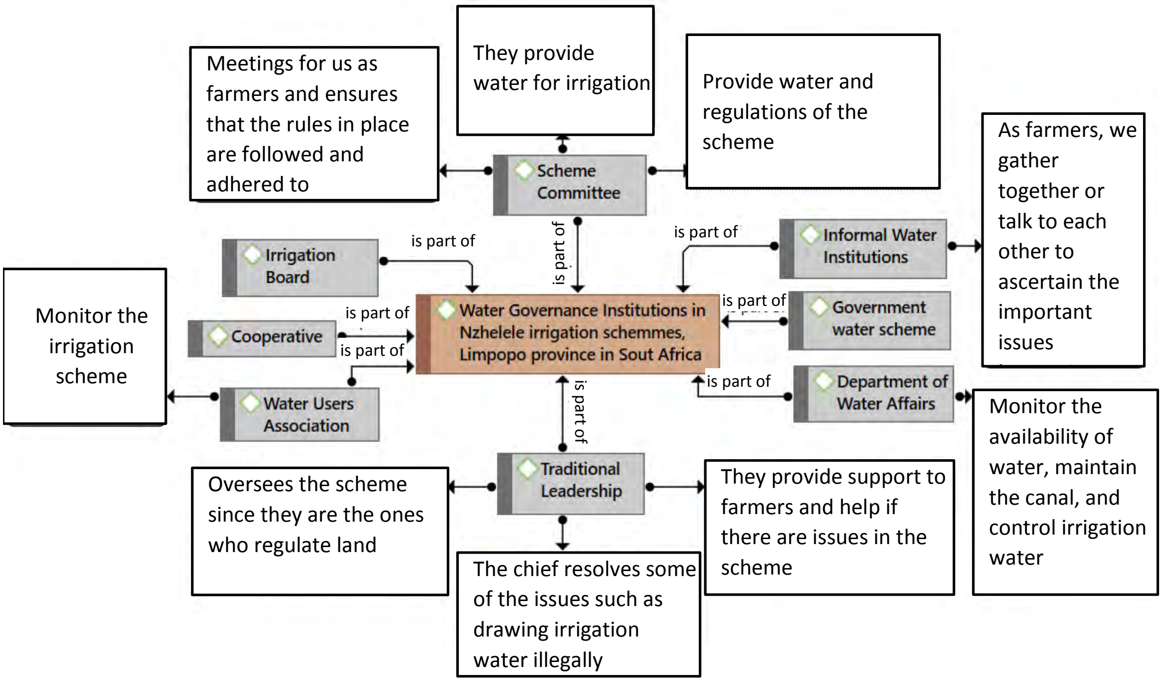

Figure 8.28 Water governance Institutions and their roles in study schemes

8.6.2 Farmer perceptions of effectiveness of governance and management

Fourteen questions were used to assess the perceptions by farmers of management and the effectiveness of governance in the three schemes. The perceptions across the three schemes were found to be similar in most aspects and the results of the overall perceptions are shown graphically on Figure 8.29. It is observed that most of the farmers consider the management and governance to be satisfactory in most aspects. The unfavourable issues scored by more than 20% of the respondents relate to illegal water abstractions and the penalising of farmers who do not follow the rules. The results also indicate that there is a large proportion of farmers who are not be willing to pay for water use although a larger proportion informed that there is willingness to pay for water.

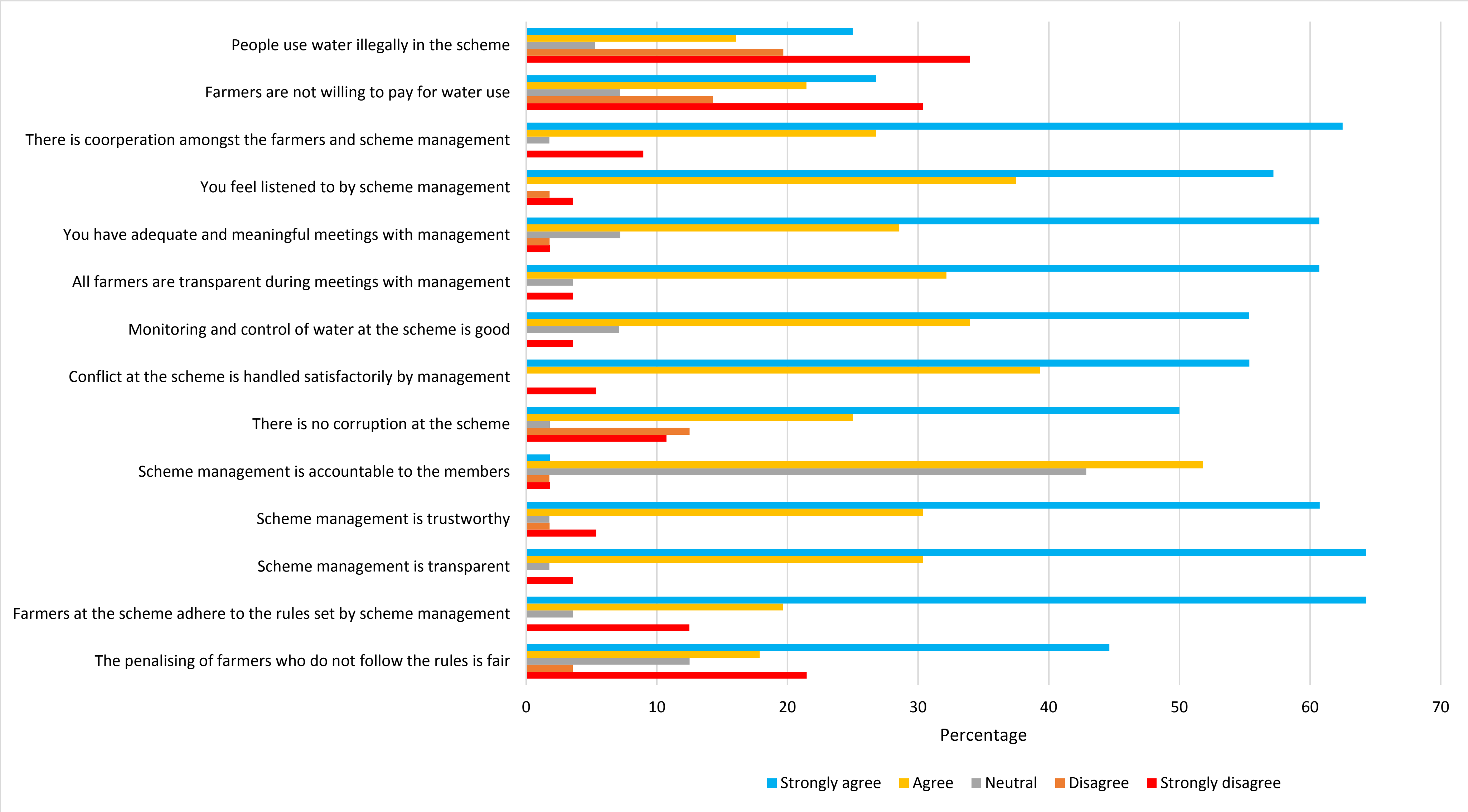

Figure 8.29 Farmers' perception of management and governance in the study schemes

8.6.3 Factors considered by scheme committee in water allocation

Table 8.11 shows the factors that the six scheme committee members consider in allocating water to individual farmers. All six scheme committee members consider the need to distribute water equally to all farmers and to minimise wastage. The results also indicate that all scheme committee members take into consideration the views of farmers when allocating irrigation water.

Table 8.11 Factors considered by scheme committee in water allocation

Factor	Number of scheme members
Size of the plot of each farmer	3 (50%)
The need to distribute water equally to all farmers	6 (100%)
The amount of water that can be delivered by the canal and the scheme	3 (50%)
The need to minimise wastage of water	6 (100%)
The views of the farmers	6 (100%)

8.6.4 Challenges that smallholder farmers face in study schemes

Some of the main findings relating to the water supply challenges faced by the farmers at the study schemes are illustrated in Figure 8.30. The challenges include ineffective irrigation water governance institutions, vandalising of irrigation water infrastructure, blockage of main canals to disrupt the flow of irrigation water, lack of irrigation water due to unregistered farming, poor agricultural produce and poor adherence to the set irrigation schedules.

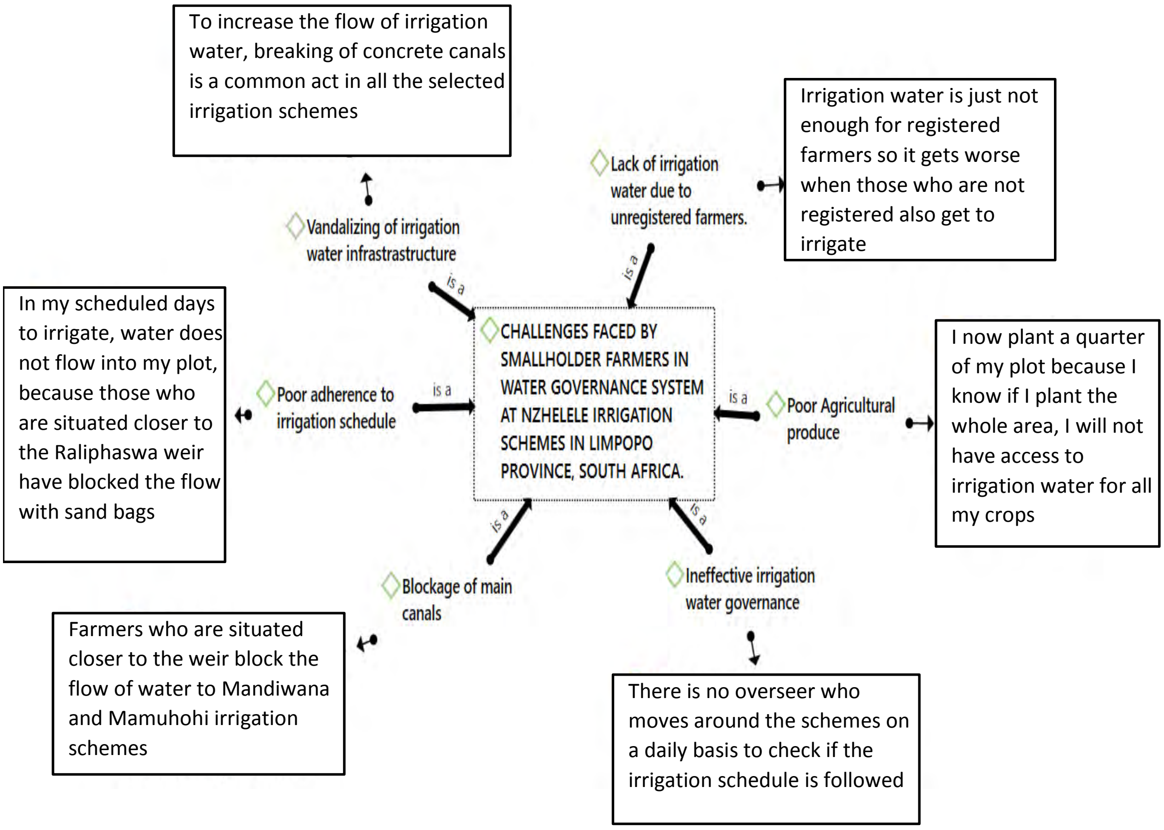

Figure 8.30 Challenges faced by smallholder farmers in water governance systems at selected irrigation schemes at Nzhelele area, Vhembe district

The field survey revealed that some farmers deliberately do not follow the set of rules and regulations because they view the governance for implementing the rules, which is also assigned to other farmers in the scheme, as ineffective.

One of the farmers informed, “I divert water using sandbags because there is just not enough water for every farmer to effectively irrigate. Moreover, I know that if I get to be reported for that, the disciplinary measures will only be in talking.”

Another farmer alluded, “I do irrigate in days which are not allocated to me, because chances are that I might be seen or not be seen by the management because there is no overseer who moves around the schemes on a daily basis to check if the irrigation schedule is followed.”

The field visits to the study schemes revealed vandalism of the canals and the questionnaire survey confirmed that this is common.

One farmer informed, “To increase the flow of irrigation water, breaking of concrete canals is a common act in all the selected irrigation scheme.”

While another farmer indicated, “We are tired of contributing money to patch vandalised infrastructure because of selfish farmers.”

8.6.5 Opportunities for improving water governance

The strategies that could be considered for improving water governance in the study schemes include:

I. engaging an independent full-time overseer of scheme operation
II. increasing the fines for failure to comply to the rules and regulations
III. registering the unregistered farmers to enable better control of water allocation
IV. ensure that those vandalising canal infrastructure are held accountable for the required repairs.

Given the nature of the challenges to governance, the proposed enhancement strategies are rather punitive. Since governance also applies to maintenance activities, punitive action to non-adherence to agreed-upon maintenance schedules could also be used.

The above strategies are illustrated in Figure 8.31 which also includes respective suggestions made by some of the interviewees of the field survey.

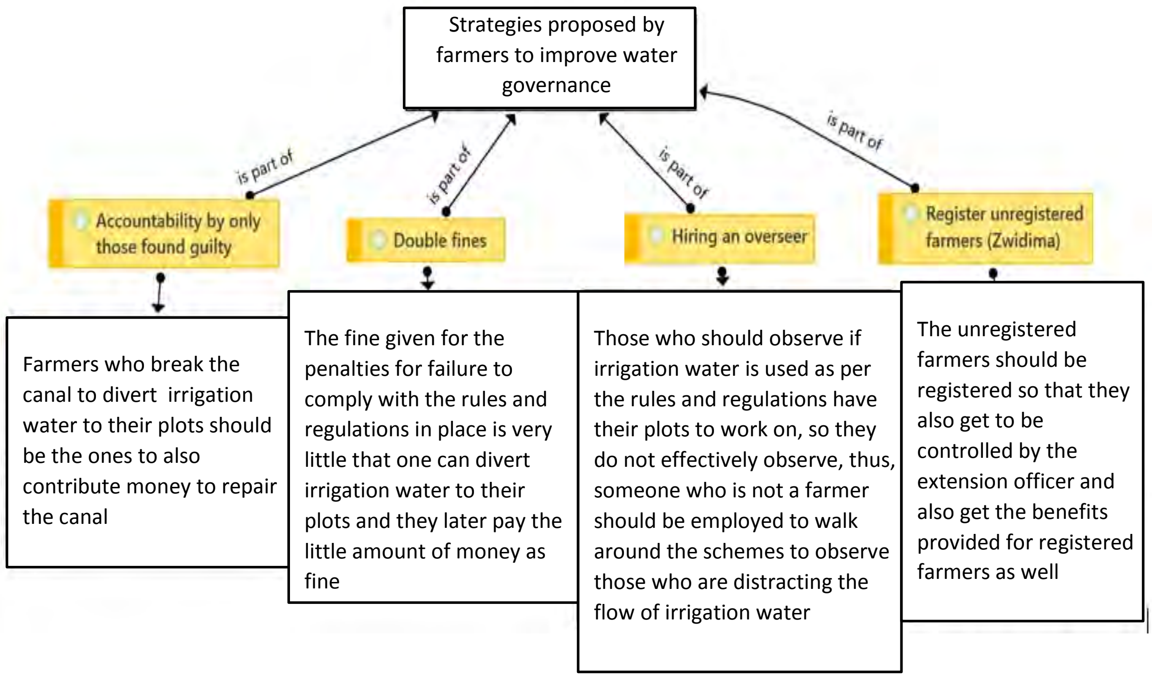

Figure 8.31 Proposed strategies for improving water governance in study schemes

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9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The general aim of this study was to assess the opportunities for improving the operation of smallholder canal schemes in Vhembe, Limpopo Province. The project aimed to achieve this through the following objectives:

I. Review factors causing underutilisation of existing SIS with specific reference to water, land and irrigation infrastructure
II. Document and assess (i) existing design, operation and management of water resource distribution and (ii) existing institutions and organisations governing access to land and water on selected canal schemes.
III. Identify opportunities for improved design, operation and management for equitable water resource distribution and for institutional and organisational reform on these schemes.
IV. Assess the applicability of socio-hydrologic modelling to aid decision making to improve the design, operation and management of SIS

In attempting to achieve the study objectives, the following activities were undertaken.

i. A review of the literature to examine existing knowledge on factors affecting underutilisation of smallholder irrigation schemes in South Africa.
ii. The selection of appropriate smallholder irrigation schemes to for the study.
iii. Desktop data collection of the selected smallholder canal schemes and the selection of the modelling approaches and data that would be needed towards achieving the study objectives.
iv. A detailed diagnosis of the current condition of the scheme infrastructure of the study schemes.
v. The collection of field data consisting of a detailed hydraulic survey of the irrigation infrastructure and a questionnaire survey of the selected smallholder irrigation schemes.
vi. The formulation of a detailed smallholder canal scheme conceptual socio-hydrologic model.
vii. The search for opportunities for improving the performance (water availability and governance) of the study smallholder canal schemes and an evaluation of the applicability of socio-hydrologic modelling for this.

9.1.1 Literature review

The review of the existing knowledge on factors affecting underutilisation of smallholder irrigation schemes in South Africa mainly focused on the design, operation and management of canal schemes and the land and water institutions that exist on them. The review provides a summary of the available information on smallholder irrigation in South Africa and an overview of the people, agriculture and irrigation in the Vhembe District of Limpopo Province, which is the study area of the project. The range of factors that have been identified as causing the underutilisation of smallholder schemes globally and in South Africa are then summarised. Other related aspects that are reviewed include: the history canal design, operation and management in South Africa, the social, water and land institutional structures that govern smallholder canal schemes and the lessons learnt in studies that aimed at improving the performance and sustainability of these schemes. The interconnectedness of the infrastructure and the farmers' decisions and actions within the range of socio-economic and hydrological conditions are found to essential for sustainable scheme performance leading credence to the objective of assessing the applicability of socio-hydrology to finding opportunities for improving scheme performance.

9.1.2 Scheme selection

In order to meet the study objectives within the time and resource constraints, criteria were formulated for shortlisting the potentially suitable schemes within Vhembe district and to make the final selection out of the shortlist. A week-long field visit to Vhembe was made for this and the Raliphaswa, Mandiwana and Mamuhohi complex was selected as the study site. The schemes were established in 1964 and fall under the quaternary catchment A80B of the Nzhelele River Catchment although they obtain irrigation water from a weir located at the end of one of the tributaries of catchment A80A. The farms at Raliphaswa, Mandiwana and Mamuhohi are intrinsically linked by virtue of sharing this common water source, and a linked water conveyance infrastructure. They can therefore be considered as hydraulic sub-units of one unit.

9.1.3 Desktop data collection and selection of modelling methods

The lockdown during the COVID-19 pandemic prevented field visits for situation analysis and desktop data collection and the selection of the required modelling approaches were therefore undertaken. The lockdown also provided an opportunity for the project team to undertake preliminary hydrologic and hydraulic modelling. The initial socio-hydrologic modelling was also developed and applied in the formulation of a detailed questionnaire aimed at providing the data required for the modelling and the search for opportunities to improve scheme performance.

9.1.4 Diagnosis of current state of scheme infrastructure

The state of the canal and storage infrastructure at Raliphaswa, Mandiwana and Mamuhohi irrigation schemes were diagnosed in the basis of field work done on 02 November 2020 and 19 November 2020. This included the determination of the locations of flow control structures and their state of functionality and maintenance; the functionality of the canals based on the existence of blockages by objects, vegetation, sediments, leakages and overflows, condition of canal lining and stability of canal surroundings (in cut/ infill banks); and the existence and locations of illegal/ informal abstraction. Illegal water abstraction using by pumping via a pipe and water diversion using rocks were observed at two locations during the field study.

9.1.5 Hydraulic survey of infrastructure and questionnaire survey

A detailed hydraulic survey and further assessment of the irrigation infrastructure was carried out in January 12-13 2021. It included the measurement of flow rates, water depths and other data to enable the calibration of the hydraulic model for the infrastructure. A piloting of the questionnaire survey was carried out on 11 and 12 March 2021 at two locations in the schemes and refinements to the questionnaire were made based on the pilot. The pilot questionnaire survey experience was applied in planning the main survey that was undertaken over several periods between July and October 2021. The survey interviewed 56 out of the 114 farmers in the three schemes and there were challenges in scheduling the interviews and in having the farmers available to undertake the interviews. It was also observed that the interviewees could not answer several of the questions and the data from the 56 farmers had considerable gaps.

9.1.6 Smallholder canal scheme conceptual socio-hydrologic modelling

This initial socio-hydrological model was further developed and used to formulate process relationships applicable to the human-water dynamics of small-scale irrigation schemes. These process relationships were then summarised into an influence diagram that shows the main causal relationships of the socio-hydrological model.

Opportunities to improve smallholder canal schemes sustainability and the applicability of socio – hydrologic modelling

The search for opportunities to improve scheme performance and the extent to which the conceptual socio-hydrologic model could be applied for this was the final phase of the study. Aspects of water availability, water distribution scheduling, infrastructure maintenance and enhancement, and governance were included in the exploration of these opportunities. A thorough attempt to formulate quantitative socio-hydrologic relationships for the implementation of the socio-hydrologic conceptual modelling proved unsuccessful and the conceptual socio-hydrological model could therefore not be implemented. Consequently, a change in the approach of incorporating the social (human) aspects into the analysis was required. Since the social (or human) aspects relating to governance and management impact on the operation, maintenance and adequacy of infrastructure of irrigation schemes, these could be used as a surrogate for the social (human) aspects. It was therefore decided to incorporate the social aspects into the analysis by undertaking scenarios of hydrologic/hydraulic modelling that correspond to various levels of adequacy of operation, maintenance and state of infrastructure of the study schemes. For this, three scenarios reflecting a) the current state, b) a moderately improved state, and c), a comprehensively improved state were decided upon.

For the current state scenario, the current state of infrastructure maintenance and operation, as obtained in the hydraulic survey was assumed. The moderate improvement scenario assumed that the unregistered farmers would be prevented from accessing the water in the canal system and the informal rock weirs used by these farmers to divert water would be removed through improvement of governance. Gates were assumed to be installed at all offtakes and that the vandalised structures rehabilitated to their initial design. Sedimentation levels were assumed to be at 50% due to an improved maintenance effort. To obtain the comprehensive improvement scenario, an attempt was made to further improve water supply to the three schemes by reducing operational water losses and promoting equitable distribution of water, particularly under low flow conditions. The proposed improvements were obtained from an iterative process using the calibrated hydraulic model of the schemes.

The hydrologic analysis obtained expected monthly inflows into the Raliphaswa weir that supplies the study schemes and the hydraulic partitioning of these inflows and consideration of the canal capacity to the start of the scheme resulted in a flow-duration curve of water availability to the schemes. The maximum possible inflow into the scheme was found to be 0.186 m^3/s and this could be met 63% of the time. For 26% of the time, no flow is expected into the schemes. For each scenario, two flow rates; one representing normal hydrologic conditions (0.186 m^3/s), and the other low flow conditions (0.093 m^3/s) were used to drive the hydraulic analyses for seeking improvements to scheme performance.

The hydraulic modelling revealed significant improvements to water depths for Mandiwana and Mamuhohi with moderate and comprehensive improvements. The moderate improvements scenario reduced water supply to Raliphaswa and would therefore not be modified before any consideration for implementation. The comprehensive improvement scenario retains the current supply levels in Raliphaswa while supplying much more water to Mandiwana and Mamuhohi and to unregistered farmers. This scenario is therefore much more likely to be actionable. The proposed comprehensive improvements include three new formal canal regulating structures (long weirs) and alterations to nine existing ones.

Mass balance at the farm level based on the crop water requirements of maize (the dominant crop in the schemes) for the three scenarios were then carried out for irrigation land usages of 100 and 50%. This analysis revealed a reduction of the impact of the proposed hydraulic improvements although these improvements led to significant reductions in water deficits especially for the 50% land usage rate. Further improvements, such as increasing the hydraulic capacity of some of the constraining channel sections and providing reservoir storage at an appropriate location may be required to offset the crop water deficits. These options were however not studied in any detail and are recommended for further studies into the options for improving the performance of the study schemes. Such considerations could more appropriately be assessed as part of the broader water resource master planning in catchment and the region. Without such interventions, persistent water shortage and punitive governance and management are likely to predominate.

The search for improvements in management and governance revealed the Scheme Committee as the main water governance structure, while traditional leadership and informal water institutions (gatherings of farmers) also have significant recognition and roles.

An assessment of the perceptions of management by farmers and the effectiveness of governance in the three schemes informed that most of the farmers considered the management and governance to be satisfactory in most aspects. The unfavourable issues scored by more than 20% of the respondents relate to illegal water abstractions and the penalising of farmers who do not follow the rules.
Some of the main findings relating to the water supply challenges faced by the farmers at the study schemes include: ineffective water governance, vandalising of irrigation water infrastructure, blockage of main canals to disrupt the flow of irrigation water, lack of irrigation water due to unregistered farming, and poor adherence to the set irrigation schedules. Several farmers highlighted that this leads to lack of water and therefore to low crop yields and the reduction of land use for farming.

Based on the above challenges, the following strategies were proposed for improving water governance in the schemes:

I. Engaging an independent full-time overseer of scheme operation
II. Increasing the fines for failure to comply to the rules and regulations
III. Registering the unregistered farmers to enable better control of water allocation
IV. Ensure that those vandalising canal infrastructure are held accountable for the required repairs.

9.2 Recommendations

The above summary of the study indicates that the general aim and the four objectives of the study were broadly met. The hydraulic and hydrologic analysis on the study schemes reveal gross inadequacy of the current infrastructure for supplying water and large inequity of supply to the individual schemes. Furthermore, it is found that even with improvements to improve water supply and equity of supply, significant crop water deficits would still be experienced even at 50% land utilisation. Hydraulic analysis reveals that the proposed hydraulic improvements would reduce water wastage within the canals to low levels of 10-15% indicating that only major infrastructure developments could achieve adequate levels of water supply to the study schemes. It is recommended that such considerations be made in future work geared to improving the performance of the study schemes and other smallholder irrigation schemes in Vhembe and other parts of South Africa. The study informs that the Scheme Committee is generally considered to manage and govern the scheme reasonably well by farmers in most aspects except those relating to competition for the inadequate water resource. Understandably, several of the farmers in the schemes propose punitive measures such as increased the severity of penalties for breaking the set rules in order to improve governance. The researchers here are in agreement with such measures although improving the water supply is likely to lead to more significant and more sustainable improvements and a diminished need for punitive governance.

The study found that quantitative socio-hydrology could not be applied with the data obtained from the field survey as no realistic quantitative socio-hydrologic and socio-economic relationships could be obtained from the data. The quantitative data were collected from verbal interviews in the surveys and were not based on actual records. They are therefore estimates and probably have large error margins.

There were also large data gaps as many of the interviewees did not answer several of the questions. Recorded socio-economic, operational and management data could not be acquired within the time and resource-limitations of the study and it is recommended that the acquisition of recorded data be included in future attempts to undertake quantitative socio-hydrological modelling that has substantial action research orientation.

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11 APPENDICES

11.1 Appendix A: Condition of infrastructure

Appendix A Condition of Infrastructure

Scheme Section / Canal Infrastructure / Condition	Photo
Raliphaswa C1 Exposed concrete aggregate. Light density overhanging vegetation affecting flow	
Raliphaswa C2 Concrete is in good condition. Medium density overhanging vegetation affecting flow. Aquatic grass in canal.	

Raliphaswa C2 Concrete is in good condition. High density overhanging vegetation affecting flow. Light sediment accumulation.	
Raliphaswa CR1 Accumulated sediment wedge. Gate valve can be operated via wrench - no steering wheel.	

<table>
<tr><td>Raliphaswa
C3
Concrete is in good condition. High density overhanging vegetation affecting flow.</td><td></td></tr>
<tr><td>Raliphaswa
C3
Exposed concrete aggregate. Light density overhanging vegetation affecting flow</td><td></td></tr>
</table>

Raliphaswa	
CR2	
Accumulated sediment wedge. Damaged concrete liner due to overtopping. Gate valve operated via steering wheel.	
Raliphaswa	
UD1	
Rocks were used to increase the canal head. High density overhanging vegetation affecting flow.	

Raliphaswa	
PD1 and SI1	
Rocks are used to control the water diverted to PD1. There is also evidence of previous blocking of SI1 grid inlet. Aquatic growth.	
Mandiwana	
SI3	
SI3 has a grid inlet which gets blocked from time to time. There is also high density vegetation overgrowth affecting inlet conveyance.	

Mandiwana SO3 Medium density vegetation overgrowth affecting outlet conveyance.	
Mandiwana C9 High density overhanging vegetation affecting flow. Medium sedimentation along canal invert.	

Mandiwana CR3 Accumulated sediment. Light density overhanging vegetation. Cracking and damage to the weir, reducing effectiveness of weir. No gate valve.	
Mandiwana C10 High density overhanging vegetation affecting flow. No access possible.	

Mandiwana CR4 High density overhanging vegetation affecting flow. No gate valve.	
Mandiwana C11 Light density overhanging vegetation affecting flow. Light sediment accumulation along the invert.	

Mandiwana CR5 Light density overhanging vegetation affecting flow. Light sediment accumulation along the invert. No gate valve.	
Mandiwana C12 Medium density vegetation overgrowth affecting outlet conveyance.	

Mandiwana	
CR6	
Slight damage to the normal leg of the long weir. Gate valve steering wheel is in place.	
Mandiwana	
C13	
Medium density vegetation overgrowth affecting outlet conveyance and vegetation growing through the contraction joints.	

Mandiwana ICR1 Rocks are used to increase the canal head for distribution through the offtake.	
Mandiwana C14 Light density overhanging vegetation affecting flow. Light sediment accumulation along the invert.	

Mandiwana	
CR7	
Light sedimentation evident at the long weir. Offtake invert is also noticeably higher than the other offtakes above the canal invert. Long weir is also slightly damaged. Gate valve has no steering wheel but can be operated with a wrench.	
Mandiwana	
C15	
Heavy density overhanging vegetation affecting flow.	

Mandiwana	
CR8	
Medium density overhanging vegetation. Gate valve steering wheel is also in place.	
Mandiwana	
C16	
Heavy density overhanging vegetation affecting flow.	

<table>
<tr><td>Mandiwana</td><td rowspan="3"></td></tr>
<tr><td>SI4</td></tr>
<tr><td>Significant settled sediment cause by physical and hydraulic erosion around the inlet due to livestock and people. There is also a 50mm diameter pipeline going through the culvert.</td></tr>
<tr><td>Mandiwana</td><td rowspan="3"></td></tr>
<tr><td>SO4</td></tr>
<tr><td>Significant settled sediment cause by physical and hydraulic erosion around the inlet due to livestock and people. There is also a 50mm diameter pipeline going through the culvert.</td></tr>
</table>

<table>
<tr><td>Mandiwana</td><td rowspan="3"></td></tr>
<tr><td>C17</td></tr>
<tr><td>A portion of this section is laden with sediment along the invert. Some structural cracks were observed. And some light density overhanging vegetation.</td></tr>
<tr><td>Mandiwana</td><td rowspan="3"></td></tr>
<tr><td>ICR2</td></tr>
<tr><td>No rocks were present at the day of inspection. However, the offtake invert seemed also to be quite low.</td></tr>
</table>

Mandiwana	
C18	
The canal is highly sediment laden.	
Mandiwana	
SI5	
The inlet has a grid and is prone to blocking from debris. Also some vegetation just upstream of the inlet.	

Mandiwana SO5 Minimal vegetation and minor sediment along the invert.	
Mandiwana C19 The canal is lightly sediment laden.	

Mandiwana	
CR9	
Some accumulated debris was observed at the offtake. No gate valve steering wheel seen, however valve can be operated by means of a wrench.	
Mandiwana	
C20	
Medium density overhanging vegetation with minor sedimentation along the canal invert.	

Mandiwana CP6 Leakage was observed.	
Mamuhohi S1 C20 has a free overfall into S1.	

Mamuhohi	
SF2	
Exposed concrete aggregate and cracking along the spillway. Also some overhanging vegetation.	
Mamuhohi	
DS	
Also fitted with a thin plate weir that can be used for measurement and a manually operated steering wheel for gate valve.	

Mamuhohi C21 Light to medium density overhanging vegetation	
Mamuhohi CR10 Slight damage to the normal leg of the long weir. Gate valve steering wheel not in place. Light overhanging vegetation.	

Mamuhohi C22 Light density overhanging vegetation.	
Mamuhohi CR11 Structurally damaged weir resulting in only partial regulation of water level. Normal weir section is 80% sediment laden. No gate valve.	

Mamuhohi	
C23	
Heavy density overhanging vegetation affecting flow.	
Mamuhohi	
ED1	
Low density overhanging vegetation was observed	

Mamuhohi	
SI6	
The siphon appears to have a drop inlet structure and the entrance has a grid.	
Mamuhohi	
SO6	
The siphon outlet is submerged and the head is controlled by CR12.	

Mamuhohi	
CR12	
Structurally damaged weir resulting in only limited regulation of water level. No gate valve.	
Mamuhohi	
C24	
Light sedimentation and light overhanging vegetation.	

Mamuhohi CR13 Structurally damaged weir resulting in only partial regulation of water level. No gate valve was installed.	
Mamuhohi C25 Light overhanging vegetation.	

Mamuhohi UD3 Buckets and rocks were observed, used by the locals to abstract water.	
Mamuhohi CR14 Structurally damaged weir resulting in only partial regulation of water level. No gate valve was installed.	

Mamuhohi	
C26	
Light overhanging vegetation.	
Mamuhohi	
CR15	
No structural damage to structure. Light overhanging vegetation. Offtake is not equipped with a gate valve.	

Mamuhohi	
C27	
Light to medium overhanging vegetation.	

11.2 Appendix B Hydraulic survey of hydraulic infrastructure

11.2.1 Appendix B1: Canal shape size water depths and velocities

Scheme	Canal No.	Shape	Total depth (mm)	Water surface depth (mm)	Total top width (mm)	Top water surface width (mm)	0.2 × depth velocity (m/s)	0.4 × depth velocity (m/s)	0.8 × depth velocity (m/s)
Raliphaswa	C1	Parabolic		320	1070	830	0.600	0.800	0.800
Raliphaswa		Parabolic		325	1100	870	0.700	0.800	0.800
Raliphaswa	C2	Parabolic		420	1100	985	0.400	0.500	0.500
Raliphaswa	C3	Parabolic		330	1100	890	0.500	0.600	0.600
Raliphaswa		Parabolic		300	1150	845	0.700	0.800	0.800
Raliphaswa	C4	Parabolic	425	425	980	980	0.200	0.400	0.600
Raliphaswa	C5	Parabolic	-	-	-	-	-	-	-
Raliphaswa	C6	Parabolic	-	-	-	-	-	-	-
Mandiwana	C7	Parabolic	-	-	-	-	-	-	-
Mandiwana	C8	Parabolic	-	-	-	-	-	-	-
Mandiwana	C9	Parabolic		390	950	890	-	0.400	0.100
Mandiwana	C10	Parabolic	-	-	-	-	-	-	-
Mandiwana	C11	Parabolic	450	283	950	785	0.400	0.4 - 0.5	0.400
Mandiwana		Parabolic	-	380 (285 above sediment)	960	854	0.200	-	-
Mandiwana	C12	Parabolic	-	375	930	860	-	-	-
Mandiwana	C13	Parabolic	-	225	1005	680	-	-	0.800
Mandiwana		Parabolic	-	310	-	770			
Mandiwana	C14	Parabolic	-	325	990	890	-	-	-
Mandiwana	C15	Parabolic	-	353	1000	895	0.011	0.072	0.371
Mandiwana	C16	Parabolic	-	350	1020	905	1.980	0.227	0.297
Mandiwana	C16	Parabolic	-	-	-	-	4.770	0.380	0.095
Mandiwana	C17	Semi-circle	-	275	1030	820	0.250	0.098	0.226

Scheme	Canal No.	Shape	Total depth (mm)	Water surface depth (mm)	Total top width (mm)	Top water surface width (mm)	0.2 × depth velocity (m/s)	0.4 × depth velocity (m/s)	0.8 × depth velocity (m/s)
Mandiwana	C18	Semi-circle	-	510	1130	960	0.119	0.147	0.239
Mandiwana	C19	Parabolic	-	350	1020	890	0.076	0.037	0.032
Mandiwana		Parabolic	-	200	985	680	0.104	0.225	0.203
Mandiwana	C20	Parabolic	-	239	1010	745	0.010	0.156	0.128
Mandiwana		Parabolic	-	270	865	650	0.121	0.228	0.102
Mandiwana		Parabolic	-	290	870	680	0.091	0.097	0.167
Mamuhohi	C21	Parabolic	-	210	690	486	0.006	0.269	0.269
Mamuhohi			-	300	780	680	0.054	0.126	0.125
Mamuhohi	C22	Parabolic	-	170	630	410	0.114	0.095	0.165
Mamuhohi			-	120	800	440	-	0.211	0.144
Mamuhohi			-	190	790	530	0.136	0.207	0.109
Mamuhohi			-	130	720	410	-	0.374	0.482
Mamuhohi			-	250	690	595	0.073	0.122	0.147
Mamuhohi	C23	Parabolic	-	130	520	300	-	0.377	0.331
Mamuhohi	C24	Semi-circle	-	190	680	510	0.165	0.150	0.067
Mamuhohi		Semi-circle	-	250	720	620	0.054	0.095	0.043
Mamuhohi	C25	Semi-circle	-	180	720	540	0.086	0.090	0.044
Mamuhohi		Semi-circle	-	110	660	370	-	0.065	0.170
Mamuhohi		Semi-circle	-	90	670	430	-	0.147	0.259
Mamuhohi		Semi-circle	-	110	700	400	-	0.185	0.154
Mamuhohi	C26	Semi-circle	-	-	-	-	-	-	-
Mamuhohi	C27	Semi-circle	-	-	-	-	-	-	-

11.2.2 Appendix B2: Condition and functionality of canal regulators

Scheme	Canal regulator No.	Functional or not ? *	Ease of operation **	Is there Interference or not ? ***
Raliphaswa	CR1	Yes	Easy	Yes
Raliphaswa	CR2	Yes	Easy	Yes
Mandiwana	CR3	Yes	Easy	Yes
Mandiwana	CR4	Yes	Easy	Yes
Mandiwana	CR5	Yes	Easy	Yes
Mandiwana	CR6	Yes	Easy	Yes
Mandiwana	ICR1	Yes	Difficult	Yes
Mandiwana	CR7	Yes	Easy	Yes
Mandiwana	CR8	Yes	Easy	Yes
Mandiwana	ICR2	No	Difficult	No
Mandiwana	CR9	Yes	Easy	Yes
Mamuhohi	CR10	Yes	Easy	Yes
Mamuhohi	CR11	No	Easy	No
Mamuhohi	CR12	No	Easy	No
Mamuhohi	CR13	No	Easy	No
Mamuhohi	CR14	No	Easy	No
Mamuhohi	CR15	Yes	Easy	Yes

* Functional if the regulating structure controls the flows.

** Ease of operation: "Difficult" is used when there is no formal regulating structure and rocks have to be used.

*** Interference indicates that the structure has an adverse impact on the behaviour of other structures.

11.2.3 Appendix B3: Size and condition of flow distributors

Scheme	Distributor No.	Diameter of offtake (mm)	No. of offtakes	Water depth measured from offtake invert (mm)	Offtake Control conditions	Gate Valve	Distributor opening	Functional*	Ease of operation **	Interference ***
Raliphaswa	D1	160	1	340	Inlet	Yes	Fully open	Yes	Cumbersome	No
Raliphaswa	D2	160	1	~360		Yes	Fully open	Yes	Easy	No
Mandiwana	D3	110	1	130	Inlet	No	Fully open	No	Difficult	No
Mandiwana	D4	110	1	130		No	Closed but leaking	No	Difficult	No
Mandiwana	D5	110	1	270		No	Closed but leaking	Yes	Easy	No
Mandiwana	D6	110	1	355		Yes	Fully closed	No	Difficult	No
Mandiwana	D7	110	1	150		No	Partially blocked	Yes	Cumbersome	No
Mandiwana	D8	110	1	130	Inlet	Yes	Fully open	Yes	Easy	No
Mandiwana	D9	110	1	250	Inlet	Yes	Partially open with gate valve	Yes	Easy	No
Mandiwana	D10	110	1	300		No	Fully closed	No	Difficult	No
Mandiwana	D11	110	2	360	Inlet	Yes	One partially blocked, the other is fully open	No	Difficult	Yes
Mamuhohi	D12	110	3	240		Yes	2 blocked but leaking offtakes, 1 fully open offtake	No	Difficult	Yes
Mamuhohi	D13	110	1	285		No	Partially blocked	No	Difficult	No
Mamuhohi	D14	110	1	300	Inlet	No	Partially blocked	No	Difficult	No
Mamuhohi	D15	110	1	270	Inlet	No	Fully open	No	Difficult	No
Mamuhohi	D16	110	1	290	Inlet	No	Partially blocked	No	Difficult	No

Scheme	Distributor No.	Diameter of offtake (mm)	No. of offtakes	Water depth measured from offtake invert (mm)	Offtake Control conditions	Gate Valve	Distributor opening	Functional*	Ease of operation **	Interference ***
Mamuhohi	D17	110	1	175	Inlet	No	Partially blocked	No	Difficult	No
Mamuhohi	D18	110	2	0		No		No	Difficult	Yes
Mamuhohi	D19	110	2	0		No		No	Difficult	Yes

* Functional if the gate valve is controlling flows into the distributor.

** Difficult when there is no gate to operate and cumbersome when there is no wheel to operate the gate with.

** Interference if the structure has an adverse impact on the behaviour of other structures

11.2.4 Appendix B4: Shape, size, water depths, velocities and condition of siphon inlets and outlets

Scheme	**Inlet No.**	**Shape**	**Total depth (mm)**	**Water surface depth (mm)**	**Total top width (mm)**	**Top water surface width (mm)**	**0.2 × depth velocity (m/s)**	**0.4 × depth velocity (m/s)**	**0.8 × depth velocity (m/s)**	**Functional**	**Ease of operation***	**Interference****
Raliphaswa	SI1	Parabolic		290	1130	800	0.200	0.300	-	Yes	Easy	Yes
Mandiwana	SO1	-	-	-	-	-	-	-	-	-	-	-
Mandiwana	SI2	-	-	-	-	-	-	-	-	-	-	-
Mandiwana	SO2	-	-	-	-	-	-	-	-	-	-	-
Mandiwana	SI3	Parabolic	610	500	1205	1050	0.000	0.000	0.100	Yes	Cumbersome	Yes
Mandiwana	SO3	Parabolic	695	-	-	-	-	-	-	Yes	Difficult	No
Mandiwana	SI4	Circular	600	310			-	0.383	0.534	Yes	Cumbersome	Yes
Mandiwana	SI4	Circular	600	270			4.770	0.380	0.095	Yes	Cumbersome	Yes
Mandiwana	SO4	Circular	600	270			0.237	0.320	0.192	Yes	Cumbersome	No
Mandiwana	SI5	Semi-circle	-	510	1130	960	0.119	0.147	0.239	Yes	Cumbersome	Yes
Mandiwana	SO5	Parabolic	-	600	1280	1170	0.034	0.007	0.358	Yes	Easy	No
Mandiwana	SO5	Parabolic	-	350	1020	890	0.076	0.037	0.032	Yes	Easy	No
Mamuhohi	SI6	Parabolic	-	130	520	300	-	0.377	0.331	Yes	Cumbersome	Yes
Mamuhohi	SO6	Parabolic	-	210	710	560	0.141	0.119	0.081	Yes	Difficult	Yes

* Ease of operation is easy if structure can be cleaned easily

** Interference occurs when the structure has an adverse impact on the behaviour of other structures