AN EVALUATION OF PRIORITY AND FRACTIONAL METHODS OF WATER ALLOCATION IN THE SAND RIVER CATCHMENT, SOUTH AFRICA

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ABSTRACT

The development and apportionment of water resources is a critical issue, both globally and locally in South Africa. This is particularly true in the development and allocation among states sharing watercourse systems. The competition inherent in access to water resources is increasing. In particular, pressure is being placed on water resources from several activities including irrigation, domestic consumption and industrial requirements. Water allocation mechanisms are therefore critical to sustain the existing allocatable water resources while attempting to combine both efficiency and equity principles. The National Water Act of South Africa (Act 36 of 1998) (NWA (36, 1998)) incorporates both institutional and legal policy which promotes the efficient, equitable and sustainable management of water resources. The aims of the NWA (36, 1998) are achieved by a movement away from a Riparian Rights system (a property adjacent to a water course is allowed reasonable use) to an Administrative System (Hallowes *et al.*, 2008). The inception of an Administrative System for the allocation of water in South Africa is vital given that a number of catchments in South Africa have reached a state of being fully developed and more than 50% of the 19 water management areas in South Africa are water stressed, i.e. the demand exceeds the supply (DWAF, 2004). The NWA (36, 1998) makes allowance for only one right to water; that being the Reserve, which consists of two components, the ecological requirement and basic human needs. The management of the resource is important because the NWA (36, 1998) states that the water resources within South Africa are to be protected, used, developed, conserved, managed and controlled in accordance with the National Water Resources Strategy (DWAF, 2004).

The water allocation method currently applied in South Africa is referred to as a Priority-based River and Reservoir Operating Rule (PRROR) institutional arrangement. Under PRROR, when there is a risk of a reservoir or river failing to meet the supply demanded, restrictions are applied to abstractions. The priority extends not only to those who have the priority of use but which users will relinquish water to the higher priority users and by what quantity. Disadvantages of PRROR include the inability of the Water User to manage their water to meet their needs and are then forced into using it when the water is available. Possible alternate allocation methods include Fractional Water Allocation and Capacity Sharing (FWACS), public water allocation and prior rights systems. The PRROR as currently implemented leads to high priority sectors having dominance over access to water which may

lead to those sectors not using water efficiently. The introduction of FWACS creates an atmosphere of water awareness and being responsible for managing water use.

In this study, the MIKE BASIN model was used in the simulation of the processes of the PRROR and the FWACS allocation methods. The model routes water based on rules specified for the allocation method under review. The efficiency of each allocation method was evaluated in terms of the reliability of supply to Water Users. In the catchment used as a case study (Sand River Catchment), limited information on Environmental Water Requirement (EWR) was available and the EWRs were set as minimum flows at each reservoir and then set as a minimum flow requirement at a downstream node to prevent Water Users downstream of the dam from immediately abstracting the EWR release. Based on data used in the case study and the rules applied to each scenario, the results from the initial study indicated that PRROR provides a 4% higher reliability of supply in comparison to FWACS in the catchment under investigation. This is true when the supply to a Water User is similar between scenarios. However, if the fractions allocated in FWACS are varied away from this baseline, results indicate that a 50% increase on the original FWACS fractions provides for better reliability of supply. Thus the results show that although PRROR is an alternative method for determining water allocation to water users, FWACS+50 is able to improve on the water reliability of supply within the Sand River Catchment.

DECLARATION - PLAGIARISM

I, …………………………………………….……………………., declare that

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2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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Signed

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LIST OF ABBREVIATIONS

AAMG	Amalgamation of Agrohydrological Modelling Groups
ABRESP	A-horizon to B-horizon response
BFRESP	B-horizon to groundwater response
CMA	Catchment Management Agencies
COIAM	Coefficient of Initial Abstraction
CS	Capacity Sharing
DSL	Dead Storage Level
DSS	Decision Support Systems
DWS	Department of Water and Sanitation
EWR	Environmental Water Reserve
FSC	Full Supply Capacity
FWA	Fractional Water Allocation
FWACS	Fractional Water Allocation and Capacity Sharing
GUI	Graphical User Interface
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
NWA	National Water Act, Act 36 of 1998
NWRS	National Water Resources Strategy
PRROR	Priority-based River and Reservoir Operating Rule
QFRESP	Quickflow Response
REALM	REsource ALlocation Model
USBR	United States Bureau of Reclamation
WRAP	Water Rights Analysis Package
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WUE	Water Use Efficiency

DEFINITIONS

Administrative system	A system of licensing and hierarchical structure and central management.
Flow network	Simplistic representation of a complex environment by use of a diagram, indicating important features and systematic flow of water through the system.
FWACS	Fractional Water Allocation and Capacity Sharing
Irrigation scheme	A collection of irrigators who operate as a collective for bargaining power and efficiency.
PRROR	Priority-based Reservoir and River Operating Rules.
Riparian rights	Land adjacent to a water source may have reasonable use of water by the fact of proximity.
Riparian rights system	See Riparian rights.
Water stressed catchment	A catchment in which water demand/allocation comes close to equalling water supply from the catchment in the form of Mean Annual Runoff.
Water User	An individual water user.
Water user	A group of water users
Water use efficiency	Achieving the maximum output per unit of water used.

1 INTRODUCTION

The development and apportionment of water resources is a critical issue, both locally in South Africa and in many regions and sub-regions of the world, especially where water demand is greater than water supply. This is particularly true in the development and allocation among states sharing watercourse systems and catchments, especially if they are located in arid areas (Caflisch, 1996). Additionally the deterioration of rivers over the past three decades, linked to anthropogenic impacts on the waterways which has altered river flow regimes (Symphorian *et al.*, 2002), has increased the demand for clean water. The competition for water resulting from increasing pressure from the population, stricter environmental standards and competing "reasonable uses" is placing increasing stress on water resources, particularly in developing areas (Griffin and Hsu, 1993; 2000; Nkomo and van der Zaag, 2004). This realisation has led to many countries initiating steps to halt or reverse the deterioration caused by the altered flow regimes (King and Tharme, 1993).

The competition inherent in access to water resources is increasing in South Africa. In particular, pressure is being placed on the water resources from several activities. For example, the Olifants River Catchment is expected to have no water available for allocation from 2010 (Farolfi and Perret, 2002). The chief competitor for water in the Olifants River Catchent is mining, in the form of new mines and expansion of current mine operations. The Komati River Catchment currently experiences a consumptive water use of 70% of the mean annual runoff, which places it as a water stressed catchment. Competition for water comes from intensive small scale irrigation farming, the development of public irrigation infrastructure, un-adapted cultivation methods (i.e. using water intensive methods rather than modern technologically advanced methods such as flood irrigation used in inappropriate environments) and crops, as well as the rapidly growing population. These factors have all been increasing the pressure on natural resources in general, and on water resources in particular (Chakravorty and Roumasset, 1991; Farolfi and Perret, 2002; Wallace *et al.*, 2003). Evidence suggests that low benefits are derived from the water resource available to the above irrigation activities (Chakravorty and Roumasset, 1991). The reasons for the low benefits experienced are poor on-farm water use efficiencies that result from water charges that are low and are often unrelated to water use. For example, farmers at or near the head-waters of a catchment, are said to consume a disproportionate share of irrigation water, while farmers near the outlet are left with inadequate and unreliable residual supplies (Chakravorty and Roumasset, 1991; Aeschbacher *et al.*, 2005).

The NWA (36, 1998) places a great deal of importance on the protection of water resources for their sustainable utilisation (Xu *et al.*, 2002). The institutional arrangements i.e. allocation rules, which have developed in response to the promulgation of the NWA (36, 1998) have had, and continue to have a large impact on the management of water and its use in South Africa. Furthermore, those arrangements which provide for positive incentives to use water more efficiently have a greater likelihood of being successful in the uptake and implementation of best water management practices (Lecler, 2004a).

The NWA (36, 1998) recognises the importance of the responsibilities of the local stakeholders in advising and guiding the management and development of the catchment. Involving stakeholders in the decision making process with regard to the control of water resources is an important aspect, albeit that local people are one of several groups which may have a vested interest in the catchment. State departments are experiencing a decrease in their expertise and knowledge base with a corresponding increase in the knowledge base of stakeholders. This change in the balance between the state knowledge base and stakeholder knowledge base has important implications for the development and implementation of water allocation methods in the social process (Dent, 2001).

Changes in cropping practices and an increase in the agricultural diversity over the past two decades have resulted in the historical water allocations no longer meeting the current demands (Tisdell and Ward, 2003). More than 50% of the 19 water management areas in South Africa are currently over-allocated with regard to the demand for water and the ability to supply the required water resources (Farolfi and Perret, 2002; DWAF, 2004; Hallowes and Pott, 2005; Pott *et al*, 2009). The increase in agricultural cropping areas and the over-allocation of water resources places a high degree of stress on the agricultural sector as approximately 60% of the country's water resources are used by agriculture (DWAF, 2004).

South Africa currently allocates water on a Priority-based River and Reservoir Operating Rule (PRROR) system (Hallowes and Pott, 2005). In this system, irrigators with a low priority pay a lower cost per unit of water while exposing themselves to a higher degree of risk in surety of supply of water as compared to, for example, residential Water Users who require a greater security in water supply and therefore pay a higher cost per unit of water, even if they are using less (Frezghi and Smithers, 2007). Some disadvantages of the PRROR allocation method include the following (Hallowes and Pott, 2005):

- If Water Users do not use their allocated water, the entitlement to this water is lost and may be used by other users under water shortage conditions. Although this is to the advantage of a water user who has a water deficit, as they now may have has access to additional water, it is to the disadvantage of the water user who has a surplus of water as that user may be charged for water on the basis of their water permit, irrespective of whether the water is used or not.
- The allocation method is data intensive in auditing of users and as such, a high degree of accuracy required is not achieved.
- The centralised management of the allocation method means that officials are out of touch with local users needs. This leads to local users not being encouraged to manage their water use efficiently.
- The different levels of supply between the Water Users leads to complexity in attempting water trading.

Allocation methods which provide an alternative and possibly an improvement in comparison to current methods are being investigated in order to jointly lower the unit cost and improve the surety of supply of water (Dinar *et al.*, 1997). Allocation of the available water resources needs to be conducted in such a manner that the allocation is of the most benefit (Dinar *et al.*, 1997; NWA, 1998). There are several criteria used in the comparison of water allocation methods and these include (Howe *et al.*, 1986):

- flexibility, (i.e. can water be moved in space and time ?),
- security, (i.e. can water availability be assured ?),
- real opportunity cost, (i.e. is the user aware of the real cost of the water ?),
- predictability, (i.e. how certain is the desired outcome ?),
- equity, (i.e. is the process fair ?), and
- political and public acceptability (i.e. is the process socially responsible ?).

Water allocation mechanisms are therefore critical to sustain the existing allocatable water resources while attempting to combine both efficiency and equity principles (Chakravorty and Roumasset, 1991; Dinar *et al.*, 1997).The difference between efficiency and equity may be explained as equity strives to achieve a fairness between different groups while efficiency attempts to direct or distribute a resource or commodity to the user who will achieve the greatest return on the use of the resource (Dinar *et al.*, 1997).

The rapid growth in population and rising demand for irrigation are increasing the pressure on water resources (Symphorian *et al.*, 2002). As a result of dramatic land use changes over the past decade, abstractions from perennial rivers have resulted in repeated exceedance of their water supply limits, particularly during low flow periods and droughts (Aeschbacher *et al.*, 2005). In order to manage the demand for water by water users, various methods of allocating the water have been devised. Alternative methods to PRROR, prior appropriation, first-come first-serve, marginal cost pricing and Fractional Water Allocation and Capacity Sharing (FWACS).

The FWACS allocation method describes the allocation of water from a river or stream under the Fraction Water Allocation (FWA) component and the allocation of water from a reservoir from under the Capacity Sharing (CS) component (Hallowes and Pott, 2005). Because these two components of FWACS, namely FWA and CS can be clearly defined and measured, they lend themselves to be accountable. The accountability promotes the creation of a water trading market or environment. The notion of water trading may be described as the temporary or permanent transfer of the right to consume water from one water user to another, for a monetary value in return (Chong and Sunding, 2006). The freedom within a water allocation method, to transfer water use between users creates an enabling environment for water management and promoting efficiency. Through the policy implemented as part of the water trading, water will be distributed or redirected to achieve a social optimum between competing water users (Chong and Sunding, 2006).

Countries facing water shortages under current water pricing systems, such as South Africa, should investigate water trading as an alternate way to reallocate water resources (Easter *et al.*, 1999). The NWA (36, 1998) makes an allowance for the "transfer of water use authorisations" in contrast to "water trading". As most of the water resources have been allocated to Water Users in a user class (e.g. domestic, agriculture or industrial/manufacturing), the water trading option is increasingly becoming the only method by which new users are able to obtain access to water (Bjornlund, 2003). Many believe that a more definitive water policy is currently needed, even without taking the potential negative impacts of global climate change on water availability into consideration (Wollmuth and Eheart, 2000).

As an aid to the allocation of water resources, computer modelling or decision support tools have been incorporated in the process, thus providing water managers with tools to assist in their decision making processes. Simulation models are used worldwide by water management authorities for the planning and operation of water supply systems (Perera *et al.*, 2005). The role of hydrologic modelling within water resource management is twofold. Firstly, it supports improvement in the understanding of the key physical, chemical and biological processes which occur in the environment and their interaction and, secondly, it provides decision support for the management and protection of the water environment (Storm, 2005). Computer modelling and the use of decision support tools have an impact in the decision making process by ensuring that the allocation of water is based on optimality rather than productivity. According to Reddy (2002), allocation needs to be based on optimality as it combines economics as well as social benefits rather than being based purely on productivity. Water mismanagement has led to environment degradation on a large scale due to the push for water to increase productivity rather than provide food security at a household level (Reddy, 2002).

The objective of this study is to compare the reliability of supply, i.e. water requested by water users relative to the amount which was actually received (i.e. water allocation efficiency), for two water allocation methods, PRROR and FWACS, using the Sand River Catchment as a specific example. Although there have been studies done on systems using either different fractions or different priorities (Doertenbach, 1998, Dudley and Musgrave, 1988, Dudley, 1990, Natsa *et al*., 2000, and as cited by Lecler, 2004b) few, if any, have compared different allocation methods in a specific catchment. As water allocation efficiency is based on reliability of supply the water allocation method can greatly influence the supply to demand ratio.

The PRROR allocation method has been used for several decades and is thus a familiar means of providing a supply of water under various catchment conditions (Lecler, 2004a). As demand has increased, the supply of water to the lower priority level of water users has been impacted on by the demand generated from higher priority users. The FWACS allocation

method is hypothesised to offer an alternate rule set to PRROR method as it provides the users with greater control over available water resources (Lecler, 2004a).
Thus, in order to meet the objectives of this study which essentially are to assess the reliability of supply of using PRROR or FWACS allocation methods in the Sand River Catchment, current PRROR demands were used. The FWACS allocation method was modelled using the same demands as used under the PRROR allocation method. The reasoning for this is two-fold. Firstly, it is a catchment, with existing water users with existing demands which reflect the realities of water demand in the catchment. Secondly, the objective is to see whether under current demands FWACS or PRROR more reliably met these demands. In order to ensure that the fractions allocated were in the correct range, allocations will be varied in order to assess the sensitivity of the FWACS method in the Sand River Catchment.

In this study water allocation methods are assessed with respect to their functioning and ability to meet the criteria mentioned above. This includes a discussion of their advantages and disadvantages. In determining the applicability of an alternative allocation method in South Africa, both the South African National Water Act and the National Water Resources Strategy are reviewed in Chapter 2. Several allocation methods place an emphasis on the reliability of supply for users. The result of users implementing water savings techniques and technologies, and not increasing their land area under production, is a surplus of water. The surplus may then be available to the user to use as is seen fit, but within the legal constraints of the allocation method. In over-allocated catchments, the trading of potential surplus water is seen as the only means of new water users entry into the sector without withdrawing allocations of water from current users. Furthermore, the dynamics of water markets are investigated and finally decision support tools are reviewed which may give guidance and assistance in the integration of the above listed components.

The implementation of allocation rules to contrast the results achieved under the PRROR method requires a system which allows for the setup of a rule-based environment. In particular, there is an alternative to the PRROR allocation method available, FWACS, as reviewed in Chapter 2, which is transparent, simple to apply, encourages water use efficiency, and enables and promotes equitable distribution. A collection of potential simulation programmes, alternatively termed decision support systems (DSS), are briefly reviewed in Chapter 3. A description of the test catchment is contained in Chapter 4 followed by a description of the setup and implementation of the selected DSS to be able to simulate the PRROR and FWACS allocation methods. The results of the PRROR and FWACS simulations are shown in Chapter 5. These results are repeated in Appendix A as a pull out for easy reference.

In summary, the hypothesis to be tested is that FWACS, as an alternate to the PRROR allocation method, will improve the reliability and assurance of supply to water users in the Sand Rive Catchment.

The following chapter contains a review of water resource management in South Africa under the National Water Act and the National Water Resources Strategy. The chapter also contains a review of water allocation method, including the PRROR and the FWACS allocation methods.

2 WATER ALLOCATION

The allocation of the limited water resources to water users requires an understanding of the policy governing the resource in South Africa as well as the structures put in place to manage the resource for the benefit of the population and the environment. The benefit may be in the form of food security at a basic level or, at its most complex, the strategic undertakings of the country in its development and obligations with and to international entities. The current PRROR allocation method is described in this chapter and the steps required to apply the allocation method. The proposed alternate method, FWACS, is also discussed followed by methods applied by water authorities in other countries.

2.1 Water Resource Management in South Africa

The South African government promulgated a comprehensive water policy act which emphasised the importance of water resource management (Reddy, 2002). The NWA (36, 1998) strives to incorporate policy, institutional and legal changes which allow for the better management of the water resource. The aims of the NWA (36, 1998) are achieved by a movement away from a riparian rights system to an administrative system (Hallowes and Pott, 2005; Hallowes *et al.*, 2008). The rights system provides land, adjacent to a water source, a right to reasonable use of that water (Ruhl, 2003). In contrast, the administrative system requires that all forms of water use (abstraction of water, storage of water and stream flow reduction activities) be licensed, unless exempt as Schedule 1 users (Stein, 2005; DWAF, 2006). The licensing has created an enabling environment for improved water resource management with greater focus being placed on individual water rights (Reddy, 2002; Hallowes and Lecler, 2005; Hallowes and Pott, 2005; DWAF, 2006).

Under the administrative system implemented in South Africa with regards to the management of the water resources, a right for water for the environment and basic human activities exists (DWAF, 2006). This is known as the Environmental Water Requirement (EWR). The ecological Reserve is required to remain in the rivers to maintain a healthy biophysical environment (Grové and Oosthuizen, 2002; Smits *et al.*, 2004). The Reserve, which is assigned priority allocation of available water, determines the allocable water which is available for other uses (Scholes and Meyer, 1993; Natse *et al.*, 2000a; DWAF, 2006), i.e. total water available less the Reserve is the amount of water available for allocation to other users. However, it may not be practical to enforce the flow of water past water users, in times of water scarcity. Water Users fall into four categories according to DWAF (2006):

- Schedule 1 Use – water generally used for household use which has little potential negative impacts on the water resource.
- General Authorisations – larger volumes of water which receive a general authorisation in a catchment. This may also be for a specific type of water or category of water.
- Existing Lawful Use – water use which lawfully took place two years prior to the implementation of the NWA (36, 1998) in 1998.
- Licensed Water Use – water use which has been authorised per license in accordance to the NWA (36, 1998).

2.1.1 National Water Act

The South African National Water Act, Act 36 of 1998, emphasises the importance of the country's water resources from several aspects. The spatial variability of water resources in the country leads to the requirement for active and efficient management of the resource NWA (36, 1998). Through efficient management, the allocation of available water resources is necessary to achieve an equitable allocation following the discriminatory allocation of resources (Sithole, 2011). The reallocation of water resources may impact a Water User detrimentally and where this takes place, a person may apply for compensation for financial loss. The exploitation of the compensation for water resources lost is prevented when the reallocation was for; providing a reserve, correction of an over allocation or to bring back in a line unfair water use (Sithole, 2011). The reallocation of water may thus be described as the redressing of prior discriminatory and excessive water allocation (Sithole, 2011).

Equitable allocation of the water resource in South Africa is made possible as water has been declared a public good. While the equitable allocation aims to provide water for people from historically disadvantaged backgrounds for beneficial use, the ultimate aim of the reallocation is to achieve sustainable use of the temporally and spatially variable water resources in South Africa (NWA, 1998).

The inception of an administrative system for the allocation of water in South Africa is necessary given that a number of catchments in South Africa have reached a state of being fully developed. The over development of catchments in South Africa, where demand exceeds supply, places water stress on the local users who depend on the supply of water from local sources (DWAF, 2004; Hallowes *et al.*, 2008). For this reason, the NWA (36, 1998) places a high level of importance on decision making at the local scale. In order for this to be achieved, the National Water Resources Strategy (NWRS) requires the Department of Water Affairs and Sanitation (DWS) to establish Catchment Management Agencies (CMAs), who will interact with stakeholders, local members of the community and government to manage the water resources of a catchment (Dent, 2001; Hallowes and Pott, 2005). The inclusion of stakeholders is an important aspect, as currently much knowledge lies outside of state departments and in the hands of the stakeholders, who are often the Water User themselves (Dent, 2001).

The CMAs role within the guidelines for equity redistribution is to:

- establish where water is available to support growth,
- influence and be a part of the planning processes in water stressed areas to promote and support growth and development initiatives, and
- encourage the establishment of enterprises that are less water intensive (DWAF, 2006).

Rogers *et al.* (2000) suggest that while the incorporation of water use for development and protection of the water resource are important and admirable, the problem which this creates for the CMAs, entrusted with managing water resources, is considerable. In the creation of CMAs, the axiom of “form to follow function” is not being given due diligence. The need to implement CMAs has meant that the structures put in place before the true CMA inception are failing to provide for their intended function (Rogers *et al.*, 2000).

2.1.2 National Water Resources Strategy

The NWRS provides the framework from which all catchment management strategies will be prepared and implemented in a manner that is consistent throughout the country. A catchment management strategy is the framework for water resources management in a water management area. The Minister will also make use of the NWRS to inform South African society of concerns or changes in the management of water resources.

The management of the resource is important because the NWA (36, 1998) states that the water resources within South Africa are to be protected, used, developed, conserved, managed and controlled in accordance with the NWRS (DWAF, 2004). Current provisional assessments indicate that, as a national average, about 20% of the total river flow is required as ecological Reserve for the 19 CMAs in South Africa (DWAF, 2004). The latest National Resource Strategy has reduced the number of CMA's to nine. The value of 20 % is obtained from the ratio of the ecological Reserve and natural mean annual runoff (MAR).

2.2 Priority-based Reservoir and River Operating Rules Method Used in the Allocation of Water in South Africa

The method for water allocation currently used in South Africa, is referred to as a PRROR institutional arrangement (Lecler, 2003; Hallowes and Pott, 2005; Frezghi and Smithers, 2007). The system discerns between priorities assigned to different types of authorised water use, while reservoir and river operating rules govern the water restrictions imposed on the Water Users under different conditions of water availability. The current water allocation arrangement in South Africa is also described as Volumetric Water Allocation and Priority-based Reservoir and River Operating Rules (VWA-PRROR) where the water is allocated based on a volume per unit time basis at one or another assumed level of assurance (Lecler, 2004a). Thus, during dry periods, and based on their priority status, upstream users may pump a river dry, to the detriment of downstream users, even if the amount pumped may be less than their licence entitlement (Lecler, 2004b). The functioning of the PRROR relies on the assumption that a water resources system can be represented by a flow network (Hallowes *et al.*, 2008). The flow network is a schematic used to represent the natural river system. Aspects such as river flow from catchment to catchment is taken into account and displayed in the schematic as well as important features such as reservoirs and should inter-catchment transfer be present, these will be represented as well.

The allocatable water resources for South Africa are estimated using synthetically generated streamflow (Basson and van Rooyen, 2001). In the PRROR system, the catchment is managed as a single system, and licenses are issued dependent on the availability of allocable water (Hallowes and Pott, 2005; Hallowes *et al.*, 2008). The PRROR system was designed to manage the supply of water from developed water resource systems and storage infrastructure using a centralised management structure (Hallowes *et al.*, 2008). Using the PRROR system, restriction rules are applied based on the current storage levels of reservoirs and the priority of the Water User. The reasons for restriction rules are that (Hallowes and Pott, 2005):

- the rule is simple to understand, and easy to enforce,
- a high level of control can be exercised over dams (i.e. by the water control officer, who is in charge of releases from the dam), and
- dams are generally a vital source of water during periods of water shortage.

In managing run-of-river abstractions, the reduction could be linked to the river flow rather than to the storage in a reservoir. This concept could be applied to ensure that ecological flow requirements are met by curtailing users during periods of low-flows (Mallory, 2005).

Under the current PRROR allocation method, as applied to water resource systems in South Africa, when there is a risk of the reservoir or river failing to meet the supply demanded, restrictions are applied to reduce abstractions. The priority extends to which users will relinquish water to the higher priority users and by what reduction factor (Lecler, 2003). The reductions are fixed and known by the party concerned as well as at which reservoir level the reduction will take place in order to meet the demands generated by the higher priority Water Users. The restrictions are, however, enforced more strictly on the downstream users in comparison to the upstream users (Mallory, 2005). The reasons for this may be as a result of upstream users not relying on releases from the reservoir and instead relying on the tributaries which supply the reservoir (Mallory, 2005). As a result of the inequity between upstream and downstream Water Users in a catchment with a reservoir, the institutional arrangements which are part of the NWA (36, 1998) need to be able to take into consideration and deal with the interdependency of these situations (Lecler, 2004a). A greater catchment water yield may be achieved by applying and enforcing restrictions on upstream users and, as a result, an equitable supply of water during droughts may be achieved (Mallory, 2005).

The restrictions, as implemented in the PRROR allocation method, are not applied uniformly to all Water Users in South Africa. Due to the high economic cost likely to be experienced if restrictions were applied uniformly to all users, high priority users, e.g. industrial and strategic users, are seldom restricted while those users seen as less sensitive to restrictions in terms of economic returns (e.g. agricultural production) are restricted by greater amounts (Mallory, 2005). It was found by Maneta *et al.* (2009) that irrigation farmers will react to reductions in water availability by altering what they produce and the amount of water applied. According to Lecler (2004a) the restrictions applicable would be based on the PRRORs as established by the CMA in the Catchment Management Strategy (CMS). Thus, the non uniform distribution of water to Water Users, based on their perceived level of importance is a disadvantage for those Water Users considered less important. Further disadvantages of the PRROR allocation method include the following:

(i) If Water Users do adopt more efficient water use technologies, or do not fully use their water allocation (for whatever reason), the entitlement to unused water is lost, and other users may use this water during periods of water shortage (Lecler, 2004a).

(ii) The PRROR system is difficult to operationalise (Lecler, 2004a) and to audit, in that information is required regarding Water Users in a catchment (priority, location and assurance of supply) and water available in the catchment (Hallowes and Pott, 2005).

In spite of the problems associated with the PRROR system, the system is used by the majority of water resource managers, consultants and administrators in South Africa. The planning and allocation decision support tools currently used, namely the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM), are based on the PRROR system (Lecler, 2004a). These are described more extensively in Chapter 3.4.

Due to the over utilisation of water available in most catchments in South Africa, it is important that a move takes place from a water resource development era to a water resources management era (Hallowes *et al.*, 2008). Additionally, improved management of existing water resources needs to take place in order to prevent excessive restrictions being applied (Hallowes and Pott, 2005). Based on the criteria established by Howe *et al,*(1986) to compare water allocation methods, the manner of how PRROR addresses the criteria is sumarised in Table 2-1.

Table 2-1 Ability of the PRROR allocation method to address the 6 criteria for water allocation method comparison by Howe *et al.* (1986)

Criteria	**PRROR**
Flexibility (can water be moved in space and time)	Water cannot be easily moved within the PRROR framework.
Security (can water availability be assured)	Water availability is linked to the priority of the Water User in relation to the other water users. Water availability is assured to only the highest level, i.e. those users deemed to have strategic importance to the country.
Real opportunity cost (is the user aware of the real cost of the water)	The real opportunity cost of the water is not known to the Water User. Through the PRROR policy and operation, a fixed volume allocation is made and restrictions applied as dictated by environmental factors.
Predictability (how certain is the desired outcome)	Under PRROR, the water users know their allocation volume and have an understanding of the restriction levels should conditions change, resulting in these being triggered. Hence, the system has a high level of predictability for the Water user.
Equity (is the process fair)	The PRROR allocation method does not allow the recognition and subsequent transfer of water to the high value water use. Equity in allocation is therefore limited.
Political and public acceptability (is the process socially responsible)	The structure of the PRROR allocation method does not provide for a socially responsible method. The rigidity hampers the redistribution to needy parties.

2.3 Fractional Water Allocation and Capacity Sharing

FWACS may be defined as a proportional allocation of the available water in reservoirs/dams and of streamflow (Hallowes and Pott, 2005). In this allocation method, the Water Users are entitled to a fraction of the total available river flow, which forms the Fractional Water Allocation (FWA) component. Where there is storage on a river, users are entitled to a share of the Capacity Share (CS) where they can draw or store water according to their needs (Dlamini *et al.*, 2007). It should be noted that the FWACS system evaluated by Dlamini *et al.* (2007) is different to the FWACS system as discussed by Hallowes and Pott (2005). Dlamini *et al.*(2007) describe the system as allocating a proportion of the total yield. The yield value will change from year-to-year depending on hydrological conditions. The model as described by Hallowes and Pott, (2005) does not rely on annual yield but on real-time river flows and dam storages and the allocation of this to users is dependent on their water share entitlements. Thus, although Dlamini *et al*. (2007) allocate water based on stochastic simulations and Hallowes and Pott (2005) allocate it in near real-time, both require a large volume of data to operate efficiently and to accurately allocate streamflow to the Water Users and the value assigned is dynamic, based on stream flow and reservoir levels.

The operation of the FWACS system by the user will be much the same as a bank account (Lecler, 2004a; Hallowes and Pott, 2005). Inflow to a reservoir apportioned to the user will be added to the user's available water while evaporation, releases requested by the user and seepage losses will be deducted from the user's apportioned available resources. It has been described by Dudley (1990) as a Water User having access to a private reservoir on a private stream. The FWACS method requires an initial agreement on the determination of what fraction of the available streamflow is able to be allocated (Nyabeze, 2010). The Reserve (made up of human right to water and EWR) must be regarded as a user who receives preference above all others. While the inclusion of a Water User with a preference is not congruent with FWACS, the operation is not affected through a priority user as it is fictitious and merely a place-holder in assigning FWACS to Water Users. When the stakeholders assign a percentage share of a dam to the environment, it is a reflection of the relative costs which they are willing to incur to safeguard the environment (Symphorian *et al.*, 2002). As the system makes allowances for storage in reservoirs as well, volumes of available water storage infrastructure may be offered for purchase or rent by the local stakeholders (Dudley and Musgrave, 1988; Lecler, 2003), thus improving efficiency. This is because Water Users' are encouraged to use water efficiently as allocated water not used can be saved for future use or sold to other users.

For FWACS, as in any accounting system, management of the accounts is required. The reconciliation for the system will be compiled at the end of a selected time step (Natse *et al.*, 2000b). The FWACS system may be operated at a time step which is convenient for the catchment in which it is applied. The time step may be weekly, fortnightly or monthly, as decided by the CMA or similar management authority and is dependent on the accuracy with regard to water levels in reservoirs and reaches and supply capability of reservoirs in directing water to where the demand is required (Hallowes and Pott, 2005). FWACS will shift the focus to a situation of better operational management in order to improve supply assurance and increase the supply ability to the Water Users (Hallowes and Pott, 2005; Nyabeze, 2010). The most important advantage of the FWACS system is that users are given the means to manage their water supply and are able to make direct benefits from the savings that they make (Dudley and Musgrave, 1988; Hallowes *et al.*, 2008). Stakeholders in a FWACS allocation system will have improved confidence as the water savings resulting from investments can be stored and used at a later date rather than wasted in high rainfall seasons (Natse *et al.*, 2000a; Lecler, 2004a).

The FWACS allocation method is a different approach to water allocation than currently used in South Africa (PRROR). The licenses issued under FWACS allocation and management system do not reflect a true volume which the user is entitled to, but the user is entitled to a percentage/fraction of the total available reservoir storage or river flow which will be converted to a volume (Natse *et al.*, 2000b; Symphorian *et al.*, 2002; Lecler, 2004a; Nyabeze, 2010). Inflows to the reservoir are apportioned to Water Users while the water currently in the reservoir will have already been apportioned to these Water Users. The assurance of supply required by a Water User may be obtained by adjusting the proportion of inflow into the reservoir and the proportion of storage to obtain the required assurance of supply (Hallowes and Pott, 2005).

The FWA component of FWACS refers to run-of-river systems. As a result of the allocated water being part of the river, the PRROR allocation method is based on a ‘‘use it or lose it’’ principle (Dlamini *et al.*, 2007). This component (FWA) is seen as the largest threat to the non-acceptance of FWACS technology as it does not give the user the right to abstract as much as they are able to. Rather, it allows a user to abstract a percentage of the available flow which may be less than what they require and are tempted to take. Under the FWACS method, users are encouraged to manage their water resources individually, encouraging water saving and risk evaluation (Symphorian *et al.*, 2002; Lecler, 2003). The practical challenge associated with the FWA component is that it requires an extensive and accurate monitoring system (Hallowes *et al.*, 2008). The CS component of the FWACS method allows for users to bank their share of water in a reservoir. The allocation will not refer to a volume but rather to a fraction of the total available flow in the river (Lecler, 2003). When the inflows to the system are greater than the losses from the system, water user accounts will increase. When the maximum capacity of a user’s fraction is reached, addition to the user’s account contributes to the other users' accounts (Lecler, 2003). Once the dam is at full supply capacity (FSL) the users' accounts will all be at 100 %. The accounts cannot be more than 100 % full which means that overflow from the dam is lost to the users and their accounts.

The FWACS system has been successfully implemented in the Mazowe Catchment in Zimbabwe (Doertenbach, 1998; Lecler, 2004a). In this catchment, the issue arose of not all Water Users downstream of a reservoir belonging to an irrigation scheme. This meant that water needed to be allocated to other Water Users and released with the water intended for the scheme members. The irrigation scheme solved this problem by installing water metering points for each of the Water Users in the scheme, as well as immediately downstream of the most downstream irrigation scheme member (Doertenbach, 1998).

In South Africa, trials on FWACS are taking place in the Orange River and some interest in adopting the concept has been shown in the Mhlatuze Catchment (Dlamini *et al.*, 2007). As mentioned, success has been achieved using the FWACS method in Zimbabwe, in the Mazowe Catchment (Doertenbach, 1998; Nyabeze, 2010) and in the St. George water Supply scheme in Australia (Ryan *et al.*, 2000; Dlamini *et al.*, 2007). Dlamini *et al* (2007) also report on the success of a modified FWACS system that has been implemented in the Komati basin. The reason for the success in using the system has been noted by Hallowes *et al.,* (2008) as being that the FWACS system is conceptually easy to understand and the water is allocated from source and not from distribution points which are often removed from a Water User abstraction point. Based on the criteria established by Howe *et al.,* (1986) to compare water allocation methods, the manner of how PRROR meets the criteria is summarised in Table 2-2.

Table 2-2 Ability of the FWACS allocation method to address the 6 criteria for water allocation method comparison by Howe *et al.,* (1986)

Criteria	FWACS
Flexibility (can water be moved in space and time)	The FWACS method allows for water to be moved within the system. The CS portion is especially adapt at being flexible to the demands of water users.
Security (can water availability be assured)	The ability to have control over water in the CS portion means that a Water User has assured access to water.
Real opportunity cost (is the user aware of the real cost of the water)	Through the ability to transfer water either temporarily or permanently, the Water User is aware of the opportunity cost of water.
Predictability (how certain is the desired outcome)	The FWACS allocation method provides a measure of predictability under the FWA component as the fractional of river flow for abstraction is known. River flow, however, varies. The CS portion provides a known recharge rate from the reservoir inflow and a known distribution of evaporation and seepage from the reservoir. Knowledge of the inflows and outflows, provides the Water User with good grounding on which to base water use decisions.
Equity (is the process fair)	The ability to redistribute water through either temporary loan of water from a Water user or the sale of a volume of water provides for a mechanism to promote water equity.
Political and public acceptability (is the process socially responsible)	The FWACS allocation method leads to a socially responsible means of dividing up the available water resource. However, public and political understanding of the allocation process may hinder adoption.

2.4 Comparison of PRROR and FWACS

The PRROR and FWACS systems are noticeably different in their functioning. The PRROR system was developed in a time when resource systems were not heavily developed and the efficiency and current sustainability concerns were not considered to be important (Hallowes *et al.*, 2008). Different allocation methods, such as the FWACS allocation method, stemmed from a need to move away from using water more efficiently approach, to the equitable allocation of water (Dent, 2000). This is especially true in South Africa with the revised water legislation (Dent, 2001). The main functional differences between PRROR and FWACS are summarised in Table 2-3.

Table 2-3 Comparison of PRROR and FWACS functioning (Hallowes *et al.*, 2008)

Criteria	PRROR	FWACS
Transparency	Water entitlement is not defined clearly and tracking of water is difficult.	Water entitlement is clearly defined and uses both source and water distribution in its allocation.
Participatory management	None – determined by Department of Water Affairs or CMA/Water Manager.	Yes – the Water Users manage themselves on advice from a regulatory body.
Transferability of water rights	Difficult to transfer due to differences in levels of assurance.	Simple as all users have the same assurance level.
Transaction cost	Expert required therefore an increase in time and cost.	Less expensive to manage.

2.5 Public Water Allocation

The argument for water resources to be managed by public or government bodies finds support in the following points:

- it is difficult to treat water like most market goods,
- water is broadly perceived as a public good, and
- large-scale water development is generally too expensive for the private sector (Dinar *et al.*, 1997).

In addition, the public policies set by a CMA as well as by CMAs in bordering catchments influence the water allocation and water use decisions. Public policies may take the form of infrastructure for water conveyance, establishment of Water User associations and water or land use regulations (Maneta *et al.*, 2009).

Government or public allocation methods have been purported to protect the poor, sustain environmental needs while at the same time ensuring a level of water supply which will meet the minimal needs of those requiring water (Dinar *et al.*, 1997; White *et al.*, 2005). Under such an allocation method, water use permits generally include details of water use in a volume/time format. In using a method in which capacity is shared, greater equity is achieved because the storage is individually owned, but centrally managed and permit holders should achieve levels of reliability of supply which are similar to each other (Natse *et al.*, 2000a).

A major disadvantage of the government or public allocation method lies in the failure to create incentives for Water Users to conserve water and improve Water Use Efficiency (WUE). Furthermore, in practice, public or government water allocation methods typically consist of various inefficient water pricing schemes (Dinar *et al.*, 1997). This allocation method provides for a pricing scheme which contains flat rates and/or fixed charges. The flat rate and fixed charges provide an easy to manage and understandable method which is also easy for users to understand (Dinar *et al.*, 1997).

2.6 Prior Appropriation Method

The prior appropriation method works on the basis of a queue. The prior appropriation method is also known as the first-in-time-first-in-right allocation method (Natse *et al.*, 2000b; Wollmuth and Eheart, 2000). The water rights are allocated to users in the queue with the first recipient holding the highest right to the water while lesser rights are conferred on subsequent users in the queue. Granting of rights to water use is only done when the use of the water leads to beneficial use (Natse *et al.*, 2000b). According to Natse *et al.* (2000a), non-use of the water right or part of the water may lead to its forfeiture in subsequent review periods. It is this institutional arrangement which inhibits water-saving technologies from being adopted by the Water Users. Water saving technologies may include changes in irrigation method, e.g. from drag-line and centre-pivot to micro-irrigation or drip-irrigation. The result of the prior appropriation system is that Water Users need to be aware of both upstream and downstream users in exercising their rights to water use (Wollmuth and Eheart, 2000; Dole and Niemi, 2004).

In certain instances, the prior appropriation method also takes into account different types of users relative to one another. The different users will fall into one of two categories; natural or artificial. Irrigation is an artificial Water User and so in a dispute between irrigation and a natural Water User, the natural user has a right to a reasonable portion of water (Wollmuth and Eheart, 2000). The natural user is the environment and an activity which does not involve the moving of water from natural flow regimes. The advantage of the prior appropriation method is the ability of the method to secure water in times of water scarcity for early user rights and the weaknesses of the method include inequity and reluctance to adopt water saving technology. The size of the storage facility of the Water User represents the risk of failure which the user is willing to accept. Users who enjoy an early use of the water in relation to time will typically have little storage facility. The converse is true for users who entered at a later date. The late entry users typically have large storage facilities which they need to achieve similar levels of assurance of supply as the early users (Natse *et al.*, 2000a).

The availability of water for use by the Water Users with lower status in periods of surplus water is high and their water requirements are likely to be met. During times of low-flow the availability of water to all users may be limited (Natse *et al.*, 2000a). During periods of low flow it becomes the responsibility of the Watermaster to set a regulation date for the water use in the catchment. The Watermaster is the department or state official who is in charge of setting the regulation date. The regulation date specifies the year in which the water right was conferred to each user in the queue. If, for example the regulation date is set to 1985, then Water Users who were allocated water rights after 1985 may not use any water while those users allocated water rights prior to the regulation date of 1985 may use water. The use of water for the pre-1985 users remains the amount for which they legally entitled to (Dole and Niemi, 2004). The main stipulation under such a method is that the Water User must show that the use is beneficial (Natse *et al.*, 2000b). The understanding of beneficial use has historically been to the benefit of the user and not in as much as to the public. However, beneficial use has also been interpreted as the prohibition against excessive water use by community standards (Wollmuth and Eheart, 2000).

2.7 Summary of Main Findings from the Literature Review

The literature review indicates that the need for a more efficient water allocation method exists. The NWA (36, 1998) allows for implementation of new rules and the modification of existing rules to improve water use efficiencies. The overall management should remain the function of the CMA in creating an environment in which the rules are implemented and regulated which pertain to the Water Users. Although other water allocation methods are evaluated above, the focus in this study is a comparison between PRROR and FWACS and thus only these methods are considered going forward. Table 2-4 contains a summary of PRROR and FWACS based on the criteria from Howe *et al.* (1986) . The PRROR has a short-coming in the allocation of resources based on the assigning of levels of importance to Water Users. While the simplicity of the allocation method makes it an attractive option to catchment managers and large scale Water Users such as water or irrigation boards, the rigidity prevents the Water Users from being proactive to water saving initiatives. The FWACS allocation method using the CS and the FWA components in symmetry encapsulates a method in which Water Users may take proactive steps to control water use knowing that the actions taken will be to their benefit. A potential disadvantage of the FWACS allocation method is the operation of the FWA component and how each Water User views the allocation of streamflow to meet their demands.

Table 2-4 Comparison of the criteria used to evaluate water allocation methods of PRROR and FWACS

Criteria	PRROR	FWACS
Flexibility	The flexibility of the PRROR allocation method is restricted by the allocation of water volumes in the water license issued to the user. This impacts on the creation of a margin of water which is available for reallocation.	A large degree of flexibility exists in the ability to freely and easily shift water from user to user due to the structure of the allocation method. The ability to control the volume of water abstracted from the river allows for the creation of a tradable margin.
Security	The PRROR does not offer the user security in that the water is allocated on a "use it or lose it" principle and this does not promote water use efficiency.	The FWACS allocation method offers users security in that they are able to control their water supply from the CS portion of the allocation method and thus only use water when it is needed.
Real opportunity cost	The real opportunity cost is not known to the user under PRROR due to the fixed term volume license issued by the water authority, in this case DWS.	The flexibility brought about by the FWACS allocation method means that the markets are able to influence the water allocation, allowing the user to understand the real opportunity cost of the water.
Predictability	The central control structure and rigid rule structure of the PRROR means that the predictability of the method is high.	The FWACS method has a lower predictability than the PRROR method under the run of river portion. However, the CS portion of the allocation method provides a predictable system to the water user.
Equity	Equitable distribution of the water resource is hampered by the strict volume allocation of water to waters who may not receive the most gain from the water. The use it or lose it principle prevents movement of water to marginal water users.	The FWACS method provides for greater equitable water allocation due to the water user being exposed to the real opportunity cost of the water. This provides a mechanism for water to be reallocated under a voluntary means.

Criteria	PRROR	FWACS
Political and public acceptability	The rigid and easy to understand restriction rules makes for a system which is more likely to be accepted by the political and public bodies.	The ability to easily create a water segment (percent of flow) allows for the buy-in of the public and political spheres. The CS facilitates the creation and maintenance of a publicly available good (i.e. for recreation) which provides for an increased acceptability

3 DECISION SUPPORT TOOLS

The high level of assurance of supply, coupled with the high demand required by industry in South Africa, has resulted in several complex water resource systems. The systems are linked together through inter-catchment transfers and the re-use of return flows, into a system which spans more than half of South Africa and has an influence on neighbouring countries (Basson and van Rooyen, 2001).

Hydrologic modelling is used to improve the understanding of hydrological processes and the interaction between processes and also to aid in the management of the environment (Storm, 2005). The allocation methods described in Chapter 2 can be implemented using a decision support tool, or are themselves a form of a decision support system. Some of the software tools and models used to model the various allocation methods are discussed in this chapter. This review was completed to understand which model would best allow a comparison between the PRROR and FWACS method's ability to effectively allocate water to water users specifically in the Sand River Catchment.

3.1 Water Rights Analysis Package

The Water Rights Analysis Package (WRAP) is a model used to simulate water allocation under a priority-based water allocation system (Wurbs, 2001). The model has been used extensively in Texas in the USA by the Texas Water Development Board (Wurbs, 2004). The model has been designed to facilitate the assessment of water availability for existing and potential users for in-stream flows, reservoir storage and transfer schemes using a generalised system of assigned priorities. The WRAP model is able to simulate the management of water resources on a catchment scale or for a multiple-catchment region (Wurbs, 2004).

The priority system within the WRAP model is referred to as a water rights loop, calculated in order of the priorities for the water resource. At each point where the water right is considered, i.e. an abstraction point, the WRAP model performs the following tasks: (i) water available for abstraction is determined by the streamflow at the location and downstream locations, (ii) water use requirements are satisfied subject to the water availability performed in step (i) after iterative calculations have been performed for reservoir and reach evaporation, and (iii) available flow is adjusted for the location and all downstream locations to reflect the use of water right (Acocks, 1975; Wurbs, 2004).

The WRAP model, as implemented in the Texas Water Availability Modelling System, has been designed to use a monthly time-step, for the evaluation of hydrological and institutional water availability, EWR, hydro-electric power generation and reservoir storage (Wurbs, 2006; Frezghi and Smithers, 2007). The WRAP model functions as an accounting system, tracking streamflows which are subject to water releases from reservoirs, hydro-electric power demand and IFR changes due to seasons (Wurbs, 2006; Frezghi and Smithers, 2007). That fact that the WRAP model operates on a monthly time-step rather than a daily time-step is a notable disadvantage of the model.

3.2 RiverWare

The RiverWare model which was developed at the University of Colorado by Zagona *et al.* (2001), may be used in modelling a prior appropriation distribution system under a rule-based simulation solver (Frevert *et al.*, 2006). RiverWare is a general river and reservoir modelling tool that may be used in forecasting, planning, policy evaluation and other operational analysis and decision processes (Zagona *et al.*, 2001). The model represents a water resource system by using a system of linked nodes which are used to represent river system features such as reservoirs, diversions points, abstraction points and canals. In addition to a node in the model representing a feature in the system, the feature contains attributes which provide information on the feature and also the code for the physical processes. The output created from each of the features passes as input to the subsequent (downstream) feature, forming a cascade of information between features (Frevert *et al.*, 2006).

The model allows for the creation and customisation of a river network and its physical behaviour without the need for software programming (Frevert *et al.*, 2006). The flexibility of configuration for a specific catchment is an important criteria as the embedding of a catchment configuration in the software code limits the application of the model to a specific location. Hard-coded models are likely to face obsolescence as they are limited in their response to changes in operating policies. To avoid the hard-coded model route, the

RiverWare software was coded such that it was able to meet general requirements of water managers such as:

- Flexibility to meet a range of applications which require variable time-steps and to meet physical process modelling variability.
- Adaptability to an organisation's methodology for decision making, including either simulation or optimisation, thus allowing the organisation to explore new approaches to methods and decisions.
- Provision of an easy-to-use Graphical User Interface (GUI).
- Flexibility to fit into an organisation's existing model interfaces and database format.

To have an organisation which is able to provide support for the software, continually develop the software and maintenance of the software code with regard to software bugs (Zagona *et al.*, 1998).

The RiverWare model uses a user defined set of objectives based on a heuristic procedure in order to achieve the desired outcome (Perera *et al.*, 2005). A heuristic procedure may be described as a system by which the best possible answer is achieved as a result of trial and error. The rule-based simulation solver uses operating rules entered by the user, to provide logic as to the operating procedures of the features as set by the user. The RiverWare model may be run at varying time-steps, ranging from a 1 hour interval to annual (Frevert *et al.*, 2006). The RiverWare model is able to be linked to other databases and models in order to use external inputs and outputs. This service allows the modeller to link to external applications as needed to provide for a holistic system (Zagona *et al.*, 1998; Frevert *et al.*, 2006).

The Tennessee Valley Authority in the USA uses the RiverWare model in the management of the water resources due the flexibility of the model and extensive range of physical process algorithms (Zagona *et al.*, 1998; Zagona *et al.*, 2001). Additionally, the United States Bureau of Reclamation (USBR) changed the model suite which it was using in favour of RiverWare (Zagona *et al.*, 2001). The USBR places strong emphasis on the protection of water resources due to the harsh climatic conditions in the western United States (Zagona *et al.*, 2001).

3.3 MIKE BASIN

The MIKE BASIN (MB) simulation model is developed and maintained by DHI (merger between Danish Hydraulic Institute and Institute for the Water Environment) (DHI, 2009). It is a powerful model for the simulation of water allocation, that represents the hydrology of a catchment both temporally and spatially (DHI, 2009). It is accepted that catchments and water form a union and, as such, should be treated together in conflict resolution. The complexity of the interactions between land, soil and water lead to the need for efficient utilisation within a catchment to provide water for future developments within a catchment (Hallowes, 2007).

The main focus areas of the MB model include the following:

- water allocation scenario modelling,
- reservoir/hydropower operation,
- hydrological modelling,
- irrigation demand and yield assessment, and
- time series data management and analysis (DHI, 2009).

The model uses a digitised river network in the simulation process. Information regarding the river network is entered via a GUI (Sheng and Wilson, 2009). The input forms accept time series data with the most important time series being catchment run-off. From catchment runoff, other processes are simulated including water quality as point and non-point sources, groundwater and channel routing (DHI, 2009). The channel routing in river reaches are built on by adding Water User nodes, irrigation water usage, reservoirs and link channel lines (DHI, 2009). Another aspect of the model is its flexibility with regard to operating time-steps. The model may be run using a time-step ranging from as long as years down to very short time periods of seconds. (DHI, 2009). According to Hallowes (2007), this enables the model to be used in the management and planning of catchments and the immediate environment.

An important feature within MB is the ability to deal with users with multiple priorities requesting water from several different sources (Hallowes, 2007; DHI, 2009). At times, users may want to receive water from a different source, i.e. the river or a reservoir. Allocation algorithms determine how the water is divided amongst the users when water restrictions are encountered. This is generally achieved using a priority system, with the priorities assigned between the users and the source. An alternate method of allocation built in to MB is the fractional allocation of flows and capacity sharing of reservoirs (Hallowes, 2007).

An example of where MB has been used successfully is the Mun river basin in Thailand. Hydrological data for the period 1965 to 1997 was available and used in the model simulation. The simulation was run using a monthly time step. Results from this simulation showed that a management approach was achieved which provided a means for a decision from policy makers in order to achieve optimal allocation of the water resource (Jha and Gupta, 2003)

A second example of the application of MB is in the Pinhao river basin in Portugal. The MB model was used in conjunction with a geographic information system (GIS) which aided in the spatial and temporal modelling of the river basin. The MB DSS was able to assist in the decision making process as well as verifying that current water needs are met by the river basin (Fernandes *et al.*, 2013).

3.4 Water Resources Yield Model

In South Africa, the Water Resources Yield Model (WRYM) model is used to determine the allocable volume of water (Frezghi and Smithers, 2007). It is a river/reservoir model designed to operate on a monthly time step, as are most models used operationally in South Africa (Mallory and McKenzie, 1993; Frezghi and Smithers, 2007). The WRYM is also used to assess the potential impact of the addition of a new Water User within a catchment and the effect of different management techniques (Frezghi and Smithers, 2007; Juízo and Lidén, 2010).

System yield in the WRYM model is determined through a set of procedures to produce graphical representations of the reliability and/or the risk of failure of the system in meeting the demands placed on it. Thus the WRYM is able to deal with complex systems. These procedures are represented graphically in Figure 3-1.

Although this is the model of choice for DWS (Frezghi and Smithers, 2007), it is very rigid in design and as a result only able to deal with the PRROR method of water allocation. It also requires long term records and only recently has a GUI been incorporated into the model code (Frezghi and Smithers, 2007).

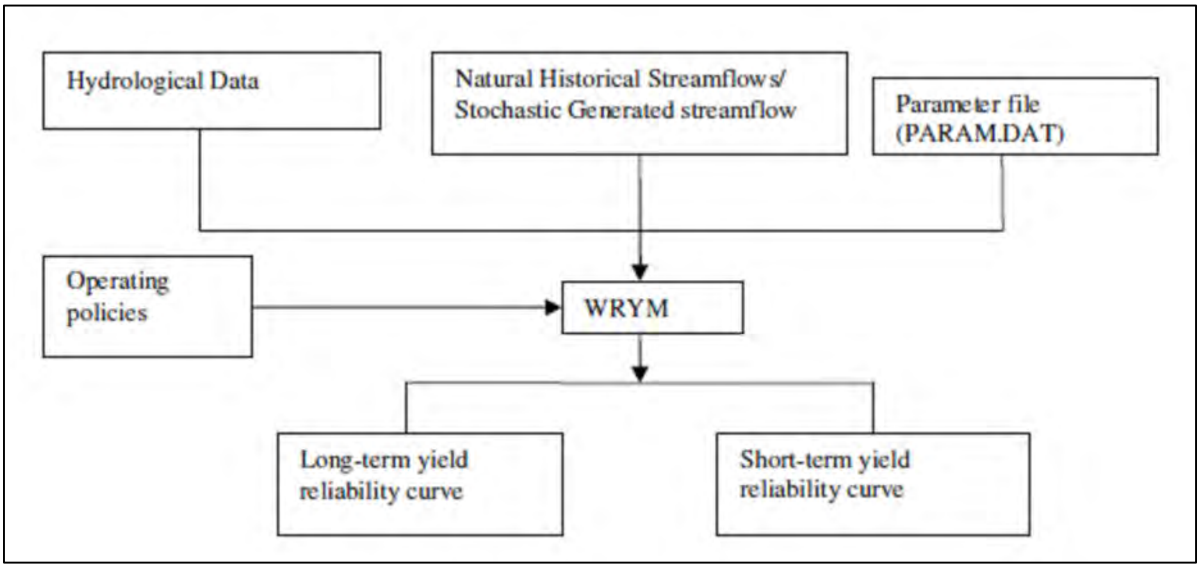

Figure 3-1 Representation of WRYM water resource yield estimation procedure (after Basson *et al.*, 1994; Frezghi and Smithers, 2007)

The hydrological data component of the WRYM can be provided by ACRU, as implemented by Frezghi and Smithers (2007). It can also be provided by the Pitman model which generates the run-off (Pott *et al.*, 2008). The ACRU model, developed by the School of Bio-Resources Engineering and Environmental Hydrology, is a physical conceptual, process based model which simulates the physical processes occurring in a catchment (Schulze, 1995). This means that the model attempts to simulate the hyrological processes as it exists in the physical environment on a day to day basis. The model uses, amongst others, inputs of historical measured rainfall, evaporation, soils parameters and vegetation variables. For this reason, the ACRU model is a more appropriate model to use as not only does it consider land uses but can also be done in daily time steps (Pott *et al.*, 2008).

3.5 MODSIM

The MODSIM model is model used in the United States of America for the management of complex catchment systems (Labadie, 2006). The MODSIM model is described as "a comprehensive DSS for the coordinated operation of multiple reservoir systems, conjunctive surface and groundwater management, and water quality management" (Labadie, 2006). The MODSIM model can be fully implemented in the ArcGIS environment through the GEO-MODSIM extension (Labadie, 2006). The MODSIM catchment model is able to take into consideration the legal and administrative ideologies in managing water use. The advantage of the MODSIM model under these considerations is that the model is not restricted to any one configuration or management structure.

The MODSIM model is specifically designed for developing strategies that are to be applied across the catchment under both long-term and short-term durations. The model is also able to assist in conflict resolution between competing water resource users (Labadie, 2006). This enables the model to not only be used in the public water allocation environment but also under the PRROR mechanism. The MODSIM model is primarily a simulation model, and is able to provide an efficient means of assessing water resource allocation based on the operating rules and priority ranking system (Labadie, 2006). However due to the fact that customisation is easily possible, there is room for error and corruption within the model. The ability for customisation is a disability of the MODSIM model. In the same breath, it is also an advantage. Care should thus be exercised when using the model.

3.6 Resource Allocation Model

REALM (REsource ALlocation Model) is a generalised computer simulation software package that models the harvesting and bulk distribution of water resources within a water supply system. It is a modelling tool, which can be applied to develop specific water allocation models (Perera *et al.*, 2005). REALM is a water balance focused model rather than a water allocation model (Perera *et al.*, 2005).

The REALM model is made up of three parts; input processing, simulation and output processing (Perera *et al.*, 2005). The composition of the three components is shown in Figure 3-2.

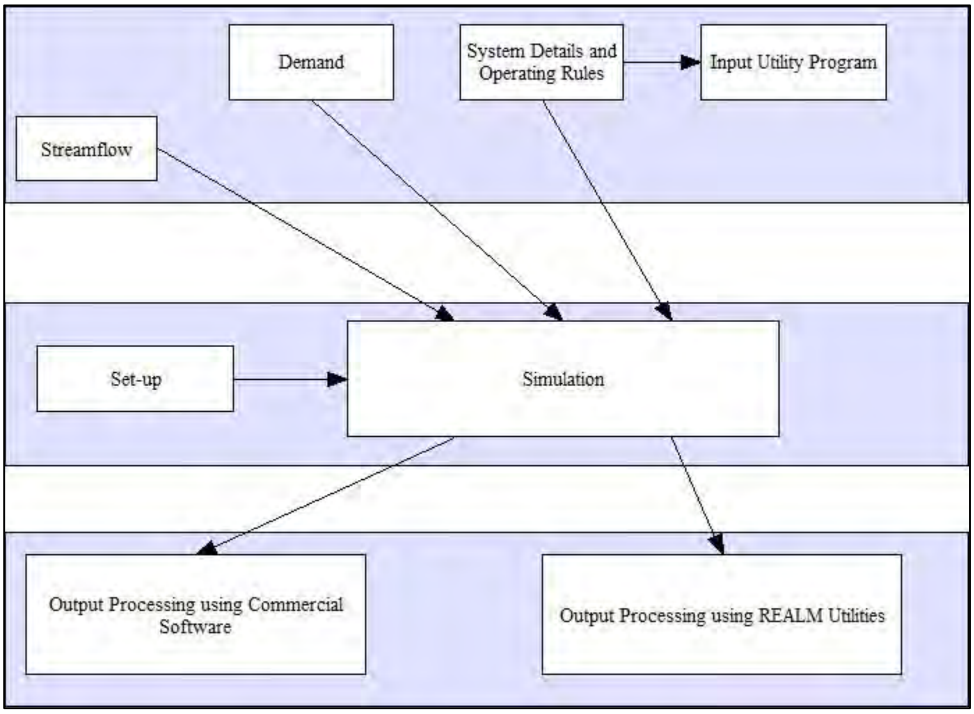

Figure 3-2 The REALM model conceptual plan (Perera *et al.*, 2005)

REALM has been used in the development of the Goulburn Simulation Model (GSM), used in the management of water resources in northern Victoria, Australia and the Melbourne Water supply of urban water (Perera *et al.*, 2005). The success of REALM in these two management areas has been linked to the flexibility inherent in the model in order to incorporate "what-if" situations.

3.7 Waflex model

The Waflex model is based on a spreadsheet (Symphorian *et al.*, 2002; Nkomo and van der Zaag, 2004) and is thus accessible with few skills required to run it. The design of the model is to aid with the allocation of a scarce resource such as water. A time step of one month is used in the calculation of changes in water resource. As water flows from areas of high altitude to areas of lower altitude, the Waflex model attempts to track the flow using equations based on continuity (Nkomo and van der Zaag, 2004).

The Waflex model accepts the addition of reservoirs by formatting three cells in the spreadsheet thus it is easy to modify. The data required for the simulation of a reservoir are inflow, storage and outflow (release). The outflow forms inflow to the downstream branch of the network. In managing the reservoir, two operating rules need to be implemented and adhered to. The first is that the storage in the reservoir may not exceed the flood rule curve and the second is that the release from the reservoir may not cause the dead storage level to be depleted. These two conditions form the external boundaries of the system (Nkomo and van der Zaag, 2004).

The Waflex model has been used in the investigation into water availability in the Komati Catchment as well as its use in the Komati Catchment (Dlamini *et al*., 2007). The use of the Waflex model by Nkomo and van der Zaag (2004) focused on the collaboration between South Africa, Swaziland and Mozambique to provide clarity on the allocation, based on equitable and sustainable utilisation.

3.8 Decision Support System Summary

The above mentioned models have been described in favour of several other models due to their potential to be used to meet the objectives of this project (i.e. water allocation efficiency between FWACS and PRROR methods) as well as the implementation of the models in conditions similar to those experienced in South Africa. The models are summarised in Table 3-1. The large number of big reservoirs in South Africa pose a problem which several models are not able to cope with, that being reservoirs releases to downstream users and the inter-catchment transfer of water. The requirement is for a model which is able to account for water throughout the system, ranging from incoming rainfall and storage to trading of water between users and the tracking of the traded water to prevent unauthorised use of the traded commodity.

Table 3-1 A comparison of the DSS models reviewed

DSS	Applicable to		Case study example	Application and comments	Disadvantages	Cost
	PRROR	FWACS				
WRAP	Yes	No	Texas USA (Wurbs, 2004)	• Assess water availability in various forms and requirements. • Multiple catchments	• Not designed for floods.	Freeware
RiverWare	Yes	Yes	Tennessee USA (Zagona *et al*, 2001)	• General river flow. • Allows forecasting. • Cascade effect allows upstream users to affect downstream users. • No programming needed.	• Modification difficult.	Expensive
MIKE BASIN	Yes	Yes	Pinhao River, Portugal (Fernandes *et al*, 2013), Mun river, Thailand (Jhu and Gupta, 2003)	• Temporal and spatial representation of hydrology. • Flexible. • Multiple different Water Users and levels of requirement. • Secure.	• Setup is difficult.	Expensive
WRYM	Yes	No	South Africa (Frezghi and Smithers, 2007)	• Determines allocable water volume. • Uses rivers and reservoirs. • Allows addition of water users.	• Very rigid. • GUI recently added. • Long term records needed.	Unknown
MODSIM	Yes	Yes	USA (Labadie, 2006)	• Multiple reservoir system. • Considers surface water, ground water and water quality. • Long and short term simulation lengths. • Powerful GUI.	• Smallest timeframe is a monthly simulation. • Room for error and corruption as model is very customisable.	Unknown but ESRI / ArcGIS license required for GEO-MODSIM.
REALM	Yes	Yes	Victoria, Australia;	• Models harvesting and bulk distribution of water.	• Only considers bulk water distribution.	Unknown

DSS	Applicable to		Case study example	Application and comments	Disadvantages	Cost
	PRROR	FWACS				
			Melbourne Water Supply System (Perera *et al*, 2005).	• User defined operating rules. • Stochastic. • Can be used to determine allocation models.	• Water balance model.	
Waflex	Yes	Yes	Save Catchment, Zimbabwe (Nkomo and van der Zaag, 2004); Komati Catchment, SA (Dlamini *et al*, 2007).	• It is a simple spreadsheet that models water flow through a catchment.	• 1 month time step • No GUI interface. • Code would need to be changed to change allocation methods.	Unknown.

The ability of the model selected to run the required rule setup for both PRROR and FWACS is the most important criteria, followed by documentation and local support. Although both MB and Riverware fit the first criterion, DHI (the distribution agents for MB) were able to provide MB at no cost with local support. Apart from these, the ability of the MB model to have variable time-steps which may be altered to obtain more detailed results for water use and flow in the reaches makes it the first choice out of those described above. The integration with a GIS environment aids in the representation of the catchment through the use of Digital Elevation Models (DEM) to create water flow paths and drainage canals is another advantage. A disadvantage of all the tools investigated is the inability to model human behaviour which is unpredictable and varies. How water users may react can only be determined using pre-implementation surveys to indicate potential changes and monitoring of changes and thoughts during and post-implementation.

A case study of the implementation and simulation using MB follows in Chapter 4.

4 CATCHMENT CONFIGURATION AND VERIFICATION OF SIMULATED HYDROLOGICAL FLOWS

This chapter includes the hydrological simulations of the allocation methods in a test configuration followed by those in the Sand River Catchment. Both the test configuration and the case study demonstrate the process used in the allocation method to account for water distribution through the allocation process. The simulation of the PRROR and FWACS allocation methods are then detailed in order to understand the simulation processes.

4.1 Application of MIKE BASIN – Test Configuration

In order to demonstrate how MB routes the water between water users, a simpler test configuration is explained first. Initially, the routing of runoff was tested in MB using varying degrees of catchment configuration complexity and water user interactions with reservoirs and reaches. The objective of the initial testing was to understand the way that the model routes the water and to systematically validate the rules that the user has selected.

Thus, both the PRROR and FWACS allocation methods can be simply tested and described using MB and simplified allocation priorities of water user demand and supply. These rules are set by the modeller and the model can then simulate carious situations including those of water shortages.

The setup as used in the description is shown in Figure 4-1 which depicts the network and the interactions between the catchments, the rivers and the water users and also shows the supply and the demand priority for the PRROR allocation method. The “D” represents the demand placed on a water resource by a water user while the “S” represents the supply by a water resource to a water user. The “S” may equally be represented by a “P” for priority.

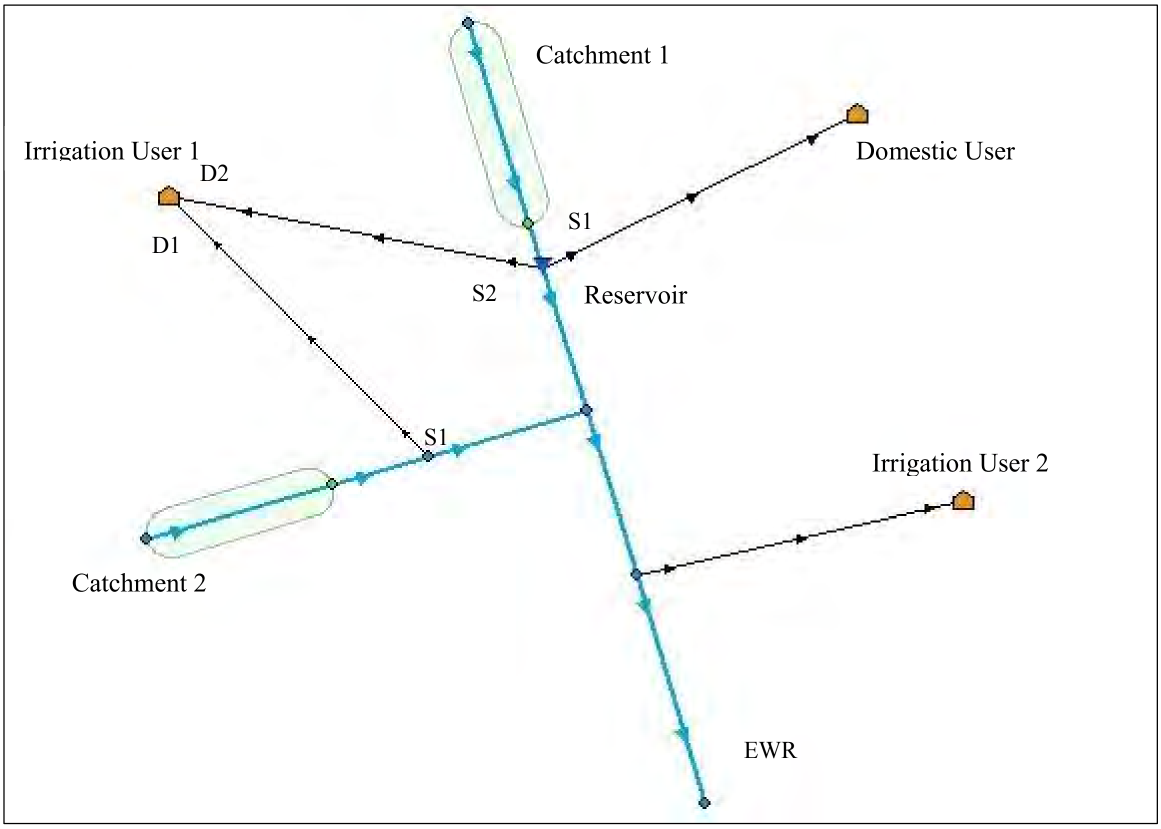

Figure 4-1 Evaluation scenario setup with water users for the PRROR and FWACS scenarios

The PRROR and FWACS method was modelled using MB with input runoff simulated by the *ACRU* model (Schulze, 1995). Within the MB model, categories of water users were assigned different priority levels and the water supply infrastructure was simulated so that water user demands were supplied in order of priority. The EWR component was attached to nodes below the reservoirs, using the reservoir as the source of water to supply the EWR. The node used to allocate the EWR is marked in Figure 4-1 as EWR. This node is downstream of the water users and as such, the water users are unable to abstract water until the flow requirement at the node has been met. It should be noted, however, that the EWR does not necessarily need to be placed at the end of a catchment, although it is convenient to place the EWR at the end of a catchment as it indicates the minimum flow required for normal river functioni ng. It also indicates the minimum input into the downstream catchment. Thus the current setup allows the EWR to flow past the water users without it being available for abstraction.

4.1.1 Configuration for PRROR

The PRROR method is currently used to allocate water resources in South Africa. The PRROR allocation method utilises restrictions placed on water users through a set of rules which are based on reservoir levels. In order to explain the mechanism by which the allocation method routes water and processes water demand in MB, the following steps were followed;

- A simulation of the PRROR model
- Implementation of PRROR

A simulation was run to form a basis of understanding of the model operation. The simulation provided a means of understanding the way the water users interact with the reservoirs and reaches, and the priority given to the water sources and water user access points. It was attempted to include situations likely to be encountered in the case study in the representation in Figure 4-1 for the simulation.

The implementation of PRROR to the catchment was completed in two steps. The first was to link water users to the reservoir where applicable. This was done to create a means of testing various configurations. The criteria for this were whether the reservoir was upstream of the water user and, within reason, whether the water user was in close enough proximity to the reservoir. The second step was to evaluate which water user has the higher priority when more than one water user are abstracting from a common water source. It was assumed that the greater the importance of the water user, the higher the priority would be. For example, in a system with two water users, the water user with a higher level was given Priority = 1 while the lower Water User a Priority = 2.

In the configuration shown in Figure 4-1, the reservoir supplies (S) *Domestic* with a Priority = 1, (S1) while *Irrigation User 1* receives water from the reservoir at a Priority = 2, (S2). This means that *Domestic User* is the preferred Water User from the reservoir. *Irrigation User 1*, however, demands (D) water first from the river (D1) and then from the reservoir (D2). As the reservoir supplies *Irrigation User 1* at Priority = 2, water will be allocated to *Irrigation User 1* once *Domestic User* has received the water demanded. If there is insufficient water in the primary water source to meet *Irrigation User 1* demand, *Irrigation User 1* will abstract from its secondary water source, that being the reservoir.

4.1.2 Configuration for FWACS

Under FWACS, water users are assigned a proportion of river flow (FWA) and may also rent or own a virtual portion of a reservoir (CS). The sum of the fractions allocated to Water Users should not exceed 1 as no more than 100% of a water resource can be allocated. Under FWA, the proportion or fraction assigned to a water user entitles them to extract that fraction of the current flow, based on their water demand. With a varying river flow, the fraction of the flow allocated to a user may exceed the water demand or be in deficit to the water requirement at a given point in time. Under CS, a water user has access to a portion of the reservoir as well as a portion of reservoir inflow, which acts to re-charge the CS portion. In the study of both the test configuration and Sand River Catchment, the inflow fraction and the capacity sharing fraction were made equal. Not only did this allow comparison of similar situations as by changing either inflow fraction or the CS, a multitude of variations becomes available, but also allowed for a more accurate comparison. In order to compare PRROR and FWACS, the model needs to conform to least flexible, PRROR, and thus compare purely on storage capacity. Although the ratios of inflow, dam size and water use can be modified to improve reliability under FWACS (Hallowes *et al*., 2008), an accurate comparison can only be made on the storage capacity and not inflow as this cannot be modified in PRROR.

MIKE BASIN is also able to account for the EWR of FWACS as various reservoir operating procedures are available. Minimum reservoir releases may be specified to either meet the required flow of the EWR at the outlet of the reservoir or to satisfy a minimum flow requirement at a downstream point and/or in a river. Releases from a reservoir to contribute to the EWR will make up river flow which is then available for abstraction by water users who are downstream of the reservoir. This is not ideal as then EWR is reduced at the off-take for the first water user which may compromise the EWR at downstream points. It is for this reason that in the setup of the simulation, the EWR node was placed downstream of the water users in Figure 4-1.

4.1.3 Simulation of PRROR and FWACS

The simulation was set up using the information and data listed in Table 4-1 and graphically represented as shown in Figure 4-1. Catchment 1 was used to generate stream flow data which flows into a reservoir i.e. the runoff generated on Catchment 1 flows into the reservoir. The reservoir storage is available to water users to meet their water demands. Overflow and releases from the reservoir are available downstream of the reservoir for downstream water users. In addition, Catchment 2 is included which generates runoff which is available to *Irrigation User 1*. Catchment 2 was included to show the impact that an additional water source may have on reservoir storage. An additional water source means that a water user does not have to only abstract water from the reservoir. Thus, the allocation priority for *Irrigation User 1* was set up such that the reach is used first [first supply priority (S1) and only when insufficient will the reservoir second supply priority (S2)] supply water to the Water User.

Table 4-1 Data and information requirements for the PRROR and FWACS allocation method simulation

Node	PRROR	FWACS
Water User	• Water demand • Water supply sources • Priority of supply sources	• Water demand • Water supply sources • Priority of supply sources
Reservoir	• Reservoir volume • FSL • Stage-storage relationship • Flood control level • Water User water demand • Source priority of supply to Water User • Restriction levels of the reservoir	• Reservoir volume • FSL • Stage-storage relationship • Flood control level • Water User water demand • Source priority of supply to Water User • Reservoir inflow recharge allocation to each Water User • Water User volume share of the reservoir
River	• Flow in the river • Source priority of supply to Water User	• Flow in the river • Source priority of supply to Water User • Fraction of river flow allocated to Water User

4.1.3.1 Simulation of PRROR

The reservoir curtailment rules used for the simulation of Irrigation water users' were setup within MB as shown in Table 4-2. At storage levels between 100% and 46% the users' are allocated 100% of water demand, between 30 % and 45 %, Irrigation users will only receive 80 % of the water demanded, while at reservoir levels below 30 % only 60 % of their water demands will be allocated. The level of 0% does not represent a dry reservoir, rather the point at which water is unable to be allocated (pumped) or removed from the reservoir, i.e. the Dead Storage Level (DSL). The curtailment rules as applied by MB for Domestic Water users are shown in Table 4-3. The reservoir is set up to supply the Domestic User with a higher priority than the Irrigation water users, who will be allocated water only once the water requirement for *Domestic User* has been met. An example of a water balance for the domestic and irrigation water users is depicted in Table 4-4. In meeting a demand, the entire demand does not have to be met in order for the allocation to be complete, as shown in Table 4-5 and Table 4-3.

Table 4-2 Reservoir curtailment corresponding to reservoir level for Irrigation users

Reservoir level	Water allocated	Level
100% - 46%	100%	1
45% - 30%	80%	2
29% - 0%	60%	3

Table 4-3 Reservoir curtailment corresponding to reservoir level for Domestic Water users

Reservoir level	Water allocated	Level
100% - 81%	100%	1
80% - 0%	80%	2

If a restriction rule states that the reservoir will supply 80% of required water it will supply less than or equal to 80% of the demand, depending on the availability of water. The allocation is considered complete and the remaining water will be supplied from a secondary source, if one is available.

Table 4-4 PRROR scenario simulation for reservoir and rivers

Date	**Inflow to Reservoir [m^3/d]**	**Reservoir Water level [%]**	**Outflow from Reservoir to Water User (*Domestic User*) [m^3/d]**	**Outflow from Reservoir to Water User (*Irrigation User 1*) [m^3/d]**	**Inflow to Abstraction Point (*Irrigation User 2*) [m^3/d]**	**Water Abstracted by Water User (*Irrigation User 2*) [m^3/d]**	**Water Leaving (*Irrigation User 2*) Abstraction Point [m^3/d]**
01/01/1980	259200	57	172800	36288	172800	6912	165888
02/01/1980	259200	56	168998	34560	172800	8640	164160
03/01/1980	259200	56	164574	34560	172800	8640	164160
04/01/1980	259200	55	161035	34560	172800	8640	164160

The current water use values from Table 4-4 show the abstraction of water from various sources by the water users to meet their demands. The demand deficits for each Water User are not included, nor are the water user demands. The ability of the water user to abstract from two different water sources is reflected in Table 4-5 where the distinction between abstraction from the reservoir and abstraction from the river water use is shown. The reservoir level is shown in Table 4-3 where it can be seen that the reservoir level is less than 80%, placing allocation in the restriction zone, providing 80% of water demand.

Table 4-5 Water allocation between reservoir using restriction rules and river abstraction for *Irrigation User 1*

Date	**Water User Water Demand (*Irrigation User 1*) [m^3/d]**	**Water User Abstraction from Reservoir (*Irrigation User 1*) [m^3/d]**	**Water User Abstraction from Reach (*Irrigation User 1*) [m^3/d]**
01/01/1980	43200	34560	8640
02/01/1980	43200	34560	8640
03/01/1980	43200	34560	8640

The water user water demand for *Irrigation User 1* is 43200 m^3/d. The primary source of this supply is the river with the reservoir providing secondary supply should the river not be able to supply the full demand (Table 4-5). The level of restriction from the river may be checked by the division of the water user abstraction from river value, 8640 m^3/d by the water user water demand value of 43200 m^3/d = 20%. The reservoir is currently 57% of FSL, Table 4-4, which places it in the Level 1 surety of supply band. This translates to a supply ability of 100% of water demanded by the Water User, as shown in Table 4-5.

In summary:

- *Irrigation User 1* water demand equals 43200 m^3/d.
- The river can supply 8640 m^3/d i.e. 20% of demand.
- The reservoir needs to supply the shortfall of (43200 m^3/d – 8640 m^3/d = 34560 m^3/d i.e. 80%) the water demand.
- The reservoir level is 56% which, when read from Table 4-2, indicates the ability to meet 100% of demand placed on it by water users.
- The shortfall of 34560 m^3/d will be supplied in full from the reservoir.

4.1.3.2 Simulation of FWACS

The model setup shown in Figure 4-1 includes the FWA component and the CS component for the *Irrigation User 1* Water User, meaning that *Irrigation User 1* has access to both the reservoir and the river as a source of water. The *Irrigation User 1* first abstracts water from the river and only when the river is unable to supply the demand is reservoir used to supply the demand.

In the example shown in Figure 4-1, there are two abstractions under FWA; the first will be from the *Irrigation User 2* located as shown in Figure 4-1. The other is the *Irrigation User 1*, where the water user also has access to the reservoir as a water source. The FWA and CS components for each water user are shown in Table 4-6. A portion of the water in the case of both the river and the reservoir is allocated to what is called an unallocated segment. Due to the volume of water theoretically increasing as one moves downstream, the allocation of FWA against a value of 1 (100%) cannot be done. Rather, a FWA should be provided to each user in such a way as to allow for EWR, where and as required. This unallocated component includes the EWR. The EWR is allocated before the balance available to other users is calculated.

Table 4-6 Fraction allocation components for Water Users

	FWA in River	CS in Reservoir
Irrigation User 1	0.40	0.25
Irrigation User 2	0.40	
Domestic User		0.30
Unallocated	0.20	0.45

An extract of the simulation for the *Irrigation User 2* is represented in Table 4-7, where the flow to the abstraction point is the sum of the flow from the reservoir and from Catchment 2 minus water abstracted by *Irrigation User 1* from the river. The combined flow at the abstraction point provides the Water User with a supply of water which is important as *Irrigation 2* does not have access to a reservoir for times when water availability is low.

Table 4-7 Example of demands and allocations to *Irrigation User 2* for FWA scenario

Date	Flow to Abstraction Point [m^3/d]	Water Demand [m^3/d]	Water Allocation [m^3/d]	Water User Water Demand Deficit [m^3/d]
02/01/80	250560	43200	43200	0
03/01/80	250560	43200	43200	0
04/01/80	250560	43200	43200	0
05/01/80	41242	86400	16497	69902

As shown in Table 4-8, water availability for *Irrigation User 1* leads to all demands being met. The Table 4-8 shows the ability of the river to meet water user water demand and not impacting on the reservoir.

Table 4-8 Example of demands and allocations to *Irrigation User 1* for FWA and CS scenario

Date	Flow to Water User Abstraction Point [m^3/d]	Water User Water Demand [m^3/d]	Water User Water Used from Reach [m^3/d]	Water User Abstraction from Reservoir [m^3/d]	Water User Water Demand Deficit [m^3/d]
08/01/80	172800	43200	43200	0	0
09/01/80	518400	172800	172800	0	0
10/01/80	518400	172800	172800	0	0
11/01/80	518400	86400	86400	0	0

The inflow to the reservoir is allocated to the water users' pools according to their inflow fraction. The model allocates the EWR from the unallocated pool by default and the pool size may be altered by the modeller in order to meet the demands.

The allocation process for the scenario follows meeting the; minimum flow requirements for the river first and then the remainder of the water is allocated to the CS pool of each user from where it is allocated to meet the demand of the Water User. The reservoir acts as a backup for situations when the river flow is not sufficient to supply the whole water demand to a connected water user as a result of the FWA share assigned to the user. With the *Irrigation User 1* having access to a river and having the river node listed as Priority = 1 for water access, the Water User's reservoir pool is able to fill, creating a storage for the Water User which creates an opportunity for extended irrigation.

4.2 Configuration of Sand River Catchment

The catchment selected as a case study was the Sand River Catchment in the Mpumalanga Province of South Africa, located as shown in Figure 4-2. The Sand River Catchment was selected due to the large number of water users, coupled with the fact that this catchment contributes to International flows (Mozambique). The Sand River Catchment forms a sub-catchment of the Crocodile Catchment, which is one of the most over-allocated catchments in South Africa (Frezghi, 2010). Additionally, the Sand River Catchment was selected as it falls within the Inkomati Catchment Management Agency (CMA) which, in 2009, was the only functioning CMA in South Africa. Since then, the Breede-Gouritz CMA has also been declared (GN 481 of 12 July 2013). It will also be one of the first catchments to undergo compulsory licensing (Jackson, 2010). Thus the water users will need to be able to assess the impacts of potential changes in allocation methods and be able to adopt appropriate adaptation strategies. Therefore the opportunity exists for the testing of a more appropriate water allocation method. In order to assess the impacts of the method of water allocation, allocations to water users in the Sand River Catchment were simulated under both the PRROR and FWACS allocation methods.

The Sand River Catchment covers an area of 1780.24 km^2 with the catchment draining in the South East corner. As shown in Figure 4-3, the topography of the region is controlled by a mountain range extending from the North West, descending to a valley in the West and ascending to a peak in the South West. Drainage lines in the form of valleys extend from the mountainous West to the plains in the East. The impact of international obligations was not simulated in this study.

The catchment was configured for the MB (DHI, 2009) river network model as well for the *ACRU* agro-hydrological model (Schulze, 1995) using the Amalgamation of Agrohydrological Modelling Groups (AAMG) extension running within the ArcGIS 9.2 environment (Pott *et al.*, 2008). Streamflow was simulated using the *ACRU* model and used as input to the MB model. Data used in the verification was obtained from the Water Availability Assessment Study (WAAS) study (Frezghi, 2010) which formed part of the WRSM 2005 project (Middleton and Bailey, 2008). Within the AAMG framework, information is provided including rainfall stations, weirs, modified Acocks land cover, cities, quaternary catchments, reservoirs and rivers, all obtained from field work, irrigation boards, consultants reports and municipal records. The municipal records and data were collated by DHI by Frezghi (2010) and was subjected to quality testing and evaluation before being used in the simulations and verification exercises.

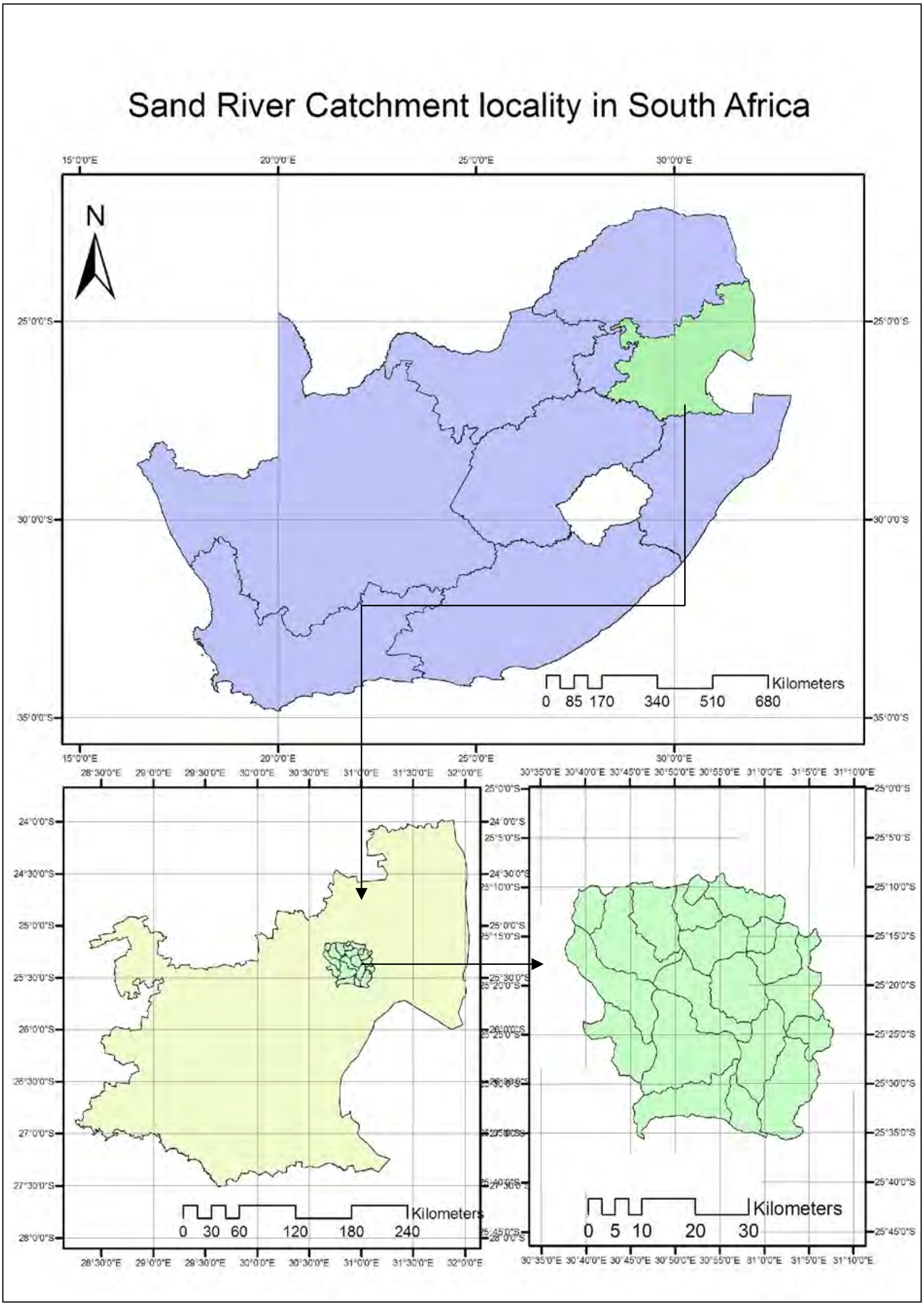

Figure 4-2 Sand River Catchment locality

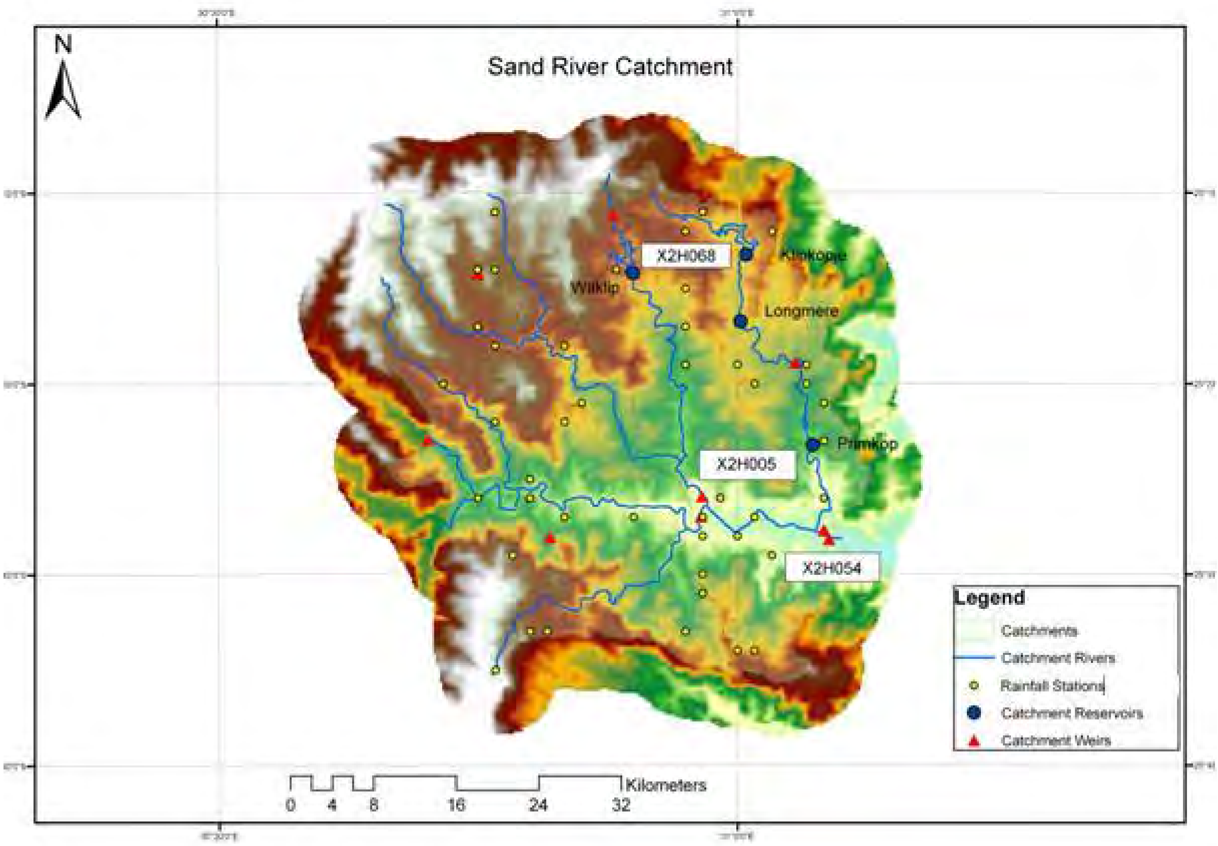

Figure 4-3 Sand River Catchment major rivers, reservoirs and gauging weirs

Water use volumes for irrigators are maintained by water associations in the catchment and were used in this study. Domestic water consumption data were also available from the local municipalities.

The Sand River Catchment contains four reservoirs, as shown in Figure 4-3 which are all located in the lower altitude Eastern portion of the catchment. The points designated with "A", "B" and "C" in Figure 4-4 are selected Water Users while point "D" is a node in the simulation, used for the monitoring of the overall effect of the allocation method. In assigning priorities for sources of water, the river was the first priority as a water source while the reservoir was the second priority. In cases where only one water source was available to the Water User, this was the first priority supply source. For example, Witklip reservoir as shown in Figure 4-3 and Figure 4-4 has 2 water users. Although all Water Users were investigated, only Water User A was examined in detail as in the current study, Water User A only has access to a reservoir to meet its water demand.

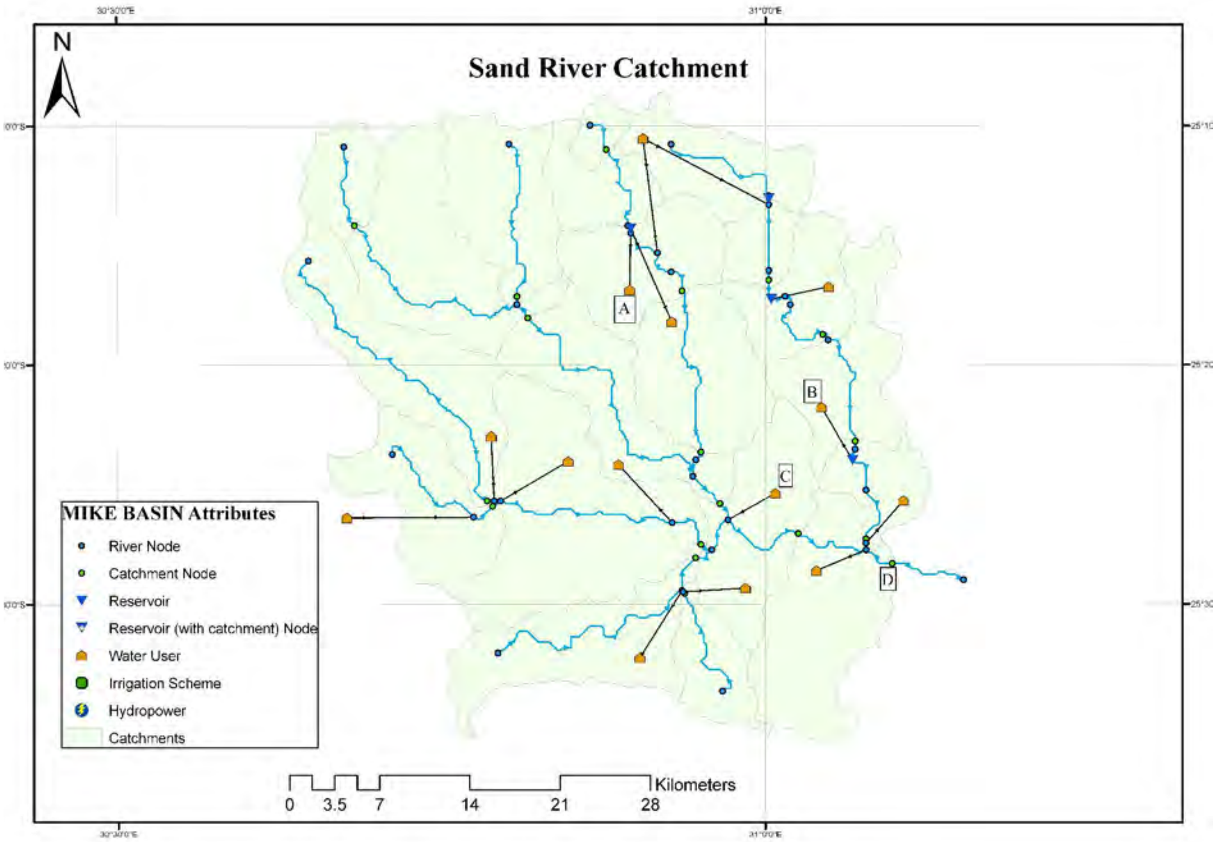

Figure 4-4 Sand River Catchment showing Water Users A, B and C and Node D and other catchment Water Users

4.3 Hydrological Simulations

The hydrological simulations were undertaken so as to test the hypothesis that FWACS, as an alternative to PRROR, can improve reliability and thus assurance of supply to water users in the Sand River Catchment.

The hydrological simulations included the following:

- Validation of model input files generated automatically using the *ACRU* Menu Generator (AAMG).
- Verifications of streamflow simulated by the *ACRU* model.
- Implementation of the allocation methods and routing of water in the river network and reservoirs using the MB model.
- Modification of FWACS allocations to test sensitivity of the model.

The catchment contains four reservoirs and sectorial water users which are classified as irrigation (agriculture), domestic (towns and cities), industrial and the environment. There are also EWR sites where minimum flows are required in order to maintain environment functionality.

The verification of the runoff simulated by the *ACRU* model in the Sand River Catchment was performed at three locations, flow gauging Weirs X2H068, X2H005 and X2H054 where suitable gauged flow data were available, as shown in Figure 4-3. The majority of the flow gauging weirs in the catchment were either unreliable or the observed flow data did not correspond with the simulation period of interest. The simulation period used is 1 January 1970 to 31 December 1999. This period was selected as it represented a period which had the highest degree of complete records as well as being relatively recent in nature so that the demands for water will be realistic and currently applicable. The locations of all the available rainfall stations are shown in Figure 4-3 although only one rain gauge was selected per sub-catchment as a driver station. The driver station for a sub-catchment was selected by weighing up several criteria which included; altitude, length of rainfall record and proximity to the sub-catchment. One rainfall station may drive more than one sub-catchment due to the appropriateness of location, altitude and period of record. When selecting driver rainfall stations it is important to be aware of the heterogeneity of the environment. The increase in frequency of small spatial scale extreme events such as a cloud burst is an example of an event which may be missed by the rainfall station network, yet plays a significant role in water storage and streamflow regimes. Monthly correction factors were therefore used to ensure that the rain gauge matched the monthly statistics for the catchment. The areas of the sub-catchments are shown in Figure 4-5. Inflow from upstream catchments is shown in Figure 4-5 as a catchment transfer point, which was used in the simulation to add water which is generated outside of the case study catchment boundary.

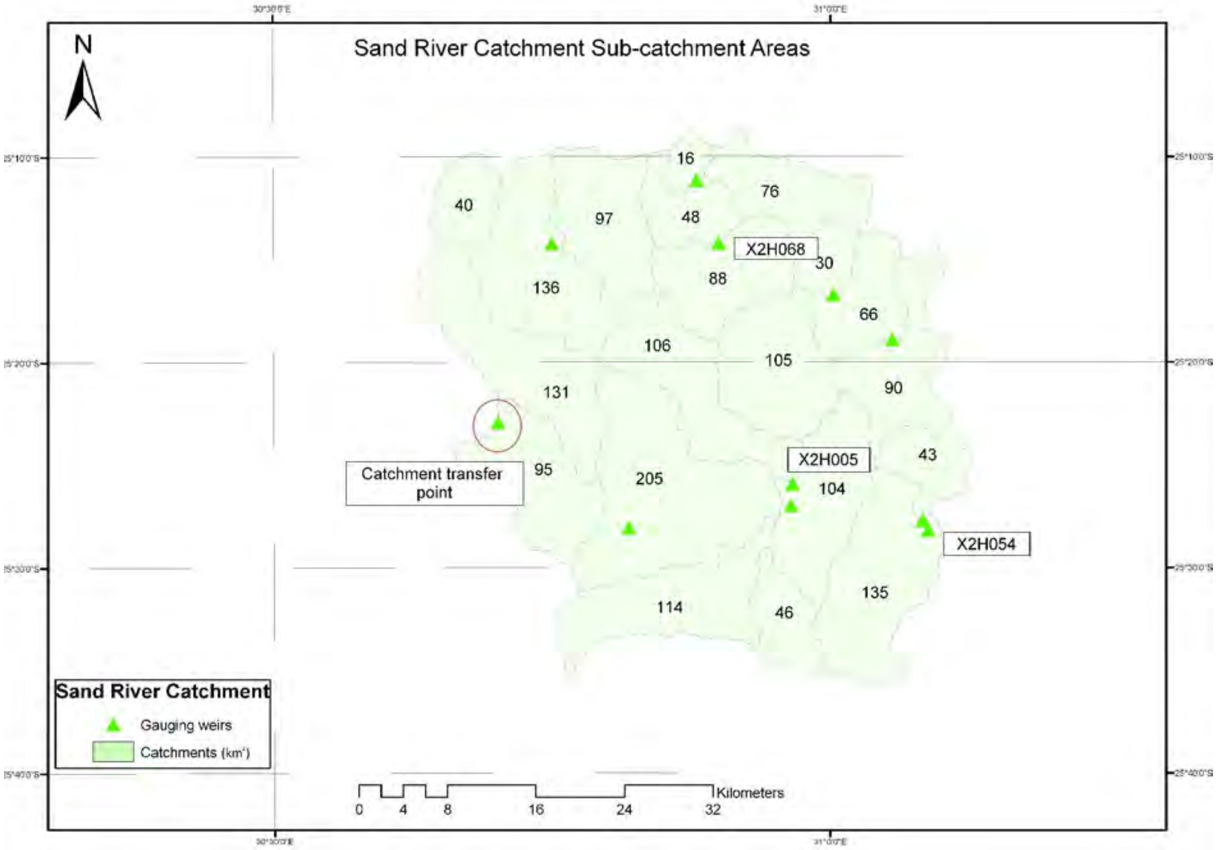

Figure 4-5 Sub-catchment areas within the Sand River Catchment

The primary source of the land cover data used in this study was Acocks (1975) which was modified for current land cover from the Atlas of Agrohydrology and Climatology (Schulze *et al.*, 2008), digitised and used as a layer within a GIS environment and queried through the AAMG application. From this, land use attributes were extracted for the *ACRU* model for the area of interest. The AAMG application was used to also extract the soils information from the Atlas of Agrohydrology and Climatology (Schulze *et al.*, 2008). The reference potential evaporation was calculated using the equation in the Hargreaves and Samani (1985), as implemented in the *ACRU* model, which requires maximum and minimum temperatures on either a daily or monthly mean basis to estimate evaporation (Schulze, 1995). Temperature data for the Hargreaves and Samani equation was obtained from the "South African atlas of climatology and agrohydrology" (Schulze *et al.,* 2008). The above approach was used on a monthly and daily time step, streamflow simulated by the *ACRU* model was used as inflow to the nodes in the MB model and the linked models were configured for the Sand River Catchment and subsequently used in the verification of the simulated streamflow.

The simulated and observed streamflow verification at Gauging Weir X2H068 is shown in Figure 4-6. This catchment has an area of 64 km^2 (16 km^2 and 48 km^2) and is heavily afforested with commercial forestry activities.

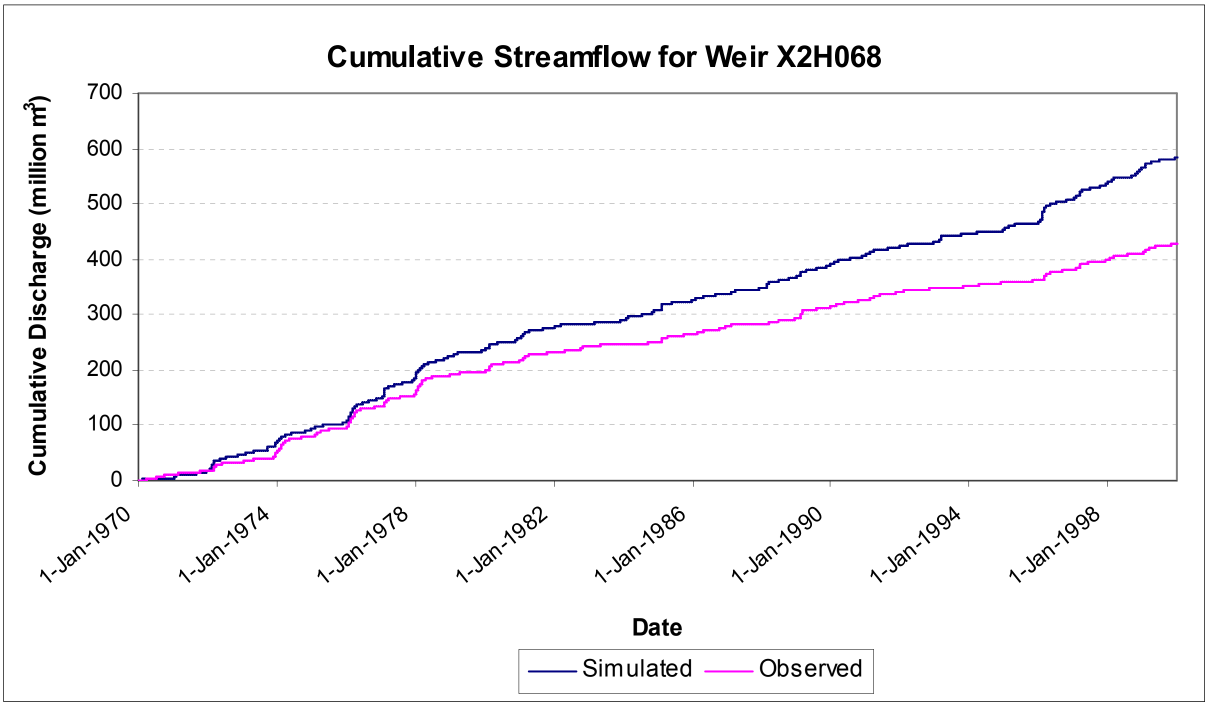

Figure 4-6 Simulated and observed accumulated streamflow of weir X2H068

The simulated and observed cumulative streamflow graphs match each other stepwise well generally, in response to rainfall events. The simulation pre-1978 showed a good relationship between simulated and observed streamflow. The period between 1970 and approximately 1972 showed a very good fit with a divergence starting where simulated streamflow began rising at an increasing rate over periods when observed showed little response. The simulated streamflow shows significant areas of no response between 1990 and 1996 where the observed shows continual gains in accumulated streamflow in the same period. Rainfall data from the driver rainfall station 0555437_W and a neighbouring rainfall station 0555794_W show a similar trend of an initial good fit but thereafter divergence, as shown in Figure 4-7. Hence, the quality of the driver rainfall station data does not suggest a reason for the noticed divergence in the observed and the simulated streamflow.

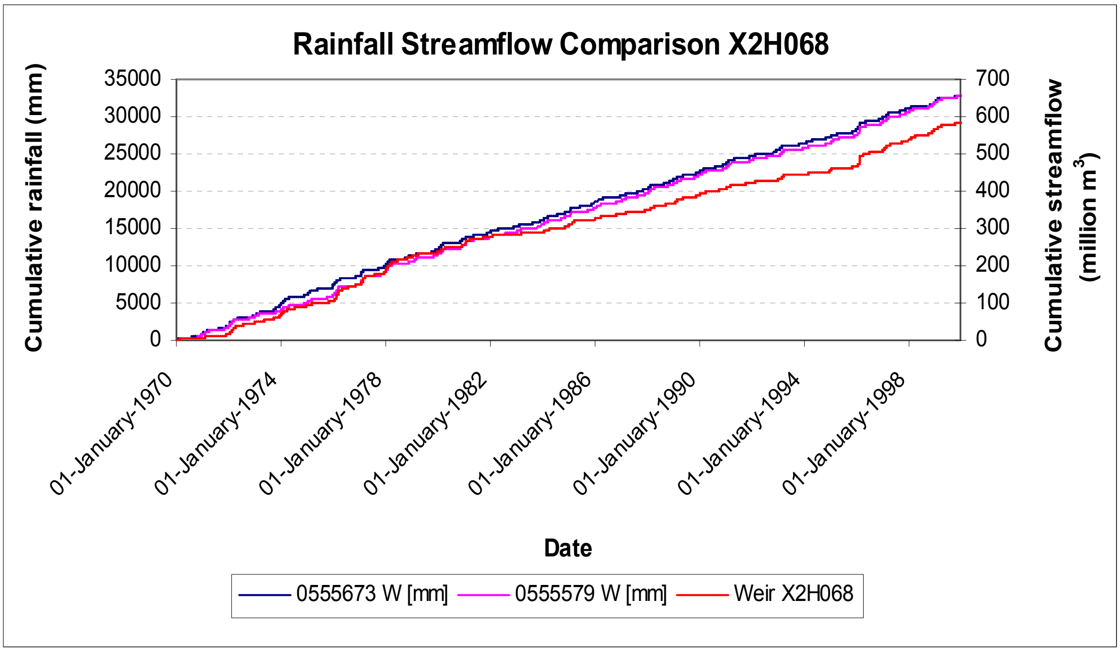

Figure 4-7 Comparison of rainfall data and simulated streamflow weir X2H068

Potential reasons for the simulated streamflow exceeding the observed may be due to many factors including increased, unmetered abstractions by agriculture and domestic users, a change in hydrological response through land cover change and management practices and heterogeneity resulting in local rainfall events not being recorded or erroneously included through the selection of a driver station. The lack of metering data in respect of individual water users rather than the use of water user groups and the difficulty in calculating afforestation water uptake means that at best, it is a combination of these factors rather than a defined effect of one of the described potential reasons. The simulation did provide for a good result with regards to closeness of fit and response of simulated to observed prior to and up to and including early 1978.

The second verification of the simulated hydrology of the Sand River Catchment was performed at Gauging Weir X2H005, located in approximately the centre of the study catchment as shown in Figure 4-5. The X2H005 weir is situated on the Nels River which is upstream of the town, Nelspruit. The weir has a contributing area of 639 km^2 which includes the upstream Gauging Weir X2H068, with simulated results shown in Figure 4-6. Results for the verification at Gauging Weir X2H005 are shown in Figure 4-8.

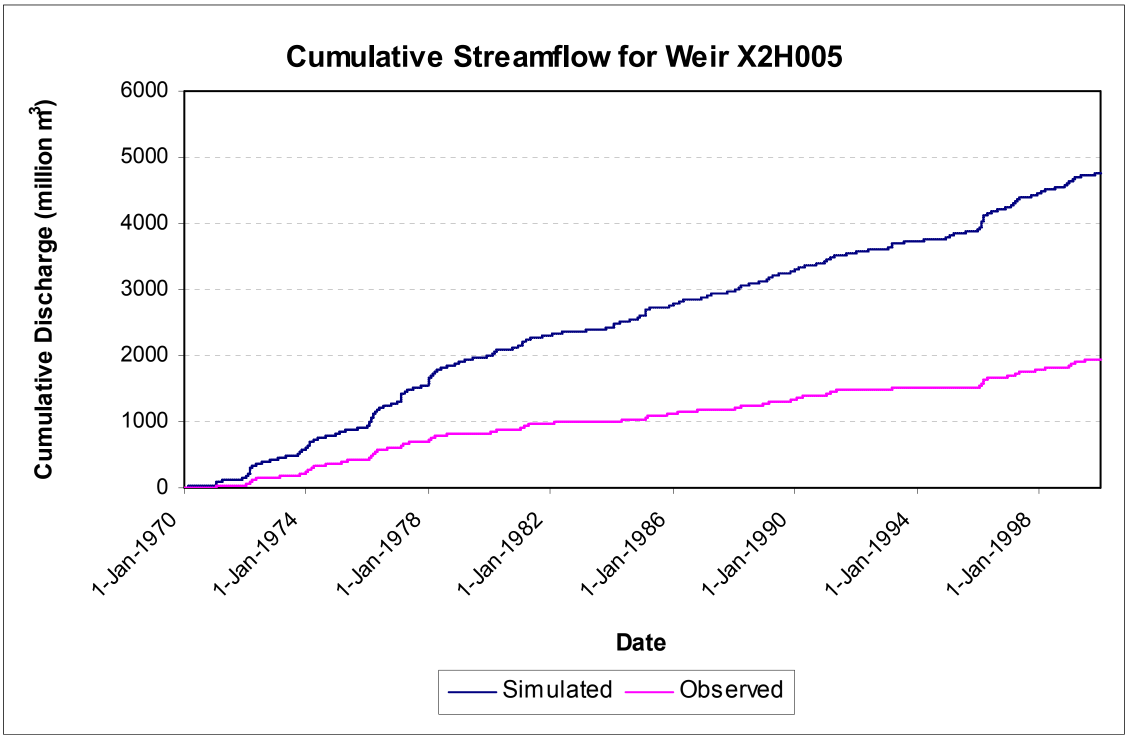

Figure 4-8 Simulated and observed accumulated streamflow of weir X2H005

The results show a significant over simulation in comparison to the observed flows. The flow gauging weir's record was checked regarding over-topping as well as overall weir functioning. Missing or erroneous data (outliers) were not considered in the comparison of the simulated and the observed streamflows. Over-topping was checked through inspection of weir records and noted as occurring when records showed a consistent level being reached several times with no events being recorded above the level. Weir functioning was checked by examining record quality in terms of data consistency and frequency of missing data or patched data. The data did show periods where patching had occurred. Patched data was removed from the dataset used in the simulation modelling process. As in Figure 4-6, heterogeneity may explain the divergence between the simulated and observed streamflow. The heterogeneity may be exaggerated due to the increase in catchment area.

The rainfall data shows a slope more consistent with that of the simulated streamflow than with the observed streamflow, as shown in Figure 4-9. The response of the observed streamflow to that of the rainfall records has a low correlation. The runoff response is more realistic for the simulated streamflow which is expected as the simulated streamflow is a result of the rainfall data to which it is being compared. The average rainfall (MAP) for the region is 1080 mm per annum. Over an area of 639 km^2 this rainfall would generate 690.1 x

10^6 m^3 of water. The Mean Annual Runoff (MAR) for the region is approximately 114 x 10^6 m^3 per annum (WR2005). That provides a runoff:rainfall ratio of 0.165 (WR2005). The simulations provide a runoff:rainfall ratio of 0.19. The runoff:rainfall ratio achieved through comparison of available data provides a reliable result for simulation use.

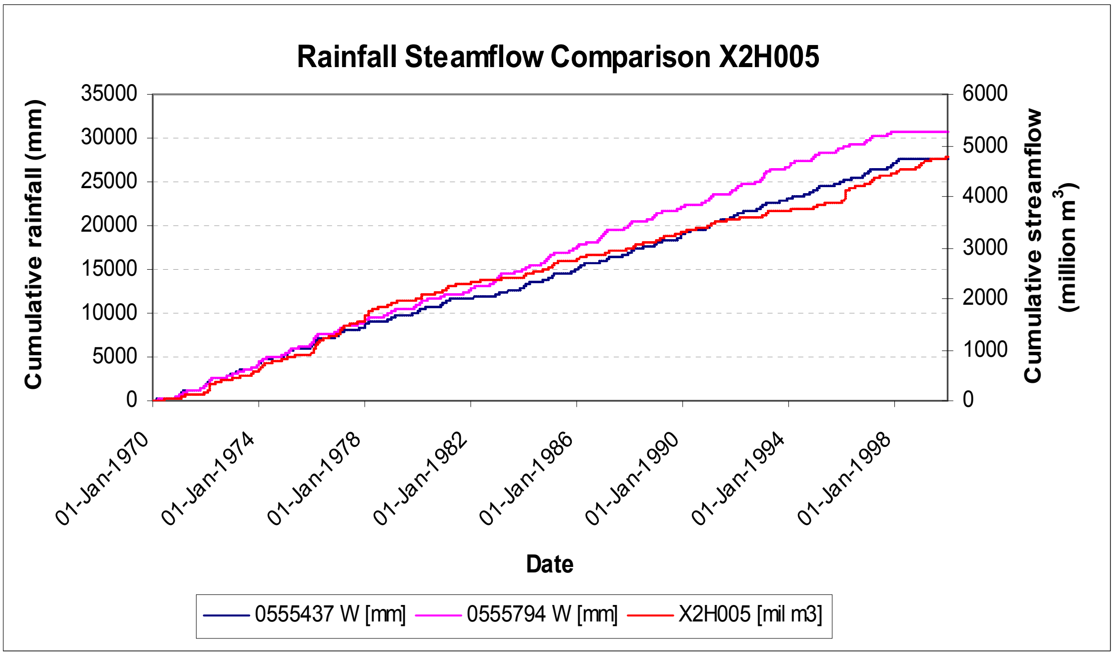

Figure 4-9 Comparison of rainfall data and simulated streamflow weir X2H005

A third verification was performed at weir X2H054 which has a contributing area of 1749 km^2. A 'transfer' of water into the catchment from the West, as indicated in Figure 4-5, was simulated by adding the flow into the corresponding sub-catchment and allowing the transferred water to cascade down the river system. This was done as the reach in the West does not originate in the study area but brings a large volume of water which would otherwise influence the water balance in the study site when doing simulations.

A comparison of simulated and observed runoff at the catchment outlet, weir X2H054, is shown in Figure 4-10. The accumulated simulated streamflow remains consistently more than the accumulated observed streamflow at weir X2H054. In examining the data, the simulated matches the observed events more closely, however the magnitude of each response is on the whole greater for the simulation. As in Figure 4-6 and Figure 4-8, the inclusion or omission of extreme events combined with the effect of increased catchment area, may contribute to the difference noted in simulated and observed streamflows.

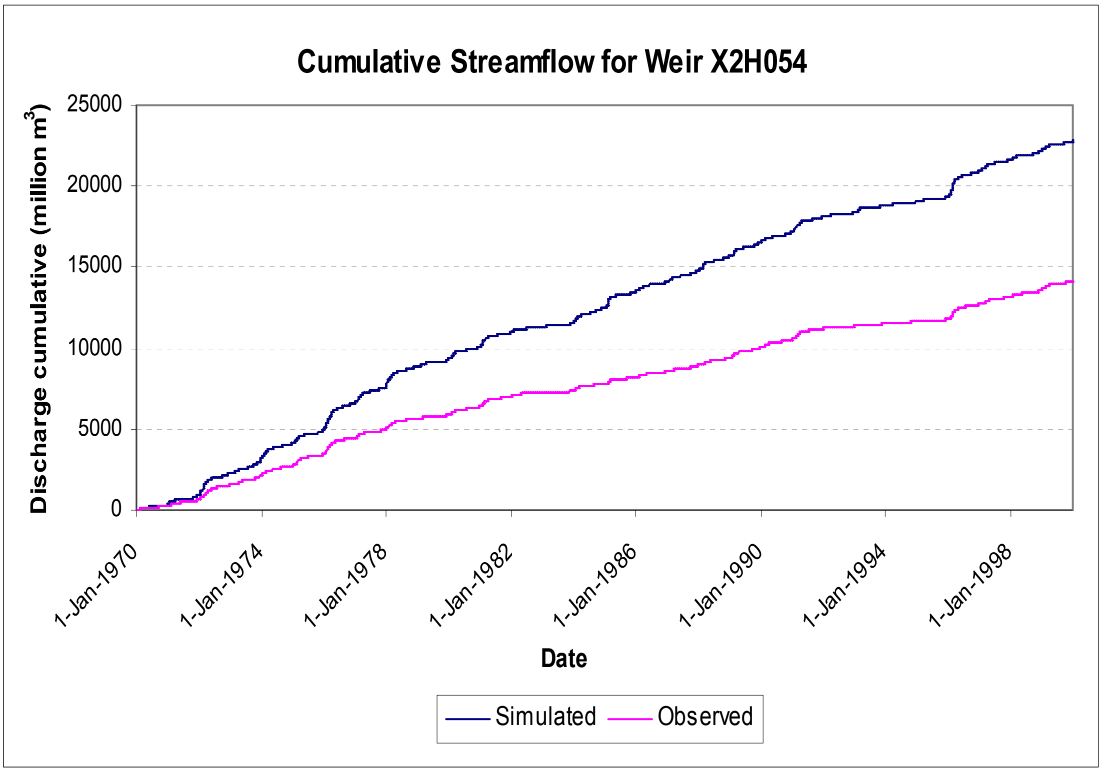

Figure 4-10 Simulated and observed accumulated streamflow of weir X2H054

The comparison of the accumulated simulated streamflow and the rainfall data shows a close relationship to each other. The precipitation events are linked to a corresponding event on the streamflow. Circa 1976, a change does take place relating to the runoff generated from rainfall events. The relationship is shown in Figure 4-11.

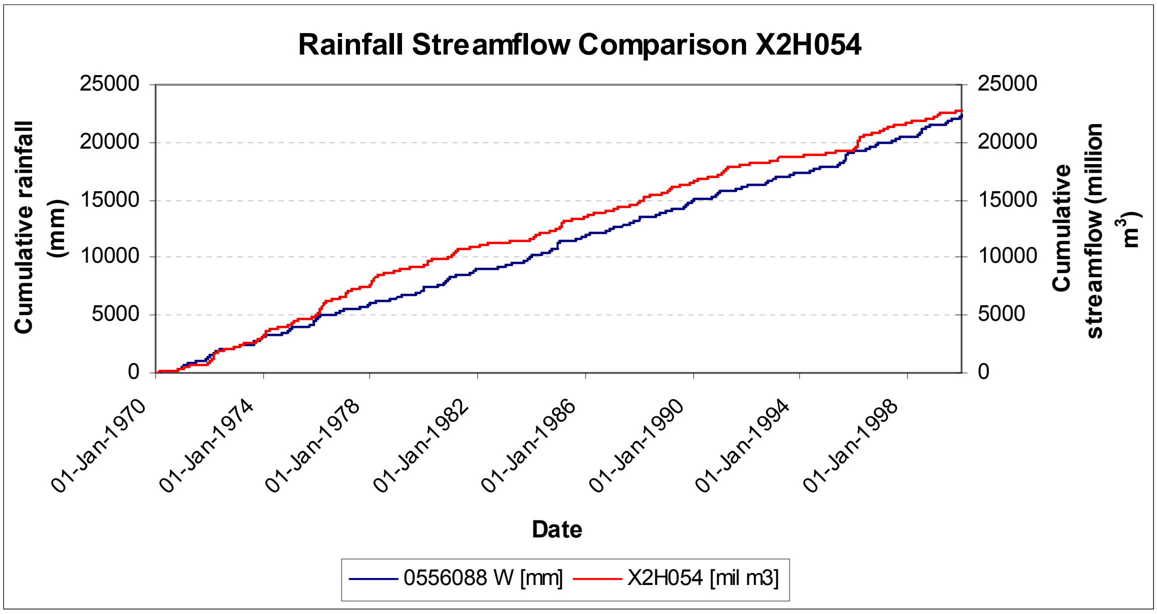

Figure 4-11 Comparison of rainfall data and simulated streamflow weir X2H054

For the above verifications of rainfall and streamflow, land cover was investigated, as a dramatic change in the land cover could lead to poor simulations. Water abstractions were checked to rule out any incorrect data which may have been entered. No irregularities were noted in the investigation.

The water abstraction data were received from an existing configuration which was compiled from information supplied by municipalities and irrigation boards and, when appropriate, the data was lumped together. The *ACRU* variables were checked and default input variable values were improved where appropriate and when a good knowledge base was available. The enhanced evaporation for forestry was enabled on the north-western sub-catchments and horizontally to the East following the northern boundary of the study site. This followed the predominant use of these catchments for commercial forestry activities.

Changes were also made to the *ACRU* input parameters. The catchments which were used in the comparison of simulated and observed flows were configured to reflect expected conditions by changing the QFRESP, ABRESP, BFRESP and COIAM parameters. These parameters deal respectively with:

- the fraction of stormflow that will runoff on the same day as the event;
- the fraction of water to be redistributed to the subsoil from the saturated top soil,
- the fraction of sub soil water to be redistributed to the groundwater store and
- the coefficient of initial abstraction which represents interception, surface storage and infiltration losses before stormflow begins.

The changes made to QFRESP where from 0.5 to 0.3, the ABRESP parameter was changed from 0.38 to 0.6 and the BFRESP was changed from 0.38 to 0.6.

It should be noted that the changes made to the *ACRU* parameters was decided on after consulting with the *ACRU* User Manual Version 4.00 (Smithers and Schulze, 2004) and were within the ranges suggested for the various input variables. The check of the monthly simulated streamflow versus the observed streamflow produced a slope of less than 1, reflecting the “Trend 2” event in the *ACRU* User Manual Version 4.00 (Smithers and Schulze, 2004).

Improvements to the simulation were attempted without significant success. As mentioned, rainfall data from the rainfall stations was checked for consistency and periods where data had been patched to supply a complete set was assessed. This included using monthly rainfall corrections factors rather than the original annual correction factor used by Frezhi (2010). The abstractions by water users were checked for apparent errors. As this information was based on records obtained from municipalities and irrigation boards it was accepted as the best available estimate. Soil depth and soil factors were checked to ensure consistency for water retention, surface flow and ground water interaction.

The simulations above were performed to ensure that the data used in the modelling of the allocation methods, as detailed in the following chapter, approximated the observed data as closely as possible to ensure realistic representation of the streamflow. Observed data could not be used as there were omissions in the data, which would impact on the reliability of the models. Simulations were based on rainfall, the main driver of streamflow, and land use factors, a secondary driver, adjusted in ACRU to allow the simulation to match the observed as closely as possible. The accuracy of such simulations is dependent on the accuracy of available data e.g. land use data and reported water abstractions. Thus some inaccuracies are to be expected. However, both the FWACS and PRROR allocation methods will be equally impacted by over or under simulated streamflow, and therefore any inaccuracies will be consistent between the allocation method models. Thus, despite the contrasting performance of the simulations at the three gauging weirs, with the *ACRU* model configured consistently for the three catchments, it is believed that the simulated streamflow results will still be able to be used to meet the objectives of this study.

The PRROR allocation method simulation was done so as to best match the current scenario of water allocation in the catchment. Under the PRROR method currently used, water users are free to abstract water from a river or stream, as long as there is sufficient water for pump operation. Those water users who abstract water from reservoirs are made to follow a curtailment rule set based on reservoir level, relative to FSL. Depending on the classification of the Water User, deductions in water abstractions is initiated at different reservoir levels. The fractions and capacity store allocated under the FWACS method, attempted to approximate the PRROR allocations as closely as possible. This was done by obtaining a ratio between the water demanded by a user and the volume of the reservoir to which the user had access. A “zero line” was required from which to begin the simulations and later expand to the sensitivity analysis. Under the FWA component, the water users were provided full access for river and stream abstractions. Under the CS component, an approximate share of the reservoir was allocated to a Water User so as to best match the PRROR water allocation scenario. This was calculated by obtaining a ratio between the water demanded by a Water User and the volume of the reservoir to which the Water User has access. In order to test the sensitivity of the FWACS method to the fraction allocated, scenarios were run were CS fractions were either increased by 10%, 20% or 50% or decreased by 10%, 20% or 50%. The CS component was altered, this being the CS of the reservoir as well as the inflow ratio allocated to the Water User, in the sensitivity test as the FWA was originally simulated at 100% of river flow being available for abstraction. The following chapter contains the results from the case study implementation and simulation of the PRROR and FWACS allocation methods in the Sand River Catchment.

5 RESULTS FROM THE SIMULATION OF PRROR AND FWACS ALLOCATION METHODS

The objective of this study was to compare the water supplied to water users relative to the amount requested (i.e. assurance of supply) for two water allocation methods, PRROR and FWACS. The results that follow show the outcomes of the simulations in the Sand River Catchment using existing Water Users and their specific water demands.

The simulation of the PRROR and FWACS scenarios represented a challenge due to the nature of the two allocation methods. The PRROR method relies heavily on clearly defined rules which operate mainly through the reservoirs but also through river abstractions. The reservoirs are more easily managed due to the requirement that water demanded by various water users is documented and recorded by the reservoir operator. The river abstractions are often not documented and therefore the control of these abstractions by water authorities is difficult. The FWACS method requires a well instrumented system rather than defined rules, where all abstraction points are monitored and fed back to a control/recording centre. The reservoir operator becomes a data manager and supervisor by virtue of the integrated recording system.

The abstraction of water from the reservoir is limited by the availability of water and the curtailment operating rule as specified above. The EWR for the catchment are currently being estimated (Jackson, 2010). Hence, in this study only water specially allocated to the environment as an estimate was released from the reservoirs. The estimates were obtained from water authorities in the case study area by DHI.

The PRROR allocation scenario was simulated and used as a benchmark against which to compare the performance of the FWACS allocation method. The conditions involved in the simulation are related to the setting up and running of the scenario. The internal workings of the model and catchment conditions along with hydrological verification in the Sand River Catchment are detailed in Chapter 4.

5.1 Results for PRROR

The PRROR scenario setup involved establishing reservoir operations, priorities between water users and the minimum flow releases from reservoirs to meet EWR. The reservoir rule curves for the Sand River Catchment are not sophisticated and for several of the dams, no operating rules exist (Frezghi, 2010; Jackson, 2010). The chief requirement is that the Witklip, Primkop and Klipkopje reservoirs remain above the 40% of full supply capacity and if demand causes water to drop below the 40% level, a large restriction is applied (Frezghi, 2010). This equated to a reduction of 80% (Frezghi, 2010) for all water users when water levels in the reservoirs dropped below 40% of Full Supply Capacity (FSC) (Frezghi, 2010).

The impact on water availability made by the allocation is evident and ranges from small scale, individual water users to large scale catchment wide impacts. Initially, the impact of the individual Water User under the PRROR method was investigated and later expanded to cover the entire catchment. The catchment has water users abstracting from both rivers and reservoirs. Each of these was investigated before moving to the catchment scale. The three water users which were considered individually are labelled as Water User A and Water User B and Water User C for simplicity. Further, these water users are all irrigators. The Water User D is a node at the Sand River Catchment exit. The location of the water users is shown in. Figure 4-4.

Water User A represents demand from irrigators who have no access to a river for abstraction for this simulation. They rely solely on the Witklip reservoir for the supply of water for irrigation requirements. The water demand and the water allocated to Irrigation Water User A is shown in Figure 5-1, where it is evident that the water allocated does not meet the water demanded on several occasions.

In comparison to Figure 5-1, Figure 5-2 shows the water allocated and water deficit of the Water User A as a percent of the water demanded by the Water User. Water deficit is the water demanded but not received. As shown in Figure 5-1, Water User A on several occasions towards the end of the simulation period, does not receive the water demanded. Wherever the blue Water Demand line shows, the water demand exceeded the water supply.

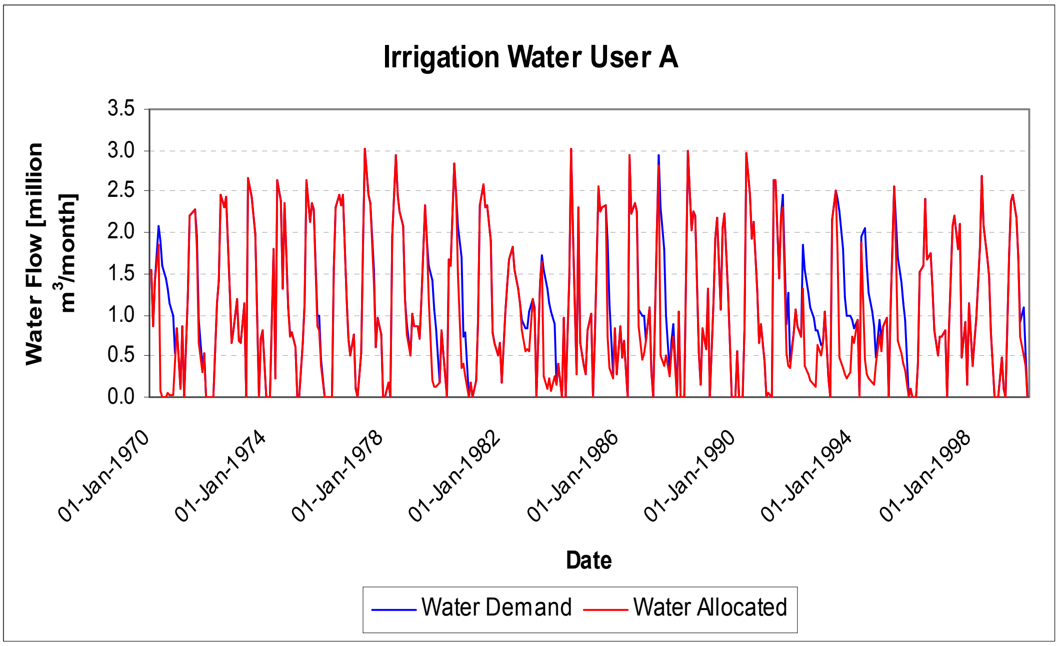

Figure 5-1 PRROR Irrigation Water User "A" water demand and the water allocated

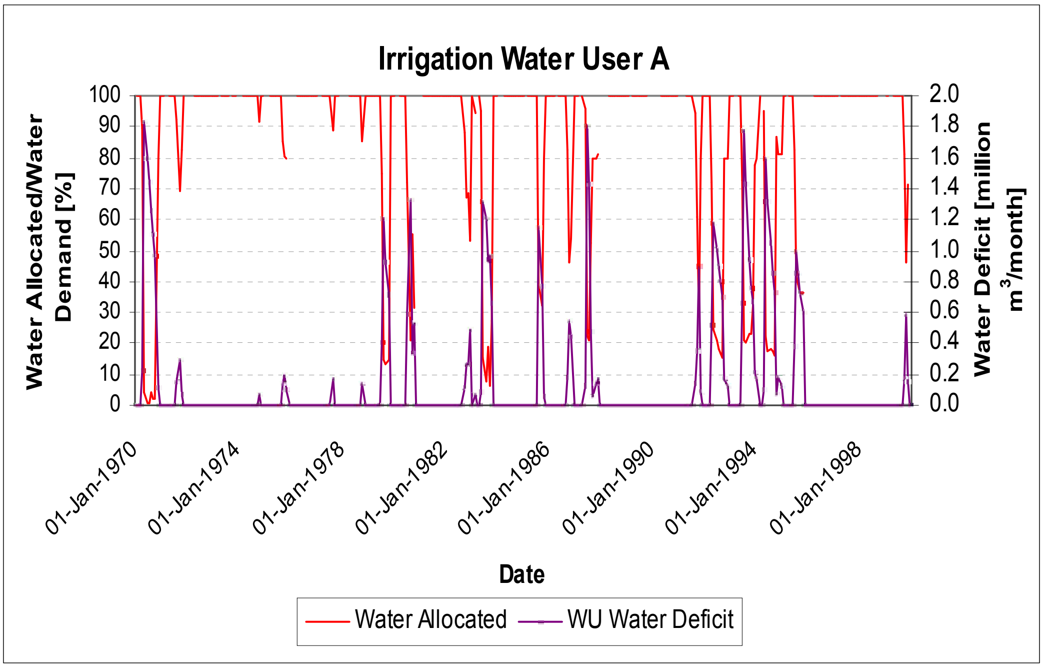

Figure 5-2 Water allocated to Irrigation Water User A as a percent of water demanded and relating water deficit of Water User

Irrigators represented by Water User B abstract water from the Primkop Reservoir. As mentioned in the literature, the PRROR allocation method has a system of reservoir rule curve restrictions for reservoirs. The Longmere Reservoir, located as shown in Figure 4-3, requires a higher level of storage and as a result imposes an 80% reduction curve when at 70% of FSC for all users (Frezghi, 2010) rather than at 40% of FSC as for the Witklip reservoir which supplies Water User A . The restrictions placed on Water Users as per the reservoir storage curves are summarised in Table 5-1 below.

Table 5-1 Summary of reservoir restriction rules

Witklip		**Primkop**		**Klipkopje**		**Longmere**	
% FSL	% Restriction	% FSL	% Restriction	% FSL	% Restriction	% FSL	% Restriction
40	80	40	80	40	80	70	80

This means that when the reservoir level drops to 70% of FSC, water users are restricted by 80%; i.e. they receive only 20% of their demand. The higher level of storage relates to the need that the reservoir should not be drawn down to below DSL through water users' activity or in meeting EWR. The operating authority of the reservoirs do not have a fixed operating rule but rather selects the value by which to restrict users based on current demands and as the situation dictates (Frezghi, 2010).

The effect of the added water security for Water User B receiving 100% of water demanded from the reservoir is evident in Figure 5-3 where the Water User B was able to receive the full amount of water demand over the simulation period. While a restriction level is implemented on the reservoir, the reservoir level does not decrease to the restriction level over the simulation period. The water security comes from the water user being linked to a large reservoir and being the only user of water from the reservoir.

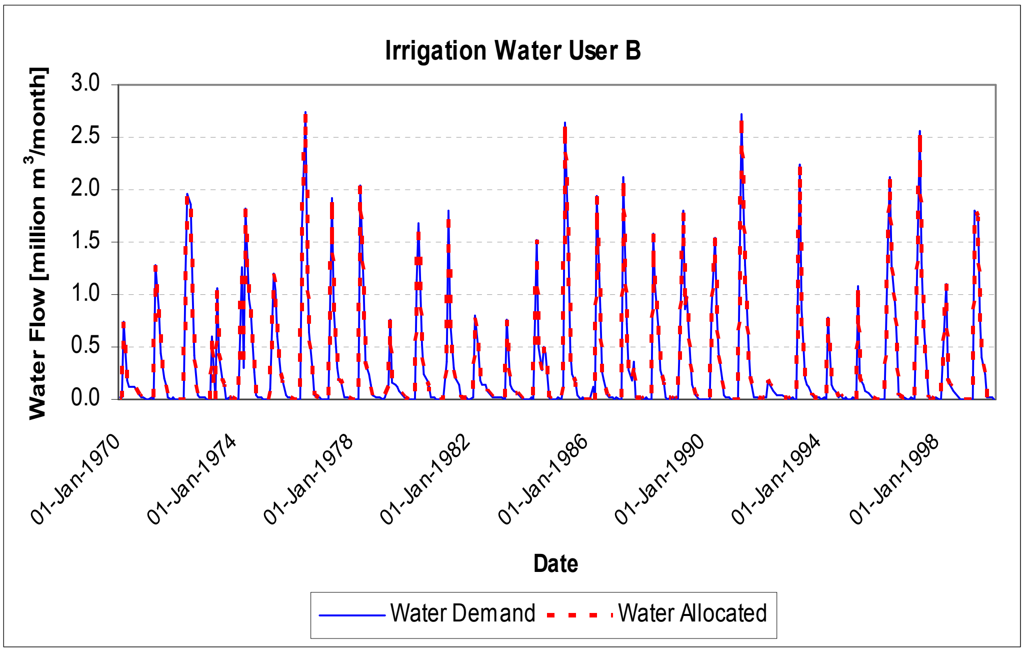

Figure 5-3 PRROR Irrigation Water User B water demand and supply

To highlight the full allocation of water to Water User B, Figure 5-4 is included showing the percentage of water abstracted as fraction of the demand from the reservoir by the Water User.

The times when water user "Water Allocated of Demand [%]" decreases to 0 in Figure 5-3, is due to the lack of water demand on the side of the Water User rather than a lack of water availability in terms of water resource.

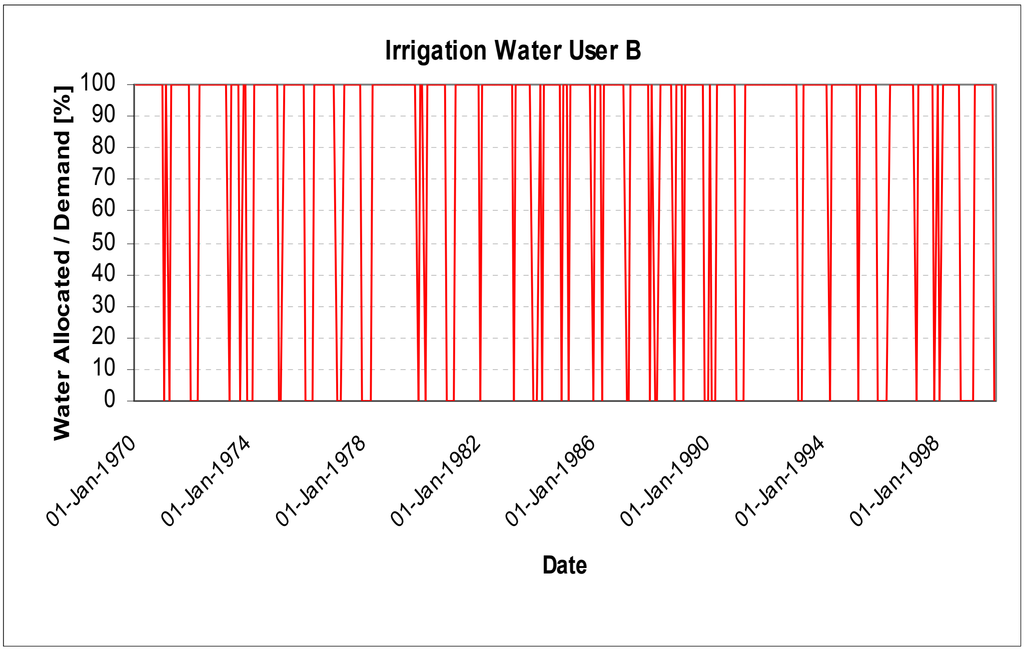

Figure 5-4 Water allocated to Irrigation Water User B in relation to water demand

Water User C abstracts water from the river but is situated at such that the abstraction is downstream of the convergence of two rivers flowing from the West. The water user and node was selected in order to investigate flow in the river after the abstraction by water users' have taken place as well as storage and the subsequent release of water by a reservoir, in this case Witklip, located as shown in Figure 4-3. The interest in the water in the river at this point arises from the concern of meeting the EWR. The flow in the river is shown in Figure 5-5 and shows the seasonality of flow in the river with large inter-annual variations. The impacts of withdrawals by upstream water users are included in Figure 5-5. The inflow to the node of interest from the West, together with the effect of a reservoir controlled release in the North provides the node with a consistent cascading flow of water, available for abstraction by the Water User.

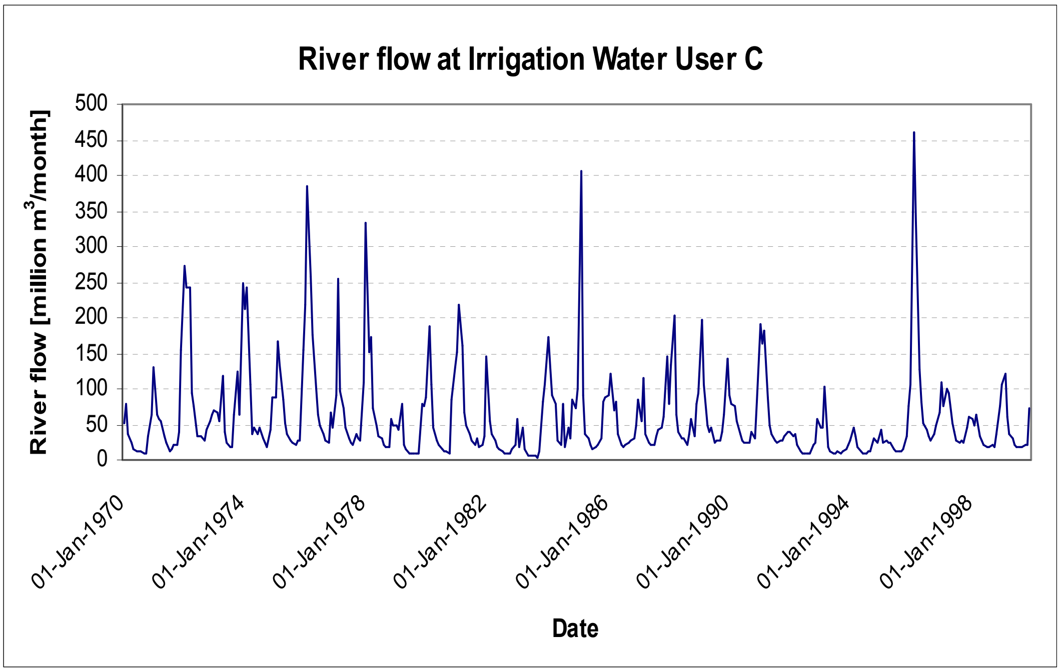

Figure 5-5 Flow at node prior to abstraction by Water User C: PRROR allocation

The effect of the convergence of two rivers at the water user provides the Water User C with a supply of water throughout the year. This is shown in Figure 5-6 where there is no instance of a water deficit for the water user over the simulation period.

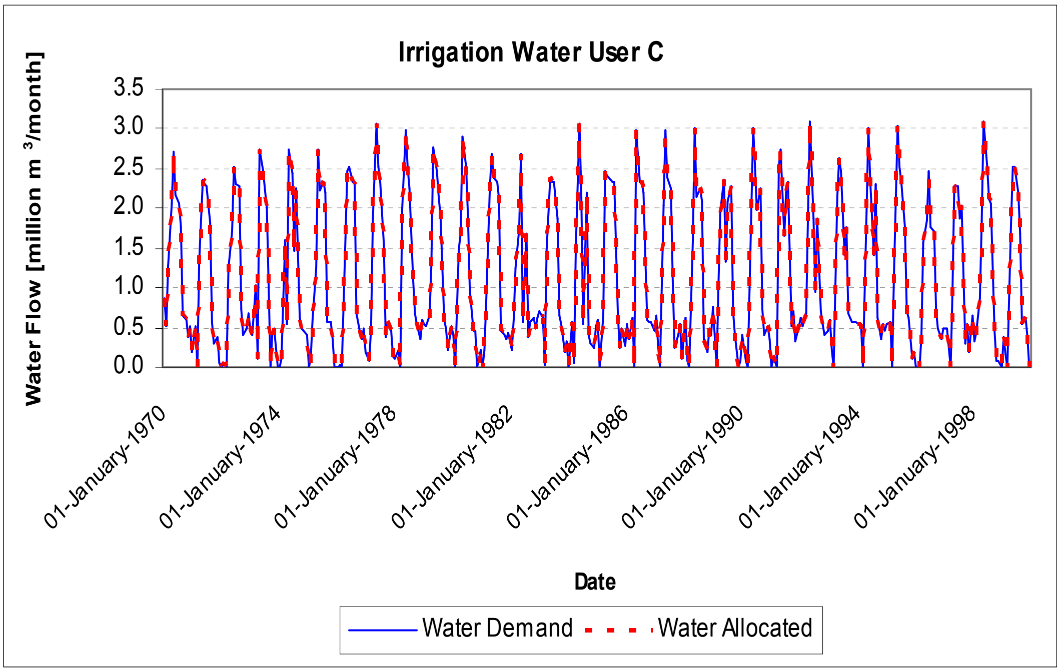

Figure 5-6 PRROR Irrigation Water User C water demand and water used

The allocation as a percentage of the water demanded is shown in Figure 5-7 and indicates that full demand was met entirely over the simulation, i.e. there was no deficit.

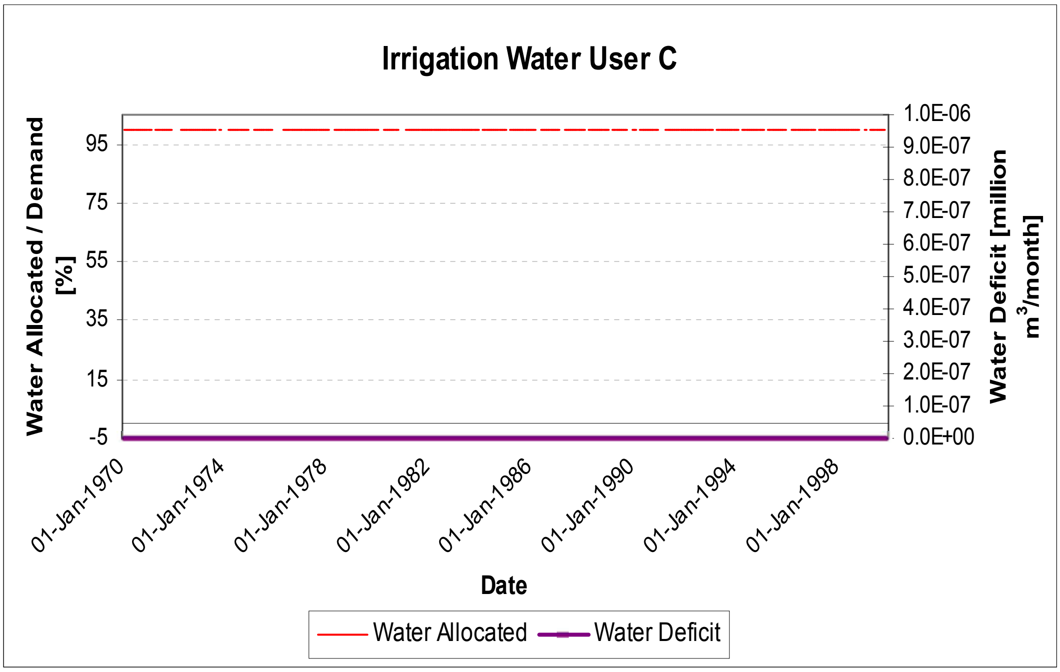

Figure 5-7 Water allocated to Irrigation Water User C in relation to water demand

The comparison and analysis of water demanded, allocated and the resulting deficit of water to each water user was undertaken for each water user in the catchment. When the entire catchment is considered, some water users may experience a deficit in water supplied while other water users, due to their location within the catchment and having access to alternate water sources, may not experience any water demand deficit. Additionally, the water users in the catchment have different water demands and having access to alternative water sources. The cascading volume of water down the catchment, towards a common exit, means that those water users situated closer to the catchment exit will potentially have a greater volume of water available to them. However, in Figure 5-8 water users in the lower catchments, who do not have access to a reservoir, do not have all their demands for water met despite being at the end of a cascading water accumulating system. The pie charts in Figure 5-8 represent the percentage of water allocated and water deficit relative to the water demanded by the water user. Water depletion must be occurring through the system and is due to abstractions by upstream users. This water availability to downstream users is dependent on equitable allocation of water to upstream users.

Over the time period of the simulation, the water allocated was totalled as well the water deficit over the simulation period. The summed value of the water allocated and water deficit will be equal to the total of the water demanded over the simulation. The EWR is not part of the representation.

The water deficit at the water users generally arise due to the lack of river flow during the low rainfall winter months (April to September) where river flow is depleted by upstream activities and recharge from lower sub-catchments is insufficient to meet the volume of water required at the abstractions points.

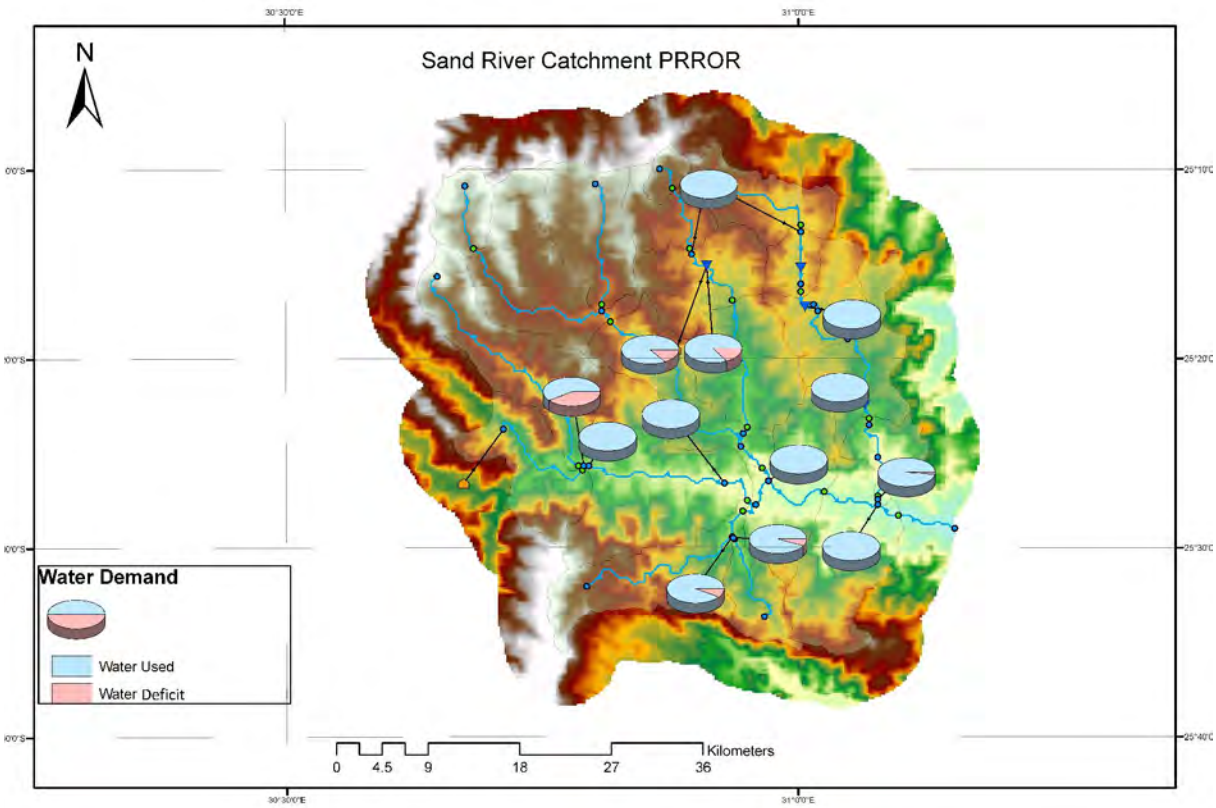

Figure 5-8 Water allocation and deficits in the Sand River Catchment under the PRROR allocation method

The overall effect of the PRROR allocation method on the water users in the catchment are summarised in Table 5-2. The values shown represent the grand total of water demanded by each Water User and the corresponding water supplied and the difference (deficit) between the demand and the supply. As can be seen, using the PRROR method, 6 out of 13 users did not experience a deficit and only 3 of the remaining water users had a deficit of more than 10%. An overall, catchment index was generated using these values in order for the two allocation methods to be compared to one another. The catchment index was generated using the water demand and water supply results for each of the Water Users in the Sand River Catchment. Water demand was summed and water supply was summed before arriving at a fraction of water supply to water demand.

Table 5-2 Individual total Water User demand and allocation over simulation period for the PRROR scenario

User	Water Demand (Total $m^3.s^{-1}$)	Water Allocated (Total $m^3.s^{-1}$)	Water Deficit (Total $m^3.s^{-1}$)	Water Deficit as percentage of Water Demand (%)
Water User 1	45.56	44.79	0.77	0.20
Water User 2 (B)	108.39	108.39	0.00	0.00
Water User 3	65.33	62.52	2.81	4.30
Water User 4	259.54	259.54	0.00	0.00
Water User 5	408.94	356.54	52.40	12.80
Water User 6 (A)	211.66	182.01	29.65	14.00
Water User 7 (C)	389.26	389.26	0.00	0.00
Water User 8	31.98	30.16	1.82	5.60
Water User 9	82.02	75.85	6.17	7.50
Water User 10	83.67	48.50	35.16	42.00
Water User 11	95.75	95.75	0.00	0.00
Water User 12	180.84	180.84	0.00	0.00
Water User 13	27.83	27.83	0.00	0.00
Sum	1990.77	1861.98	128.78	6.50

Note: Here and elsewhere in the document, Water User 2 (B) represents Water User B in the modelling. Likewise, Water User 6 (A) represents Water User A and Water User 7 (C), represents Water User C. As Node D is a catchment exit and is thus not included in the Table.

The flow at the case study catchment exit, Node D in Figure 4-4, where the river flow leaves the catchment, is shown in Figure 5-9. The flow at the Sand River Catchment exit (Node D) closely resembles the flow at Water User C. Seasonal peaks and troughs are present and the inter-seasonal variability is evident. Large magnitude events are evident, similar to Figure 5-5. The high concentration of water users relying solely on river flow for water demand leads to large abstractions taking place from the river between Water User C and Node D. The impact of the abstractions is shown in Figure 5-10, where Node D experiences a reduced winter period (April – September) low flow, in comparison to the same period at Water User C.

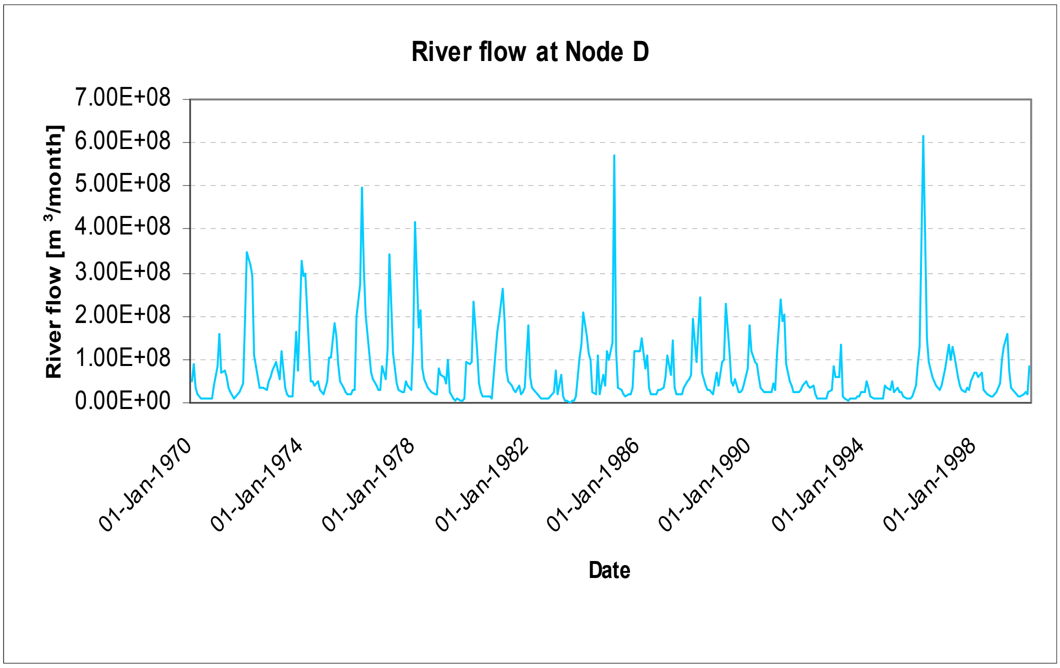

Figure 5-9 Catchment exit node D river flow PRROR

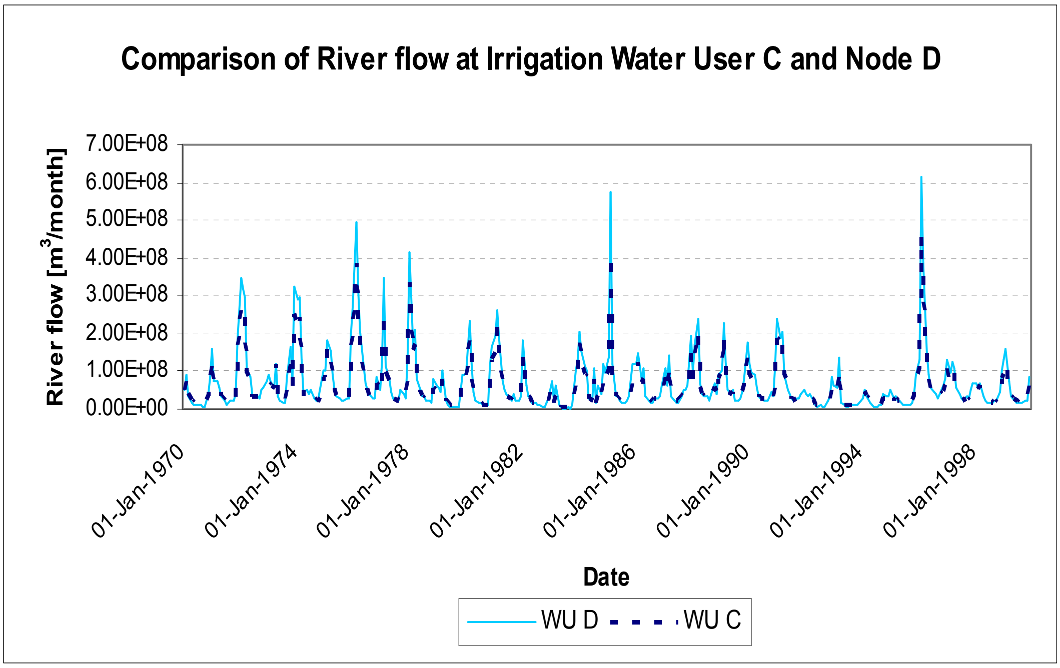

Figure 5-10 River flow at Irrigation Water User C and Node D

5.2 Fractional Water Allocation and Capacity Sharing

The operation of the FWACS method has been described in Chapter 4. The underlying concept of the method promotes the efficient use of water by individual Water Users.

Operationally, the FWACS allocation method will require greater effort for both reservoir management as well as the management of Water User abstractions from rivers compared to the current PRROR method used in the catchment. Currently, under PRROR, river abstractions are self-monitored by the user based on the allocation in the users Water Use Licence (WUL). The water user may be audited for compliance to their WUL. FWACS will require regular telemetry to a centrally accessed/managed database to inform water users of current flow conditions for abstraction purposes. This means that regardless of the environmental conditions present (drought or flood), the FWACS allocation method, requires more data (e.g. abstraction volumes) than the PRROR method. This data often requires specialised equipment (e.g. a flow meter) which not all water users will necessarily have or be willing to install. Both the FWA and CS fractions were determined from the PRROR allocation results. The simulated reservoir levels under PRROR were interrogated to establish a level which would provide water for the water users. This was also done under FWA by observing the streamflow under PRROR and then applying similar levels and fractions to FWA. As PRROR WU's have unrestricted abstraction on a river, the FWA was set to 1, indicating no restriction on abstraction. The CS was calculated by summing the water demand shown by the WU and then estimating a fraction of the total reservoir based on these results. By having a mirroring of the two allocation methods, the aim was to observe whether the FWACS would be able to supply water in quantities and reliance similar to that achieved with the PRROR allocation method. This rationale was applied in setting up the CS capacity in Table 5-3. Additionally, the sensitivity of the FWACS model was tested by modifying the fractions allocated and observing how frequently a deficit occurred and how large the deficit was. The allocation deficit experienced by the Water User is an indicator of reliability of the allocation method.

Under FWA, EWR may be accounted for by limiting abstractions by water users by implementing a monitoring system which monitors flow above a group of water users and "subtracts" water for EWR before allocating water to users. In this study for water users abstracting from a river, the FWACS scenario was configured to allow water users to abstract 100% of the river flow if required to be consistent with the configuration for the PRROR scenario.

This was done in order to be able to compare the two scenarios. However, with the lack of EWR data in the PRROR scenario, it was not possible to compare the EWR allocation under

PRROR to a fractional allocation under FWA in order to simulate the flows. The PRROR results, however, lent themselves to defining a percent for the FWA component. The reservoir capacities and reservoir inflows were configured for the reservoir to include EWR and the water users, with each allocation fraction shown in Table 5-3. Unlike with the FWA component, the CS and the subsequent simulation of the FWACS by MB allows for the creation and maintenance of an EWR segment. This allows for minimum flow release at predefined locations, downstream of the reservoir. In the case of river reach abstractions, water users were allocated 100 % in line with that of PRROR scenario allocation.

In using MB to simulate the operation of the FWACS allocation method, an unallocated pool of water had to be created so that the model would make provision for EWR. Delivery of water to meet EWR under FWACS in MB does not take place from a defined user pool. Rather, the allocation is made from an unallocated pool. The unallocated pool can be predetermined to include the portion for EWR that cannot be used by other water users. The sensitivity of the results is dependant on the demands placed on the unallocated pool i.e. if the demand on the unallocated pool is small, the change in supply to the end users will be minimal. Thus the unallocated pool is a characteristic of MB rather than a limitation of FWACS. MIKE BASIN cannot keep track of the unallocated pool spatially but it is able to visualise it with reference to time. In the present model, this virtual storage volume is representative of the EWR. It does not provide provision for errors in calculations of the CS.

Table 5-3 Allocation of inflow and capacity to water users for FWACS allocation scenario

Reservoir Name	**Reservoir Allocation**	
	Inflow Allocation	**Capacity Allocation**
Witklip	Water User 5 = 50% Water User 6 (A) = 35% EWR = 15%	Water User 5 (A) = 50% Water User 6 = 35% EWR = 15%
Primkop	Water User 2 (B) = 45% EWR = 55%	Water User 2 (B) = 45% EWR = 55%
Longmere	Water User 1 = 30% EWR = 70%	Water User 1 = 30% EWR = 70%
Klipkopje	EWR = 100%	EWR = 100%

Water demand and allocation under FWACS for Water User A is shown in Figure 5-11 and can be compared to Figure 5-1 for the PRROR method.

As shown in Figure 5-11, the water allocated frequently does not meet the water demand during peak demand periods for Irrigation Water User A. This is a similar result to the PRROR method. In Figure 5-11 the Water Demand line is visible indicating that water demand exceeds supply.

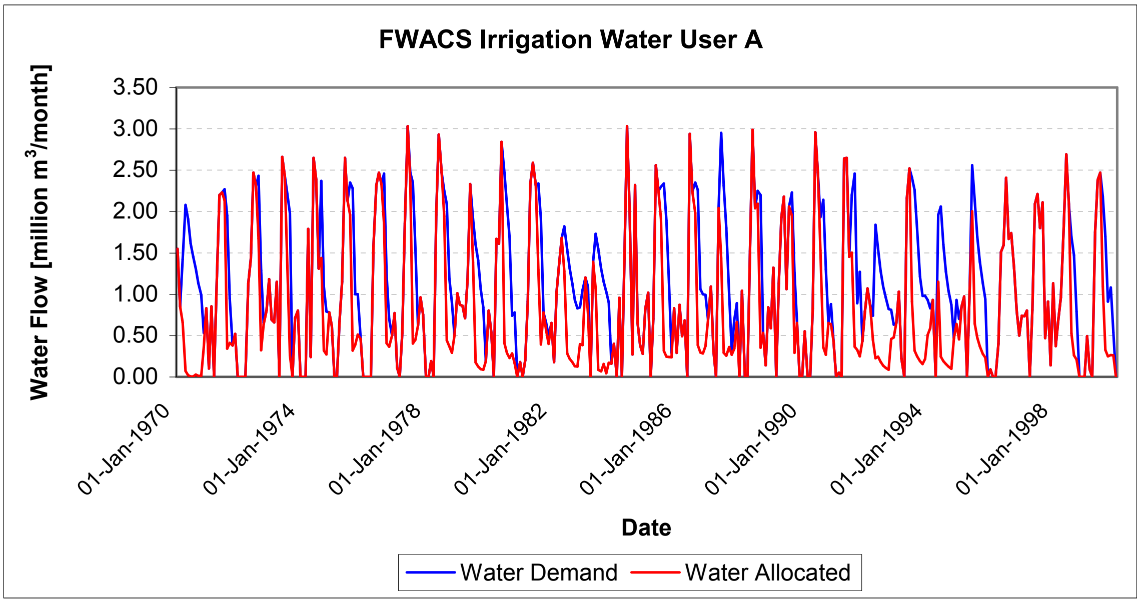

Figure 5-11 Water demand and allocation for Irrigation Water User A under FWACS

The FWACS Irrigation Water User A graph is characterised by peaks in water deficit as shown in Figure 5-12. Records indicate that there is seasonal variation in water demands. These variations are incorporated into both scenarios. However, unlike PRROR the FWACS method indicates when demand is higher i.e. in the summer months due to crop irrigation requirements. The winter months show little water demand deficit due to decreased irrigation demand as seen from the water demand information used in the simulation process.

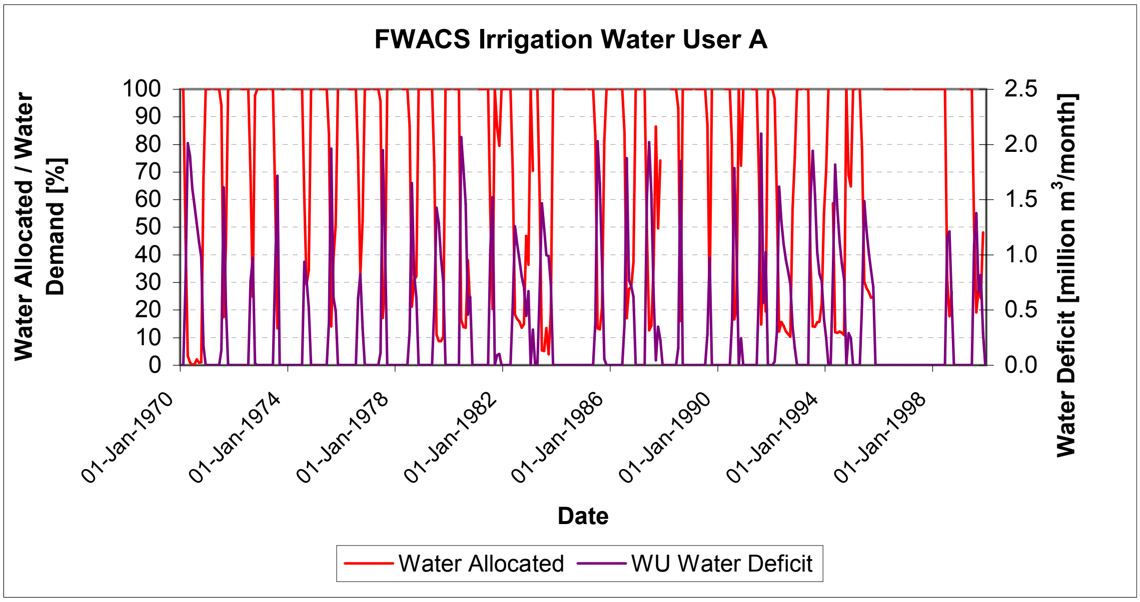

Figure 5-12 Water demand deficit for Water User A in relation to water demanded

The water allocated and water deficit total of the simulation period shown in Figure 5-11 has been changed to percentage of water allocated based on water demand and the resulting water deficit, as shown in Figure 5-12. The water allocated peaks are correlated with peaks in water demand, but supply limitations result in water deficits. The reductions in water allocated are demonstrated in Figure 5-12 which shows the water deficit volumes for Water User A over the simulation period. The rise and fall of the deficit is seen as steep (seasonal), indicating a sudden rather than prolonged water shortfall.

In order to meet water demand as prescribed by the Water User, abstractions are made on the water resource, Witklip reservoir. The abstractions and their effect on the reservoir level are shown in Figure 5-13. Peak water abstractions occur when the reservoir is fuller, indicating a seasonal demand and then a recovery period. The effect on the Water User's Capacity Sharing in Witklip is shown in Figure 5-14 where the Water User pool is represented as a percentage, relative to maximum or full pool capacity. As this Figure 5-14 indicates, using the FWACS method, there are periods where there is abstraction even though the Water User pool is empty. This indicates that the Water User is using reservoir inflow directly.

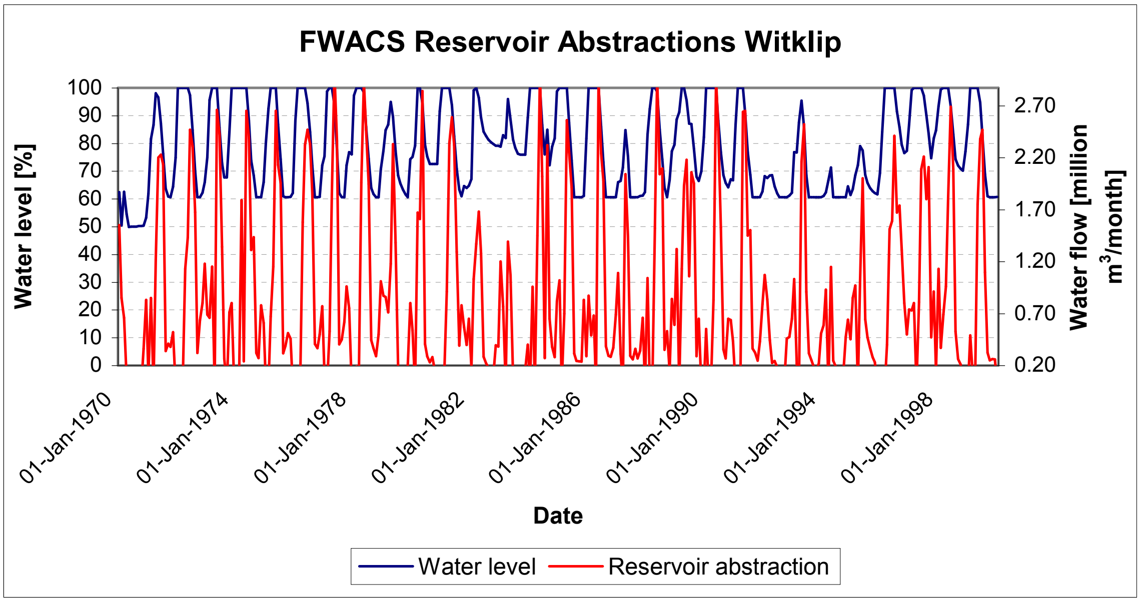

Figure 5-13 FWACS Irrigation Water User A reservoir abstractions and reservoir water level

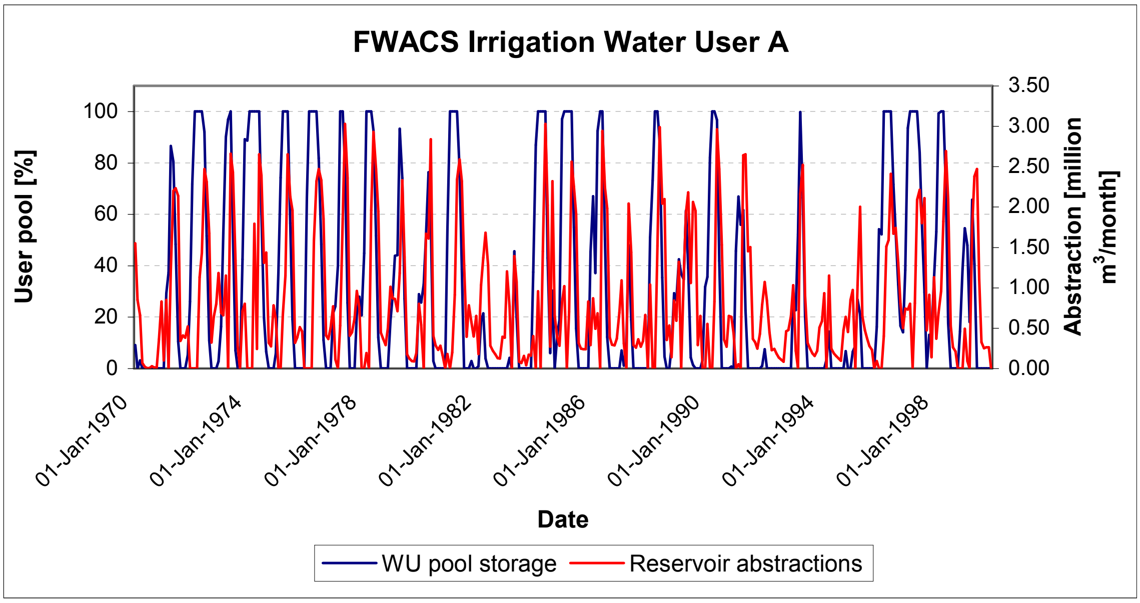

Figure 5-14 FWACS Irrigation Water User A reservoir pool and abstractions

Under the FWACS scenario, Irrigation Water User B has access to a reservoir as a means of water supply. The Irrigation Water User B was allocated 45% of the dam FSC and the remaining 55% was allocated to EWR to fulfil minimum releases scheduled from the reservoir. The water used in relation to water demanded is shown in Figure 5-15, where the full volume of water demanded is supplied to the Water User and can be compared to Figure 5-3 for the same user under the PRROR method. The FWACS Water User B water flow (water allocated) is very similar to the PRROR Water User B water flow.

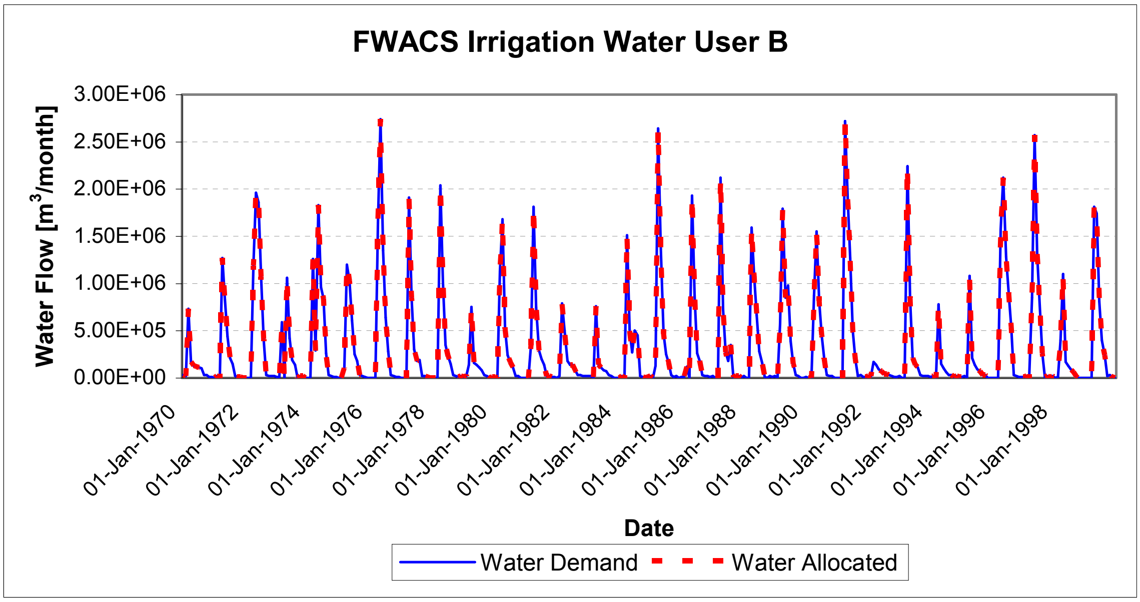

Figure 5-15 FWACS Irrigation Water User B water demand and water used

The Water User at B receives the full quantity of water demanded. The source of the water which is used to meet the demand can be investigated by observing the frequency with which water is abstracted from the reservoir to which the Water User is connected. The reservoir from which the Water User abstracts water is the Primkop reservoir and abstractions are shown in Figure 5-16. As indicated by Figure 5-15, water demand does not exceed water allocation for the Water User.

The more important aspect for the FWACS allocation method is the effect of reservoir abstractions on the Water User's pool. If this volume is depleted, the Water User does not have access to water even though the reservoir may be above 40% of FSC as explained in the model assumptions of FWACS method. The Water User's reservoir allocation restriction levels are implemented at this level, limiting Water User abstraction to reservoir CS recharge rate and not impacting on overall reservoir level and water availability for other water users.

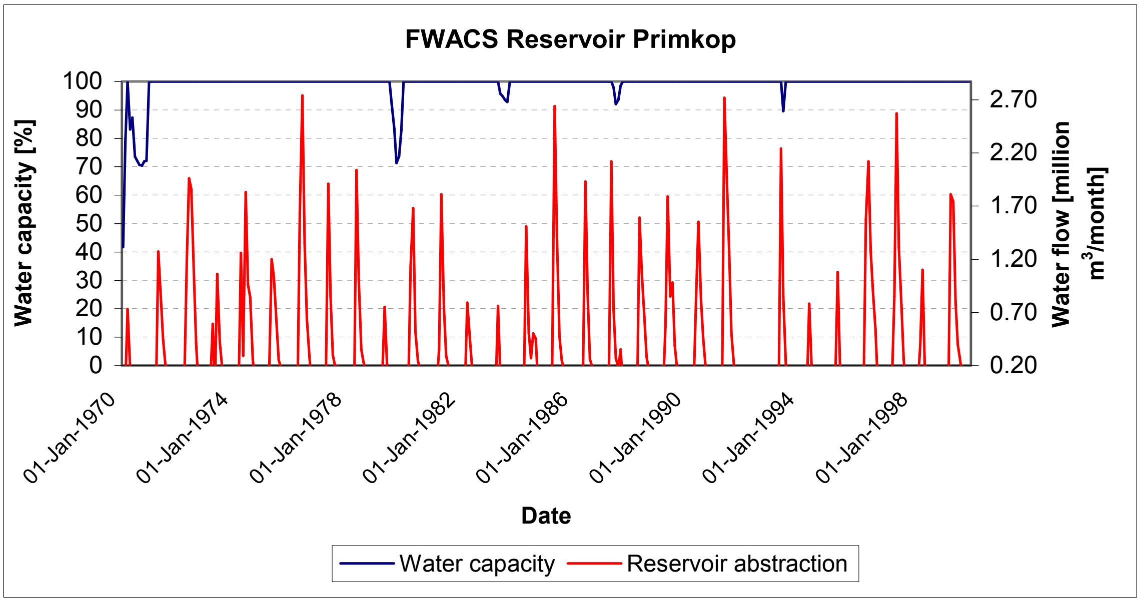

Figure 5-16 FWACS Irrigation Water User B reservoir abstractions and reservoir water level

The reservoir abstractions to meet water demand and the effect on the Water User reservoir store are shown in Figure 5-17.

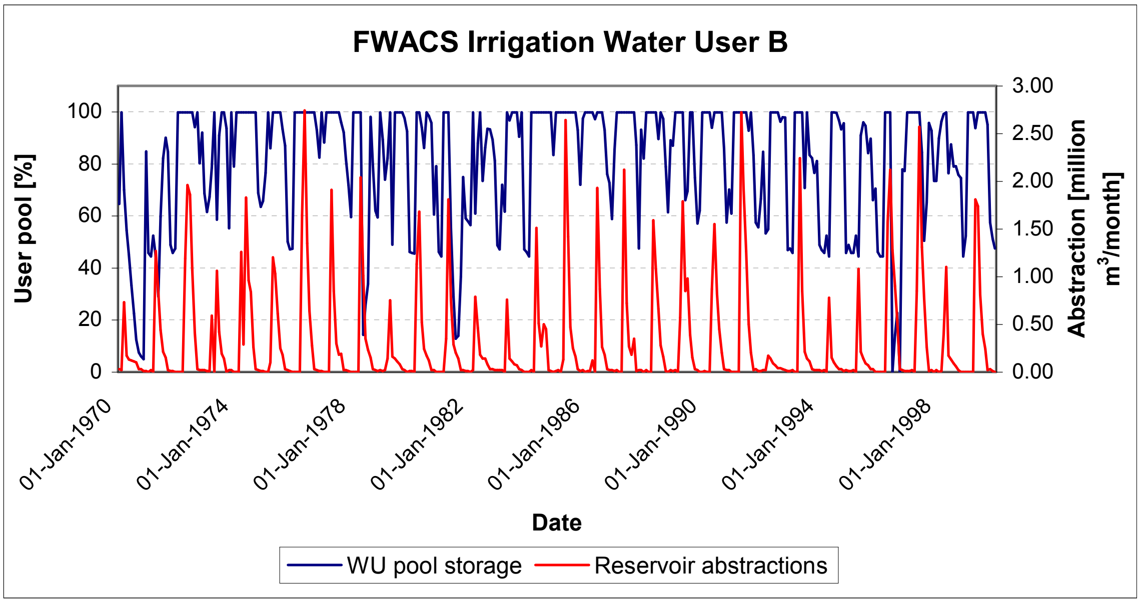

Figure 5-17 FWACS Irrigation Water User B reservoir pool and abstractions

The impact of the allocation method in making water available through efficient water management practises needs to be determined through a comparison of the river flow at Node C, which is the abstraction point for Water User C, for both the PRROR and FWACS allocations methods. The water demand and water used by Water User C is shown in Figure

5-18 for the period simulated. The comparable PRROR simulation result can be found in Figure 5-6.

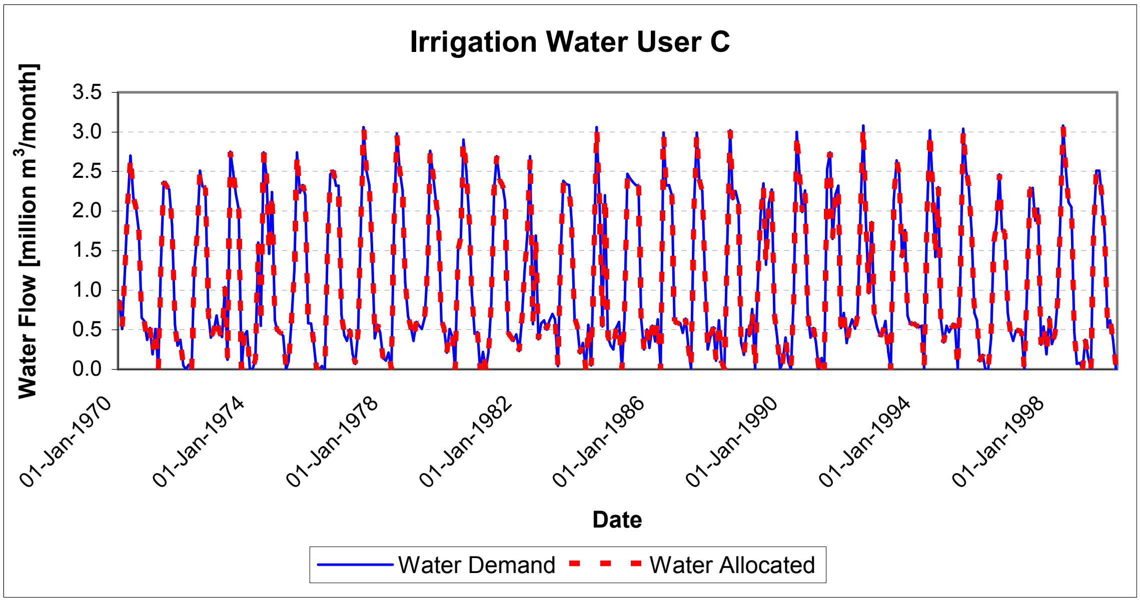

Figure 5-18 FWACS Irrigation Water User C water demand and water used

The total volume of water after allocation to Water User's under the FWACS method is shown in Figure 5-19. The equivalent result for the PRROR method is shown in Figure 5-9. This Figure represents the outflow of water from the study catchment and thus forms the inflow to downstream water users' not considered in the study. Differences between the PRROR method and FWACS method are discussed in Section 0.

The results for the FWACS method are summarised in Figure 5-20 with the equivalent PRROR method Figure 5-8, and also in Table 5-4. Under the FWACS method, as with PRROR, 6 out of 13 users received the water they demanded with 7 users experiencing a water deficit. Of these, 2 WU's had a deficit greater than 10%. However, the average deficit was 9.5% (in comparison to an average deficit of 6.5% under PRROR).

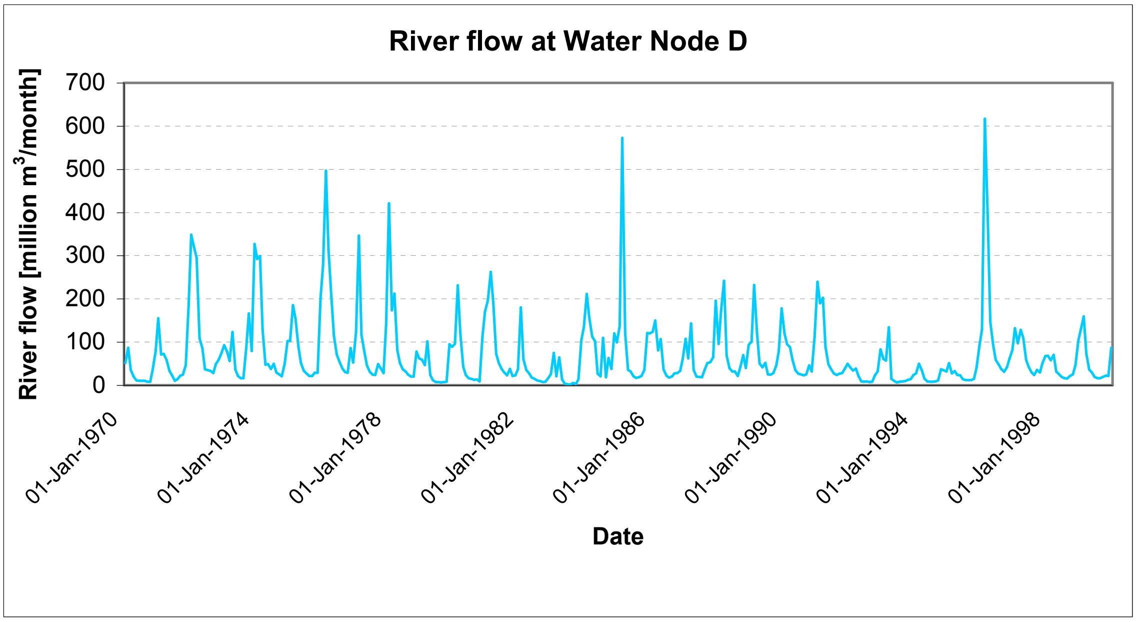

Figure 5-19 Catchment exit Node D river flow

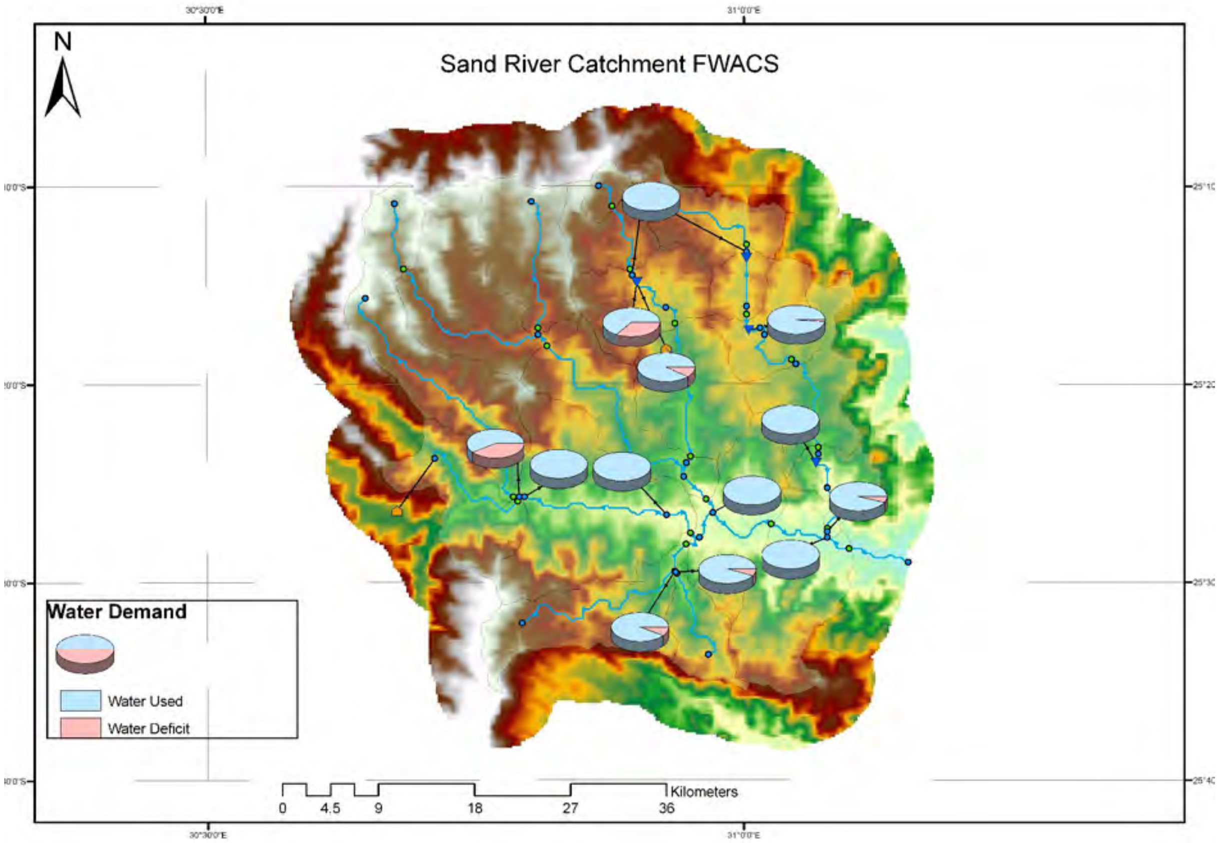

Figure 5-20 Sand River Catchment under FWACS allocation method

Table 5-4 Individual total Water User demand and allocation over simulation period for the FWACS scenario

Water User	**Water Demand** (Total 10^6 m^3)	**Water Received** (Total 10^6 m^3)	**Water Deficit** (Total 10^6 m^3)	**Water Deficit as percentage of Water Demand (%)**
Water User 1	45.56	45.47	0.10	0.20
Water User 2 (B)	108.39	108.39	0.00	0.00
Water User 3	65.33	61.98	3.35	5.20
Water User 4	259.54	259.54	0.00	0.00
Water User 5	408.94	289.82	119.12	29.10
Water User 6 (A)	211.66	191.17	20.49	9.70
Water User 7 (C)	389.26	389.26	0.00	0.00
Water User 8	31.98	30.16	1.82	5.70
Water User 9	82.02	75.85	6.17	7.50
Water User 10	83.67	48.50	35.16	42.00
Water User 11	95.75	95.75	0.00	0.00
Water User 12	180.84	180.84	0.00	0.00
Water User 13	27.83	27.83	0.00	0.00
Sum	1990.77	1804.56	186.34	9.40

5.3 Comparison of FWACS and PRROR

A comparison between the two allocation methods was performed in order to evaluate their effect on the general water users and international downstream obligations. Water Users were assigned certain fractions and streamflows, based on current PRROR allocations, which resulted in limitations as to how water demands were met. Though different set of fractions and capacity shares could have been assigned, which would have resulted in different allocations, assurance levels and water levels in the rivers and dams, the fractions allocated were specifically done to match the current allocation methods. This is illustrated by Figure 5-21 which is specifically for Water User C, where, in order to show the affect, the time scale has been shortened to cover two years, 1981 to 1982. Water User C was selected due to its central position in the catchment, i.e. it is far enough down the catchment to be affected by Water Users' located above it while low enough to affect downstream Water Users'. The results indicate that the two methods provide essentially the same outcome with regard to river flow.

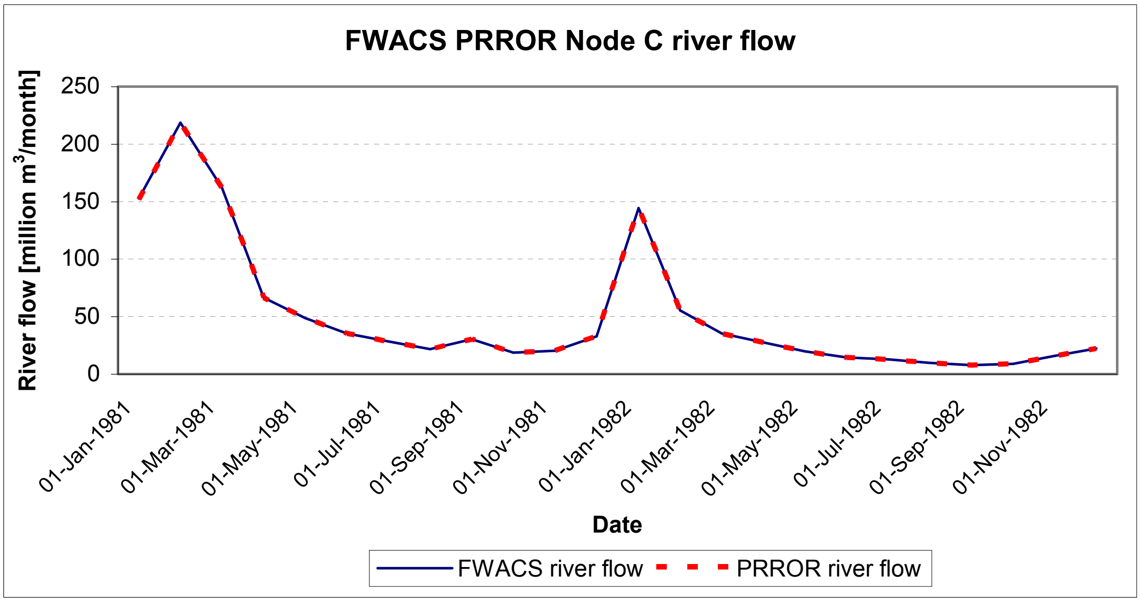

Figure 5-21 River flow for PRROR and FWACS at Node C for two year comparison period

The minimum flow rules with the FWACS method prevent the abstraction of water from the river by firstly forcing a required volume of water to be present at the node and then back calculating and allocating when surplus water is available in the reach.

The relationship between water supply and water deficit is shown in Figure 5-8 for PRROR and Figure 5-20 for FWACS. Although both methods supply water reliably (in both simulations, 6 users did not experience deficits), the deficit was generally greater under FWACS. In Table 5-5, all Water User's in the catchment are considered for PRROR and FWACS and the water demanded as well as the water received and the resulting deficits are summarised.

Table 5-5 Individual average Water User use over simulation period for the FWACS scenario

Water User	Water Demand (Total 10^6 m^3)	FWACS			PRROR		
		Water Received (Total 10^6 m^3)	Water Deficit (Total 10^6 m^3)	Water Deficit as percentage of Water Demand (%)	Water Received (Total 10^6 m^3)	Water Deficit (Total 10^6 m^3)	Water Deficit as percentage of Water Demand (%)
Water User 1	45.56	45.47	0.10	0.20	44.79	0.77	0.20
Water User 2 (B)	108.39	108.39	0.00	0.00	108.39	0.00	0.00
Water User 3	65.33	61.98	3.35	5.20	62.52	2.81	4.30
Water User 4	259.54	259.54	0.00	0.00	259.54	0.00	0.00
Water User 5	408.94	289.82	119.12	29.10	356.54	52.40	12.80
Water User 6 (A)	211.66	191.17	20.49	9.70	182.01	29.65	14.00
Water User 7 (C)	389.26	389.26	0.00	0.00	389.26	0.00	0.00
Water User 8	31.98	30.16	1.82	5.70	30.16	1.82	5.60
Water User 9	82.02	75.85	6.17	7.50	75.85	6.17	7.50
Water User 10	83.67	48.50	35.16	42.00	48.50	35.16	42.00
Water User 11	95.75	95.75	0.00	0.00	95.75	0.00	0.00
Water User 12	180.84	180.84	0.00	0.00	180.84	0.00	0.00
Water User 13	27.83	27.83	0.00	0.00	27.83	0.00	0.00
Sum	1990.77	1804.56	186.34	9.4	1861.98	128.78	6.5

The results in Table 5-5 , shows that the Water User who experiences the greatest water deficit is Water User 5 under FWACS, yet Water User 10 experiences the highest percentage deficit. The ability of the reservoir to meet water demand is in question due to the trend observed in Figure 5-14, which indicates that there are periods where abstraction is needed although the Water User's pool is empty. The intricacy of FWACS means that to ensure a greater supply of water to the Water User, either the other Water User attached to the reservoir needs to transfer some of their share of the reservoir or the flow assigned as a remote inflow needs to be decreased. The two above mentioned users could together relinquish a share to ensure that the Water User A (6) receives a greater allocation. A comparison of allocation between PRROR and FWACS for Water User A is shown in Figure 5-22 below, followed by a frequency analysis, Figure 5-23 which shows that under lower non-exceedance, FWACS supplies some water compared to the PRROR which does not supply water 10% of the time. However, the PRROR scenario provides greater assurance of supply above the 20 non-exceedance percentile.

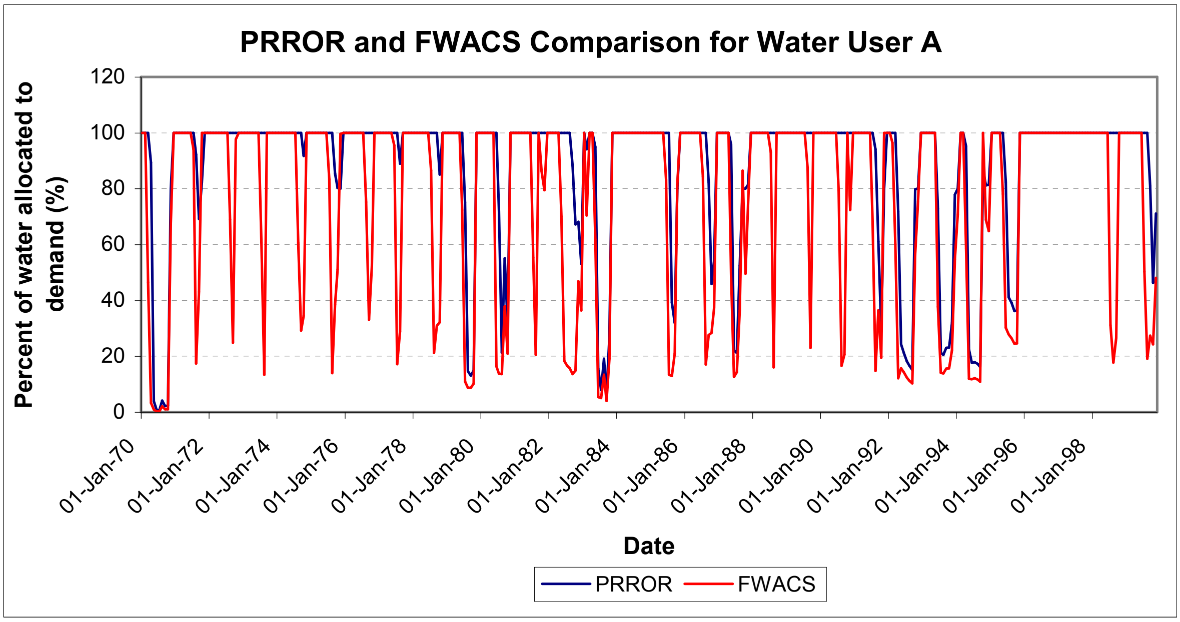

Figure 5-22 A comparison of water allocated in relation to demand between the PRROR and FWACS methods for Water User A

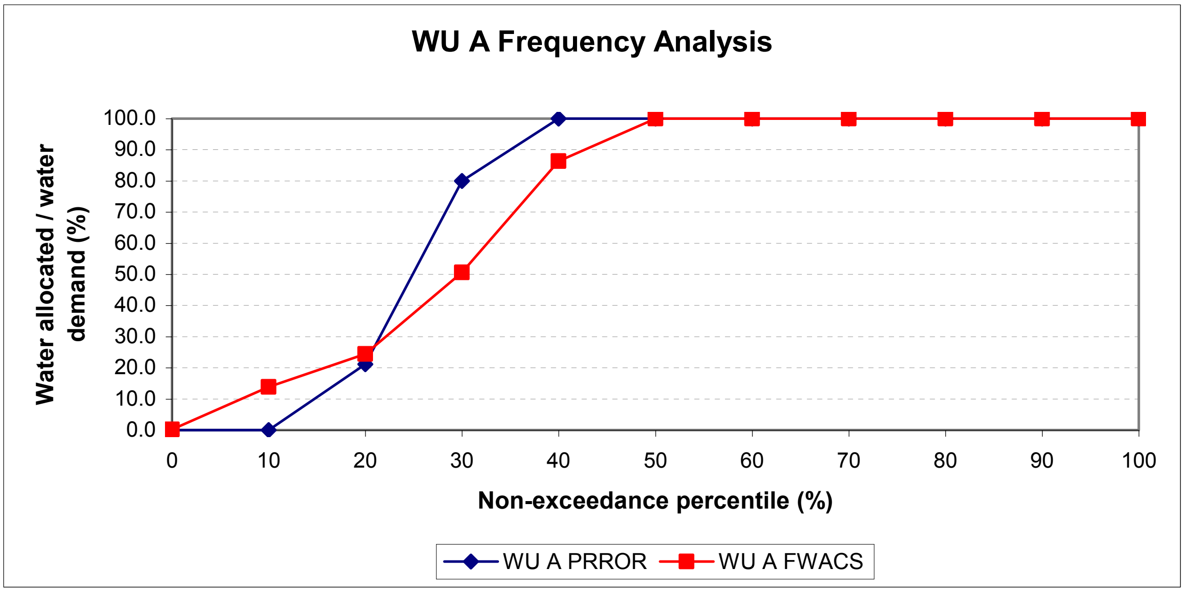

Figure 5-23 Water User A frequency analysis for PRROR and FWACS simulations

The overall effect on each of the water users for the two allocation methods is shown in Figure 5-24. The water demand by the water users is included in order to represent the ability of the allocation method to meet the demand placed on the water resource. The results show that Water Users 1 to 4 achieve similar water reliability under the two allocations methods. However Water User 5 fairs better under the PRROR method whereas Water User 6 demands are better matched under the FWACS method. The structures in place regarding reservoir function i.e. reservoir rule curves, are the main reason for the difference in water supplied to the water users. This means that under PRROR, water users are restricted based on their assurance of supply and the reservoir level whereas under FWACS, users are self-governed as they control how they use the capacity share allocated to them.

The trend seen with the first 4 water users is matched for the remaining water users, where they achieve similar reliability in terms of water supply. The increased reliability supply of water for the PRROR allocation method shown in Figure 5-24, however, is achieved at the cost of a decreased water volume in the river reaches. This is confirmed by the FWACS scenario having a net gain in water at Node D of 7.31×10^7 m^3. However this is negligible as this is over the entire study period of 30 years, i.e. 2.4 million m^3/year on average, as indicated by Figure 5-25.

The river flow from the Sand River Catchment is compared at the Nodes C and D. The flow is expected to increase as a result of runoff contribution by the lower sub-catchments. Under PRROR, the lower water users were able to abstract water when water was present in the reach. With the implementation of minimum remote flow requirements in the FWACS allocation method, the downstream Water Users under FWA are expected to be able to meet water demand more regularly in comparison to the PRROR allocation method.

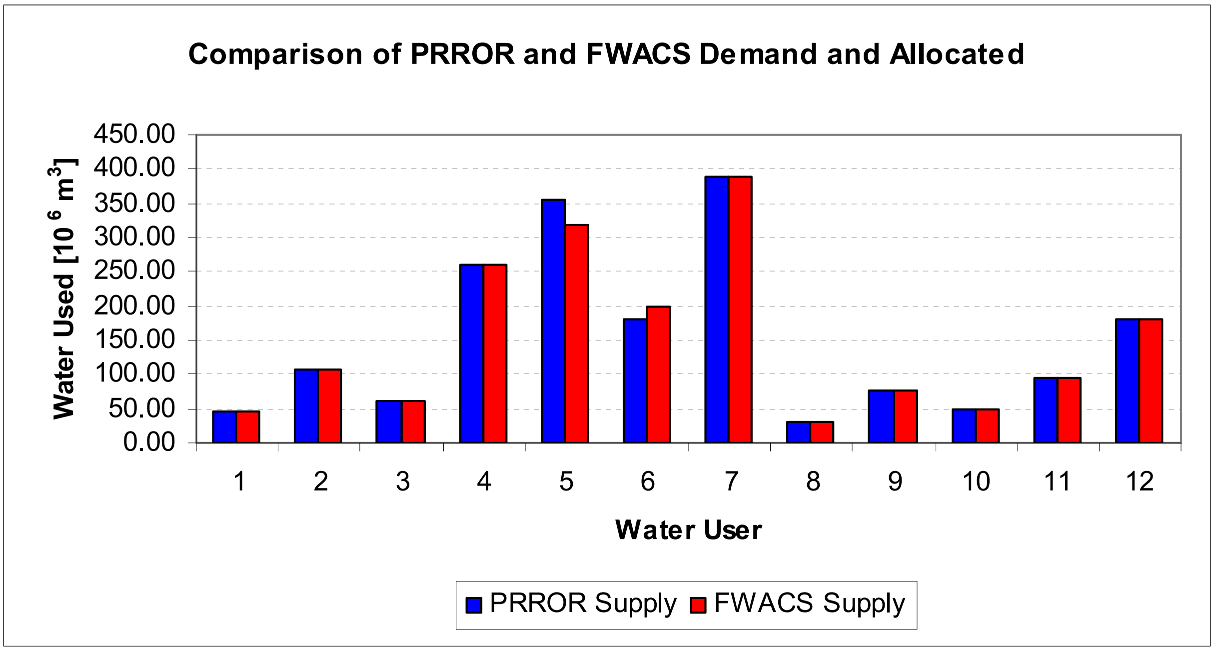

Figure 5-24 Comparison of PRROR and FWACS water demanded and allocated

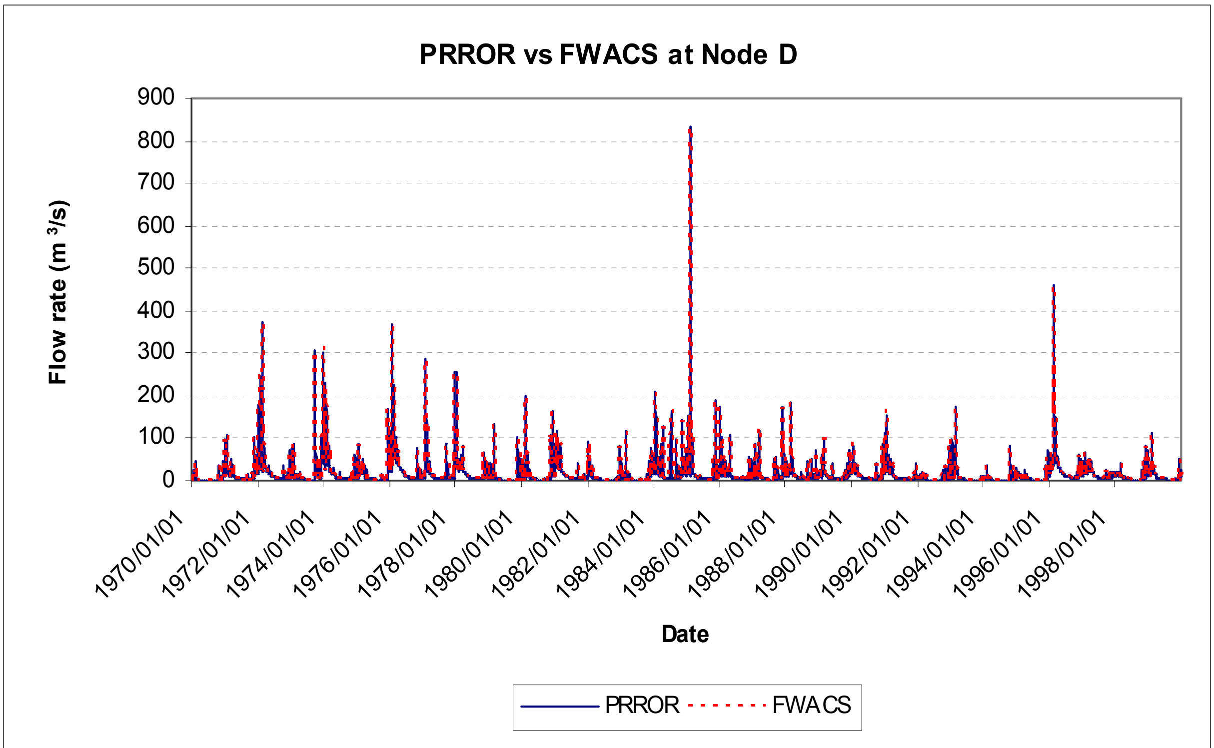

Figure 5-25 Comparison of river flow rate at Node D between the PRROR and FWACS methods over the 30 year study period

The effect on the catchment as a whole by the allocation method is described using an index. The index is calculated as the ratio of the sum of the water allocated divided by the sum of water demanded. Thus the closer the value is to 1, the more water demanded matches water allocated. Under the PRROR allocation method the index is 0.93 (1834.15 water used/1962.94 water demand) and is 0.91 (1776.59 water used/1962.94 water demand) for the FWACS allocation method i.e. PRROR allocated water more closely to demand than FWACS did. The accumulated net flow leaving the Sand River Catchment was used to assess the river flow for the two allocation methods, as indicated above in Figure 5-25. Further for the reservoirs, an averaged storage was used over the simulation period to determine the average stored volume within each of the reservoirs, shown in Table 5-6. If, on average, the reservoir storages are lower under FWACS than under PRROR, it implies that releases from FWACS are greater than under PRROR. The releases are likely to be used by the downstream water users.

Table 5-6 Reservoir storage difference between PRROR and FWACS scenario

	PRROR Reservoir Storage [10^6 m^3]	FWACS Reservoir Storage [10^6 m^3]	Reservoir difference [%]
Reservoir			
Witklip	5.56	7.63	27.16
Klipkopje	11.50	11.49	-0.11
Longmere	4.16	4.32	3.61
Primkop	1.92	1.92	0.01

The large gain made in the storage of water in the Witklip reservoir comes at the cost of water supply to downstream users, when compared to the water allocation achieved under PRROR. The remaining differences between the two allocation methods is less than 3% which indicates that the combined water abstraction from reservoirs by water users and releases, is closely matched between the allocation methods, using different controls.

5.4 Sensitivity of Fractions used in FWACS

Descriptive statistics on the water allocated and water deficit were calculated. Data were also analysed for normality. As the data was all not normally distributed regardless of transformations, the non-parametric Kruskal-Wallis test was performed with multiple comparisons used to determine differences between the models (PRROR, FWACS, FWACS +10%, FWACS+20%, FWACS+50%, FWACS-10%, FWACS-20% and FWACS-50%). These comparisons are further detailed in Table 5-7. These percentage changes were selected as they represented a realistic change to WU allocation and at the far ends, represented a 100% range across the original value.

Table 5-7 Sensitivity analysis comparison

Criteria	Description
PRROR	Original PRROR reservoir rule curves and streamflow allocation as reported in the results above.
FWACS	Original FWACS allocations regarding FWA and CS.
FWACS +10%	The CS portion of each of the WU's investigated above was increased by 10%. This was done for the reservoir inflow as well as the portion held of the reservoir.
FWACS +20%	The CS portion of each of the WU's investigated above was increased by 20%. This was done for the reservoir inflow as well as the portion held of the reservoir.
FWACS +50%	The CS portion of each of the WU's investigated above was increased by 50%. This was done for the reservoir inflow as well as the portion held of the reservoir.
FWACS -10%	The CS portion of each of the WU's investigated above was decreased by 10%. This was done for the reservoir inflow as well as the portion held of the reservoir.
FWACS -20%	The CS portion of each of the WU's investigated above was decreased by 20%. This was done for the reservoir inflow as well as the portion held of the reservoir.
FWACS -50%	The CS portion of each of the WU's investigated above was decreased by 50%. This was done for the reservoir inflow as well as the portion held of the reservoir.

The descriptive statistics indicated no differences in water allocated / demand between models for Water User B and Water User C, only data for Water User A was investigated further. This is most likely as Water User A shares the reservoir with another water user. This leads to a situation where an increase in water allocation to the one Water User, results in a decrease in the water allocation to the other Water User. Water User B has sole access to a reservoir.

Statistics indicated that the water allocated by PRROR and FWACS was significantly different for Water User A ($H_{7;2880} = 47.061$, $p < 0.001$; Figure 5-26). The H_7 indicates n = 7 (sample size) and the $H_{x:2880}$ indicates the degrees of freedom based on the sample size. The FWACS+50 provides the highest mean allocated water across the 7 simulations analysed. The next best water allocation scenario is the PRROR method. As may be expected, the FWACS-50 provides the lowest mean water allocation result.

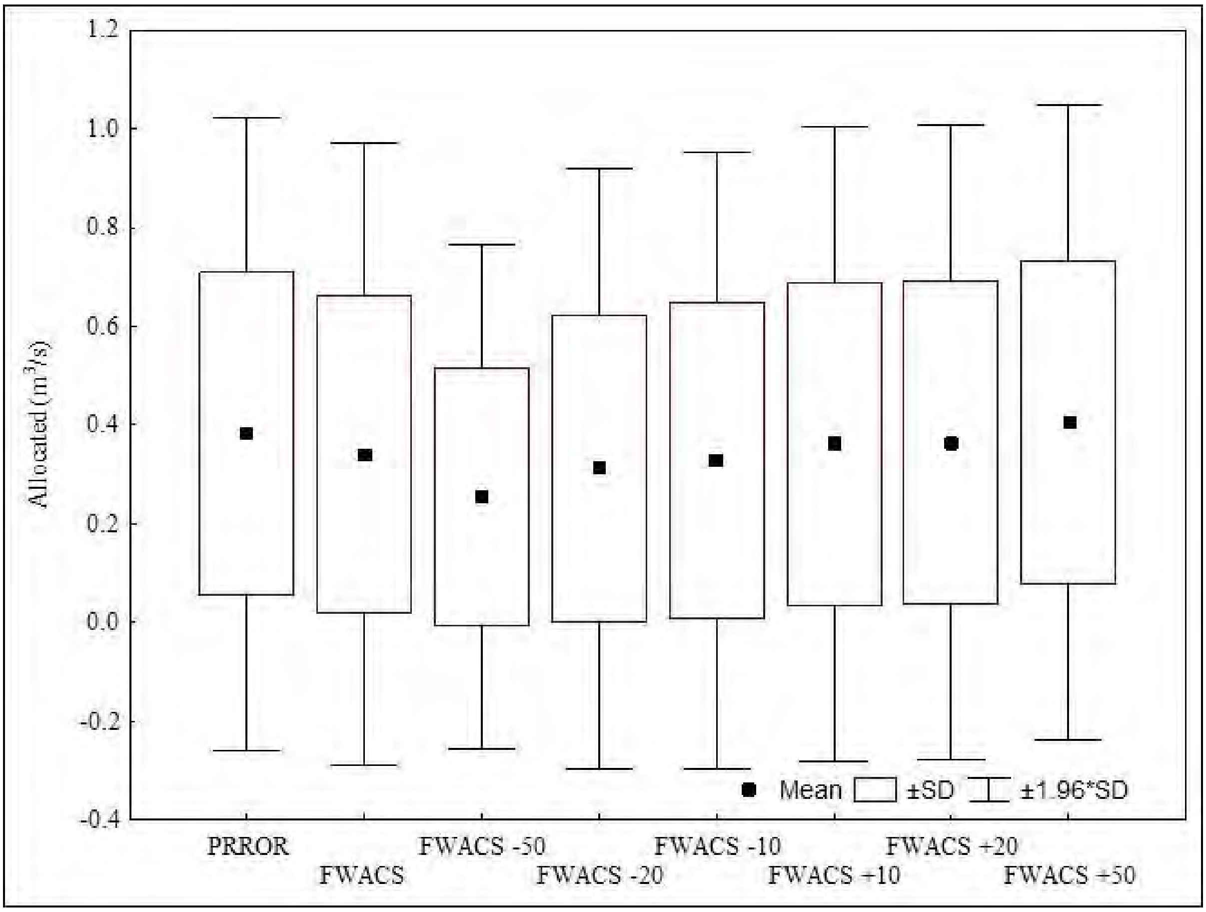

Figure 5-26 Water allocated to Water User A under the different scenarios

The comparisons indicated significant differences between the FWACS-50 method and the PRROR, FWACS+10, FWACS+20, FWACS+50 ($p < 0.001$). This is to be expected due to the large variability of up to 100% of the water allocated. FWACS+10, FWACS+20 and FWACS+50 appeared to most closely match the PRROR allocations but no significant correlations were found.

Although the allocations may be similar, there are important differences in the volume of the deficit as well as how often allocations are not met. For the water users, this translates into the reliability of reliable water supply. Apart from FWACS+50, the average deficit of Water User A was less for the PRROR method than for the FWACS model Figure 5-27.

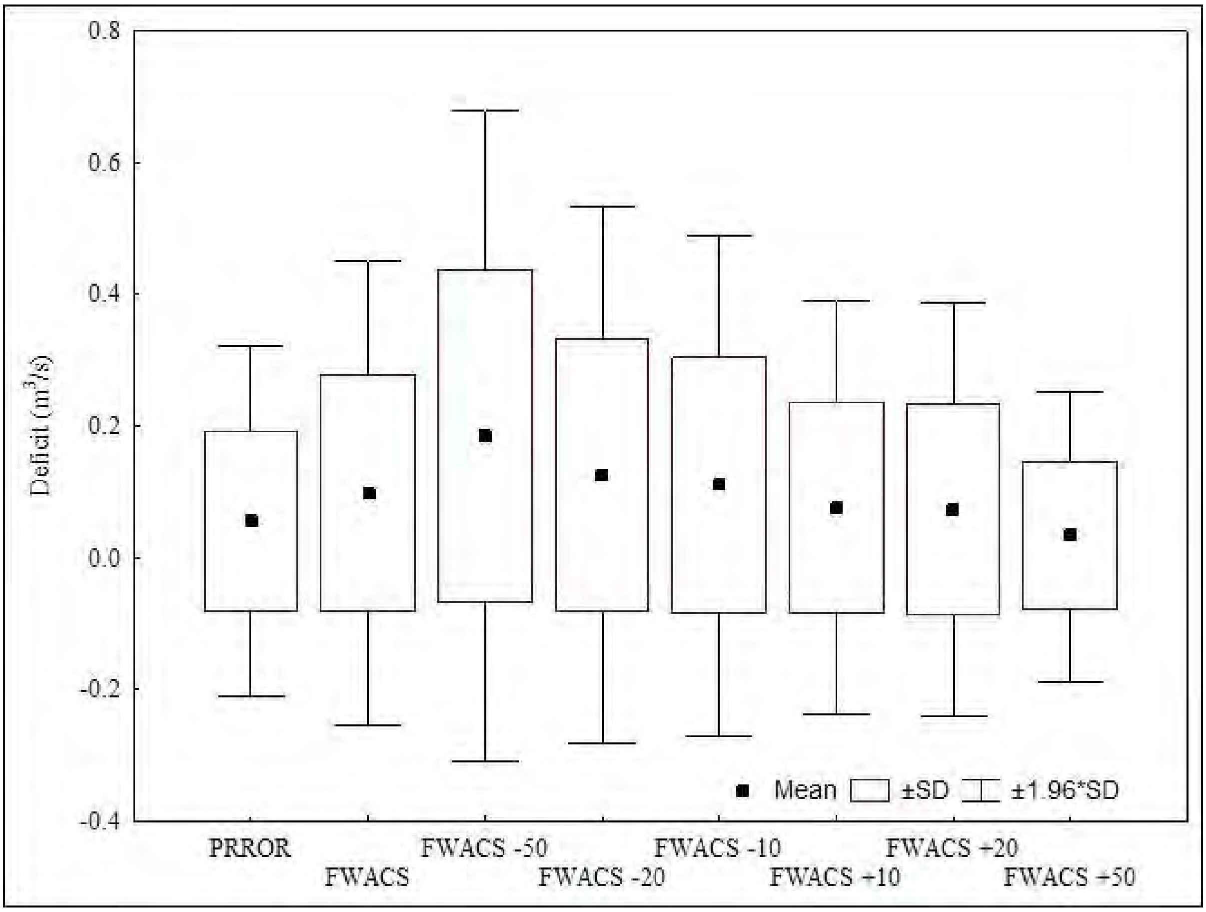

Figure 5-27 Water deficit for Water User A under the different scenarios

These deficits between PRROR and FWACS were significantly different (Kruskal-Wallis test, $H_{7;2880} = 139.9548$, $p < 0.001$). Multiple comparisons indicated that the average deficit for the PRROR allocation method was significantly less than for the FWACS-20 and FWACS-50 methods ($p < 0.001$). In fact, the FWACS-50 had significantly greater deficits than all other scenarios, apart from FWACS-20 ($p < 0.001$). These differences are mirrored by the FWACS+50 simulation which had a significantly smaller deficit than FWACS+20 and PRROR. In terms of the frequency of deficits, FWACS+20 and FWACS+50 experienced fewer deficits than all the other methods (Table 5-8). As expected, due to the higher allocations, FWACS+50 is expected to experience the least shortages. Likewise, FWACS-50 is likely to experience the most shortages as less water is allocated.

Table 5-8 Total number of deficit events for Water User A

Method	No. of times a deficit was simulated for Water User A
PRROR	96
FWACS	118
FWACS+10	105
FWACS+20	93
FWACS+50	51
FWACS-10	125
FWACS-20	135
FWACS-50	170

These results indicate that the most reliable predictor of deficits is the allocation method employed (PRROR vs FWACS), in combination with the fractions allocated in FWACS. This is only emphasised when the fractions allocated in FWACS are located at extremes of the ranges i.e. FWACS +50 vs FWACS -50 and deficits, or lack thereof, are significant. This implies that the FWACS method is relatively insensitive to changes in allocation fractions.

The statistical results also confirm that although the FWACS +50 method experiences 45 fewer deficits over the simulation period, the PRROR method provides a result not significantly different to the FWACS+50 scenario.

6 DISCUSSION AND CONCLUSIONS

The need for water allocation has grown in importance globally and locally, starting approximately two decades ago. The interdependence of water users to manage the quality and quantity of the water which they use, and the return flows which result from the use of water, has reached a point where competitive uses add to the complexity in allocating the resource. On a local scale, South Africa has a high degree of water scarcity which creates a greater need for the efficient and equitable allocation of water between competing users. Currently water is allocated based on the priority allocation concept. Based on experiences drawn from similar, water scarce countries, the feasibility of an alternate and potentially more efficient allocation method required investigation. The importance of water supply within South Africa is highlighted by the steps taken through the creation of the NWA (36, 1998) and the subsequent implementation of the CMAs, to manage the use of water from a more appropriate or local scale.

The literature provided in the preceding chapters presents the current PRROR allocation method and the proposed, selected and simulated FWACS allocation method. Advantages and shortcomings of each allocation method are compared. In this study, the FWACS allocation method was selected and compared to the currently used PRROR allocation method. The comparison was made on the basis of water user demand and the water deficit that the water users experienced in meeting those demands. In addition to the water used and deficit experienced, water flowing in the catchment rivers was investigated in order to qualify if either of the allocation methods was able to maintain a greater volume of water flowing through the study catchment. This was done simultaneously in establishing the ability to meet the demands from downstream water users, while satisfying the demands as frequently as possible of those water users abstracting from the rivers.

The PRROR provides a rigid and theoretically non-complex rule set by which to manage the water resources within a catchment or group of catchments. The water users are assigned varying priorities with a linked restriction, to be applied under a predetermined condition, being either river or reservoir based. Flexibility of the allocation method is not a requirement; rather administrative effectiveness is the desired outcome. The prescription of PRROR was done under conditions of surplus water resources while the current environment is one of water resources not being able to meet all demands. The term “water resources management era” has been coined to describe the current need to manage the limited available resources.

The rigidity of the PRROR method is replaced by flexibility in the FWACS method. One aspect of this change is the expected shift in focus to improved operational management in order to improve supply assurance. The flexibility is created through the involvement of the water users in managing their water supply and to benefit from savings that they may make through infrastructural investments and greater water use efficiency. Fundamentals of licensing remain with the use of the FWACS method. Without the use of a licensing platform, the division and allocation to water users would not be recorded through fractions allocated to water users in terms of FWA and CS respectively.

Similar to the disadvantage of the rigidity of PRROR, the FWA component of FWACS is potentially the part which may pose the largest threat to its acceptance. The fact that water may be available in a river, yet the Water User is unable to extract their full demand due to a reduction factor linked to the user, may cause frustration and dissatisfaction.

The streamflow used in the comparison of PRROR and FWACS was initially simulated using the *ACRU* model which generated a streamflow file, cascading to downstream, linked catchments. The results of the simulated streamflow from *ACRU* were presented in Chapter 4 as well as the comparison of the simulated streamflow to the observed streamflow at selected weirs within the case study catchment. Additions to the simulated streamflow were required in order to add runoff which was generated in a neighbouring catchment which was not simulated. Simulation results varied widely from the observed data obtained from DWS. Variations and differences between the simulated and observed data may be as a result of the data obtained from the relevant sources being inaccurate. The assumptions made in selecting the model parameters together with the large data set which includes seasonal and annual variation in demand and supply means that the modelling process reflects a real world situation. The streamflow data generated by *ACRU* was used consistently in both the PRROR and the FWACS simulation thereby ensuring that the two results are comparable to one another.

The hypothesis investigated was that FWACS, as an alternative to PRROR, can improve the assurance of supply to water users. The water requested was compared to the water allocated for both the FWACS and PRROR methods, using current priorities as a basis, in the Sand River Catchment. Water Users were assigned certain fractions which resulted in limitations in how demands, assurance levels and water levels were met. A different set of fractions may have resulted in a different supply. The sensitivity analysis indicated that although the FWACS method was not overly sensitive to a small change in allocation, when increasing or decreasing allocation by 50%, significant differences in supply and deficit were experienced by WU A. However the original fractions were allocated specifically to match current allocations. Comparing the two allocation methods, using one calculated simulation contributes to the understanding of how different allocation methods may fit into the real world and are not simply theoretical scenarios that cannot or are not applied. This is true for the scenarios which provide for up to 50% more or less storage. At this level of change, the question of whether this is realistic to the water user (i.e. can the user either still operate with 50% less storage or is a 50% increase in storage) needs to be asked. Is it a realistic action to operate with 50% less water or considering the likely costs associated with this potentially large storage?

6.1 Comparison of PRROR and FWACS

The PRROR and FWACS allocation methods both allocate water to competing water users while prioritising the allocation of water for the environment and human activities. They are, however, markedly different in their operations. The differences and similarities of the two allocation methods have been discussed in Chapter 2 and Chapter 4. The criteria used to evaluate the two methods as described by Howe *et al.,* (1986), previously listed in Chapter 1, are assessed in Table 6-1 which shows the PRROR allocation method does not have flexibility, security or real opportunity cost associated with it. Starting with flexibility; the PRROR allocation method does not provide an enabling environment for the movement of water to a future, user selected date of use because of the competition inherent in the water stored in the reservoir or as a run of river flow. A direct result of the competition for the water resource is the lack of security. High competition for the water resources in a system which does not promote water saving, means that water is used not only because there is a justifiable use, but also because it might not be available at a later date, so users are encouraged to use what is available. The need to use water on a use-it or lose-it basis instils a lack of understanding of the real opportunity cost of the water. Water is used against a license allocation without the Water User realising the cost of the water being used. However, the predictability of the PRROR allocation method is high due to the simple yet effective rules used in its operation. Water Users know their allocation and this does not change until review of the water license. The fixed nature of water within the PRROR means that reallocation on the basis of equity; to new entrants to the area requiring water as well as realigning previous water allocation volumes is difficult to achieve. Ultimately, this leads to a learned perception (positive or negative) of the allocation method from a public and political view point. The inability of the PRROR to show flexibility, security and real opportunity cost, together with a low equity means that it is not an ideal, socially responsible allocation method.

In comparison, the FWACS allocation method does have the flexibility in the system to move water to a selected user at a future, user selected date. Under the CS segment, this is relatively simple as the Water User has control over the storage of water in their portion of the reservoir. It is also possible under the FWA component through controlled fraction of flow abstraction limits placed on upstream users to provide a downstream user with water. The control of the CS provides the Water User with security of water availability and ultimately water allocation. The added security through the control of the water resource allows for the realisation of the real opportunity cost of the water. The flexible operating environment provides a means of maintaining a low opportunity cost in the system. Overall predictability of the FWACS allocation method is high. The CS segment provides complete predictability of the water available while the FWA provides a known fraction of river flow which may be abstracted. The entry of new water users is a simpler task to handle under FWACS. Water fractions for river abstraction (FWA) can be easily altered, with some protest from water users a likely result. However, the reallocation of the CS may be easier to achieve through a willing buyer, willing seller arrangement. This relates back to the opportunity cost being realised of excess stored water. Finally, the flexibility of the system, inherent security and ability to provide an equitable allocation, places FWACS as the preferred allocation method in terms of political and public acceptance.

Table 6-1 Assessment of criteria for PRROR and FWACS in the Sand River Catchment using MB

Criteria	PRROR	FWACS
Flexibility (can water be moved in space and time)	No	Yes
Security (can water availability be assured)	No	Yes
Real opportunity cost (is the user aware of the real cost of the water)	No	Yes
Predictability (how certain is the desired outcome)	High	Low for FWA but higher for CS
Equity (is the process fair)	No	Yes
Political and public acceptability (is the process socially responsible)	No	Yes, but understanding of FWACS is lacking

In order to compare the allocations methods and be able to draw similarities and differences, a simulation model was required. The simulation model may also be referred to as a DSS due to the nature of simulations that information is provided upon which decisions are based. The MB model was selected due to the availability of local support by knowledgeable distributors and under financial criteria in that the model was provided for use, free of charge by the distributor. Additionally, MB was able to effectively simulate both the PRROR and FWACS methods using the same data set but implementing different rules. The model provided this option through a tick box style interface. However, due to human error and interface complications, MB occasionally provided errors in the allocation of the CS in the FWACS method. This resulted in initial setup delays but, once overcome, the program executed the simulations efficiently.

Water users in the case study of the Sand River Catchment under both the PRROR and FWACS method were not limited with regard to river abstractions. The limitation of river abstraction under FWACS is possible but, as a result of the PRROR method not being able to limit the abstractions from the river, no limitations to abstractions from rivers was simulated in this study for the FWACS allocation method. The FWA was thus set at 100% for the simulation in order to mimic the allocation under PRROR where the abstraction rate is not limited. EWR was released from reservoirs as a minimum requirement which is released from the total storage under PRROR. Under FWACS the EWR was accounted for in the unallocated pool. The results obtained through the simulation in Chapter 5 show that there are small differences between the PRROR and FWACS allocation methods. Differences include reduction in magnitude of deficit for the same user under PRROR and increased downstream water availability under FWACS.

The simulation of the EWR component in both allocation methods was limited. The limits of the EWR component was a result of little information available from water authorities. Implementation of the EWR was further limited as the control point used in the maintenance of EWR at various points in the catchment was not known. The result was that each reservoir was simulated with a minimum flow supplied from the unallocated user pool. A control node within the case study catchment was setup for each allocation method to ensure that the minimum flow was simulated at that point. The EWR was always supplied downstream of the study catchment. The selected point was chosen several nodes downstream of the reservoir in order to overcome the situation where EWR released water becomes available for the first water user downstream of the reservoir.

The method used to calculate user fractions for use under FWACS was one where the total Water User demand over a season is compared to the volume of the reservoir from which the Water User abstracts water. This data is generally readily available and the ratio provides the Water User with a realistic indication of available supply to demand. This was the method used here in order to obtain initial fractions. It also assured real demands and not theoretical comparisons were made. The sensitivity analysis of the scenarios and fractions within each scenario would indicate whether a different fraction would provide a better result.

Comparing the results under the PRROR and FWACS scenarios for irrigation Water User A, as shown in Figure 5-1 and Figure 5-11 respectively, the water supply differences are discernable in the pattern of the water use. Under PRROR water demands are met but in times of water scarcity, below 20% non-exceedance percentile value in Figure 5-23, the FWACS method provides greater reliability of water supply.

In comparison to Water User A, Water User B was not connected to a river as a means of access to water. Rather, Water User B had access to a reservoir. Under the setup, the Water User B was allocated a portion of the reservoir which was based on licensing fees and estimated water demand through previous water requirements. Under both the PRROR and the FWACS scenario, the Water User B receives the full volume of water demanded. The FWACS scenario using the CS reservoir allocation fares well, failing only once during the simulation. Large drawdowns by the Water User B shown in Figure 5-17 are reflected in Figure 5-16 although the drawdowns are diminished due to dilution over the total volume of the reservoir.

The success of the CS part of the FWACS is evident for Water User B in Figure 5-15. The segmentation of a reservoir and its subsequent lease of “water pools” to water users for individual management can, firstly, be simulated through a DSS such as MB and secondly, that it provides results similar to the PRROR method which lumps water users, rather than a water user having an individual segment under FWACS.

The overall effect of each allocation method in terms of water used and water deficit are shown in Figure 5-8 and Figure 5-20 respectively. The pie charts show the water used and the water deficit experienced by each water user in the Sand River Catchment. Further, the ability of each allocation to meet the demand of each user is shown in Figure 5-24. Overall, for water users in the catchment, the PRROR simulation has a water supply index of 0.93 while the FWACS simulation index for the catchment is 0.91. Under the current operating variables and environment, the PRROR allocation method supplies water users with water more reliably than FWACS. However, the FWACS allocation method leaves more water available in river reaches. From the baseline data available and the results achieved over the original simulation, the FWACS allocation method achieves a similar result against the current PRROR method. Although the FWA and CS components of FWACS can be controlled and the method is adaptable, due to the reliability and smaller deficits experienced under PRROR, PRROR is a better allocation method for the Sand River Catchment using the current fractions. However, when changing the fractions allocated under FWACS, the outcome changes substantially. FWACS+50 appears to allocate water to the Water User so they experience less of a deficient less often. Although this is obviously a better situation for Water User A, the questions future studies could attempt to answer is whether this is a realistic allocation (i.e. is that volume of water available) and how this affects other users, especially reservoir users when they need to start drawing from other sources in times of deficit. The results indicate that for FWACS+50, the end water user in this simulation (Water User D) has slightly more water (70 405 156m^3 /month over the 30 year simulation period) than for PRROR 70 335 694m^3/month over the 30 year simulation period). This translates to an additional 2 285m^3/day for the FWACS+50 method. Thus an understanding of Water Users and their needs is essential in order to ascertain which model, and what fractions would best allocate water in this system. For this reason, even though FWACS at higher allocations than the original fractions appears better, the PRROR method cannot be discounted.

Possible reasons include;

- Less stringent rules for reservoir operation in PRROR than those found in the FWACS method resulting in one Water User benefiting if others water users do not use their full complement of allocated water.
- FWACS allocating a set fraction of river flow to a Water User rather than a set volume. Thus, under FWACS a Water User is allocated 20% of the river flow. If the base flow is 10m^3/s it translates to 2m^3/s, however during peak events the river flow may be 20m^3/s and as a result the Water User is able to extract 4m^3/s, even though this exceeds his water demand and/or he may not have the ability (e.g. pumps, storage volume) to abstract this volume.
- FWACS may affect other WU's differently and should be investigated in further studies.

In the case study performed and under the assumptions made, the improved assurance of supply hypothesis was not true using the FWACS+50 allocation method compared to the PRROR allocation method. However, the FWACS+50 provides significantly fewer water deficit events, Table 5-8, 51 vs 96. This represents a 47% reduction in water deficit events compared to PRROR.

It is proposed that the operating rules used under the PRROR for the Sand River Catchment are too simplistic as there is little control of flows to meet EWR where this has been specified or assumed. The reservoirs are not strictly controlled with regard to water level, with the exception of the restrictions imposed when storage was less than 40% of the FSC as a general limit. At this point the simplistic rule base needs mention again. Data availability concerning reservoir operation was limited such that not all the reservoirs in the case study catchment had operating rules. Where rules were available, it usually entailed one curtailment level which imposed a significant reduction in water availability, i.e. 80% reduction when the storage was below 40 % of FSC.

6.2 Recommendations for Future Research

In order to comprehensively compare the two allocations methods, several aspects need to be refined and additional information and data made available. The advantages of the FWACS were seen in the ability to match the PRROR despite limited data. It therefore is an attractive allocation method for use in catchments which experience high water availability stress, such as the Sand River Catchment used in this study. However, the high data requirements and costs associated with obtaining this data are limiting. For this reason, it is worth re-visiting the priorities and allocations under PRROR to ensure more equitable allocations.

In terms of data preceding the simulation of the allocation methods, work needs to be done in several areas. Due to the nature of simulations under taken using *ACRU*, rainfall data is the most important input to the model and drives the simulation. Rainfall data was available in the case study catchment; however the rain gauge network is dispersed with rain gauges located towards the centre of the catchment, not receiving maintenance and providing limited data. In addition to the observed rainfall data, improved streamflow and water use monitoring is required especially for FWACS. The simulation results in Chapter 4 showed evidence of a discrepancy between simulated streamflow and observed streamflow in the middle and lower sections of the catchment. Accuracy of the data in the collection and capture of the data is imperative for the later use in simulation studies, but first and foremost for the legal compliance of Water Users with water use licensing.

Water rights require a thorough and complete undertaking to calculate, implement and monitor EWR in the catchment. The lack of readily available EWR was a short-coming encountered in the study. An area which impacts on EWR through restricting Water Users is the reservoir rule curves used in the PRROR allocation method. Information obtained through investigations showed the reservoir rule curves were simplistic and once reservoirs limits were met, restrictions were sudden and severely limiting on the Water Users.

Additional future studies could include:

- The use of simulated irrigation values in place of the provided abstraction values for water users. This may provide for more realistic water use across the catchment.
- Increasing the number of water users to assess whether a future increase in users will affect the effectiveness of the allocation method.
- Simulating river abstractions to investigate the effects of reliability of FWACS and deficits experienced.
- Compare FWACS and PRROR using the same methodology but in other catchments to assess the applicability of FWACS elsewhere in South Africa.
- Compare PRROR with another allocation method in the Sand River Catchment to assess whether another allocation method may be more applicable in this area.
- A more in-depth analysis of how different fractions will affect current WU's, not investigated in this study and an understanding of how changes in flow regime will affect all the users.
- Inclusion of other aspects and factors not included in the MB model such as diversions, hydro-electric power stations and access to groundwater by water users may affect the water availability which in turn will affect the reliability of water supply to the users.

However, the relevance and importance of the results from this study and the suggested future studies can only realistically be assessed by implementation of the FWACS method, in a pilot study, to gauge the effectiveness of any changes.

6.3 Conclusion

This study provides a working model that clearly demonstrates the advantages and disadvantages of each allocation method in the Sand River Catchment. For both methods it is important to have accurate and reliable data. This data should include data on evapotranspiration, soil classifications, dynamics of land cover and land use at both a local and regional scale, and abstractions made. This will allow a more accurate comparison of the allocation methods.

Thus, although Water Users were assigned fractions and capacities based on current allocation which may have limited water supply, the current study allowed a comparison between the FWACS and PRROR methods. The results of this study can be applied to assist water management within the Sand River Catchment, to the benefit of the water users. Although there have been simulations done before on systems, with different allocation fractions or different priorities, the current study is one of the few that compares methods on a specific catchment. Based on the findings summarised in Table 6-1, a higher degree of predictability in the PRROR method results in Water Users receiving their demanded water more frequently, than in the initial FWACS method. Although the FWACS is conceptually a better method it is very data intensive and requires daily stream and reservoir monitoring. The capital for this equipment would be difficult to motivate for in a country where other developments which contribute to social upliftment take precedence. Additionally, the present study was based on 30 years of data which takes into consideration inter and intra-year variability. The Sand River Catchment is located in a high rainfall area which may account for the PRROR method outperforming the initial FWACS method, in this instance. The results achieved under the sensitivity analysis shows that, although PRROR is an alternative method for determining water allocation to water users, although unrealistic, the FWACS+50 is able to improve on the water reliability of supply within the Sand River Catchment, at least in the short term.

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8 APPENDIX A: SAND RIVER CATCHMENT RESULTS

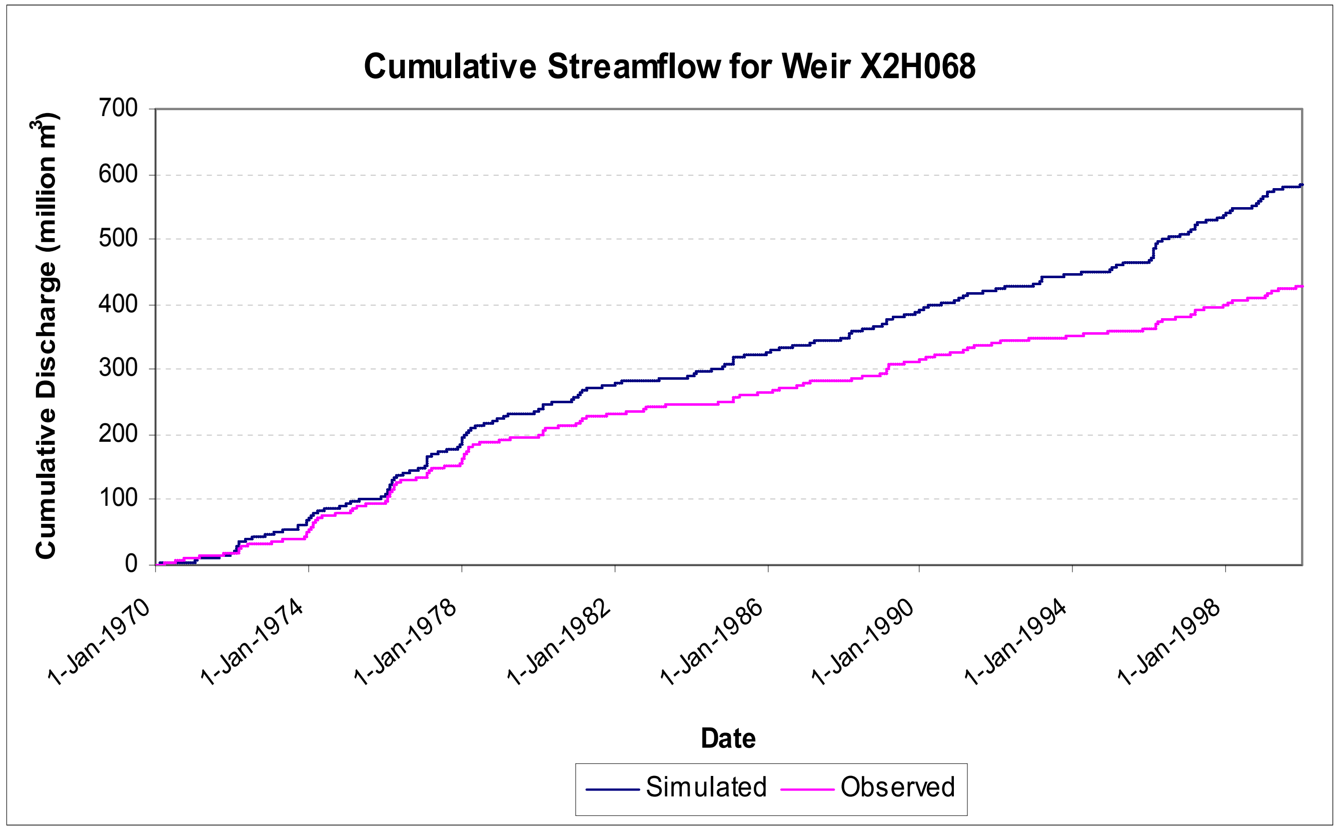

Figure 8-1 Simulated and observed accumulated streamflow of weir X2H068

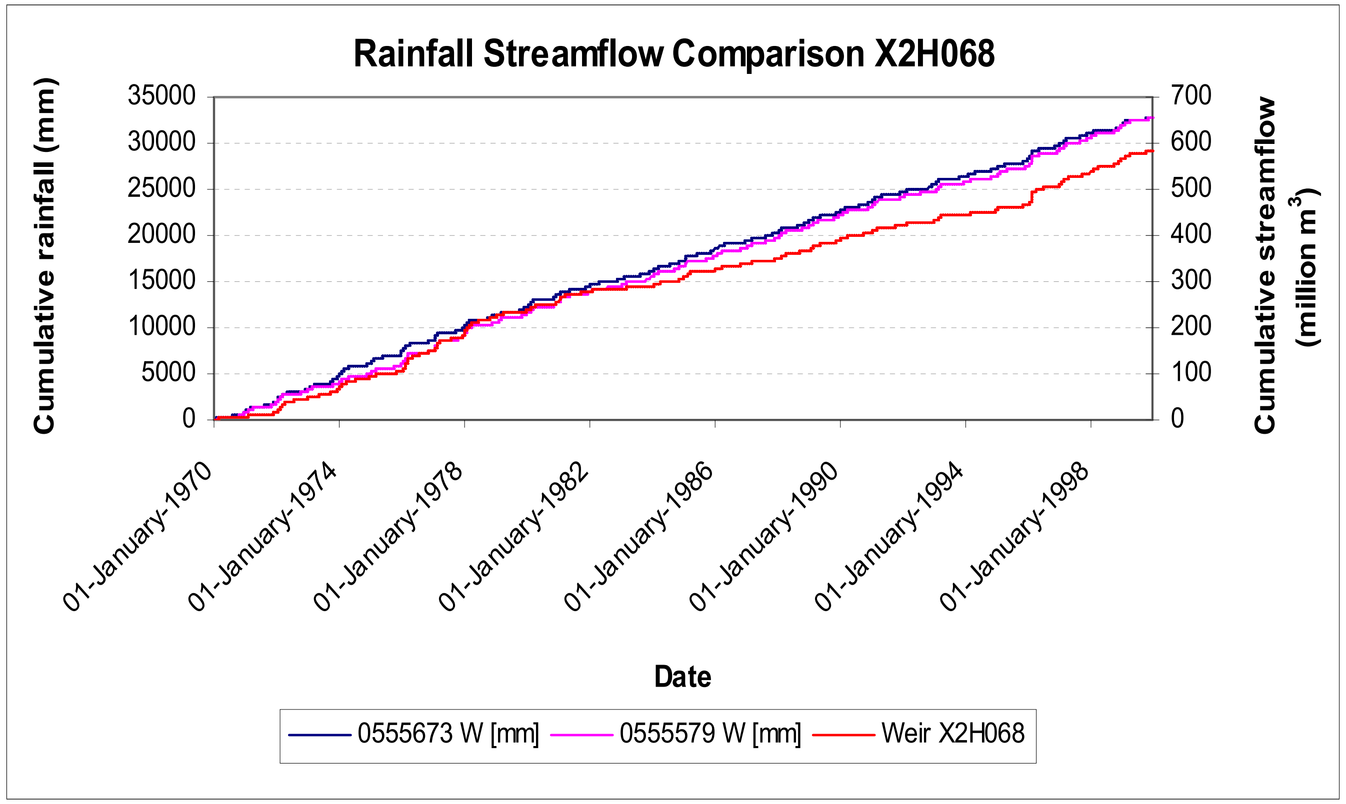

Figure 8-2 Comparison of rainfall data and simulated streamflow weir X2H068

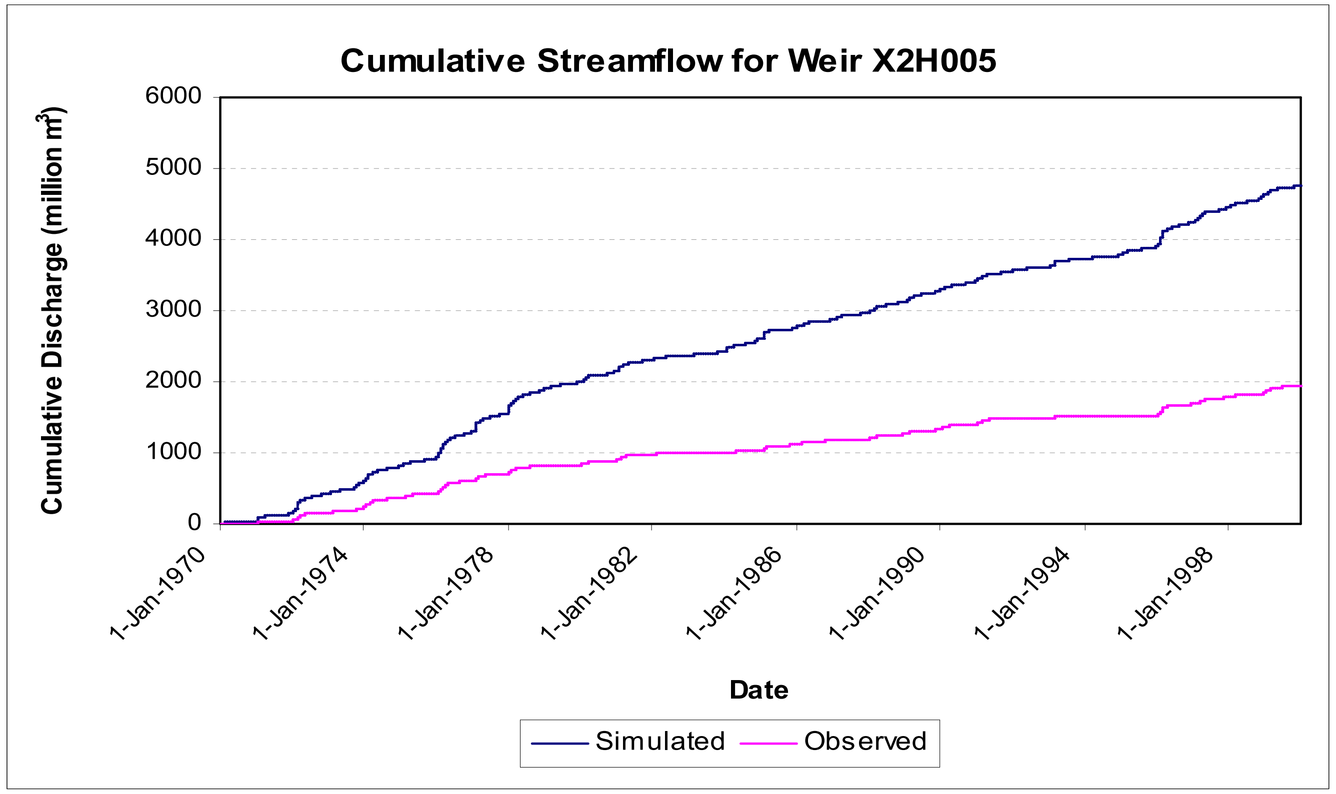

Figure 8-3 Simulated and observed accumulated streamflow of weir X2H005

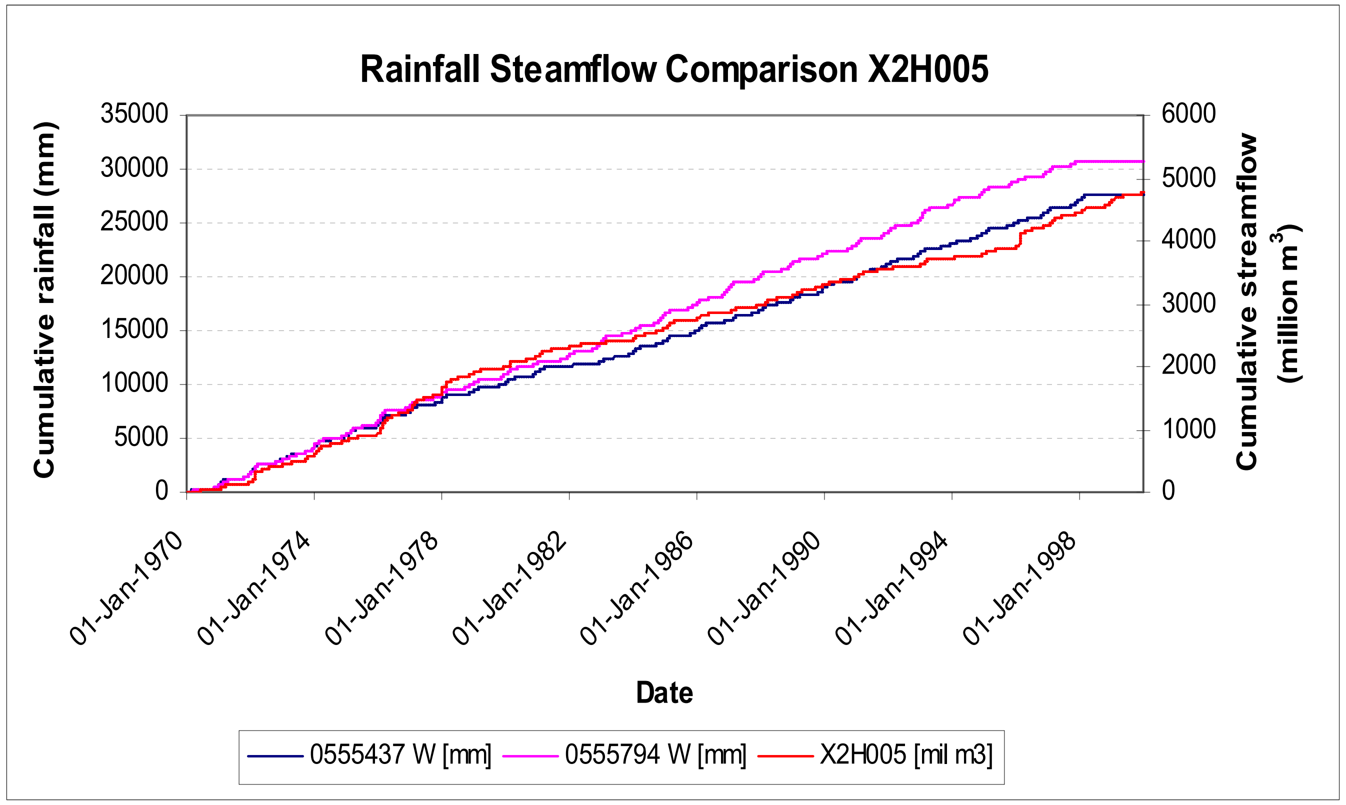

Figure 8-4 Comparison of rainfall data and simulated streamflow weir X2H005

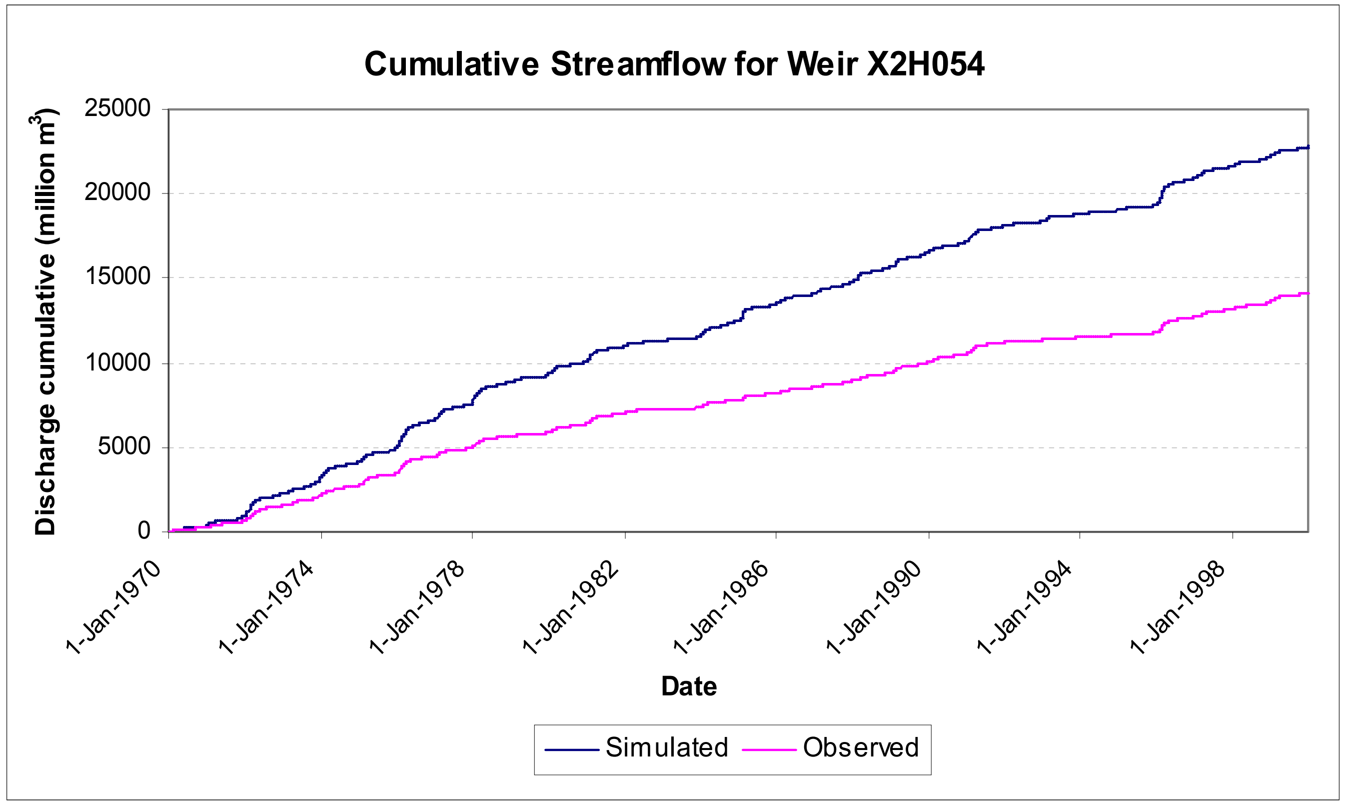

Figure 8-5 Simulated and observed accumulated streamflow of weir X2H054

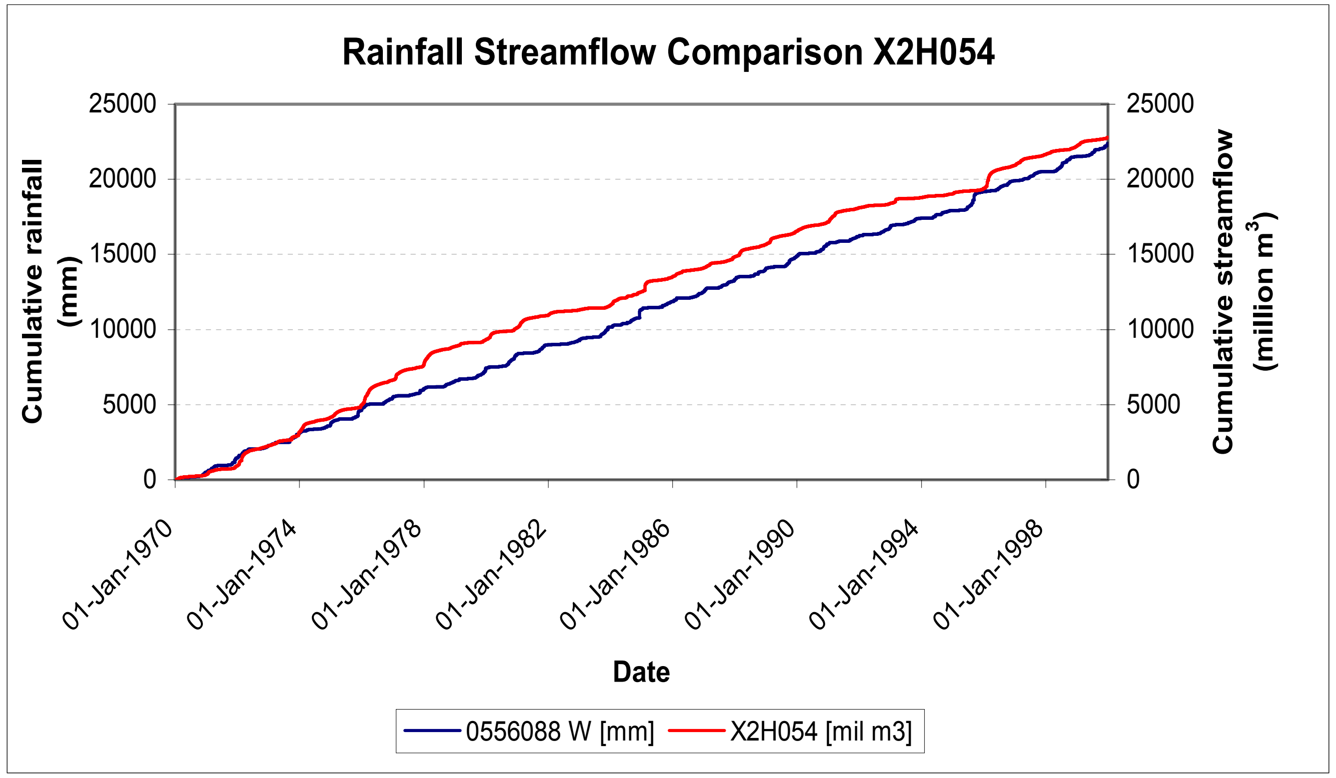

Figure 8-6 Comparison of rainfall data and simulated streamflow weir X2H054

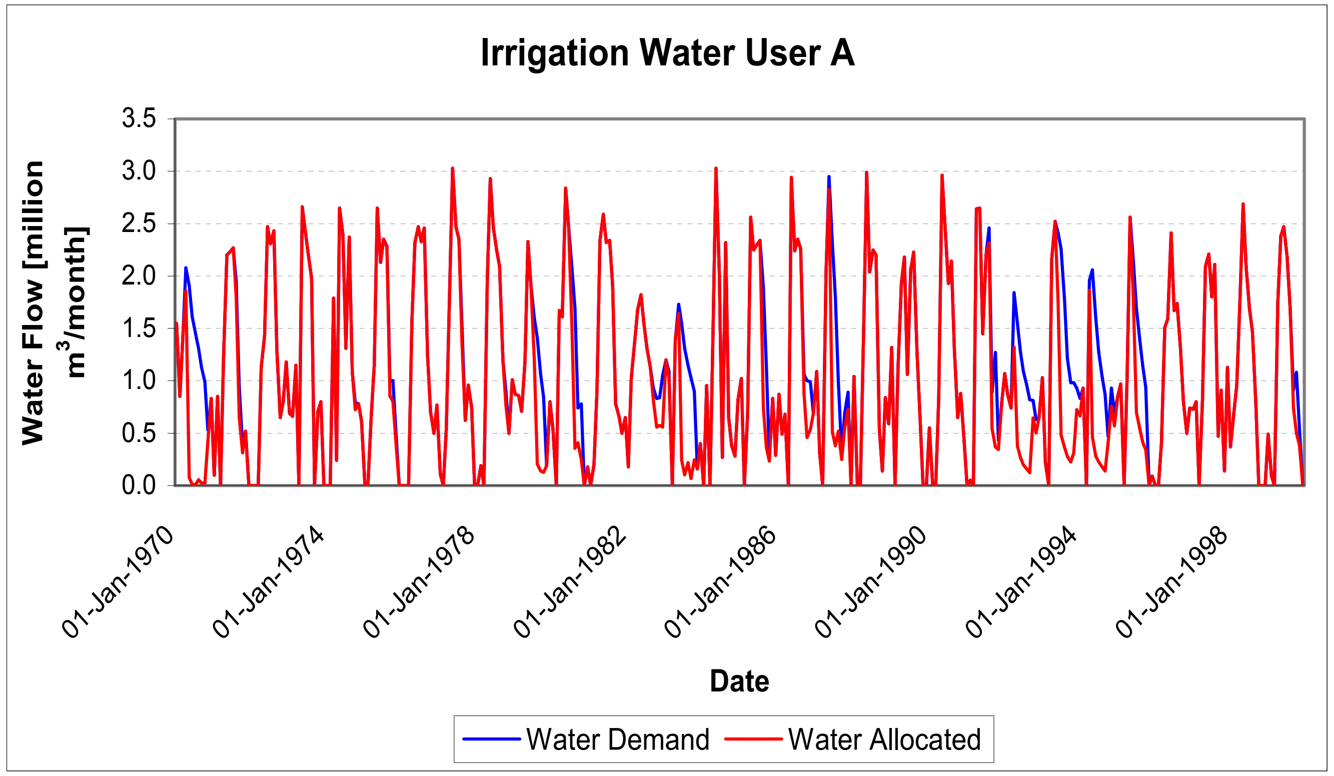

Figure 8-7 PRROR Irrigation Water User "A" water demand and the water allocated

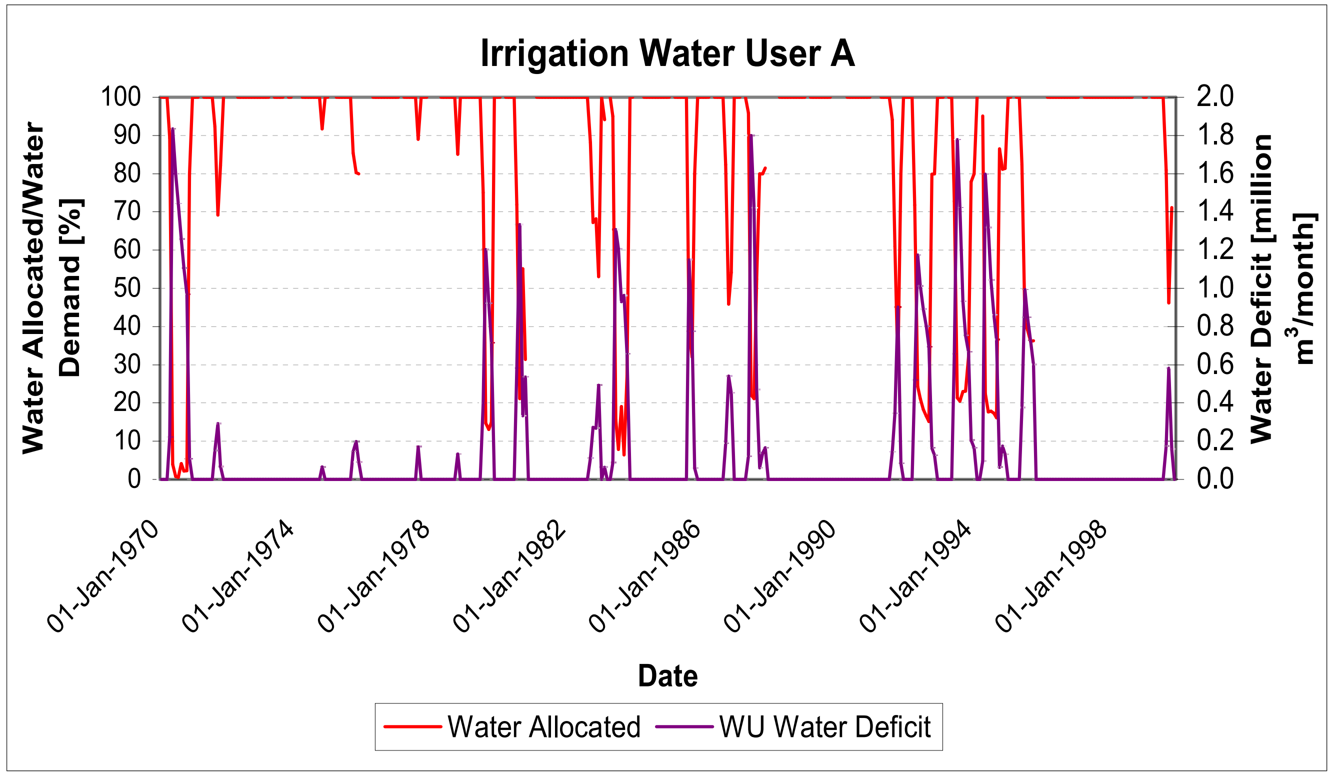

Figure 8-8 Water allocated to Irrigation Water User A as a percent of water demanded and relating water deficit of Water User

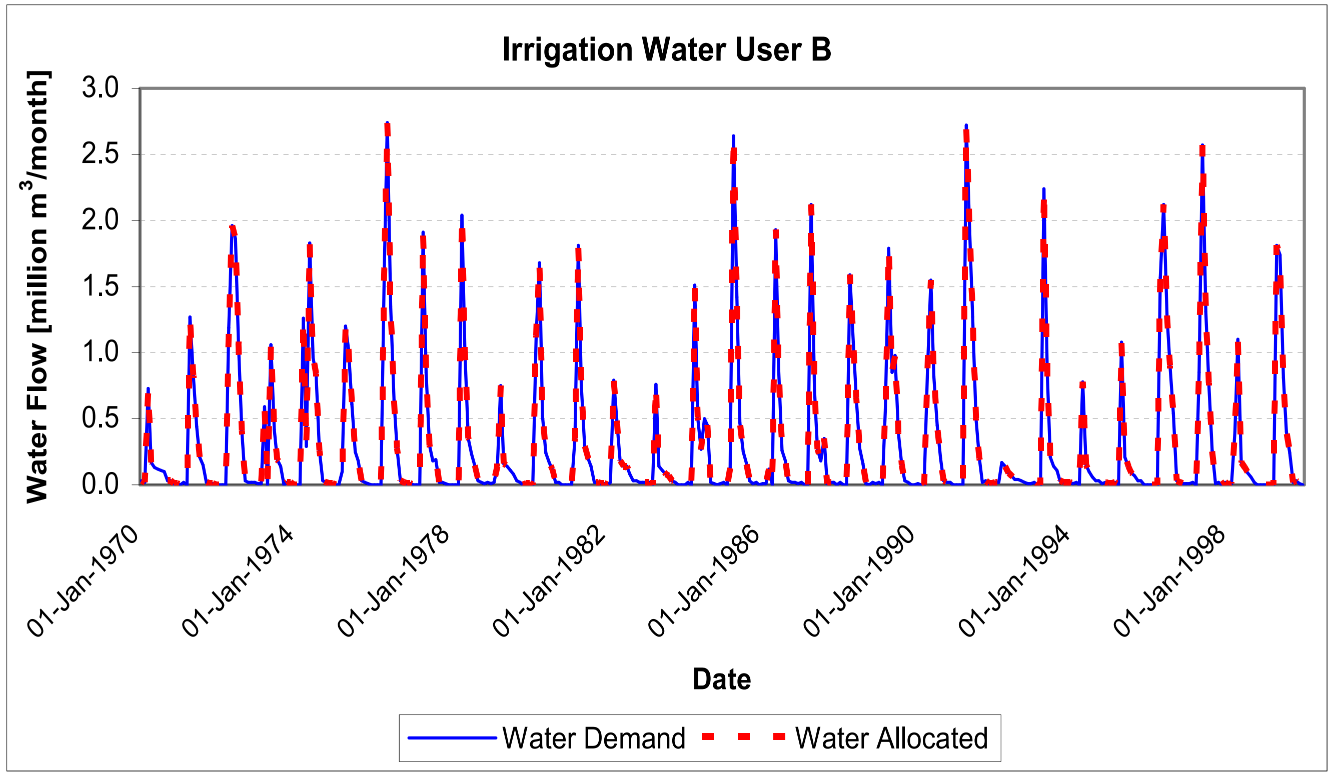

Figure 8-9 PRROR Irrigation Water User B water demand and supply

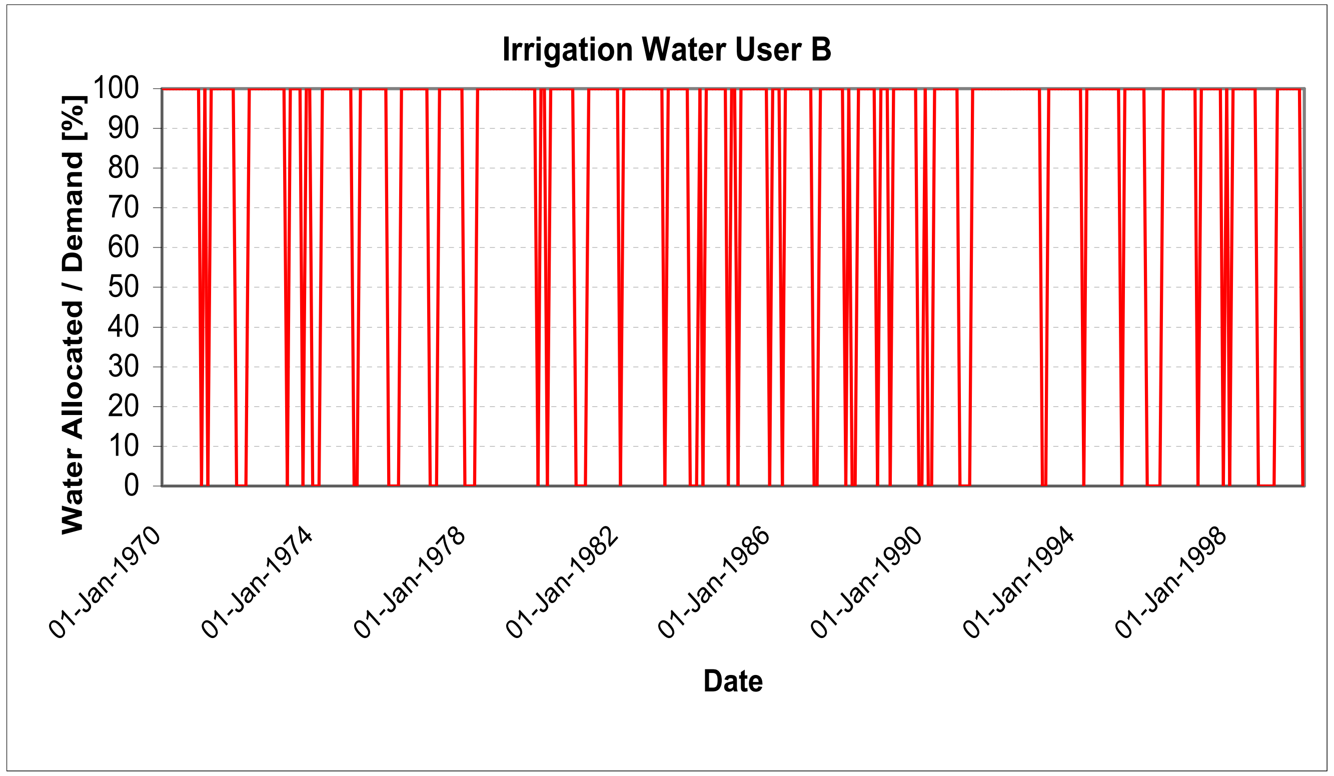

Figure 8-10 Water allocated to Irrigation Water User B in relation to water demand

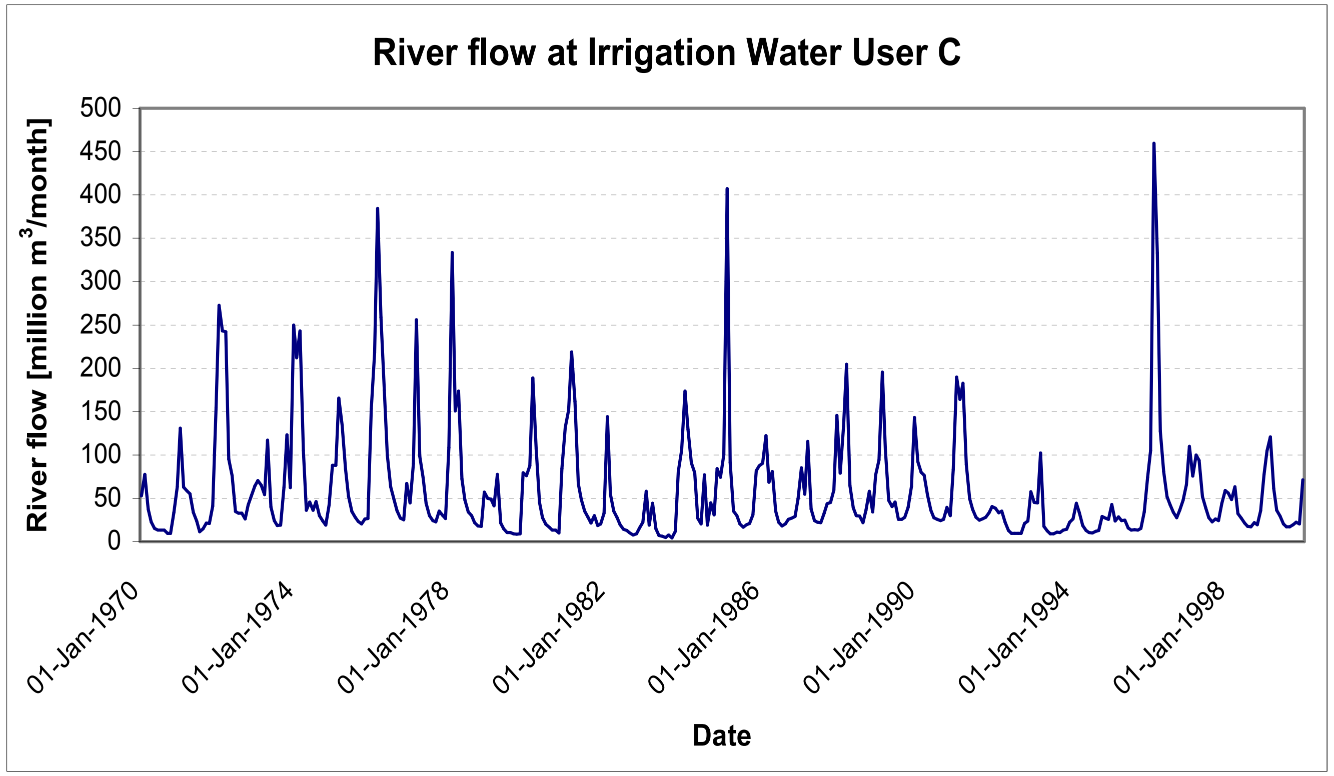

Figure 8-11 Flow at node prior to abstraction by Water User C: PRROR allocation

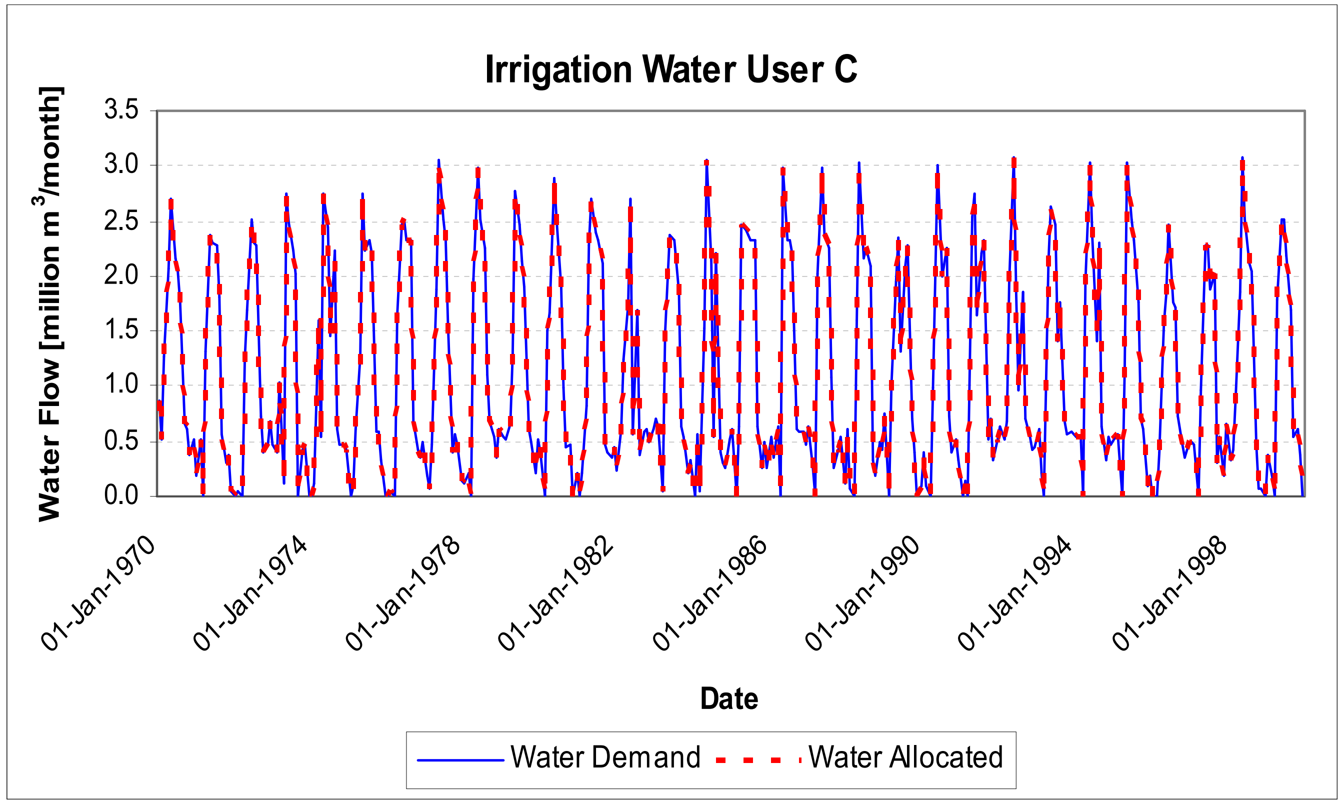

Figure 8-12 PRROR Irrigation Water User C water demand and water used

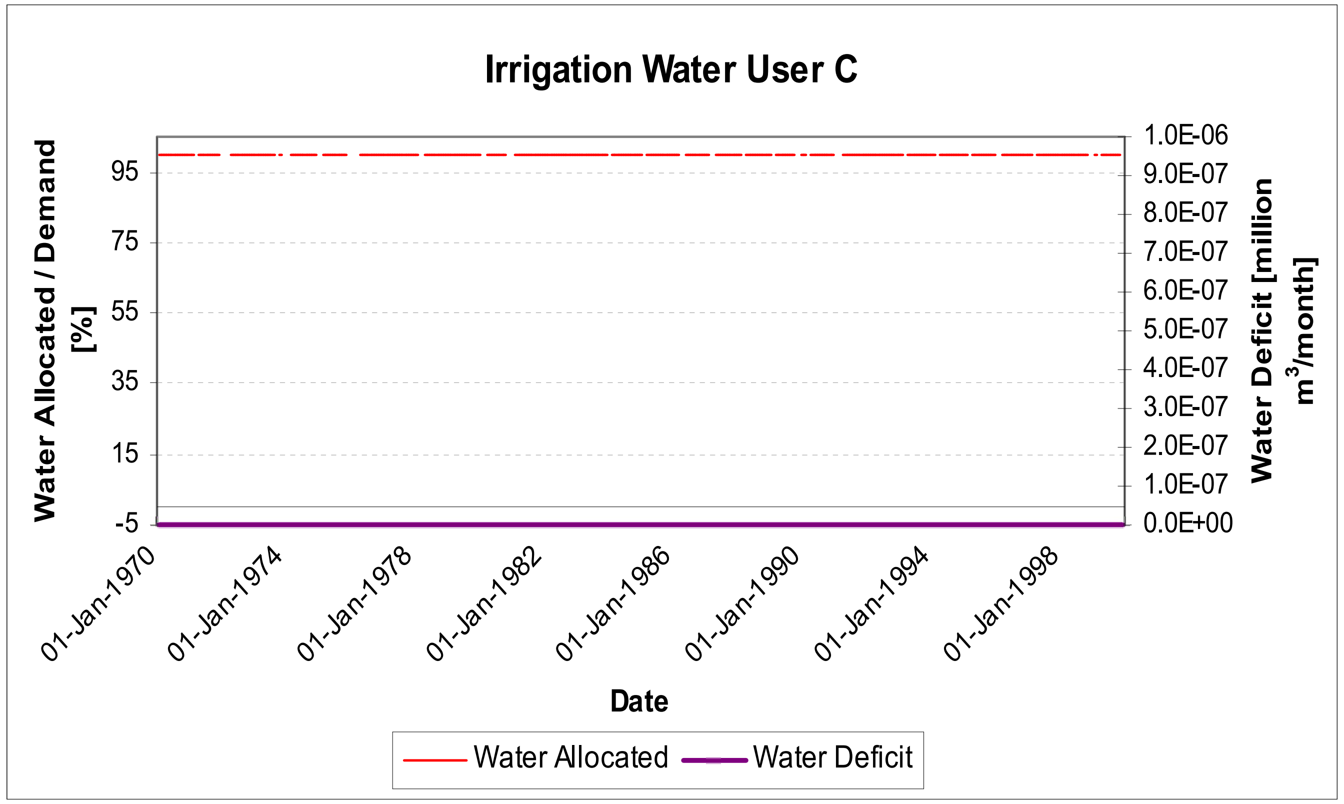

Figure 8-13 Water allocated to Irrigation Water User C in relation to water demand

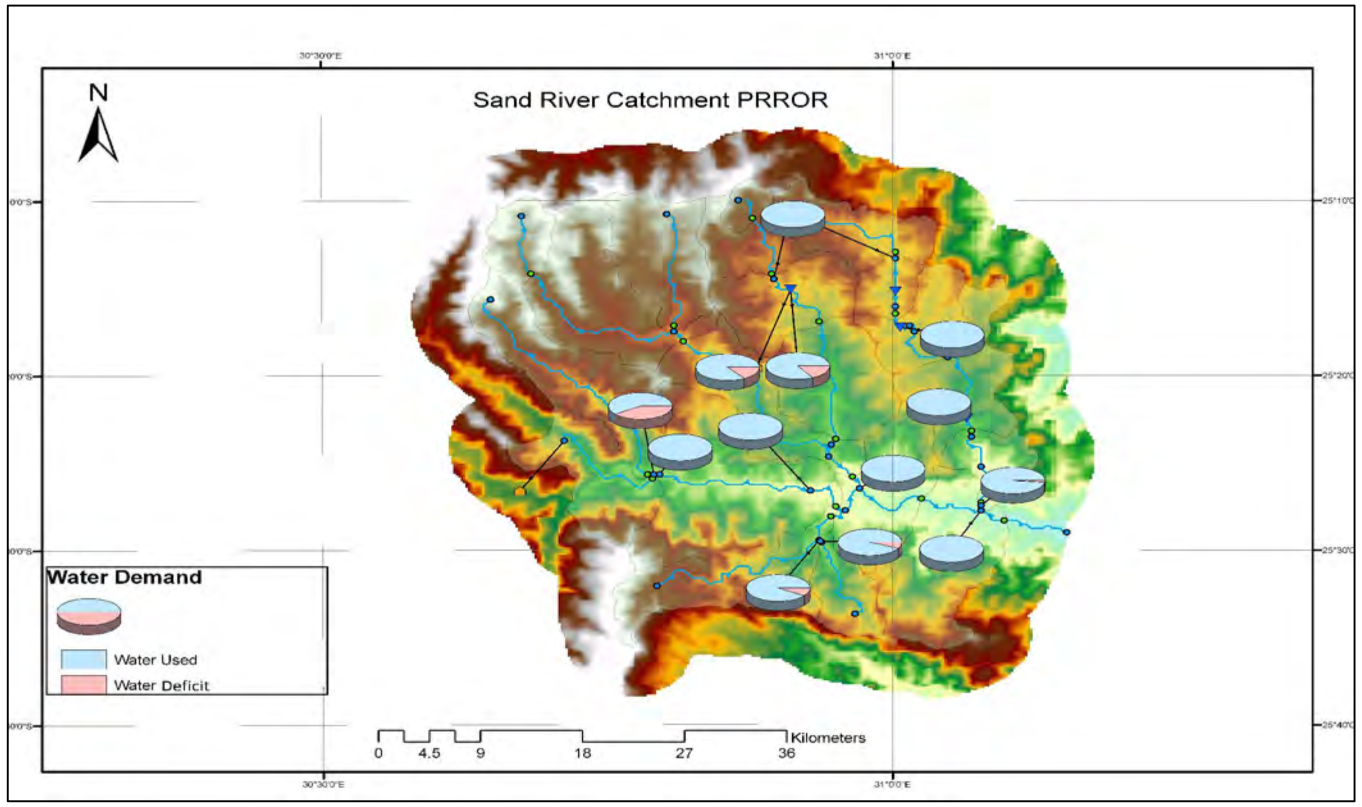

Figure 8-14 Water allocation and deficits in the Sand River Catchment under the PRROR allocation method

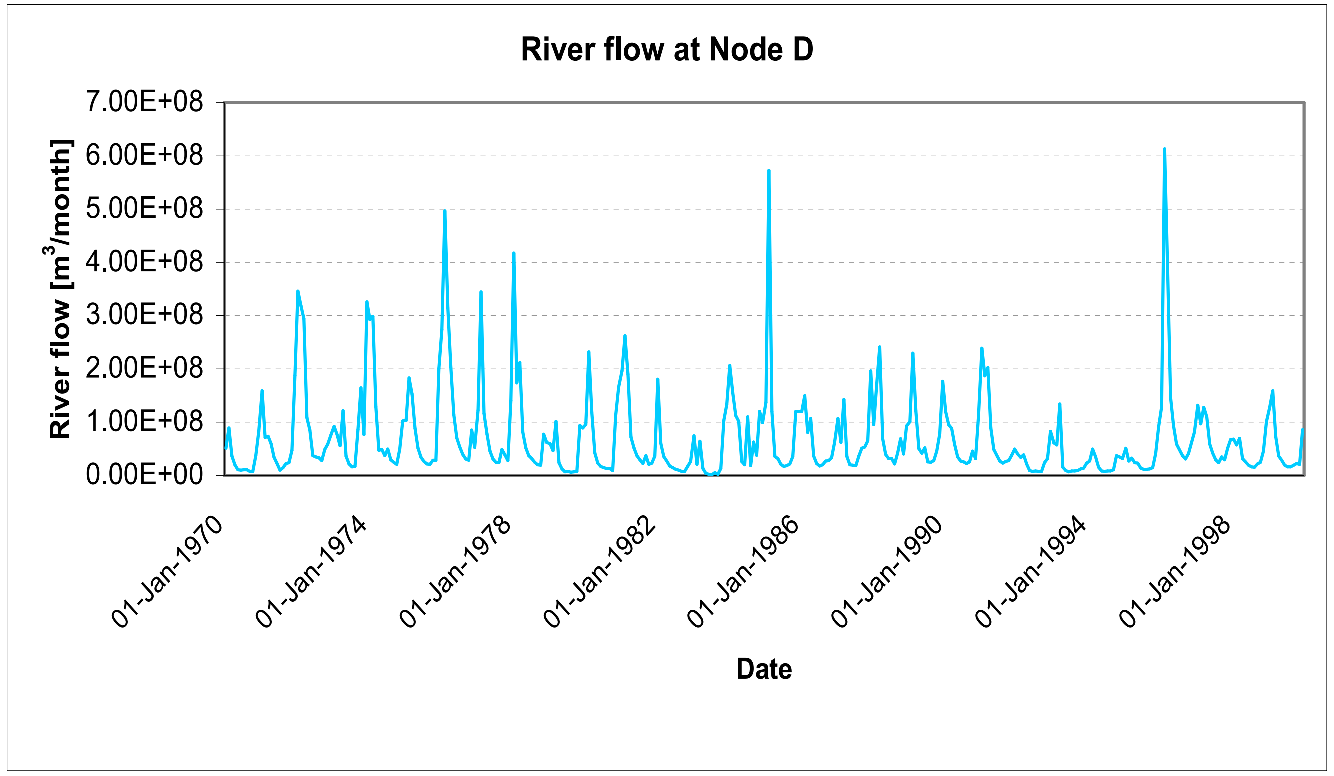

Figure 8-15 Catchment exit node D river flow PRROR

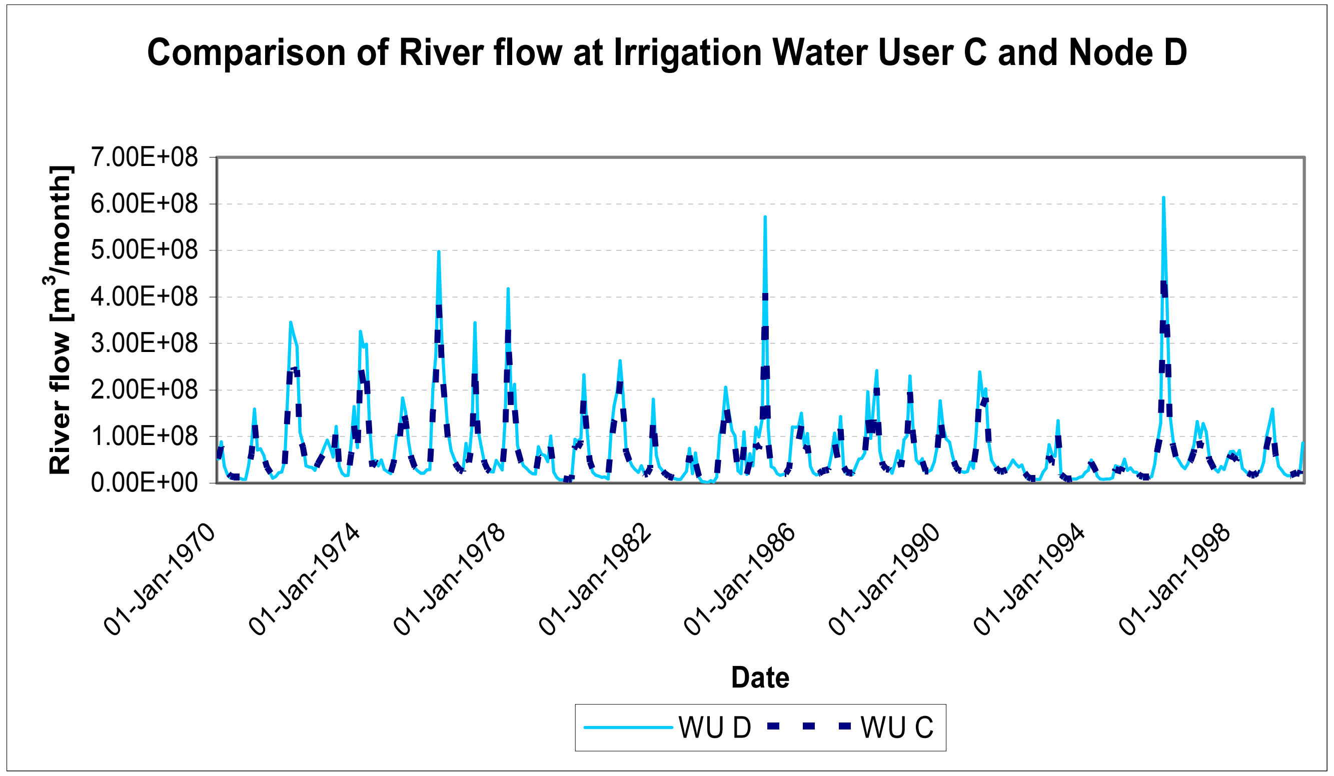

Figure 8-16 River flow at Irrigation Water User C and Node D

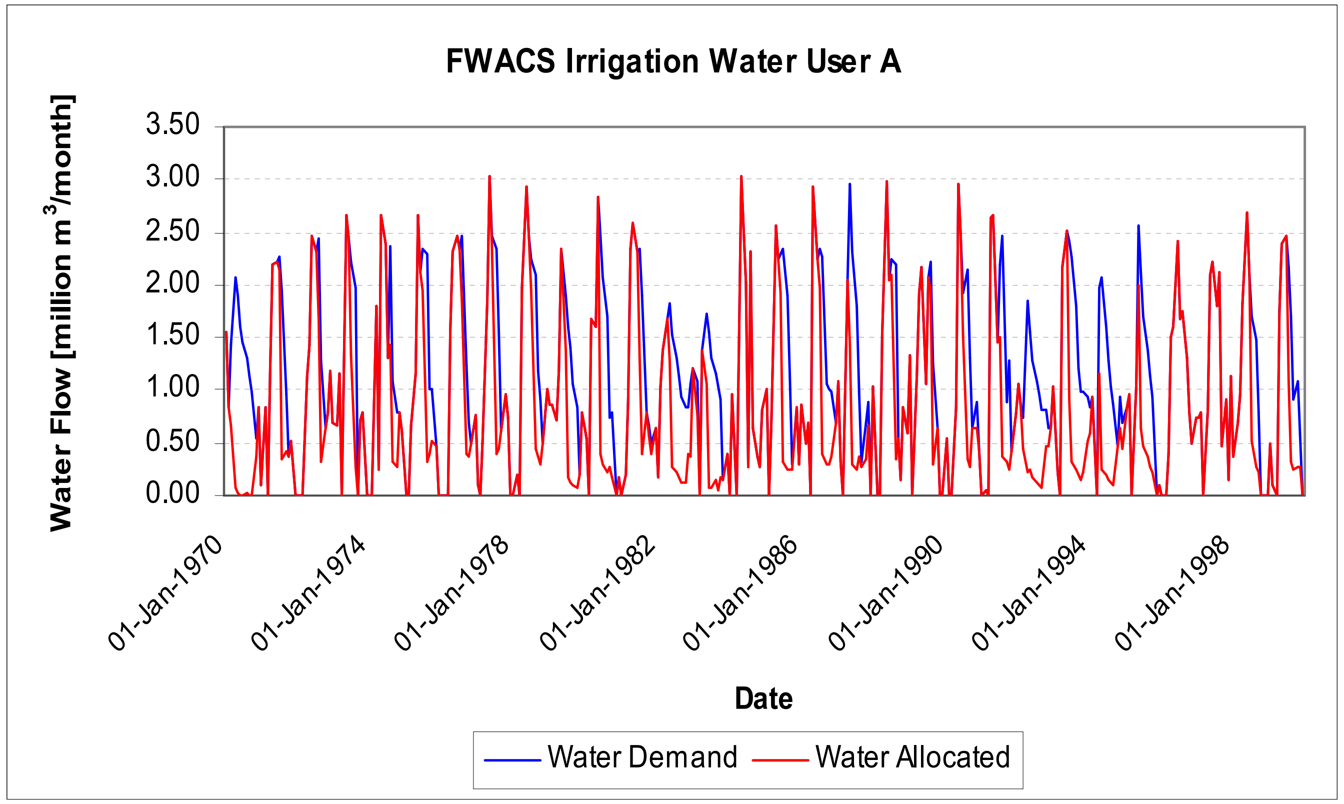

Figure 8-17 Water demand and allocation for Irrigation Water User A under FWACS

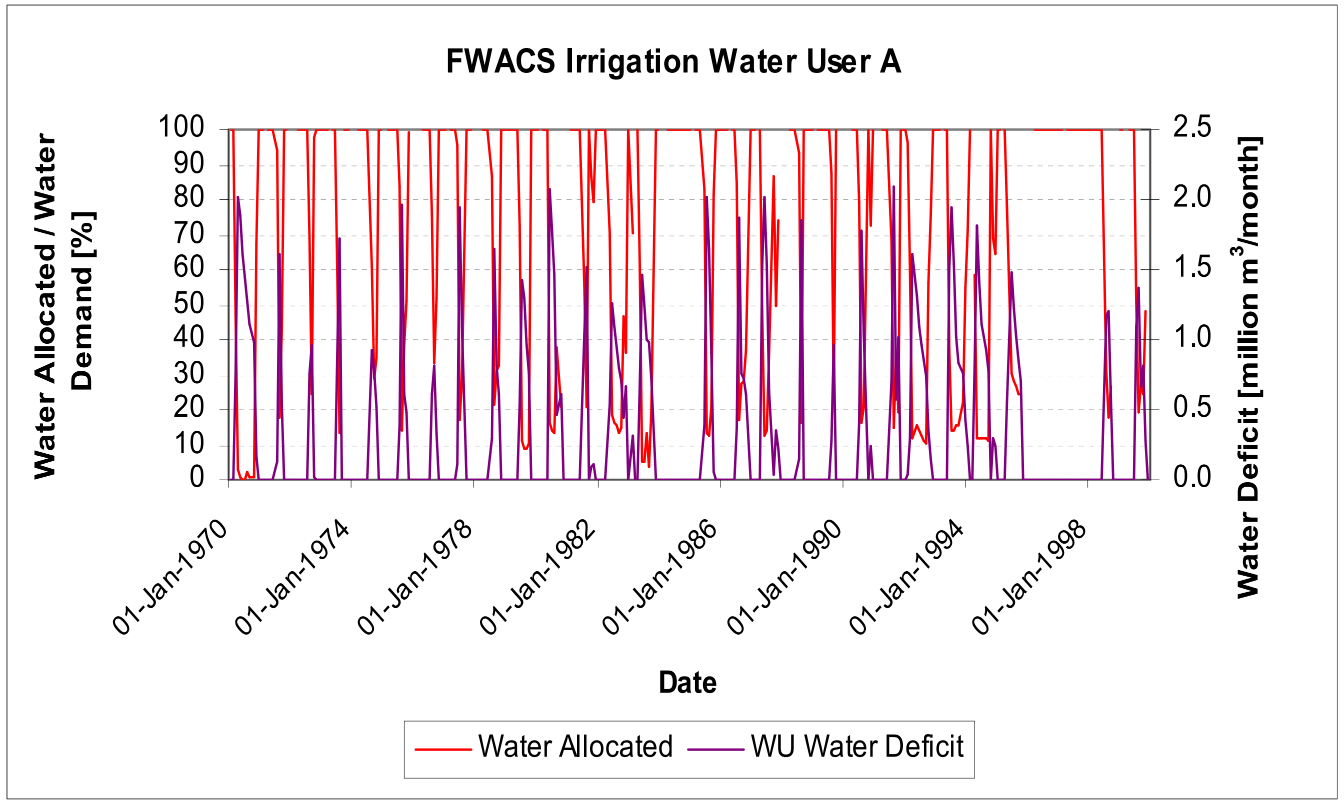

Figure 8-18 Water demand deficit for Water User A in relation to water demanded

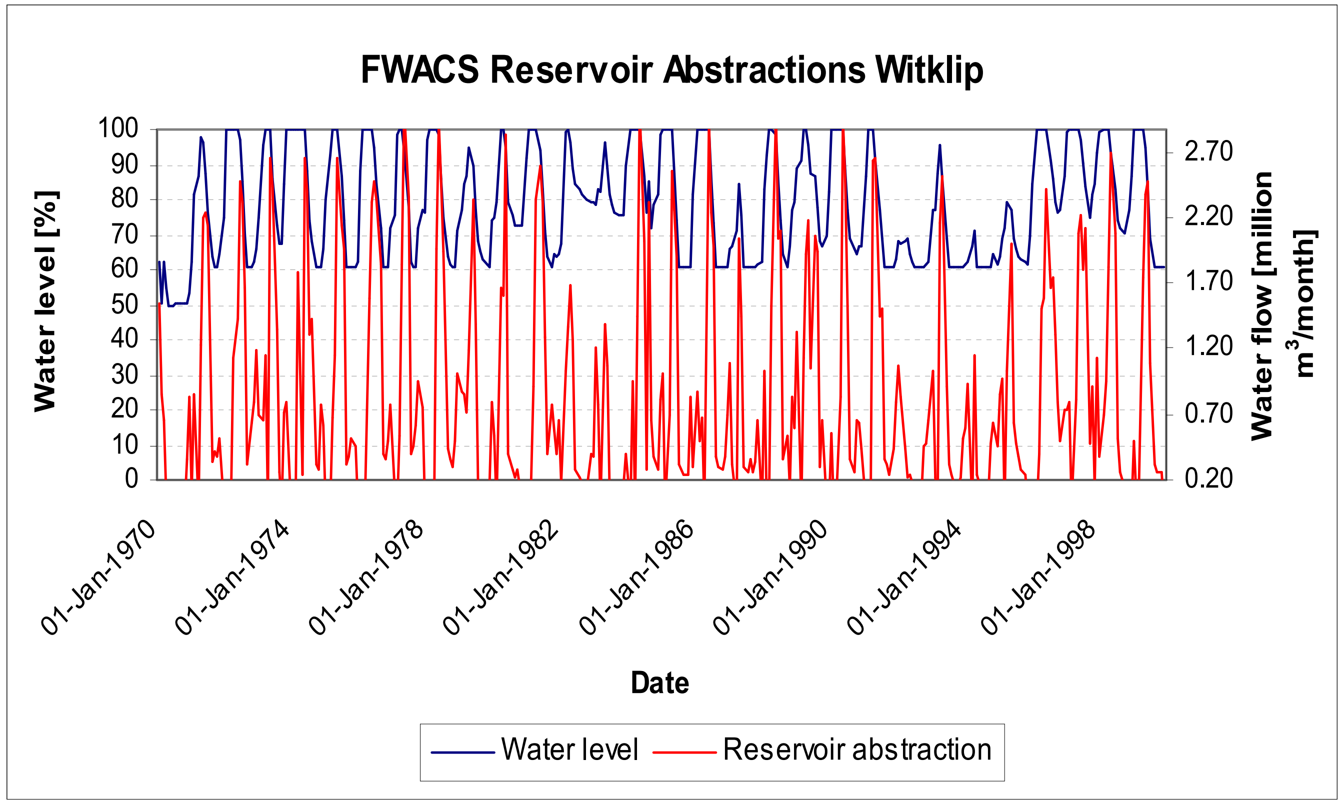

Figure 8-19 FWACS Irrigation Water User A reservoir abstractions and reservoir water level

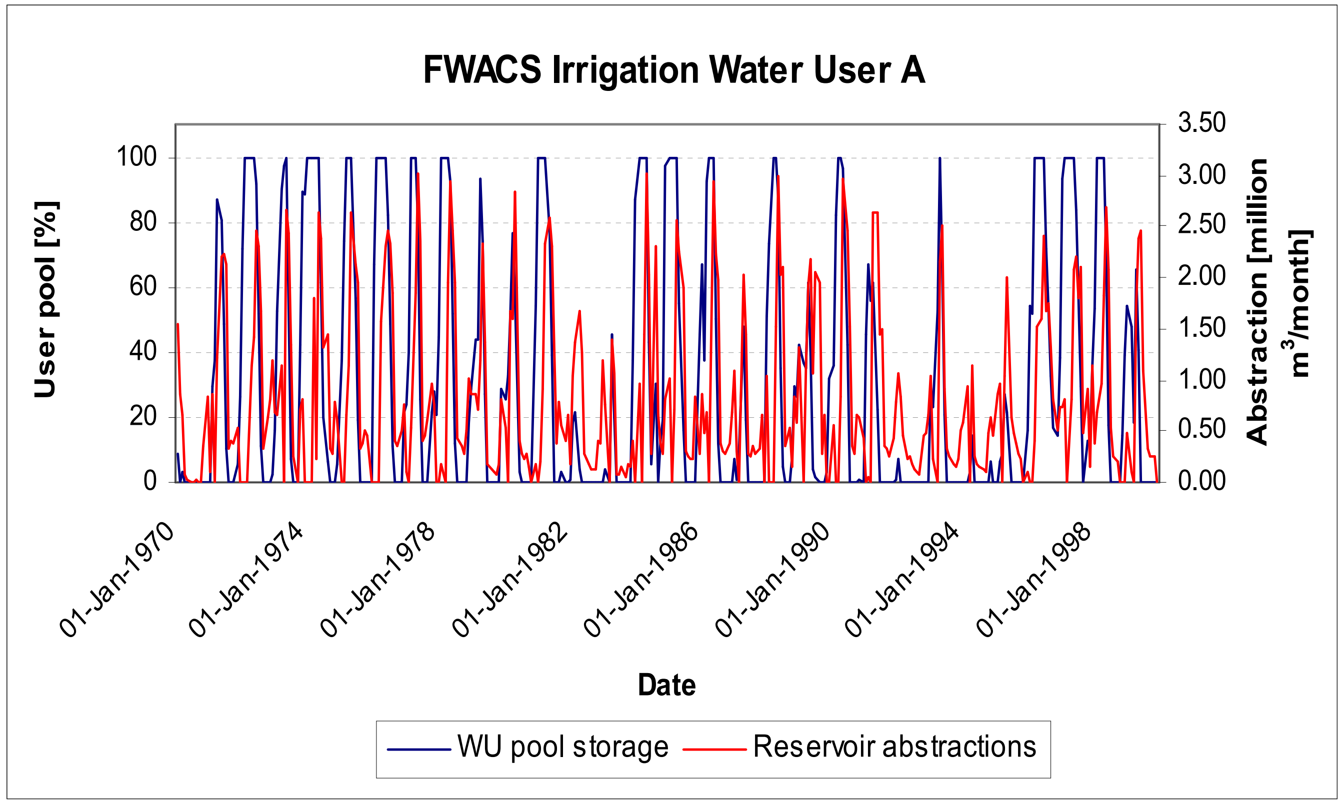

Figure 8-20 FWACS Irrigation Water User A reservoir pool and abstractions

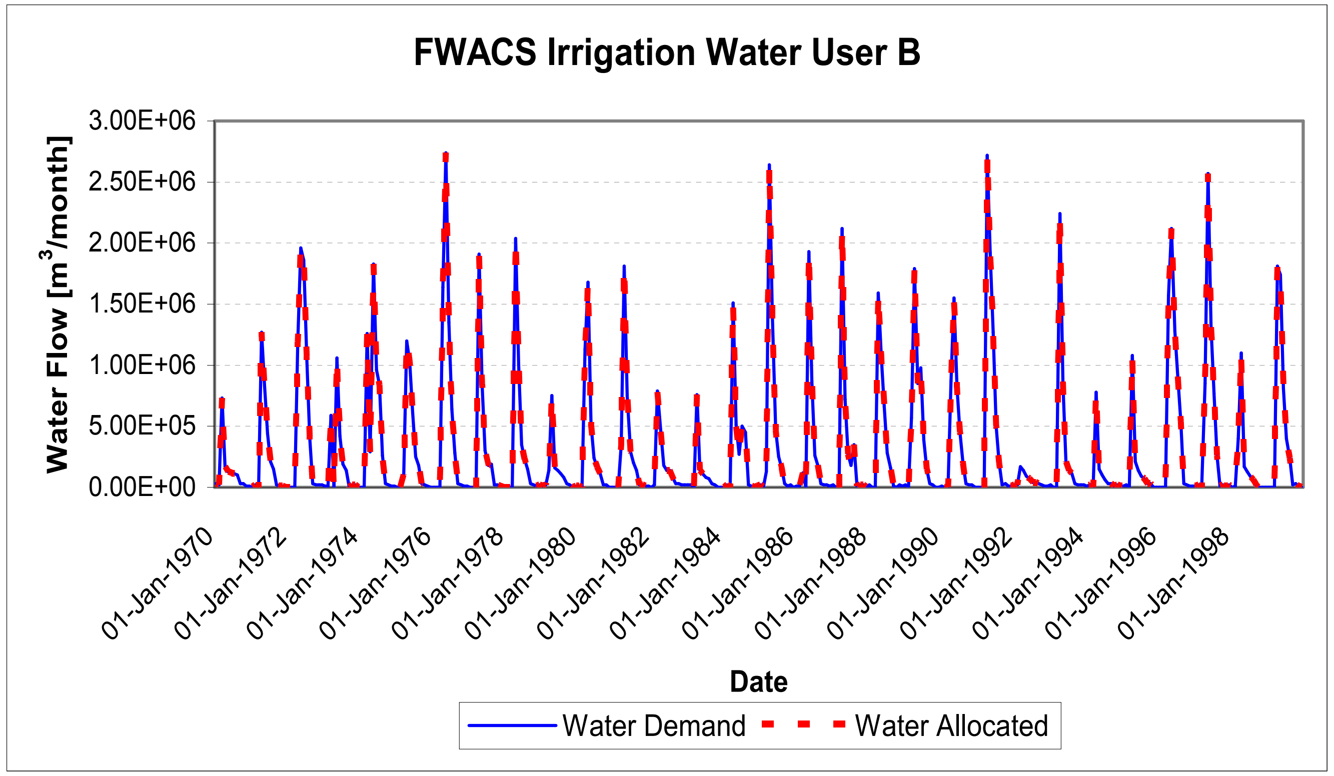

Figure 8-21 FWACS Irrigation Water User B water demand and water used

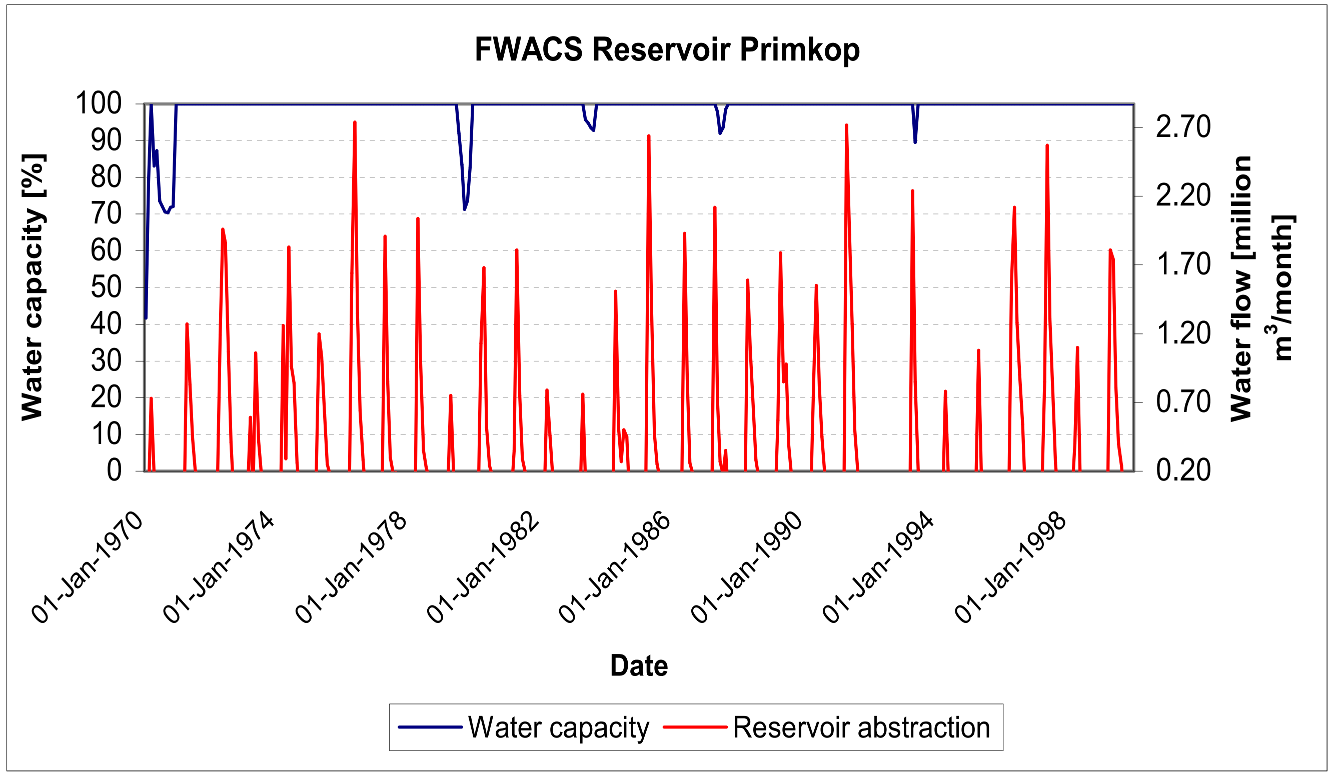

Figure 8-22 FWACS Irrigation Water User B reservoir abstractions and reservoir water level

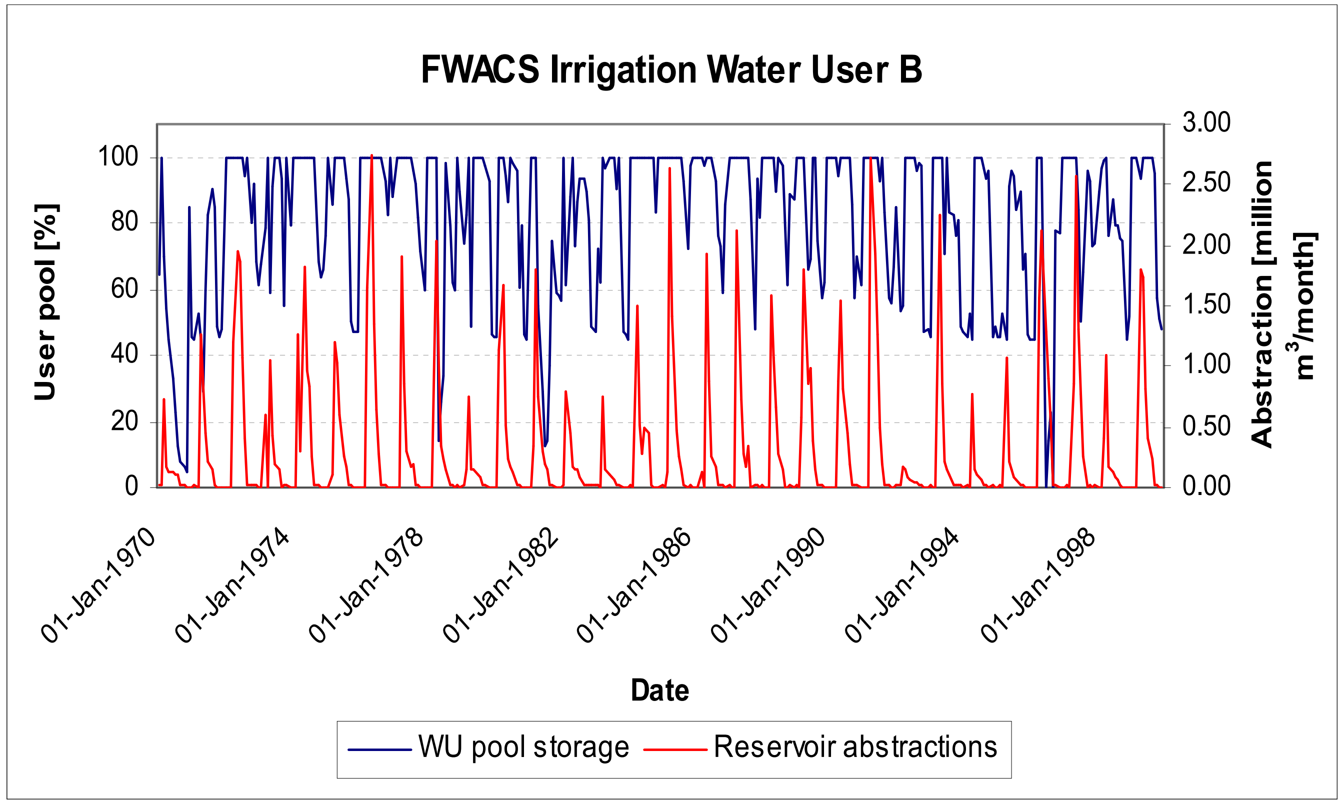

Figure 8-23 FWACS Irrigation Water User B reservoir pool and abstractions

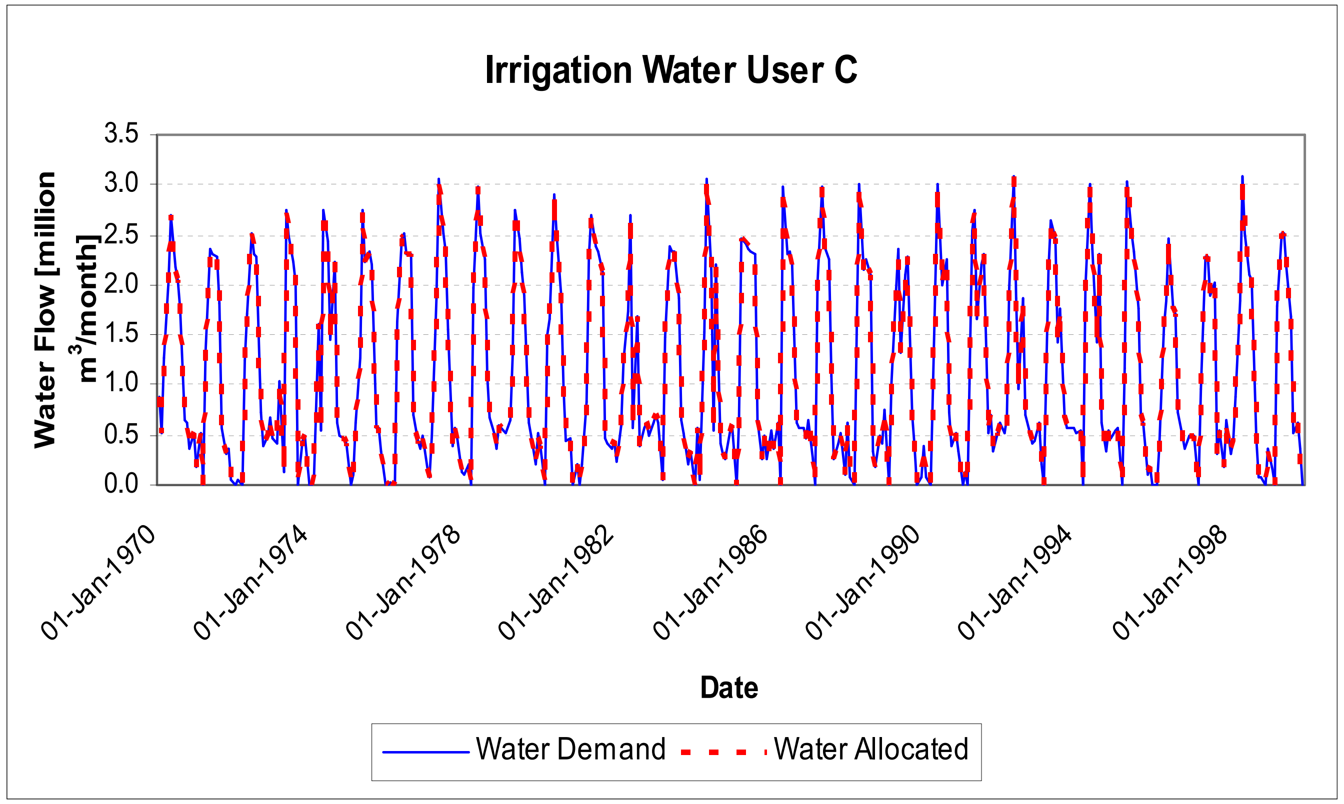

Figure 8-24 FWACS Irrigation Water User C water demand and water used

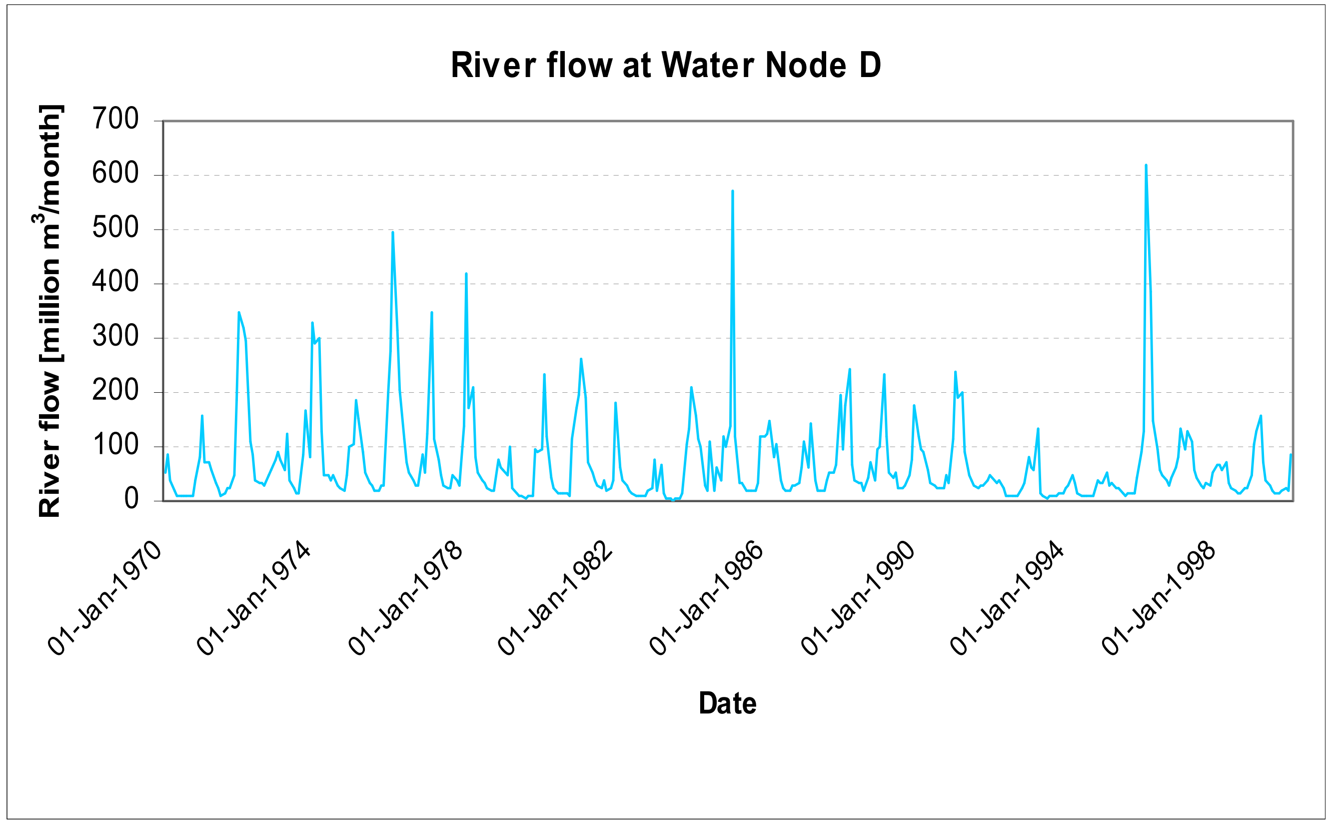

Figure 8-25 Catchment exit Node D river flow

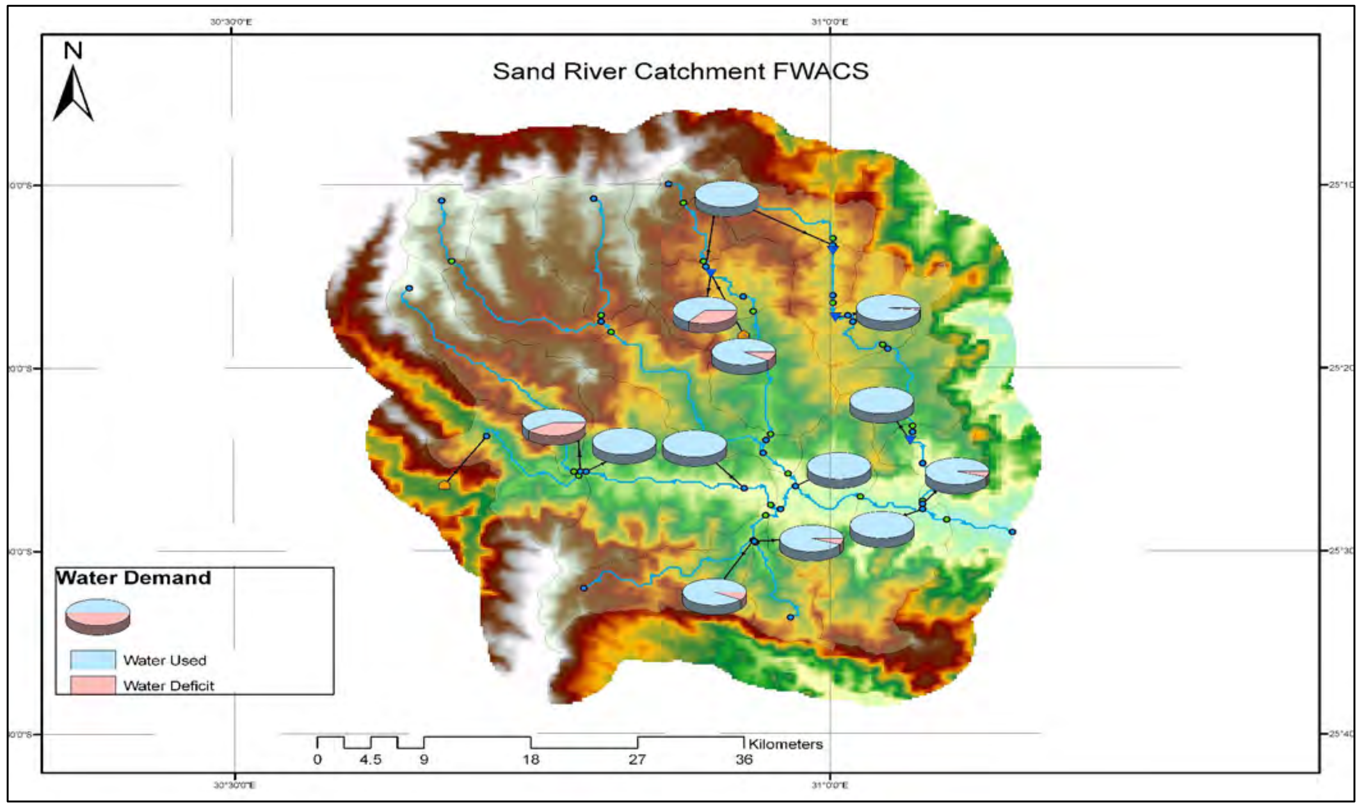

Figure 8-26 Sand River Catchment under FWACS allocation method

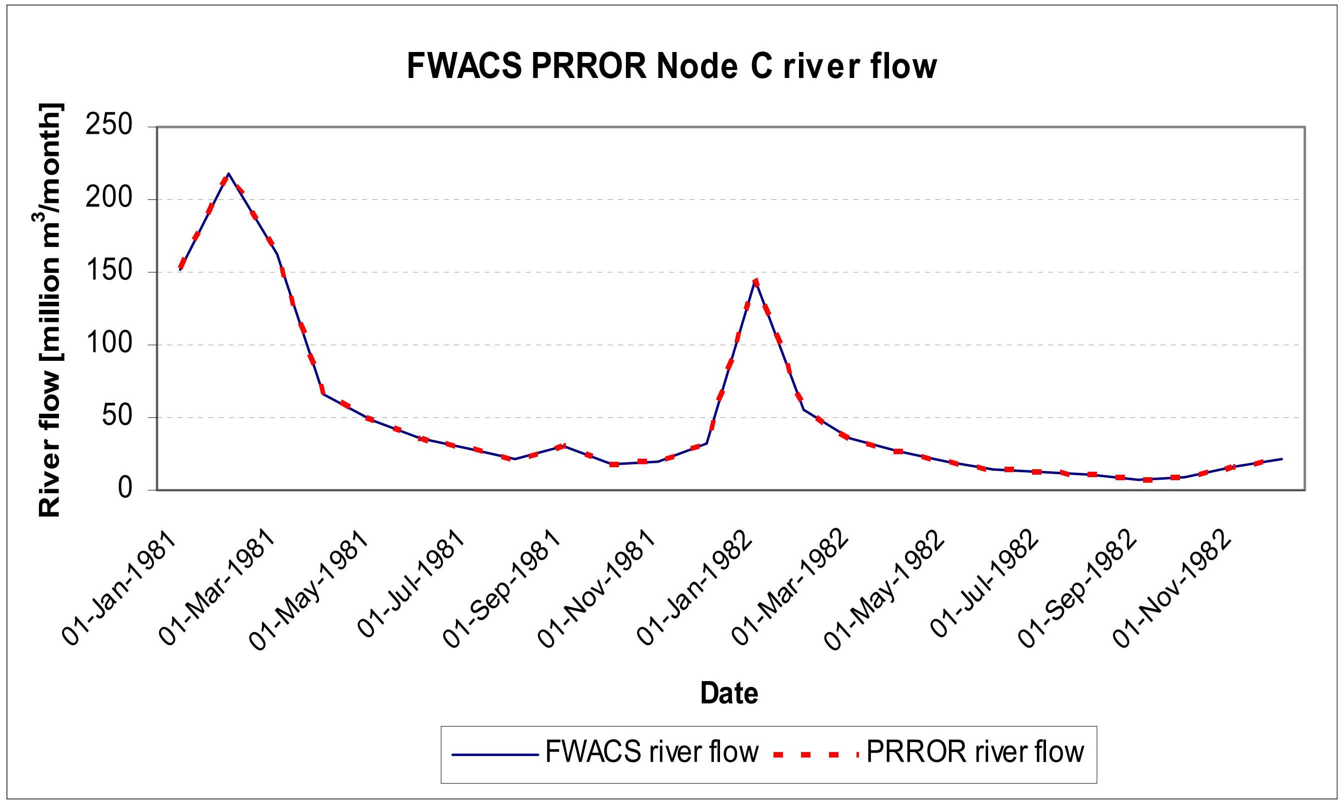

Figure 8-27 River flow for PRROR and FWACS at Node C for two year comparison period

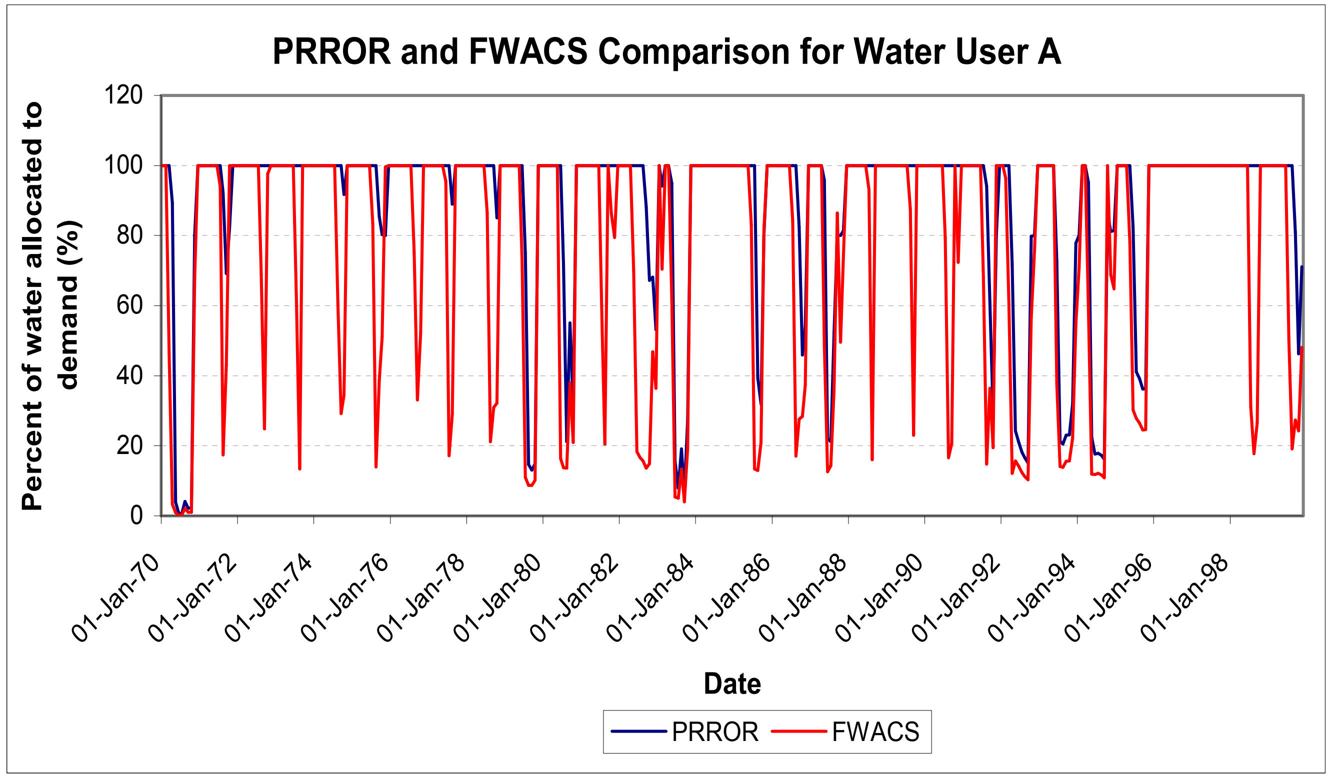

Figure 8-28 A comparison of water allocated in relation to demand between the PRROR and FWACS methods for Water User A

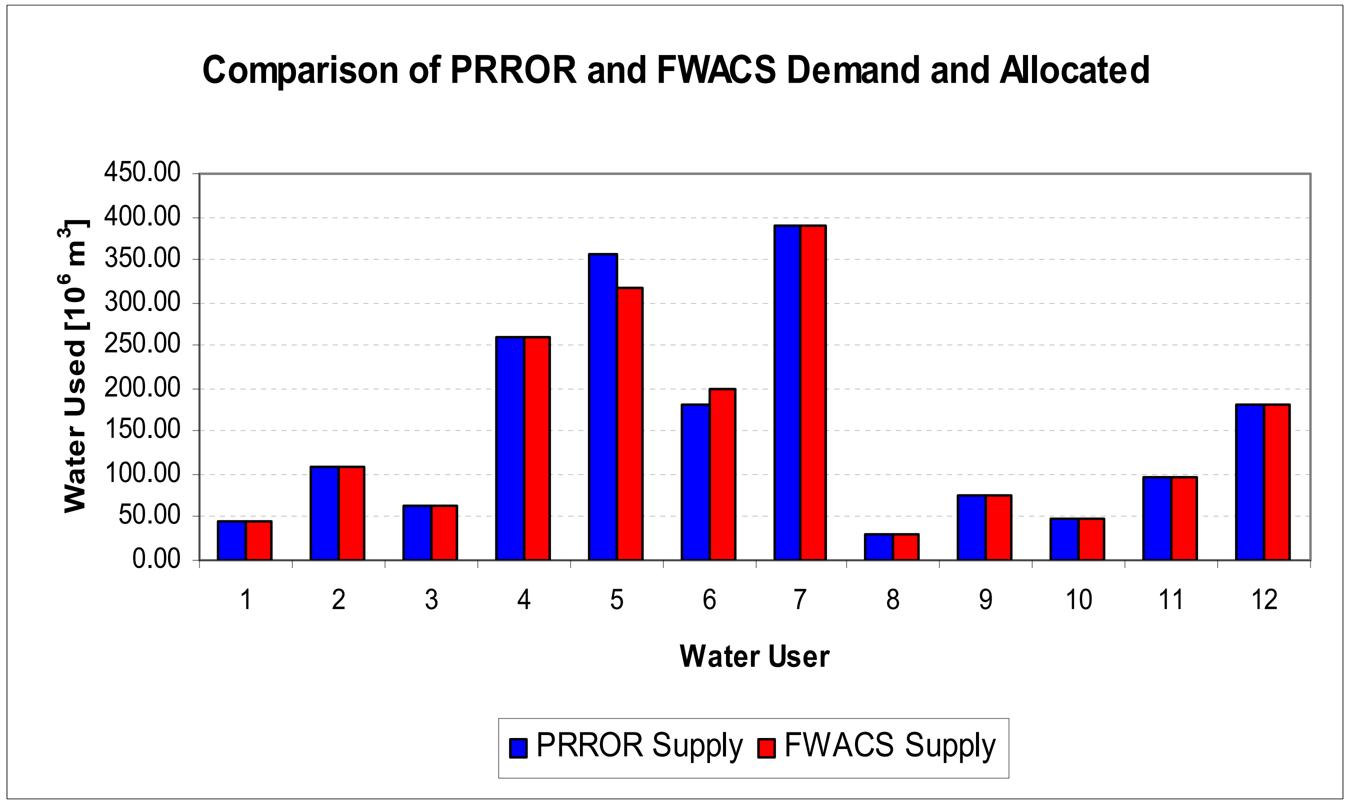

Figure 8-29 Comparison of PRROR and FWACS demand and allocated

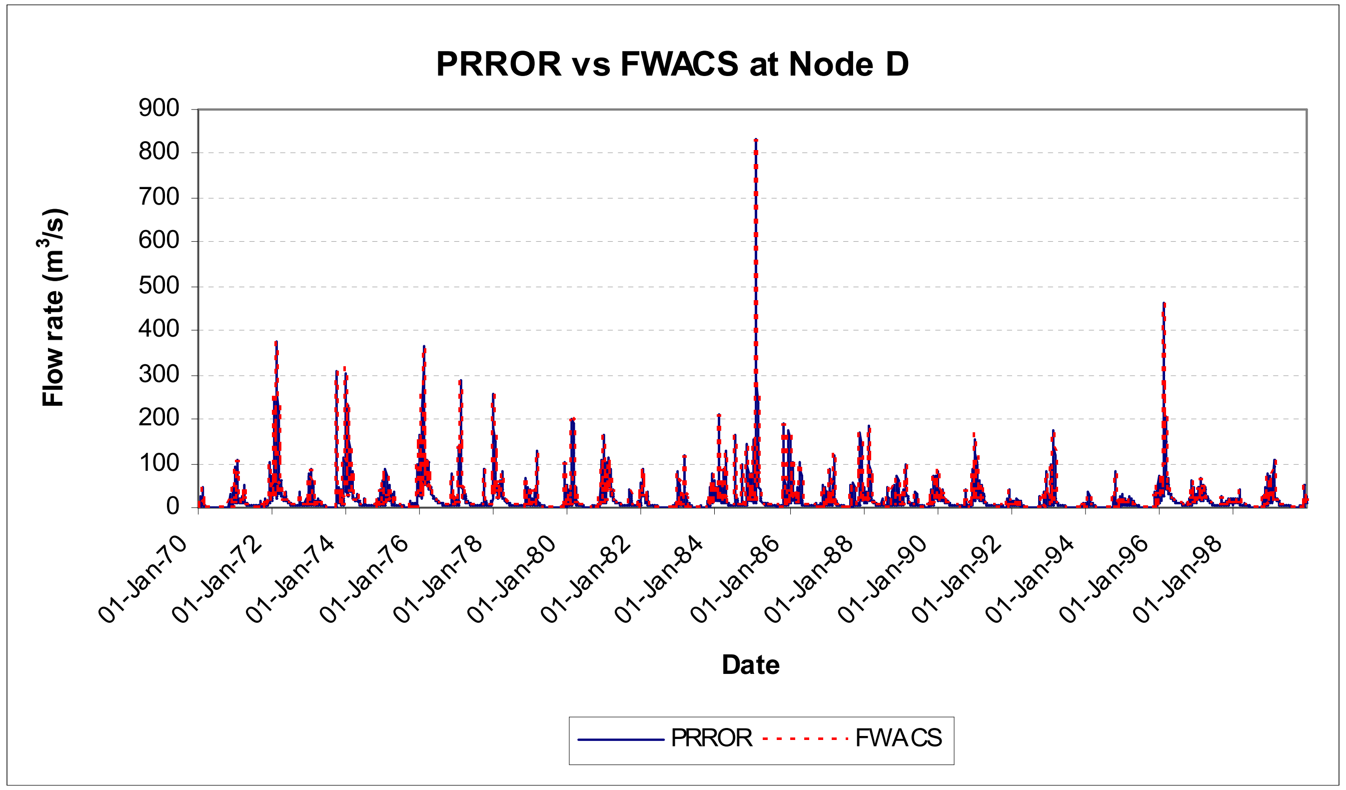

Figure 8-30 Comparison of river flow rate at Node D between the PRROR and FWACS methods over the 30 year study period