AN ASSESSMENT OF INSTREAM FLOW REQUIREMENTS IN THE SABIE-SAND RIVER CATCHMENT

Marco Lourenço Vieira

A Dissertation submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science.

16th of February 2015 in Johannesburg, South Africa

Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Marco Lourenço Vieira

16th day of February 2015 in Johannesburg

Abstract

This dissertation is an assessment of the compliance with and performance of the Instream Flow Requirement (IFR) system and the Building Block Methodology for the Sabie-Sand River. Firstly, a comprehensive exploration of aspects of the ecological system in the Sabie-Sand Catchment is set out and explored in an attempt to garner an understanding of the pertinent ecological components of the river, in the form of a literature review. This is done with a view to gaining insight into where potential ecological failure may occur should flows in the Sabie-Sand be inadequate for ecological maintenance. A range of abiotic and biotic factors are investigated, and the manner in which they might change in response to changing flow conditions is set out.

Evidence in the preliminary work for this dissertation showed that actual river flows were likely to be inadequate to fulfil the requirements for IFR. On this basis, investigations into potential sources of pressure on water resources that may mitigate the potential to fulfil IFR's were explored. Due to changes in South African water law and the changing agricultural landscape in SA, forestry and irrigated agriculture was deemed to play a smaller role than water for sanitation in terms of increasing water use from these sectors since both are now highly regulated and unlikely to grow. Water use for sanitation was seen as a sector with the potential to place greater demand on water resources of the Sabie-Sand River. Upon further investigation, it appears that demand from this sector is also diminishing and is not responsible for placing greater demand on water resources in the Sabie-Sand River, at least during the period of analysis. This is due to shrinking populations and lower levels of sanitation through the period of analysis (1996 – 2001).

IFR compliance at four sites on the Sabie-Sand River showed poor compliance levels with both base and higher flow IFR specifications for both maintenance and drought conditions. The levels of compliance differed across all four sites, with synchronous non-compliance evident. The broad temporal pattern shows that levels of compliance with base IFR's are lower towards the end of the dry season, and that higher flows compliance is always lowest during December and February when specifications are relatively large. This pattern holds for both maintenance and drought years.

In the face of regular IFR non-compliance, abiotic responders such as sediment, dissolved and suspended materials and hydraulic and hydrological features of the Sabie-Sand River have undergone considerable change. Juxtaposed to this, extensive literature searches have shown no recent extinctions of any biota in the Sabie-Sand River although it is evident that some species are finding current conditions in which IFR compliance is low less favourable than in the past. One example is the tree *Breonadia salicina*. From this investigation, it is evident that the biota of the Sabie-Sand River appear to be resilient to low flows, high flows and highly variable flows intra- and inter-seasonally, using various means to perpetuate themselves during these specific flow periods. On the basis of this research, my recommendation is to lower the IFR thereby liberating much-needed water for the people living in the catchment, many of which are in poverty.

Towards the conclusion of the research, the means by which the ecological reserve is maintained in the Sabie-Sand River switched from the IFR system to a less rigid real-time reserve model that specifies flow requirements on weekly time-scales. The required flow volumes under the new management regime are lower than that of the IFR system. This supports my recommendation to lower the IFR.

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The support, love and endless patience that my family has shown over the considerable time that this degree has taken to complete is testament to their loving characters and our bond as a family. I appreciate everything with a kind of gratitude that cannot be adequately expressed in any words or language. I love you all.

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List of Acronyms

BBM	Building Block Methodology
CMA	Catchment Management Agency
DAFF	Department of Agriculture, Forestry and Fisheries
DRIFT	Downstream Response to Imposed Flow Transformations
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
IUCMA	Inkomati-Usuthu Catchment Management Agency
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirement
IQWS	Institute for Water Quality Studies
GIS	Geographical Information System
KNP	Kruger National Park
KNPRRP	Kruger National Park Rivers Research Programme
MAR	Mean Annual Runoff
MCM	Million Cubic Metres
mm	millimetre
m^3/s	cubic metres per second
NWRS	National Water Resource Strategy
p.a.	per annum
PHABSIM	Physical HABitat SIMulation Model
POM	Particulate Organic Matter
RCC	River Continuum Concept
RVA	Range of Variability Approach
SA	South Africa
SAM	Strategic Adaptive Management

SFRA	Stream Flow Reduction Activity
SO	Southern Oscillation
SPAM	Scientific Panel Assessment Method
TPC	Threshold of Potential Concern
USA	United States of America
VIP	Ventilated Improved Pit
WEAP	Water Evaluation and Planning System
WRMAIS	Water Resources Monitoring and Assessment Information System
ZAR	South African Rands

Note: Reference is made to DWAF, the Department of Water Affairs and Forestry, and DWA, the Department of Water Affairs. After the May 2009 SA general election, DWAF was split and Forestry merged with Agriculture and Fisheries. In May 2014, the Department once again changed name to become the Department of Water and Sanitation.

1. Chapter 1 – Introduction

1.1. Rationale

South Africa is a semi-arid country supporting a large and growing population that is predominantly poor, relying on clean surface water (World Resources Institute 2005). Average annual rainfall for the country is approximately 450 millimetres per annum (mm p.a.), and recent calculations show a population of 52,83 million people growing at a rate of 1.34% for the year 2013 (DWA 2013; StatsSA 2013). If we use the StatsSA definition of "upper-bound poverty", which equals ZAR 577 of expenditure per person per month, 52,3% of South Africans would be considered poor (StatsSA 2012). Upper-bound poverty is defined as the household expenditure needed to fulfil the required energy intake for one person for one month, plus the average expenditure on non-food items of a household whose total monthly food expenditure is equal to the food poverty line of ZAR 305 (StatsSA 2012).

An improvement on this state of affairs will require a concerted and cohesive effort by government to provide adequate and clean water for all South Africans into the future as a baseline from which to reverse poverty figures, improve access to sanitation and economic opportunity and improve the general health of the population. Management of freshwater resources is thus very challenging in this developing country with many competing interests and lingering inequity issues (Dungumaro 2007). The Sabie-Sand River Catchment is a microcosm of the problems facing South Africa, since it exhibits many of the issues facing the country albeit at a smaller scale, including the extension of service delivery to under-resourced areas, alleviation of poverty, maintenance of water supply infrastructure and provision of sufficient water for environmental maintenance. For this reason, it offers a very interesting and informative case study, providing a template for management of multifaceted catchments where ecological and human systems may be in conflict. Besides this reason, the Sabie-Sand Catchment was one of the first to use the Building Block Methodology (BBM), one of a relatively new family of holistic river flow assessment models (King et al. 2008). These models are the most comprehensive and are believed by many aquatic managers and scientists to be the tool of choice for successful river management. Arthington (1998) even went so far as to say "there does not appear to be any competing paradigm for environmental flow assessment and management within the context of sustaining water-dependent environmental systems". Perhaps as a result of the high regard such methodologies are held in, the state of research in the field has not advanced significantly since the advent of holistic methodologies. These methods and their application in diverse multi-stakeholder environments are therefore primed for critical evaluation. By evaluating Instream Flow Requirements (IFR) compliance for the Sabie-Sand River and the over-arching Strategic Adaptive Management (SAM) framework in which IFR's are used, this dissertation will make a contribution towards filling that gap.

A part of the challenge in managing the Sabie-Sand River Catchment lies in the variety of different stakeholder types (i.e. residential households, forestry plantations, subsistence farming, commercial agriculture and a national park) present in the catchment (le Maitre et al. 2002). Importantly, the catchment supplies much of the daily water requirements for a population of approximately 650 000 people. Also significant is the fact that it is the largest river flowing through the Kruger National Park (KNP), which is one of South Africa's most valuable natural areas and certainly one of its biggest tourist attractions, attracting approximately one million visitors annually since the year 2000 (du Toit et al. 2003). The Sabie-Sand River is also the most fish species rich (49 species) river system in South Africa (Rivers-Moore and Jewitt 2007), serving as another example of the necessity for good management to maintain the biological integrity of the catchment while providing water for all stakeholders in sufficient quantity (Kamara and Sally 2003). The river catchment area is shared with Mozambique and so the effects of management practices are not confined only to South Africa, although the effects that are manifest beyond the South African border will not form part of this dissertation.

The management protocol for this catchment, and indeed all basic human needs and ecological Reserves for catchments, needs to balance the needs of all stakeholders. Ecological water management protocols in South Africa are developed using the Instream Flow Requirement (IFR) method which is guided by the South African National Water Act of 1998 (No. 36 of 1998). The IFR is the guideline that catchment managers use to maintain the ecological portion of the Reserve. The basic human needs and ecological Reserve are flows that are specified in terms of timing, duration, quality and volume with the aim of maintaining sufficient water of amenable quality in the river for basic human consumption as well as the ecological integrity of the river and its biota (DWAF 1998).

In accordance with Part 3: The Reserve of Chapter 3 of the SA National Water Act of 1998 (No. 36 of 1998), management of the water resources of a catchment must strive to ensure that both basic human needs and ecological components of the Reserve are always met (DWAF 1998). This is an attempt to guarantee that all of the stakeholders in the catchment have the necessary water for household requirements and other activities including plantation forestry, as well as subsistence and commercial farming. These requirements however, can only be met after the Reserve has been fulfilled as well as any international obligations to neighbouring states. Meeting the Reserve would also mean the concurrent achievement of meeting environmental sustainability in the Sabie-Sand River in the KNP as well as ensuring that we meet our international obligation to send sufficient water to Mozambique. The preamble to Chapter 1 of the National Water Act of 1998 (No. 36 of 1998) stipulates that river ecosystems are to be maintained in a healthy state, and provides assurance that ecological sustainability is and can be maintained.

All of the goals outlined above are explicit in the National Water Act of 1998 (No. 36 of 1998) which replaced the antiquated Water Act of 1956 (No. 54 of 1956). The Water Act of 1956 (No. 54 of 1956) was adapted from European law and countries where water is relatively abundant, and this was not suitable for South Africa where water is an overallocated resource. Furthermore, the Water Act of 1956 (No. 54 of 1956) ensured access to water for small groups of economically powerful users, i.e. private water rights over which the state had limited control, with inadequate access to members of the population that did not own land, i.e. all black South Africans (at the time of the Water Act of 1956 (No. 54 of 1956)). As a result of the major shifts in policy that came with the advent of democracy in South Africa, the National Water Act of 1998 (No. 36 of 1998) advanced a number of major ideological and practical elements aimed at redressing the inequitable access to water due to the Water Act of 1956 (No. 54 of 1956). Some examples of this include the change from a riparian rights-based law, where the owner of land on which a body of water was situated had the right to use that water as they pleased. The National Water Act of 1998 (No. 36 of 1998) views water as a common property resource and licences to use the resource must be applied for from the Department of Water and Sanitation even if that water is situated on land owned by the applicant. The only right that citizens have to water is found in “Part 3: The Reserve” of Chapter 3 of the National Water Act of 1998 (No. 36 of 1998). This is for the purposes of drinking, hygiene and food preparation as the basic human needs component of the Reserve. A paradigm shift in terms of ideological aspects of the law include a change from an emphasis on supply side matters such as government building dams and other large infrastructure (eg: pipelines, reservoirs), to national government and other water services institutions at local level creating awareness among the populace about demand side management strategies such as the implementation of tariff structures that curb wastage, and other measures that reduce inefficient and uneconomical water use. Although the National Water Act of 1998 (No. 36 of 1998) was promulgated some 15 years ago, the magnitude and nature of the change from its 1956 predecessor (Water Act of 1956 (No. 54 of 1956)) has meant that many aspects of the National Water Act of 1998 (No. 36 of 1998) have been difficult to implement (Bohensky and Lynam 2005).

Due in some part to this major ideological shift and diminishing technical expertise in water resources management in South Africa, the new water legislation and IFR system have proven very difficult to enforce and demand for water almost always exceeds supply. Since the basic human needs and ecological Reserve is prioritised in "Part 3: The Reserve" of Chapter 3 of the National Water Act of 1998 (No. 36 of 1998) (DWAF 1998), followed by water available for industry and commercial food production, this state of affairs is ongoing and requires urgent attention and intervention. Significant human population growth in the catchment area will in all likelihood exacerbate the problem of a scarcity of water for all stakeholders. Furthermore, if the complexity of climate change is added to the problem, the implementation of management directives will be fraught with difficulty. North-eastern South Africa is set to experience an increase in rainfall, with more intense storms with shorter dry periods (Davis 2010). This type of rainfall is conducive to flooding, and flood flows are difficult to manage and contain for human uses.

Management and allocation of freshwater in SA is an almost intractable problem. South African water legislation is held up as an example worldwide, yet we struggle with implementation. Managers are also challenged by the relatively high magnitude of interannual and seasonal variation in discharge, a characteristic of South African systems (Puckridge et al. 1998). The consequences of improper management of catchment IFR's includes the potential violation of South African legislation and threats to biodiversity (Hope et al. 2008). In addition, mismanagement of flows in the Sabie-Sand River could also cause the risk of a lack of proper water supply and sanitation, and reduction in business potential. This status quo is unacceptable, especially in a catchment that includes the KNP. This project will quantify and explore potential sources of pressure on water resources in the catchment (Chapter 2), evaluate the spatio-temporal compliance at the prescribed IFR sites (Chapter 3), and finally explore, using a literature study, the possible ecological effects of changes in flow and the efficacy of SAM as a management paradigm in the Sabie-Sand River catchment (Chapter 4). Section 1.4 on page 57 gives a detailed dissertation outline.

1.1. Project Aim

The aim of the project is to assess spatial and temporal compliance with instream flow requirements for the Sabie-Sand River, and explore the ecological consequences of meeting or not meeting the IFR.

1.2. Project Objectives

1) What are the flow dynamics and ecology of the Sabie-Sand River, and how do these change in response to changes in streamflow?

2) Explore potential future pressure on Instream Flow Requirement compliance using domestic sanitation as a case study.

3) Evaluate the spatio-temporal compliance of observed flows from 1978 to the present against Instream Flow Requirements.

4) What are the potential ecological implications of compliance or non-compliance with IFR, and by extension, changes in flow volume?

1.3. Literature Review

1.3.1. Overview of Sabie-Sand River Catchment characteristics:

South Africa is a large country (1 221 037 km^2), and encompasses a large range of precipitation (Compact World Atlas 2006; Schulze and South Africa 2008). This varies from less than 100 mm per annum in parts of the Northern Cape to more than 1200 mm per annum in northern Kwazulu-Natal, Mpumalanga and Limpopo Provinces (Schulze and South Africa 2008).

For the purposes of this investigation, I will focus on the Sabie-Sand River Catchment (7 096 km^2). Rainfall in this catchment falls opposite to the general east-west aridity gradient for the entire country (as shown in Figure 1.1). This highlights the need for fine-scale resolution of problems pertaining to water management and provisioning of services (Schulze 2000). The National Water Act of 1998 (No. 36 of 1998) (DWAF 1998) devolves management of water resources to finer-scale units such as Catchment Management Agencies (CMA's) as opposed to national level bodies such as the Department of Water and Sanitation in a bid to address local nuances and requirements (Schreiner and van Koppen 2002; Pollard and du Toit 2005).

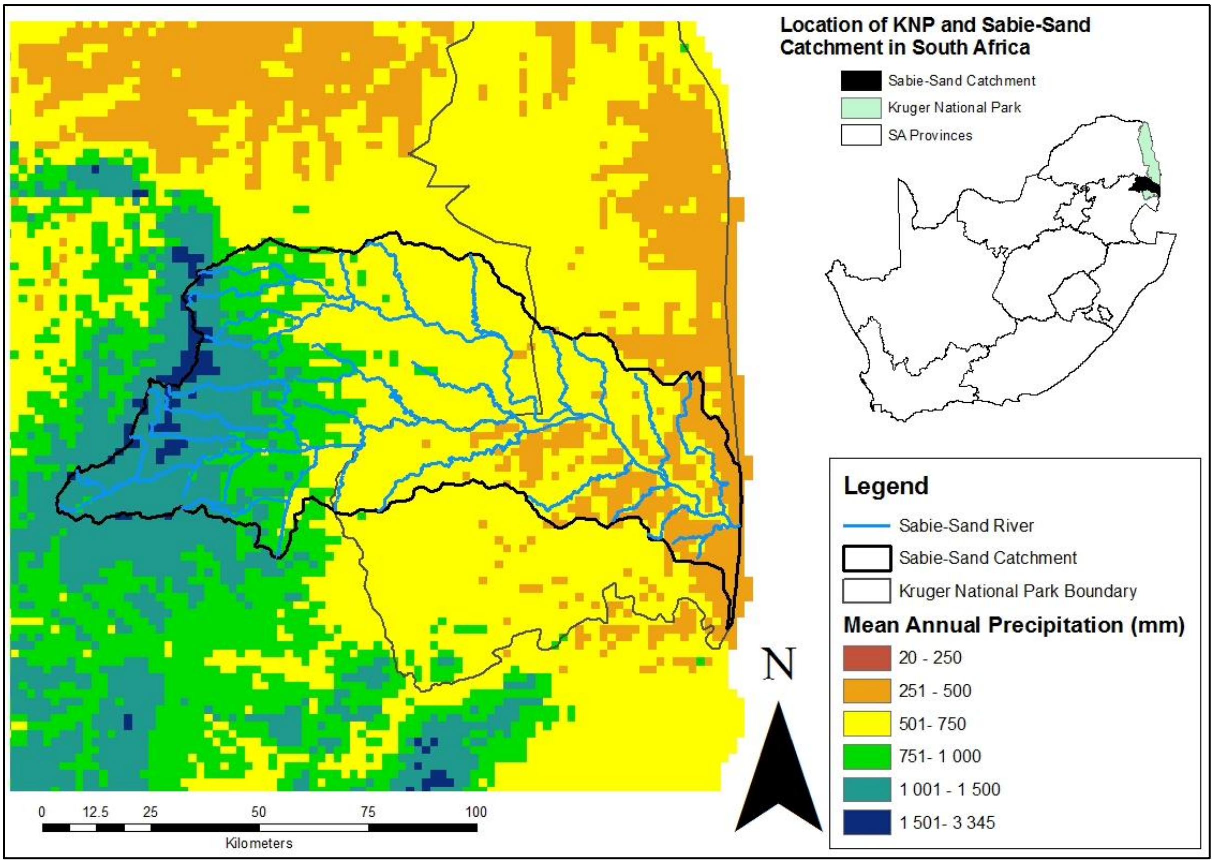

Figure 1.1. Map showing the Sabie-Sand River Catchment, its location within South Africa and mean annual precipitation for the catchment. Derived from the South African Atlas of Agrohydrology and Climatology (Schulze 2008).

Orographic precipitation associated with the Drakensberg Mountains in the west of the catchment accounts for the higher rainfall areas of the Sabie-Sand Catchment (Heritage et al. 1997; Smakhtin et al. 1998b). Occasional cyclonic intrusions into the eastern part of the country bring heavy but localised rainfall (Shackleton 1999). Rare and very light snowfall may occur on the western highground (Mpumalanga Highveld) of the catchment.

The western part of the catchment is characterized by large-scale pine and eucalyptus plantation forestry which cover approximately 16% of the catchment (le Maitre et al. 2002). The water demand from forestry is reported to have reduced flows adjacent to plantations in the upper tributaries of the Sabie River by between 17 and 45%, and by 31% in tributaries of the Sand River (Moon et al. 1997; le Maitre et al. 2002). Virgin flow in the Sabie River is estimated to be approximately 606 million m^3 per annum, and around 158 million m^3 per annum in the Sand River (Pollard and Walker 2000). This amounts to forestry-related losses of between 103 and 273 million m^3 per annum for the Sabie and 49 million m^3 per annum in the Sand River Catchment. About a third of the Sand River length is under conservation in the KNP, while 57% of the Sabie River's length in South Africa flows in KNP (le Maitre et al. 2002). In the middle reaches, in the southern part of the catchment (see Figure 1.2), irrigated sub-tropical fruit production prevails in commercial agricultural areas, while subsistence agriculture is practised in the high-density communal lands further north in the Sand River sub-catchment, and adjacent to the border of KNP (le Maitre et al. 2002). Irrigated agriculture uses about 14% of the natural flow in the Sabie-Sand Rivers, while only 1% is used for residential use and livestock production (le Maitre et al. 2002). This again emphasizes the inequality of the current apportioning of water since a larger proportion of water is consumed by tertiary users in forestry and commercial farming while many poor people have inadequate access to water for drinking and cooking purposes. Even though water and sanitation infrastructure for the poor has always been underdeveloped in the catchment, current levels of water exploitation have left very little water, at low assurance of supply, for their use and this is compounded by delivery problems.

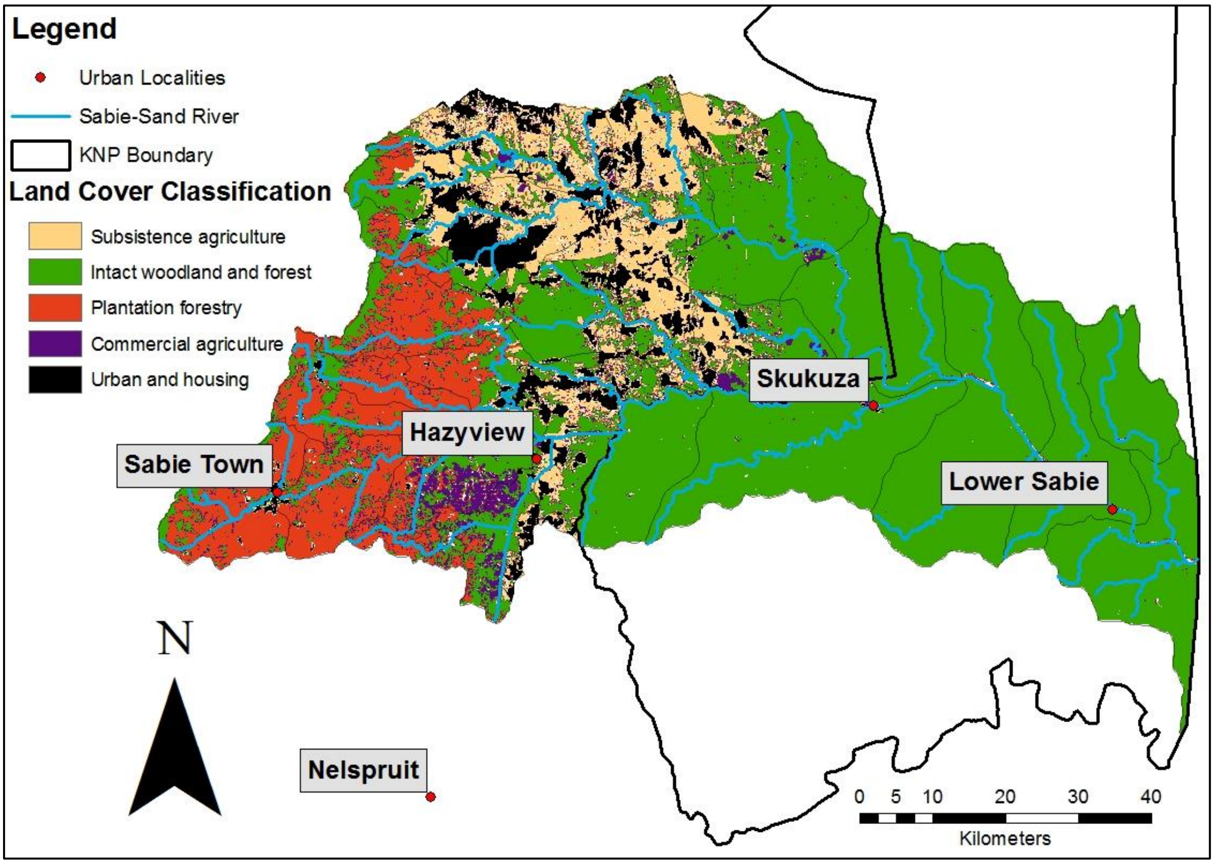

Figure 1.2. A map of the study region showing urban centres and dominant land use in the Sabie-Sand River Catchment. Derived from the National Land Cover classification (2006).

Dams are important for water storage and diversion, flood management, hydropower generation (not in the Sabie-Sand River) as well as ensuring the flows required to maintain IFR's. There are over four hundred impoundments and natural non-perennial water bodies in the Sabie-Sand Catchment. Impoundments play an important role in the catchment, since most of them are filled using water either pumped directly from the Sabie-Sand River and its tributaries, or are built on the smaller tributaries of the main river. As a result they are responsible for exacerbating seasonal attenuation in flows, and in some instances the complete prevention of flow by interception. These dams are concentrated in the forestry region of the Sabie-Sand River catchment. The Kruger National Park has the lowest density of impoundments in the catchment area. The majority of the impoundments in the catchment are small-scale and therefore not directly managed by the Incomati-Usuthu Catchment Management Agency or Department of Water and Sanitation (DWS) but rather by the owner of the land on which the impoundments are found. Two large dams in the Sabie-Sand River catchment are operated by DWA for a range of purposes, and one of these purposes is the maintenance of the IFR's. While this study does not specifically examine aspects of the dams and their management, since the IFR's are maintained through the dams owned by DWA a brief description of the two dams operated by DWA will follow. The dams remain the most direct means by which to manage flows so as to meet IFR's; other operations such as managing land cover in the catchment could have an affect but this would be difficult to measure.

Inyaka Dam on the Marite tributary has a capacity of 124 million m^3 (see Figure 1.3), and was built with the primary purpose of providing domestic water to the Bushbuckridge Municipality region. This dam, officially opened in 2002, is adjacent to the town of Bushbuckridge and serves on the order of 500 000 people with drinking water. In addition to this, it has also allowed 2000 additional hectares of irrigated land to be utilised in the catchment with concomitant benefits for job creation.

Da Gama Dam (capacity 13.5 million m^3) was built in 1967 and is found in the upper southern region of the catchment. The dam is on the White Waters tributary of the Sabie River. It is surrounded by plantations, and supplies the forestry industry and the irrigation needs for commercial farming operations that are situated in the vicinity of the dam. In most years, almost none of the water that flows in the White Waters tributary is available for users downstream of the dam as it is completely utilised by the plantation managers and farmers in the upper reaches (Woodhouse 1995).

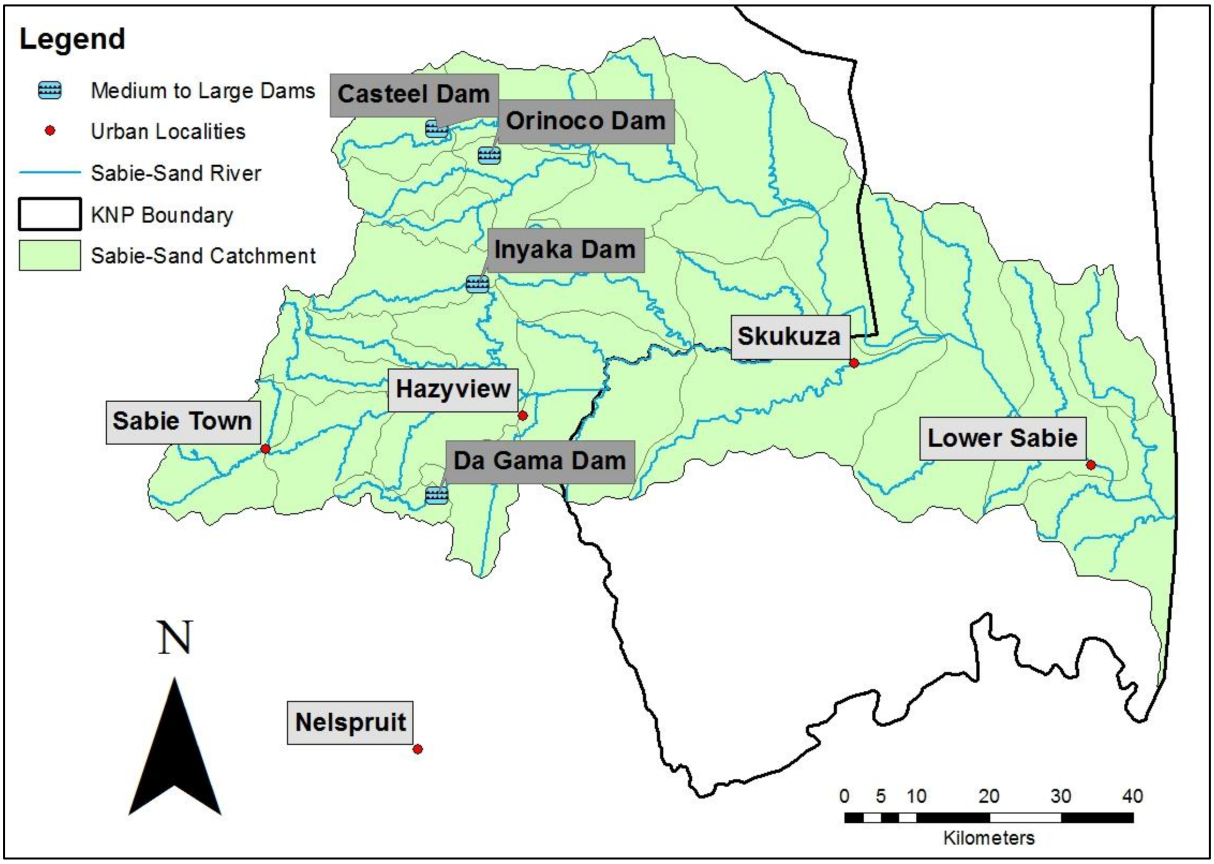

Figure 1.3. A map of the study region and the two major dams managed and operated by Department of Water and Sanitation on the Sabie-Sand River system.

A number of smaller dams such as Orinoco Dam (capacity 1.62 million m^3) on the Mutlumuvi Stream, and the Casteel Dam (capacity 1.35 million m^3) on the Tlulanziteka Stream were built during the apartheid era in the former homeland of Gazankulu (Pollard et al. 2008). Their purpose is solely for agricultural irrigation and they are now under control of the Department of Agriculture, Forestry and Fisheries (DAFF) (Pollard and Walker 2000). These dams and the smaller privately owned dams are not used in the management of IFR flows because the water in them is under the jurisdiction of another department and therefore cannot be allocated for a purpose that is the responsibility of DWA. In addition, these dams are far smaller than either the Da Gama or Inyaka Dams and so would not be useful for the purposes of IFR management. This is because large proportions of their stored water would be used in the maintenance of IFR’s leaving very little water for irrigation purposes. These dams will not be discussed further.

1.3.2. Change in water use per user sector in the Sabie-Sand River Catchment as a potential source of pressure on IFR compliance:

Compliance with IFR specifications is necessary if we are to maintain the Sabie-Sand River in an ecologically viable state. Identification of large water users in the catchment is crucial so that effective strategies to manage unreasonably large demand can be devised. This will help to equitably share water so that water is available for all sectors and users therein while complying with IFRs.

With the advent of the National Water Act of 1998 (No. 36 of 1998), legislation has successfully stabilised water use by the forestry and irrigated agriculture sectors by requiring that operators in these sectors obtain water use licenses or at minimum register their water uses to have the volumes verified in the case of irrigation (FSA 2013; le Maitre et al. 2002). Since these sectors make use of mainly groundwater or direct abstraction from streams, the water use licensing system has been effective in curbing their water use since stringent license conditions have reduced the granting of new licenses to a trickle while simultaneously ensuring that water use license holders in these sectors use water more efficiently. Legislation and increasing water tariffs for forestry and irrigated agriculture will likely prove to be the most effective long-term means of stabilising and even reducing consumption in the sectors. Other factors have also led to the decline of forestry in the Sabie-Sand River including but not limited to the global financial crisis and lower demand for forestry products, importation of cheaper timber products from other countries and the uncertain current status of land restitution and expropriation (in Mpumalanga, Limpopo and Kwazulu-Natal) in the sector, hampering investment and development (FSA 2013). Forestry South Africa has recorded declines in production country-wide for three consecutive years including 2013 (FSA 2013). Coetzer et al. (2010) also report a decline in plantation forestry in Mpumalanga in their landcover analysis.

Allthough their work suggests that real declines are difficult to quantify since forestry practises show cyclical afforestation and clearfelling, the declines are between 2.0 and 7.1% in 2006 from 1993 figures.

Irrigated agriculture is on the decline in the Sabie-Sand River Catchment, possibly also as a result of land claims and expropriation although this is not confirmed in reputable sources but nevertheless present in a number of mainstream media articles and grey literature (du Toit 2004). Information in this regard is difficult to come by, but Chapman (2006) states that while still in a semi-functional state, the Sand River Irrigation Scheme is utilised, but highly inefficient. The scheme is comprised of four small dams in the catchment with a total combined storage of 6.19 million m^3 (compared to the 124 million m^3 capacity of the Inyaka Dam). Flood irrigation is the method for the scheme, and this is highly wasteful and not cost-effective. Coupled to this is the state of the canals, diversion weirs and distribution infrastructure, which will be too expensive to repair from their current state (Chapman 2006). Since repairs or extensions are too costly, it is fair to assume that the Sand River Irrigation system is showing stable water use volumes; no additional dams have been built to augment the scheme since no funds are available to do so (Chapman 2006). Government has expressed that they wish to encourage small-scale farming, and so funds may be made available for repairs and maintenance to the scheme. If this is the case, it is likely that at least some of this money will be utilised to convert the scheme into a more efficient one, likely by the use of drip irrigation and so investment in the scheme may not necessarily mean it uses more water. As for irrigated agriculture in the the Sabie River catchment, it has historically been a large water user and employer albeit at a smaller scale than the Blyde Irrigation Scheme or irrigation in the Komati Catchment (ICMA 2013). Irrigated agriculture in the Sabie Catchment historically contributed just over 50% of GDP in the Sabie Catchment, and around 50% of total employment, although the information in the referenced report does not provide a date for when these data were applicable (ICMA 2013). Four major irrigation abstraction points have been identified in the Sabie Catchment according to the Inkomati Water Availability Assessment Report (Mallory and Beater 2009). These are Albany, Boschoek, Hoxani and Lisbon. Information on these abstraction schemes has proven to be very difficult to obtain, but it appears that the Hoxani works has been co-opted for use in domestic water supply and no longer operational for irrigation purposes. Information on the Albany and Boschoek offtake was not available despite efforts to contact the Inkomati-Usuthu Catchment Management Agency (IUCMA), the White Waters and Sabie River Irrigation Boards, and DWA. Data on abstractions at Lisbon were also not available, although information in the mainstream media has lamented the demise of the Lisbon Citrus and Mango Estate on which the abstraction occurred. Subsequent investigations showed that the Estate has indeed shut down and Google Earth imagery from

16/09/2013 has shown that all dams and reservoirs on the Estate are dry or partially dry. This major water user (approximately 20 000 m^3 storage capacity) is no longer abstracting water for irrigation purposes (Mallory and Beater 2009). It appears that it is not likely that additional stress on water resources will come from either forestry or irrigated agriculture for the foreseeable future.

Chapter 2 of the National Water Act of 1998 (No. 36 of 1998) makes provision for the National Water Resource Strategy (NWRS). Implicit in the National Water Act of 1998 (No. 36 of 1998) is a call for the NWRS to set out approaches for reducing wasteful water use through various means, one of which is a demand management scheme (DWAF 1998). Demand management is a contemporary concept that has come to the fore in the quest for sustainable use of resources. In the recently released second edition of the NWRS, by its own admission, states that the first version of the NWRS failed in producing a strong demand management directive for water administration with an obvious coincident lack in control of sustainable water use (DWA 2013). Water demand initiatives are necessary since they can be applied in the short and medium term and thereby delay capital intensive infrastructure such as dam building and pipeline construction for water transfer schemes (DWA 2013).

In contrast to forestry and irrigated agriculture, domestic water users are not required to apply for water use licenses and so a different means of managing water use in this sector must be employed. Demand management through differential tariffs where large domestic consumers pay the most per unit of water has proven effective across the globe (Savenije and van der Zaag 2002). Consumer education, effective metering and loss control should also be used in an integrated approach to save water and attenuate large demand from the domestic use and sanitation sector (Stephenson 1999). However, control over domestic consumption has proven more nebulous in terms of legislation partly because both the Water Services Act (No. 108 of 1997) and the National Water Act of 1998 (No. 36 of 1998) require that water become more accessible to previously disadvantaged South Africans and both are therefore not strict in the sections that pertain to human use of water. This leaves room for exploitation by all domestic users. Therefore, any additional pressure on water resources in the Sabie-Sand River catchment will likely come from extensions and construction of reticulation systems for servicing the sanitation requirements of people living in the catchment. For this reason (among others) I have chosen to focus on the sanitation sector in this investigation (see Chapter 2).

If the Water Services Act (No. 108 of 1997) and the National Water Act of 1998 (No. 36 of 1998) are to prove successful in their quest to provide better access to domestic water supply and sanitation for all South Africans, it follows that water resources in the country will be under ever increasing pressure as time passes. As the populace moves up the developmental ladder from public taps and unimproved sanitation through the various stages of development, so the amount of water required for these services grows, particularly if water-borne sanitation schemes are used to do this. While this aspect of the provision of services is not part of the basic human needs Reserve of the National Water Act of 1998 (No. 36 of 1998) since only the most basic needs are covered in the National Water Act of 1998 (No. 36 of 1998), knowledge of how population and per capita water consumption is changing in the catchment will shed some light on whether we can expect additional pressure from the sanitation sector on IFR compliance.

Four possible permutations regarding changes in population and sanitation exist with regard to water use:

- Increasing population and increasing levels of sanitation
- Increasing population and decreasing levels of sanitation
- Decreasing population and increasing levels of sanitation
- Decreasing population and decreasing levels of sanitation

If the population is growing and attaining a higher standard of sanitation then we can expect greater pressure on water resources. This is because a roll-out of sanitation services to a growing number of people will require and use more water if the population is becoming more affluent in addition to growing in number. If the population is growing but access to sanitation is decreasing either scenario of lesser or greater pressure on water resources could be manifest. If the population is shrinking but also realising a better standard of sanitation, this too could result in either greater or lesser pressure on water resources. The reason for the ambiguity in these scenarios is that even if the population grows, should access to sanitation decrease, the net water requirement for sanitation might well decrease. However if the population grows quickly enough, even if sanitation per capita is decreasing there may still be a net increase in water requirements for sanitation purposes. Should the population be decreasing but simultaneously growing in affluence, the higher degree of sanitation per capita could require more water. But a situation could also arise in which a shrinking population, even if well serviced with sanitation infrastructure would use less water thereby reducing water demand. And lastly, if the population is shrinking and there is also a reduction in access to sanitation, this will place less pressure on water resources in the catchment. I test these scenarios with human population census data in Chapter 2.

1.3.3. Instream Flow Requirements (IFR's):

1.3.3.1. History of IFR's

The history of instream flow requirements began in the USA, where river ecologists in the 1940's began to notice a decline in economically important fish species (Tharme 2003). Simple methods of maintaining a minimum flow volume were invented in a bid to counter these declines (Tharme 2003). These methods failed to incorporate local factors and conditions, and were quite crudely applied initially (Gordon et al. 2004). Measurable progress in instream flow science was made only in the 1970's after the enactment of environmental and water-use legislation. This led to improvements in the hydrological sciences as more flow assessment methods were developed and much theoretical knowledge regarding riverine ecology was published (Tharme 2003). Early methods were simple, stipulating only low-flow criteria for rivers (Gordon et al. 2004). River ecologists hypothesized that ensuring that flows did not drop below a particular volume would ensure survival of fish. As more linkages were discovered between different flow volumes and ecological processes, these models began to grow in complexity. This led to the realisation that rivers were multifaceted systems and required a variable flow regime for ecological maintenance rather than a simple low flow volume. Consequently, more complex ideas came to the fore. These included seasonal variation in low-flow specifications (Fraser 1978), recommendations for flow regimes based on the flow duration curves of a stream's natural flow (Vogel and Fennessy 1994) and other progressively more intricate methods such as the Instream Flow Incremental Methodology (IFIM) and Physical HABitat SIMulation (PHABSIM) techniques (Gordon et al. 2004). Some of these include habitat maintenance methods that use the relationship between flow volumes and velocities to maximise habitat for target species or particular instream uses which might include anything from recreational use to supplying design flows for the entire life-cycle of a fish species (Jowett et al. 2008).

1.3.3.2. Building Block Methodology for IFR determination in the Sabie-Sand River River:

The steady accrual of information, data and experience has brought us to the present day in which the BBM and other associated holistic assessment methods are considered best practice given our current state of knowledge. Holistic methodologies are scenario-based and are the first generation of flow models that address the requirements of the entire riverine ecosystem, including the riparian components (Tharme 2003). Explicit links between changes in the biophysical components of the ecosystem and the flow regime are the defining characteristics of this type of flow model-type (Tharme 2003). The BBM has been applied in South Africa and more importantly the Sabie-Sand River and so will be discussed in greater depth, but other holistic methods include the Downstream Response to Imposed Flow Transformations (DRIFT) technique (King et al. 2003), the Scientific Panel Assessment Method (SPAM) favoured in Australia (Thoms and Sheldon 2002), the River Babingley

(Wissey) Method formulated in the United Kingdom in 1996, and the Range of Variability Approach (RVA) from the USA in 1997 (Petts 1996; Richter et al. 1997). The last two are the only known examples of holistic methodologies not to be formulated in the southern hemisphere.

The IFR's are designed by specialists using the BBM (in the case of the Sabie-Sand River here) in an attempt to mimic the most important aspects of the natural flow regime (magnitude, timing, duration and frequency of flows as well as water quality) and therefore the flows that are most important for maintenance of the riverine ecosystem in a particular and desired state (King and Louw 1998). The dimensions of the IFR for the Sabie-Sand River were derived using the BBM and mimic the natural flow regime as much as possible. Specific rivers have a signature flow-set that is a function of the topography, geology, precipitation, land use and evapotranspiration characteristics of the catchment (Gordon et al. 2004). The BBM is a process in which DWA and river scientists identify flows that are most strongly linked to particular functional aspects of the river and determine a recommended flow regime on that basis (King and Louw 1998). The prescribed flow regime always tries to mimic the natural hydrograph of the river and even maintain it where possible. Where this is successful, the majority of processes such as sediment flushing, channel and habitat maintenance will be preserved leaving water for other uses (Pike and Schulze 2000). This approach builds a flow profile additively for a river from three important components. The first components to be quantified are minimum (low) flows, which are an inherent characteristic of the climatological region in which the Sabie-Sand River is situated. Due to the distinct seasonality of rainfall and river flow in the region as compared with European or North American systems, these are assumed to have had, and continue to have an important evolutionary effect on the biota of the river (Tharme and King 1998). Secondly, flows responsible for the maintenance of channel morphology and habitat are added to low flows (Tharme and King 1998). The third "layer" of flows called freshets are short-duration, low magnitude floods occurring annually early in the wet season. Freshets are important cues for fish spawning and also for the reproduction of most invertebrate taxa (Tharme and King 1998). These flows also scour sediments that may have been deposited during the lower flow period of the dry season and are also therefore responsible for some aspects of channel morphology, along with larger flows periodically specified for major sediment flushing events. Discharges that exceed the sum of these three physically and biologically important IFR flows are deemed to be less ecologically essential and can then be harvested for human use in industry and commercial agriculture (Gordon et al. 2004).

The BBM is believed to allow for more accurate assessments than simpler types of flow models (eg: hydrological, hydraulic ratings and even habitat simulation models) as long as data are abundant, and so provides a stronger level of confidence for its recommendations (Tharme 2003). The BBM process was undertaken for the Sabie-Sand River in 1996 and was one of the most-data rich instances in which the BBM was carried out. This state of affairs is coincidentally lucky in that the catchment is both well-studied as a result of the amount of social, ecological and hydrological research undertaken over decades here in addition to having a strong network of flow gauging structures. The level of engagement by a large number of specialists coupled with this data-rich environment means that this catchment is regarded as the flagship of the BBM. Outputs from the BBM process inform the IFR and determine the timing, duration and quality of the IFR specifications, while the IFR is the operational aspect of the ecological Reserve component of the National Water Act of 1998 (No. 36 of 1998). The IFR specifications were produced by a large team of specialists as well as members of the Department of Water Affairs Water Law Review Team, with access to a comprehensive arsenal of data with which to make recommendations for flow requirements.

Implementation of the BBM requires a team of specialist scientists including aquatic ecologists and chemists, scientists from hydrological backgrounds (ie: fluvial geomorphologists, hydrologists, hydraulic engineers) and sociologists. An exploratory overview of the river is undertaken by means of aerial surveys, topographical and cadastral maps with the purpose of site selection at which changes to the ecosystem can be measured, as well as providing a reference condition for the BBM process. This reference condition allows for ecological changes to be detected, measured and countered should the change be deemed to have a negative effect on the desired state of the ecosystem. The specialists then undertake a preliminary assessment of water requirements in their area of expertise (Tharme and King 1998). These requirements are then converted into a stage-discharge relationship by the hydraulic modeller, thereby providing the scientists and managers of the river system with flow dimensions that complement their observations and recommendations. These observations must be substantiated with a review of relevant and contemporary literature for each specialist and collected as a chapter in a summary document. Once this is complete, the team meets in a workshop environment and determines the flow regime that managers will implement.

Critics of this method argue that in cases where there is a lack of knowledge of the linkage between an ecological function and flows that may be important for that function, omission of these flows could facilitate the loss of some important aspects of riverine ecology (Tharme and King 1998). A hypothetical example would be the omission of a freshet flow that is of sufficient magnitude and/or duration to provide adequate conditions for fish to spawn. Since the Sabie-Sand River exhibits a quite variable flow regime that is not very well understood, this concern is reasonable. However, if the IFR approach is dove-tailed with the tenets of Strategic Adaptive Management (SAM) (covered in greater depth in Section 1.3.3.5) and proper monitoring and timely feedback regarding the health of the river occurs, this outcome should be avoidable.

The sites at which the IFR's are monitored can be found in Figure 1.4, and the discharge volumes required to fulfil IFR's can be found in Table 1-1 - Table 1-4 in Section 1.3.3.4. These sites are selected for their accessibility, high diversity of physical habitat for both aquatic and riparian species and proximity to flow gauges (King et al. 2008).

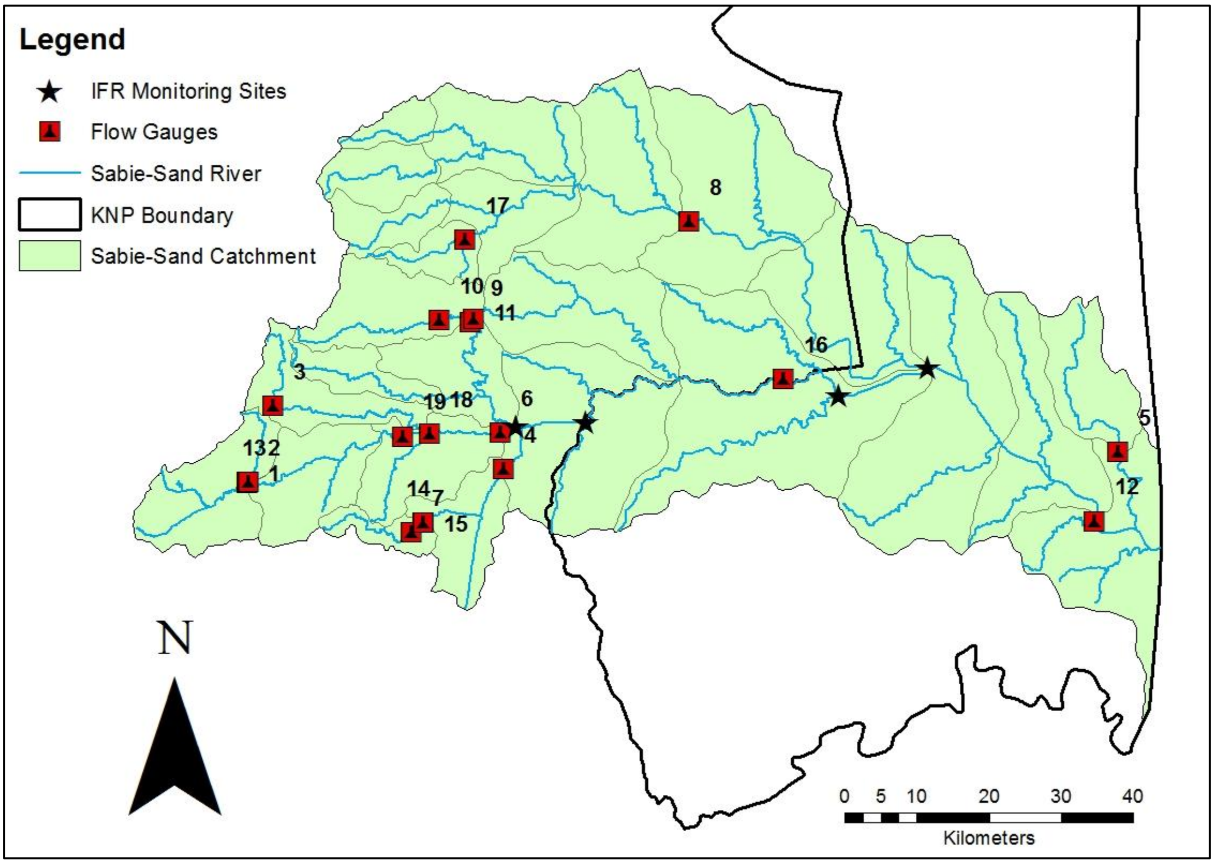

Figure 1.4. A map of the study region with flow gauges and IFR monitoring sites.

1.3.3.3. Background to the Instream Flow Requirements of the Sabie-Sand River:

The majority of the length of the Sabie River, and much of the Sand River's headwaters have been given an Ecological Management Class B status by the DWA (see Figure 1.5 below). This means that the resource is of a good quality and a greater proportion of the water in the river is allocated for the ecological reserve as compared with a river with a resource class of C or D (King et al. 2008). This is because Ecological Management Class B rivers are defined as being of high ecological importance and should remain largely natural in terms of water quality and quantity, instream and riparian habitat and biota (Palmer, 1999).

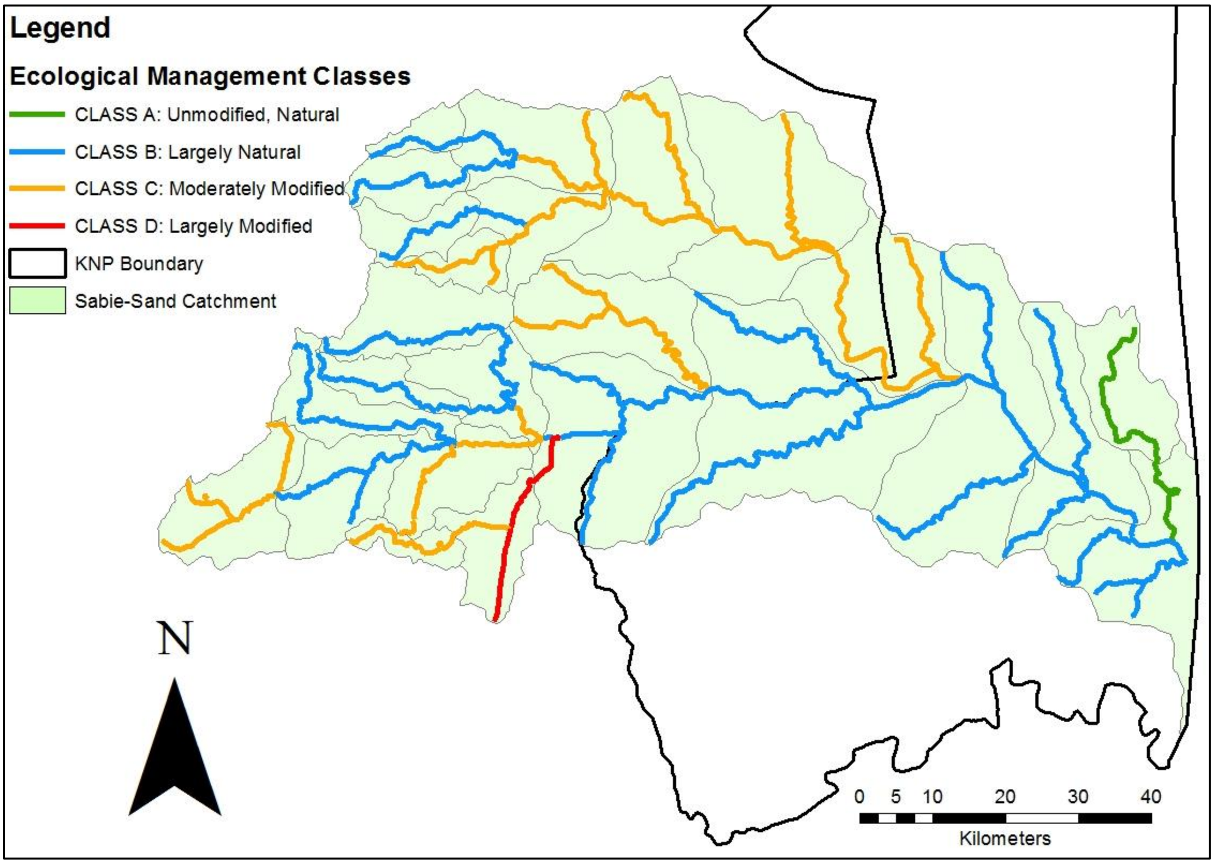

Figure 1.5. A map of the study region highlighting all Class B Ecological Management Classes in black for the Sabie-Sand River.

The IFR's for the Sabie-Sand River are split into two broad-scale classes: maintenance and drought flows. Specifications such as flow magnitude and flow volume are tailored for each of the sites described below. As the names imply, maintenance flows are those that should occur more frequently than drought flows, and are used to safeguard the "normal" functional aspects of the river (Hughes and Hannart 2003). Drought, or stressor flows are periods of low-flow conditions; these are specified because the aquatic scientific community in South Africa and globally consider these low flows to be intrinsic to the flow regime in SA's highly variable riparian systems (Hughes and Hannart 2003). Within these two classes or flow scenarios, two more are specified, namely base and higher flow specifications. These two flow-types are designed for two purposes. The base flow component functions as the "standardised flow condition", and reflects what comprises the typical flow of the river in question, or the flows that occur most frequently. The higher flows are designed to fulfil more specific functions such as providing spawning cues for biota, flushing sediments and maintaining channels and habitat.

For the Sabie River, perennial flows were historically known, and while this has continued to be the case, the long-term rainfall trends have remained stable while long-term data shows that the volume of daily flows is decreasing (see Figure 1.6) (Pringle 2001; van Wilgen and Biggs 2011). Under the assumption that the instream biota has evolved under the Sabie-Sand River's natural flow regime, the BBM has attempted to replicate historical conditions in formulating the flow specifications. These specifications exist for both the maintenance and drought conditions albeit at different flow volumes. Flow dimensions for maintenance conditions are specified in an attempt to provide protection of specific ecological functions in the river, including invertebrate and fish spawning and movement including dispersal, riparian vegetation requirements or sediment-flushing and water quality (King et al. 2008). In addition, IFR's are formulated with the intention of ensuring ecological functions that are reliant on infrequent flow dimensions are also maintained by specifying higher flows with a one-in-three-year return interval during the month of February. February is the peak flow month for the Sabie-Sand River. This situation occurs at all the IFR sites. It must be reiterated that the monitoring component of the SAM strategy is crucial in identifying where these infrequent flows are responsible for specific ecological functions that may no longer occur, but also to detect ecological responses to flows of ecologically important magnitudes (Rogers and Luton 2011).

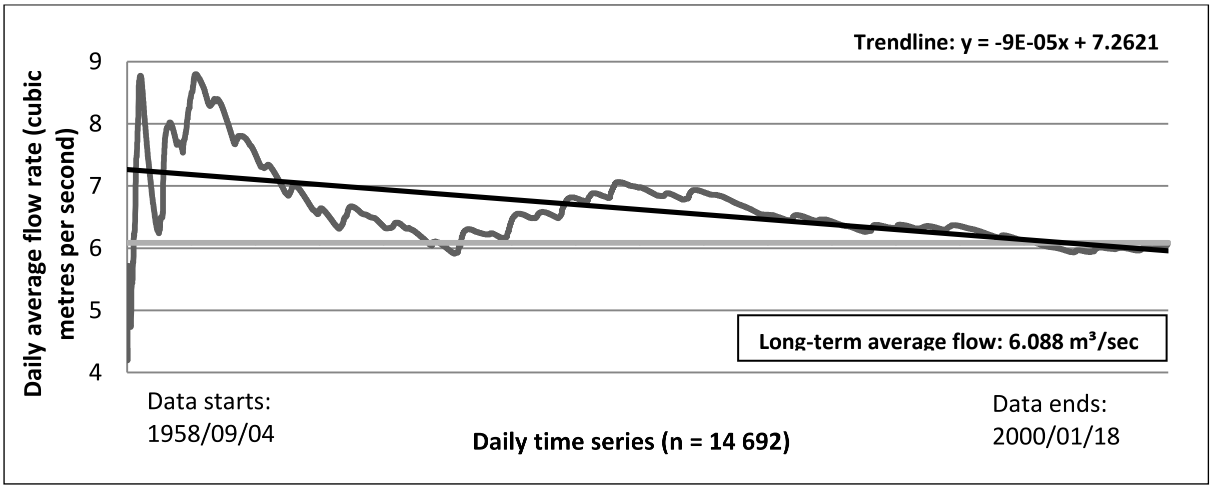

Figure 1.6. Moving average of the daily average flow rate for Gauge X3H006 Sabie River at Perry's Bridge. The length of record included all daily data for the operational period of the flow gauge (1958 – 2000).

All the data specifications in the IFR tables below (Table 1-1 - Table 1-4) follow the same prescripts, but with different flow specifications for different sites and times of year. For higher flows and some drought base flows (ie., those at the SabieSand IFR site) flow specifications do not exist in all months. The single most important aspect of the respective IFR specifications is the flow volume in the case of the base flows for both maintenance and drought scenarios. In the case of higher flows, the flow volume is not specified for all days in a month like base flow IFRs, but as shorter duration freshets of between 3 and 14 days depending on the purpose of the flow. The duration of flow is therefore as important as the flow volume in higher flow IFR specifications. IFR compliance for higher flows comprises a flow of a particular volume in a certain number of days, with both volumes and time periods differing month to month and across sites.

Some aspects of the table are merely descriptive features of the flow dimension to provide a better understanding of the specified flow dimension, but are correlated to some degree with the crucial aspect of the flow dimension, namely the flow volume. This would include descriptive factors found in the IFR table such as the flow magnitude and depth. Higher flow magnitudes generally correspond to higher flow volumes, as does greater depth of flow. Flow depths are only specified for the Skukuza IFR site and no others. Another feature of the IFR table is the column named “FDC % V”. FDC is the acronym for flow duration curve. This is another flow descriptor, and it designates the frequency of exceedance of a specified flow dimension against a long term average. Figure 1.7 below is an example of a flow duration curve of daily average flow rate for flow gauge X3H006. One can see that at flow gauge X3H006, a daily average flow close to or greater than magnitude 0.7 m^3/s should occur 99.99% of days in the sample set, while a daily average flow of 200+ m^3/s will occur on 0.007% of days over the data period at flow gauge X3H006.

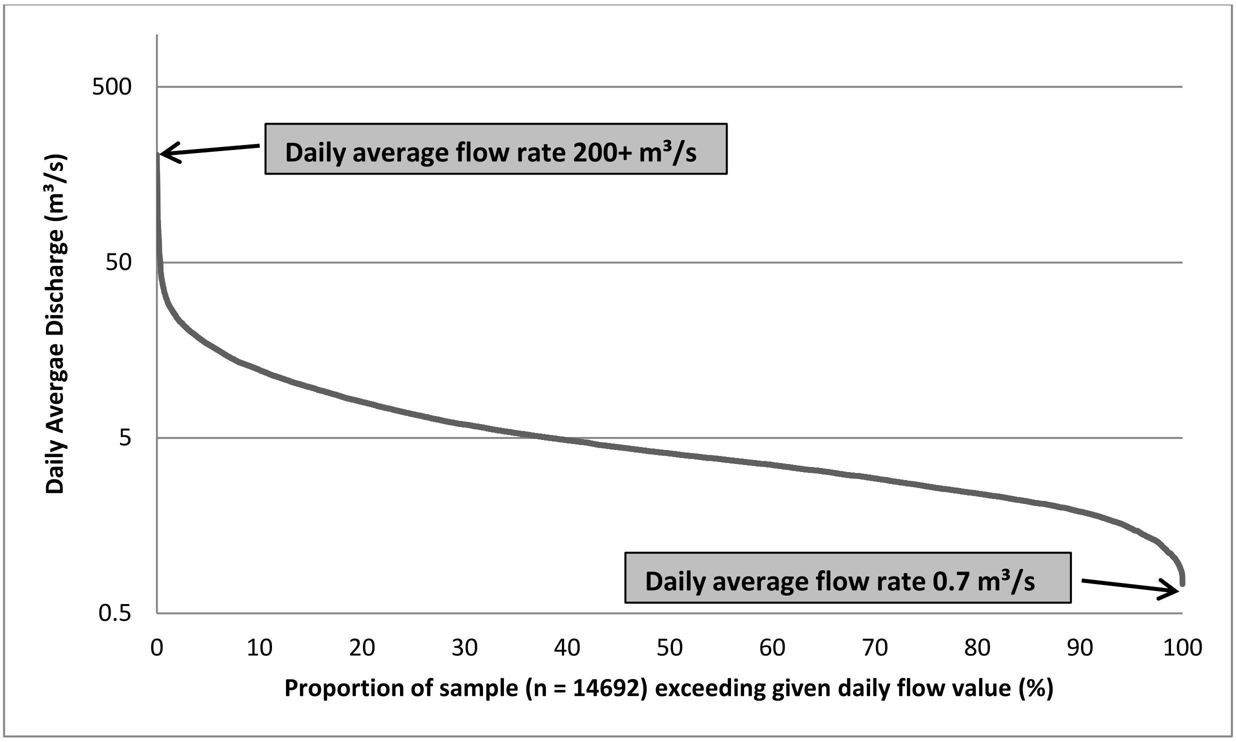

Figure 1.7. Example of a daily flow duration curve, using data for for flow gauge X3H006 for the period 1958-1999.

Another descriptor in the IFR tables is the “capping flows” column. Capping flows are defined as elevated base flows, often occurring in catchments characterised by extensive irrigated agriculture. Furthermore, these flows usually happen in the dry season months and result in seasonally aberrant (when compared with virgin flows) high flow volumes which have the potential to be as detrimental to riverine biota and ecological processes as unusually low flows might (Hughes 1999). The MariteSabie IFR site is the only IFR site for which a caveat regarding capping flows exists. However, no actual flow volume dimensions that could be defined as capping flows have been published with the IFR table. In all likelihood this is because capping flows are extremely difficult to define, and the maintenance of flow variability may be more important than flow volumes *per se*. The concept of managing for flow variability over specific flow volumes, particularly for systems with highly variable virgin flow regimes is gaining ground (Acreman et al. 2014).

1.3.3.4. Specifications and description of IFR sites in this study:

The interplay of topographical, geological, precipitation, land use and evapotranspiration characteristics gives rise to the heterogeneous nature of the Sabie-Sand River system and indeed all South African rivers (van Coller et al. 2000). This has created the mosaic of bedrock anastomosing, mixed pool-rapid, mixed anastomosing, alluvial single thread, and alluvial braided channel types that we observe in the Sabie-Sand River. These channel types are associated with flow characteristics that maintain the ecology in a particular state, and these flow characteristics differ across channel types (Moon et al. 1997). Even within a single channel type, different channel cross-sectional shapes in different parts of the river mean that maintenance of the channel type at these different locations may require different flow characteristics. Consequently, IFR's are tailored for each site and have individualised flow characteristics.

1.3.3.4.1. MariteSabie IFR Site description and specifications:

The site designated as the MariteSabie IFR is downstream of the confluence of the Sabie and Marite rivers but before the junction of the Sabie and Noord-Sand rivers (see Figure 1.8). The spatial configuration of the flow gauge network in relation to the MariteSabie IFR site means that the majority of water flowing in the Sabie River and its upstream tributaries will be captured by the flow gauges X3H006 and X3H011. Flow gauge X3H006 measures flows incorporated from the main stem of the Sabie River, as well as the Mac-Mac, Klein Sabie, Goudstroom and Sabane tributaries while the Marite River is measured by flow gauge X3H011. An unfortunate consequence of the configuration of the flow gauge network means that flows from the perennial Motitsi Stream are not measured, and no gauging structure has ever been in place on the Motitsi Stream.

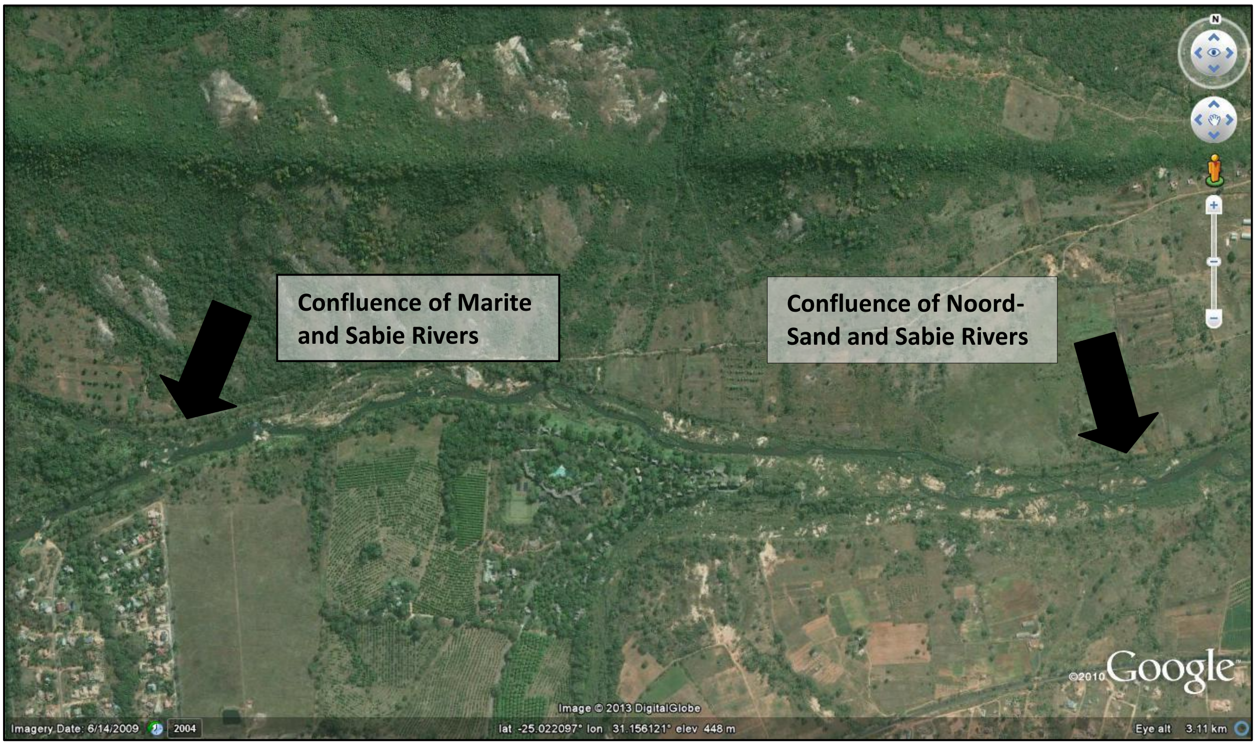

Figure 1.8. Google Earth Image of MariteSabie IFR Site, showing confluences of Marite and Sabie Rivers, and Noord-Sand and Sabie Rivers.

Table 1-1.Instream Flow Requirement specifications for the MariteSabie site (adapted from Tharme 1997).

BUILDING BLOCKS		OCT	NOV	DEC	JAN	FEB		MAR	APR	MAY	JUN	JUL	AUG	SEP
Maintenance IFR	Magnitude (m^3/s)	2	3	5	6	6		6	5	4	3.5	3	2.6	2.3
	Depth (m)													
Base flows	Volume (MCM)	5.3	7.8	13.4	16.1	14.5		16.1	13	10.7	9.1	8	7	6
	FDC % V	100	100	100	100	100		100	100	100	100	100	100	100
	FDC % V	79	87	86	76	85		86	90	90	86	86	83	80
	Magnitude (m^3/s)	9	12	30	17	50	190	16	14					
	Depth (m)													
	Duration (d)	3	3	7	5	10	14	5	5					
Higher flows	Return period (y)	1:1	1:1	1:1	1:1	1:1	1:3	1:1	1:1					
	Volume (MCM)	0.9	1.2	7.6	2.4	19	100	2.1	3					
	FDC % V	67	46	10	26	4	0.4	28	36					
	FDC % V	33	23	6	15	3	0.3	16	19					
Capping flows		Note irrigation demands												
DROUGHT IFR	Magnitude (m^3/s)	1.5	1.9	2.3	2.6	3		2.8	2.5	2.3	2.1	1.9	1.7	1.6
	Depth (m)													
Base flows	Volume (MCM)	4	4.9	6.2	7	7.2		7.5	6.5	6.2	5.4	5.1	4.5	4.1
	FDC % V	100	100	100	100	100		100	100	100	100	100	100	100
	FDC % V	90	95	97	99	98		99	99	99	96	95	94	92
	Magnitude (m^3/s)		3.8	4.6	5.2	6		5.6	5					
	Depth (m)													
	Duration (d)		3	3	3	3		3	3					
Higher flows	Return period (y)		1:1	1:1	1:1	1:1		1:1	1:1					
	Volume (MCM)		0.25	0.3	0.34	0.39		0.36	0.32					
	FDC % V		99	98	96	92		94	97					
	FDC % V		78	69	63	54		58	65					

The different channel types referenced above (Section 1.3.3.4) react differently to changes in flow characteristics, depending on which state they currently occupy. From Figure 1.8 we can see that the MariteSabie IFR site currently occupies a mixed anastomosing/mixed pool rapid state. Bare rock, sandbars, vegetated alluvium and water comprise the mosaic of patches visible in Figure 1.8 which was captured on the 14th of June 2009. Depending on whether there is IFR compliance or not this mosaic will change to another channel type, and the details of such potential changes will be explored in Chapter 4.

1.3.3.4.2. InsideKNP IFR Site description and specifications:

The InsideKNP IFR site is situated on the main stem of the Sabie River just within the border of the KNP near the confluence of the Sabie and Phabeni rivers (see Figure 1.9). If we consider the spatial configuration of the flow gauges in sub-catchment X3 once more, we see that flows from flow gauge X3H004 must be added to gain a more accurate representation of the river flow at the InsideKNP IFR site. Flow gauge X3H004 measures flow from the White Waters and the Noord-Sand Streams, and this flow plus the flows from the main Sabie River and tributaries as mentioned in the description for the MariteSabie IFR site come together and flow past the Inside KNP IFR site. Regrettably, as is the case with the Motitsi Stream, another perennial stream called the Bejani cannot be added to the analysis due to the lack of any gauging structure on the Bejani Stream.

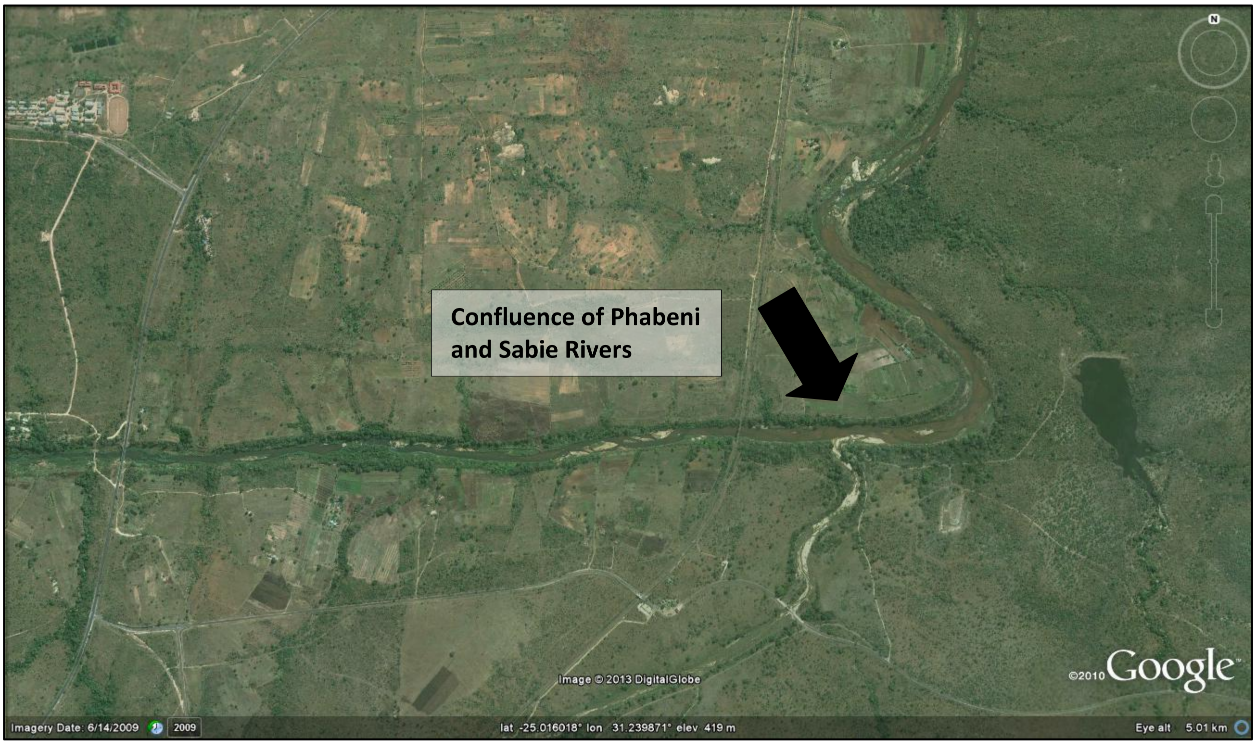

Figure 1.9. Google Earth Image of the InsideKNP IFR Site, showing the confluence of the Phabeni and Sabie Rivers.

Table 1-2. Instream Flow Requirement specifications for the InsideKNP site (adapted from Tharme 1997).

BUILDING BLOCKS		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Maintenance IFR	Magnitude (m^3/s)	4.5	6	9	10	12	11	10	8	6	5	4.5	4
	Depth (m)												
Base flows	Volume (MCM)	12.1	15.5	24.1	26.8	29	29.5	25.9	21.4	15.4	13.4	12.1	10.4
	FDC % V	94	94	90	90	82	85	89	92	95	97	98	98
	FDC % V	33	49	54	52	64	62	54	43	49	50	44	44
	Magnitude (m^3/s)	9	12	30	17	50 200	16	14					
	Depth (m)												
	Duration (d)	3	3	7	5	10 14	5	5					
Higher flows	Return period (y)	1:1	1:1	1:1	1:1	1:1 1:3	1:1	1:1					
	Volume (MCM)	0.6	0.8	6.3	1.5	16.4 100	1.1	0.9					
	FDC % V	68	47	10	27	5 0.4	29	37					
	FDC % V	34	24	6	15	3 0.3	16	20					
Capping flows	None specified												
DROUGHT IFR	Magnitude (m^3/s)	2.5	3.5	4	5	6	5.5	4.5	3.5	3	2.5	2	2
	Depth (m)												
Base flows	Volume (MCM)	6.7	9.1	10.7	13.9	14.5	14.7	11.7	9.4	7.8	6.7	5.3	5.2
	FDC % V	100	100	100	100	90	100	100	100	100	100	100	100
	FDC % V	72	80	92	92	87	89	94	93	91	91	92	88
	Magnitude (m^3/s)		7			10							
	Depth (m)												
	Duration (d)		3			5							
Higher flows	Return period (y)		1:1			1:1							
	Volume (MCM)		0.4			0.9							
	FDC % V		84			60							
	FDC % V		46			30							

The Sabie River before the confluence with the Phabeni Stream shows a well-formed alluvial structure, even tending towards an alluvial braided channel. The mosaic of patch types in Figure 1.9 shows much alluvium, water and riparian vegetation. This arrangement points towards a system currently in a stable and mature configuration or state at the time at which the image was captured (14^{th} of June 2009).

1.3.3.4.3. Skukuza IFR Site description and specifications:

The IFR site at Skukuza is downstream of the confluence of the Sabie and Nwaswitshaka rivers. As can be seen from Figure 1.4, the eastern portions of the X3 sub-catchment are serviced by far fewer flow gauges and as a result, analysis of flows at IFR sites in this portion of the catchment becomes far more difficult and less accurate. Upon examination of the flow gauge network, it was decided that the best means of remotely measuring flow compliance at the Skukuza IFR site was to utilise the data from a single flow gauge, namely X23H021. This flow gauge is the closest in proximity to the Skukuza IFR site and includes all the flows from gauges X3H004, X3H006 and X3H011. In addition, flows from the perennial Motitsi, Bejani, Saringwa Matsavana and Phabeni tributaries are all incorporated at X3H021. Unfortunately flows from the Musutlu and Nwaswitshaka tributaries are ungauged but do make confluence with the Sabie River before the Skukuza IFR site, thereby potentially introducing an unquantifiable volume of water into the analysis. However, this should not provide much of an error in the analysis as both the Musutlu and the Nwaswitshaka streams are non-perennial and therefore do not add much measurable water to the system, and in years in which they flow it is assumed that the higher volume of water coming from other (gauged and measurable) portions of the catchment would have complied with the IFR volume in any case.

Figure 1.10. Google Earth Image of the Skukuza IFR Site, showing the confluence of the Nwaswitshaka and Sabie Rivers.

Table 1-3. Instream Flow Requirement specifications for the Skukuza site (adapted from Tharme 1997).

BUILDING BLOCKS		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Maintenance IFR	Magnitude (m^3/s)	3	4	5	6	9	8	7	6	5.2	4.5	4	3.4
	Depth (m)	0.82	0.89	0.96	1.02	1.17	1.12	1.07	1.02	0.97	0.93	0.89	0.85
Base flows	Volume (MCM)	8	10.4	13.4	16.1	21.8	21.4	18.1	16.1	13.5	12	10.7	8.8
	FDC % V	100	99	99	100	94	96	98	98	98	98	98	98
	FDC % V	54	69	86	79	74	77	76	65	59	55	48	49
	Magnitude (m^3/s)	9	12	30	20	50 180	21	18					
	Depth (m)	1.17	1.3	1.83	1.57	2.21 3.54	1.6	1.51					
	Duration (d)	3	3	7	5	10 14	5	5					
Higher flows	Return period (y)	1:1	1:1	1:1	1:1	1:1 1:3	1:1	1:1					
	Volume (MCM)	0.8	1	7.6	3	17.7 100	2.8	2.4					
	FDC % V	70	66	18	65	25 5	70	80					
	FDC % V	10	25	8	40	20 1	50	42					
Capping flows		None specified											
DROUGHT IFR	Magnitude (m^3/s)	2	2.5	3	3.5	4	3.7	3.3	3.1	2.8	2.5	2.3	2.1
	Depth (m)	0.73	0.77	0.82	0.85	0.89	0.87	0.84	0.82	0.8	0.77	0.76	0.74
Base flows	Volume (MCM)	5.3	6.5	8	9.4	9.7	9.9	8.6	8.3	7.2	6.7	6.2	5.4
	FDC % V	100	100	100	100	100	100	100	100	100	100	100	100
	FDC % V	72	87	92	97	95	95	95	93	90	87	81	77
	Magnitude (m^3/s)		5	6	7	8	7	6					
	Depth (m)		0.96	1.02	1.07	1.12	1.07	1.02					
	Duration (d)		3	3	3	3	3	3					
Higher flows	Return period (y)		1:1	1:1	1:1	1:1	1:1	1:1					
	Volume (MCM)		0.3	0.4	0.4	0.5	0.4	0.3					
	FDC % V		96	97	99	96	99	100					
	FDC % V		58	78	65	77	81	85					

Figure 1.10 above shows a complex channel-form known as the mixed anastomosing channel-type at the time of capturing the image on the 14th of June 2009. Present in the mosaic represented in the image above is alluvium, bedrock, vegetation and water. The manner in which this channel-type

reacts to changes in flow characteristics is complex and difficult to predict, especially if small changes in flow characteristics occur.

1.3.3.4.4. SabieSand IFR Site description and specifications:

The SabieSand IFR Site is situated just below the confluence of the Sabie and Sand rivers before the confluence of the Nwatindlopfu and Sabie rivers. Two potential means of measuring IFR compliance at this site were considered. The first option was to sum the flows as measured at flow gauge X3H008 and X3H021. This option was not pursued due to the poor data record of flow gauge X3H008 (as described later in Chapter 2, Figure 2.8) and a shorter congruent data record between gauges X3H008 and X3H021 as compared with other options. The method utilised for the analysis of flows at the SabieSand IFR Site was to scrutinize the flows at flow gauge X3H015 and compare them with IFR specifications. The longer data record from gauge X3H015 was an attractive feature of this option, however the potential for slightly inflated flow volumes experienced at the flow gauge as compared with the SabieSand IFR Site have been noted since a number of tributaries enter the Sabie River between the site and the flow gauge. These include the Nwatindlopfu, Nwatimhiri, Lubyelubye and Salitje, but since these streams are all non-perennial the additive effect is assumed to be negligible as they experience only periodic flow and of either very small flow volumes, or substantial flows in flood seasons when IFR specifications will easily be met anyway.

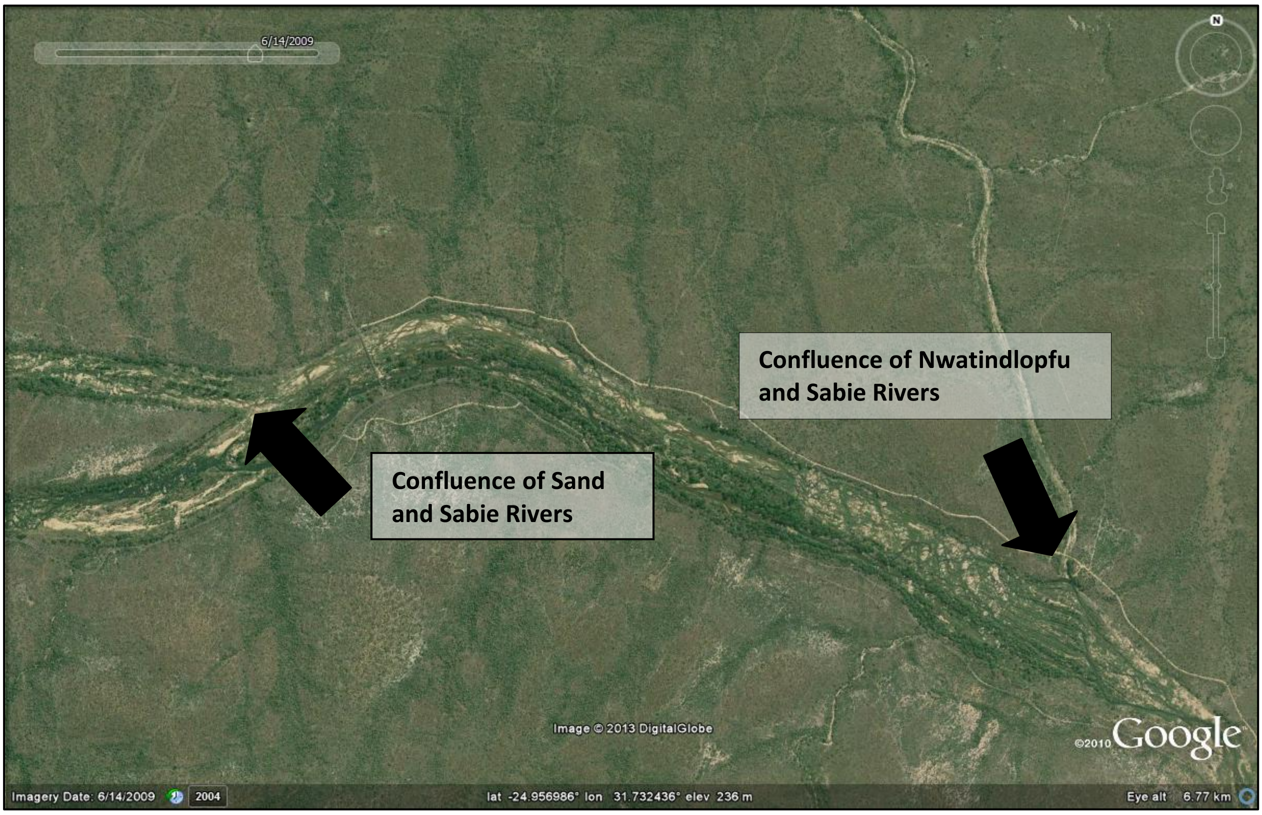

Figure 1.11. Google Earth Image of the SabieSand IFR Site, showing confluences of Sand and Sabie Rivers, and Nwatindlopfu and Sabie Rivers.

Table 1-4. Instream Flow Requirement specifications for the SabieSand site (adapted from Tharme 1997).

BUILDING BLOCKS		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Maintenance IFR	Magnitude (m^3/s)	4	8	10	13	18	14	10	8	6	4	4	3
	Depth (m)												
Base flows	Volume (MCM)	10.7	20.7	26.8	34.8	43.5	37.5	25.9	21.4	15.5	10.7	10.7	7.8
	FDC % V	96	77	87	80	71	81	93	94	96	100	98	99
	FDC % V	38	33	53	48	58	62	63	53	57	67	53	56
	Magnitude (m^3/s)	8	12	30	20	45 180	21	18					
	Depth (m)												
	Duration (d)	3	3	7	5	10 14	5	5					
Higher flows	Return period (y)	1:1	1:1	1:1	1:1	1:1 1:3	1:1	1:1					
	Volume (MCM)	0.5	0.5	6	3.7	11.7 96	1.5	1.7					
	FDC % V	81	56	15	27	8 0.9	26	33					
	FDC % V	45	30	10	17	6 0.8	16	19					
Capping flows		None specified											
DROUGHT IFR	Magnitude (m^3/s)	3	3.5	4	4.5	5							
	Depth (m)												
Base flows	Volume (MCM)	8	9.1	10.7	12.1	12							
	FDC % V	100	100	100	100	100							
	FDC % V	54	70	90	92	91							
	Magnitude (m^3/s)			12		10							
	Depth (m)												
	Duration (d)			3		3							
Higher flows	Return period (y)			1:1		1:1							
	Volume (MCM)			1		0.6							
	FDC % V			56		69							
	FDC % V			30		36							

As with the Skukuza IFR Site, the SabieSand IFR site is a mixed anastomosing channel form showing a complex mix of alluvium, bedrock, vegetation and water (Figure 1.11) at the time the image was captured (14th of June 2009). As mentioned above, shifts in the characteristics in a channel-type of this variety do not make for a simple forecasting of response to changes in flow. The inherent complex nature of these channels means that they do not respond in a uniform manner to a change in any particular driver. For instance even large deviations in flow volume from the average volume experienced at this site will have very little effect on bedrock components of the mosaic, but the same deviations have the potential to greatly enhance sedimentation or even erosion.

1.3.3.5. The role and importance of SAM in informing IFR's:

SAM is an approach that aims to ensure good connectivity at the science-management interface. There is a strong focus on learning from management outcomes by feedback to scientists (Williams et al. 2009). The modus operandi requires that managers take heed of scientific recommendations, but also that these recommendations are relevant to managers. The concept was deemed suitable to South African ecological systems due to its explicit premise of linking learning and experience with policy and the implementation thereof (Rogers 2002). The change in water legislation in the repeal of the Water Act of 1956 (No. 54 of 1956) and the enactment of the National Water Act of 1998 (No. 36 of 1998) also required a very different style of water management, with a shift from a storage and transfer function fulfilled by DWA, to an expanded water stewardship role adding management of river ecosystems to the DWA mandate (Rogers 2002). This however is a temporary responsibility with catchment management agencies set to perform this task in the future. The Sabie-Sand Catchment is managed by the Inkomati-Usuthu Catchment Management Agency (IUCMA), the first of the newly consolidated agencies to be formed. DWA will perform a supervisory role regarding catchment management once all the CMA's are all functional, in an expanded mandate over the earlier Water Act of 1956 (No. 54 of 1956), as well as performing its original role of storage and transfer of water (DWAF 1998).

SAM is a paradigm that has explicit capacity for changes in the system under management (Pollard et al. 1998). This is useful in terms of managing ecological water requirements through IFR, since the IFR volumes can and should be adjusted according to information garnered from managers in charge of the water resource, and scientists conducting research on the resource. In South Africa, knowledge of our highly variable ecological systems is continuously developing (compared with European and North American systems), and a learning by doing approach is therefore useful provided it is utilised properly. Information feedback will enhance the knowledge of the resource and thereby give greater accuracy on actual ecological requirements, which should be adjusted accordingly.

1.3.4. Important factors affecting the ecological health, structure and functions of the Sabie-Sand Catchment:

The IFR system, as determined using a holistic methodology namely the BBM, has been touted as the most comprehensive means by which to specify ecological flow requirements (Tharme 2003). While few would argue that this system uses expert knowledge (as well as flow and ecological data) on an unprecedented level, the performance of the system has not been critically evaluated by peers of the creators or other independent users, abroad or in South Africa. If managers and scientists are aware of the SAM paradigm, the flow volumes in the original IFR specification should undergo periodic review so as to be more representative of the actual ecological requirements of the Sabie-Sand River system. The flow volumes for each site and time period might then be adjusted accordingly should this be required. However, I believe that the IFR system may prove difficult to implement should there be insufficient buy-in by managers and scientists in terms of the SAM paradigm. With this in mind, in the following description, I review potential changes that may occur should IFR compliance be low, setting the scene for Chapter 4 where I review the literature for evidence of actual changes, given the patterns of compliance described in Chapter 3.

Particular flows are specified (using the BBM) to perform specific ecological functions. If these flow specifications are responsible for these ecological functions and flows are not IFR compliant, it follows that these ecological functions will cease to occur, or partially occur at best. If we observe the perpetuation of these functions in the absence of IFR compliant flows, then two important deductions can be made. Primarily, a flow specification different to the original specification is responsible for the maintenance of the function, and secondly, the original specification needs review. An example would be a freshet flow specified to allow for spawning of fish being of insufficient duration or magnitude; if this transpired then fish would not spawn and there could be a great loss of individuals of a population or even localised extinction of a species.

The framework in which these ecological implications will be considered and evaluated in this study mirrors the format of the prescribed procedure for the BBM. This allows us to find, describe and infer potential credible ecological outcomes caused by IFR non-compliance. Table 1-5 outlines the components (derived from the BBM) against which ecological change will be evaluated. These will be described in detail in separate sections below.

Table 1-5 Summary of BBM components evaluated in this study as responders to IFR compliance rates

Section Number	Component	Concise Description and/or example
Section 1.3.4.1	Management of riverine and riparian resources for riparian resources and products:	Thatching, floodplain agriculture, fish for food
Section 1.3.4.2	Ecological importance and sensitivity of instream and riparian habitat:	Changes in instream habitat units and riparian ecosystem in response to IFR compliance or non-compliance
Section 1.3.4.3	Hydrological regime and its effect on river structure and function:	Effect of the change in the hydrological regime on river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.4	The effect of hydraulics on river structure and function:	Effect of changing hydraulic processes on river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.5	The role of geomorphology in river structure and function:	Effect of changes to geomorphological processes in river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.6	The role of vegetation in river structure and function:	Effect on and effect of vegetation on river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.7	The role of aquatic invertebrates in river structure and function:	Changes in invertebrate communities and river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.8	The relationship between fish community structure and river structure and function:	Changes in fish communities and river structure and function in response to IFR compliance or non-compliance
Section 1.3.4.9	The role of groundwater in river structure and function:	Changes in river structure and function in response to IFR compliance or non-compliance

1.3.4.1. Management of riverine and riparian resources for riparian resources and products:

The National Water Act of 1998 (No. 36 of 1998) is explicit in its target to redress past disparate access to water. This is necessary since many people do not have adequate access to safe water for drinking, cooking and washing purposes (DWAF 1997). In addition to this, access to water has long been touted as a means to liberate impoverished peoples through agricultural and ultimately other economic activities (Johnston and Mellor 1961; van Koppen et al. 2005). Many rural water users are reliant on rivers for subsistence and informal economic activities, and better access to water (even directly from the river) serves as “insurance” for people against catastrophic events such as job losses, familial death or remittance failure (Dovie et al. 2002). The BBM makes provision for this in the social assessment portion of the protocol, which provides information on use of riparian and riverine resource use by rural communities.

As is the over-arching theme in the BBM, important riparian and riverine processes (in this instance exclusively processes pertinent to social use of resources) are identified in a workshop environment with the communities using natural products from the river and riparian zone. The importance of the resources such as floodplain soils for agriculture, fish, thatching, food and medicinal plants and pools are ranked, and the spatio-temporal dimensions of its use are quantified (King et al. 2008). Critical dimensions of the flow regime responsible for the maintenance of these processes are identified, described, and the corresponding flow volume that ensures the perpetuation of these functions is obtained for the stage-discharge relationship. Riparian and riverine functions of importance to humans include those related to food and health. This includes fish and other animals, as well as riparian plants such as *amadumbe* and medicinal riparian plants (van Wyk et al. 1997). Indirect uses of rivers for food include floodplains for planting of crops and areas for feeding and watering livestock, such as pools (Boone Kauffman and Krueger 1984). Rivers and riparian areas are also used for spiritual reasons and ceremonial rituals (Kapfudzaruwa and Sowman 2009). Reeds and sedges are employed in the manufacture of mats for household use, and also roofing for homesteads (van Wyk and Gericke 2000). Unfortunately, the specific details on the spatio-temporal aspects of the flow characteristics related to these services are not available despite exhaustive searches and numerous requests from the authors of the BBM documentation for the Sabie-Sand River workshop.

As described above, a varied array of stakeholders exist in the catchment but a large proportion of the people dwelling in the catchment are rural and/or people with limited access to water resources. For this reason the social aspect of the BBM is particularly important in the example of the Sabie-Sand River. However, due to the complex nature of the many and varied products and services that humans derive from the river and riparian zones, it is extremely difficult to design a flow profile from scratch that maintains and enhances the delivery of these products and services (King and Louw 1998). As a result, the expert panel that designs the IFR flows mimics the natural flow profile as closely as possible, paying particular attention to flows that are allegedly responsible for the most important products and services (King and Louw 2008). This is an example of where a strong SAM approach is important. A good monitoring programme with feedback to managers and scientists should aim to assess whether the required products and services are delivered in the catchment. Where they do not occur or are insufficient, IFR's should be adjusted accordingly or flow management should be improved.

1.3.4.2. Ecological importance and sensitivity of instream and riparian habitat:

Two main features need to be taken account of in this aspect of the BBM: riverine and riparian zones. For both riparian and instream habitat types, some are more sensitive to changes in flow than others.

A riffle is a short and shallow section of stream in which coarse sediments such as cobbles and boulders collect and finer sediments are flushed out (Raven et al. 1998). Due to the morphology and nature of riffles, they occur relatively sparsely but provide a unique and productive habitat type in rivers (Brussock et al. 1985). The fast-flowing and turbulent conditions make for a highly aerated habitat. Many invertebrates require such a habitat for portions of their lifecycle, and fish of the genus *Chiloglanis* favour this habitat (Rivers-Moore and Jewitt 2007). This genus, particularly *C. anoterus* has been used as an indicator species for the Sabie-Sand River water quality in the past (o'Keeffe 2009). Riffles are highly sensitive to changes in flow volume due to their shallow depth. Larger flows will minimise the effect that the stream bed has on the flow, thereby reducing turbulence and consequently the highly aerated nature of this habitat, while low flows may cause the reduction in size of riffle patches and pooling of anaerobic water that reaches high temperatures unsuitable for many invertebrate and piscine biota.

Rapids are sections of a stream similar to riffles, but differ in that they are usually but not always the result of exposed bedrock rather than an agglomeration of large sediment particles, and often have steeper gradients than riffles (Heritage et al. 2001). Some floods of large return interval can produce rapids by the transport and subsequent deposition of very large sedimentary material (boulders and other debris such as trees). Most are the result of attrition of bedrock by the action of sedimentary material or water (Gordon et al. 2004). Waterfalls are large rapids. Periods of high flow may drown out rapids, but this is dependent on the size of both the flood and the rapid. Smaller rapids are easily inundated in periods of higher flow. Periods of low flow, especially extended droughts will reduce the influence of rapids, and tend towards braided and even single-thread alluvial channels (Heritage et al. 2001).

Elements in the stream where the water flows at any depth, and in a mostly laminar fashion characterised with rippled and surging flow are known as runs (King et al. 2008). Runs occur in the middle to lower reaches of a river and may occur on bedrock, alluvial or mixed substrates. Runs are not as aerobically laden as riffles and rapids, or aerobically impoverished as pools and so form a suitable habitat for the anguillids (freshwater eels) and some members of the Gobiidae family (Pienaar 1978). The nature of the flow in runs means that they are stable under changing flow volumes. Higher flow periods change the nature of the flow very little in runs, except for enlarging the wetted perimeter, while lower flows reduce the wetted perimeter.

A pool is a part of the river characterised by deeper water of reduced velocity and finer sediment particles forming the substrate although rocky beds may also occur, particularly in the upper reaches of a river (Gordon et al. 2004). As a result of the reduced kinetic energy in pools, they often exhibit elevated water temperature as compared with more dynamic river components such as riffles and runs, and also lower oxygen levels. This habitat type finds favour amongst species such *Petrocephalus catastoma*, which is the only member of the genus found in southern Africa (Jubb 1967). A number of *Barbus* species also prefer to live in pools and small impoundments in the Sabie-Sand catchment (Pienaar 1978). Backwaters are similar to pools in that they exhibit low kinetic energy and therefore elevated temperature conditions and reduced oxygenation of water. Backwaters normally occur as a result of an impediment in the river channel (Gordon et al. 2004). While pools require fairly large floods or moderately severe or extended droughts before they undergo any changes of ecological consequence, a number of physico-chemical changes may occur in a diurnal cycle that may affect the biota inhabiting them. Warming of the water in pools by the sun reduces the oxygen content in the water, thereby changing the pH (Benson and Krause 1980).

Lotic wetlands differ from other wetland types in that water flows through them fairly rapidly, as opposed to the lower current experienced in lentic wetlands. These wetlands are important in terms of river health and water quality. Wetlands have long been known to reduce organic pollutant loads in streams and loss of these stream components is detrimental to water quality and consequently riverine and in some instances riparian biota (Naiman et al. 1988). Wetlands are very sensitive to changes in flow regime; too much water drowns them out or channelizes them, diminishing their purification value. Too little water may result in sedimentation and silting up of the wetland and this too compromises the wetlands ability to purify organic pollution from streamflow. While the Sabie-Sand River does not hold much typical wetland habitat, the upper reaches of the Sand River sub-catchment hosts a number of headwater wetlands (under 10 hectares), a unique variety of wetland that is under threat from erosion caused by down-cutting of the wetland during rainfall events (Riddell et al. 2012). This erosion stems from poor agricultural practises in the catchment.

Floodplains are areas of the streambed which experience inundation at far more sparse intervals than the main channel of the river. These areas are characterised by flat land adjacent to the river, comprising alluvial soils deposited during flood events, and are generally recognized as the portion of the ecosystem that experiences alternate flooding and drying (Bayley 1995). However due to the geomorphological history of the Sabie-Sand River, floodplains are not present in the catchment (Pettit et al. 2005). Rather, the Sabie-Sand River consists of a larger macro-channel and the active channels are nested within that macro-channel (Moon et al. 1997). The active channels of the Sabie-Sand River always carry water while the macro-channel is defined as that part of the landscape that shows the extent of high magnitude, low frequency flood events such as those of February 2000 (see Figure 1.12). The macro-channel is also where the riparian zone is found.

Figure 1.12. Reach of the Sabie River close to the Moçambique border, showing macro-channel and active channels. Image courtesy Google Earth.

The riparian zone is characterised by hydrophilic plants and can withstand or even requires periodic inundation, and is a landscape zone where terrestrial and aquatic environments interact (Gregory et al. 1991). In the Sabie-Sand Catchment, riparian trees are often the largest in the landscape (Naiman et al. 2008). Examples of these trees include the *Ficus sycamorus* and *Schotia brachypetala*, and these among other species provide numerous important ecological services, from food for a number of different taxa including humans, to nesting sites for birds, mammals and reptiles (Pert et al. 2010). Many of the understory species are relatively high in available nitrogen and so provide nourishing food for grazers and browsers for longer periods than uplands (Naiman and Rogers 1997). Due to the proximity of water (both subterranean water tables and surface flow) riparian plant species often stay greener for longer than upland plants and this means that many animals favour these parts of the landscape for nutrition, particularly in drought or dry conditions and seasons (Naiman and Bilby 1998). Flooding of substantial proportions can often eliminate large trees and other vegetation and reset the template of the riparian zone to one influenced primarily by bedrock (Heritage et al. 2001).

Sustained periods of low flows associated with hydrological drought may influence subterranean water flow and cause die off of riparian plants, with the consequential negative effects for animals as mentioned above.

The mechanisms by which instream habitats respond, change and are transformed due to changes in flow, operate at the level of sediment and substrate particle interactions. These interactions are described in the next two sections, and then their combined response to changes in flow is summarised in Section 1.3.4.5.

1.3.4.3. Hydrological regime and its effect on river structure and function:

The hydrological regime of a river describes the flow features of a stream in terms of volume, timing and variability at multiple spatio-temporal scales (Poff et al. 1997; Gordon et al. 2004). The theoretical underpinning of the BBM, mentioned herein on numerous occasions states that not all aspects of the hydrological regime are ecologically important and can be omitted ie: exploited for uses other than ecological maintenance (Gordon et al. 2004). Olden and Poff (2003) point out that the ecologically important aspects of the flow regime include the seasonal nature and pattern of flows, the timing of extreme flows and the frequency and duration of floods, hydrological droughts and intermittent flows. Flow variability at multiple time-scales scales is also vital, as well as the rate of change of flow. They stated most accurately that *"Assessment of these streamflow characteristics is essential for understanding and predicting the biological impact of both natural and altered flow regimes on riverine biota.*" (Olden and Poff 2003).

Anthropogenic influence has altered flow in the Sabie-Sand Catchment, albeit at a less significant proportion of flow as compared with other lowveld rivers (Pollard et al. 2011). This anthropogenic influence has far reaching and often unknown consequences, and dams along with forestry exert a large influence on flow regime in the case of the Sabie-Sand Catchment. The effect of dams on hydrological regime was explored in Section 1.3.1 of this chapter, but a more comprehensive consideration is given here. If dams are managed solely for uses that exclude maintenance of ecological systems (egs: irrigation, industrial use) then they may have extremely detrimental effects on the ecology of the stream on which they are found, altering all of the above aspects of the flow regime to the impairment of ecological functionality (Chien 1985).

Evidence has shown that dams attenuate the range of flows in a stream through the reduction of larger flow volumes downstream of the dam, and an increase of minimum flows (Magilligan and Nislow 2005). This pattern is most pronounced at short (daily) time-scales but is present through monthly and seasonal time-scales (Magilligan and Nislow 2005). At sub-daily time-scales the ecological effects of attenuation by dams of flow variability is not very well understood since most flow gauge data across the globe is specified at daily resolution at the finest scale and research is conducted that matches the available data. This attenuation in variability of flow is not appropriate for the biota that has evolved in the stream under its virgin flow regime and may suit alien biota that has invaded the riparian and aquatic zones to the detriment of indigenous biota (Richardson et al. 2007).

As regards the timing of extreme flows, this is less of a concern in South Africa in general and the Sabie-Sand River in particular. Much conceptual work regarding stream hydrology has its basis in Europe and North America where flows are more predictable, so any flows that are inconsistent with observed patterns provide catchment managers with difficulty. South African rivers are far more unpredictable (see Chapter 2) and so biota and managers are familiar with relatively erratic flow regimes. For the same reason, the frequency and duration of floods and droughts present less of a problem in South Africa than elsewhere, since native biota has evolved under these conditions. However, erratic flows due to hydrological drought and flood affect agricultural and other production negatively and people see these events as a hindrance to the functionality of the streams services. With regards to intermittent flows, the Sabie-Sand River's flow regime has a strong baseflow component and is regarded as a permanent or perennial river (Hughes 2000). Baseflow is the component of streamflow represented by the contribution of subterranean water (Gordon et al. 2004). If flows in the Sabie-Sand River became intermittent there would be severe consequences for ecosystem functionality; the biota have not evolved under conditions that include the cessation of streamflow. However, variable discharge that includes flows that incorporate ecologically important flows is desirable so long as flows never cease.

As described in Section 1.3.1 of this Chapter, dams can be used to ensure that the IFR is met. While dams are often implicated in changing the natural flow regime of a river, if good management of flow releases occurs then they can be used to ensure maintenance of the IFR, and therefore the desired flow regime. While a change in the flow regime itself does not directly affect the ecology of the river, it is an overarching process that has knock-on effects for many other aspects of the ecology of the river. Mistimed or absent flows can affect reproductive cycles of riverine biota, as well as some physical characteristics such as sedimentation.

1.3.4.4. The effect of hydraulics on river structure and function:

Although the hydraulic element of streamflow often does not come immediately to mind when investigating rivers, the physical characteristics of the catchment are shaped by the prevailing hydraulic features. Water velocity, discharge and shear stress are important characteristics of hydraulics that will change when the flow regime of a stream is altered (Gordon et al. 2004). To define these features, water velocity is simply the speed at which the water in the stream is travelling, and discharge is the volume of flow moving past a point in space in a chosen unit of time. Shear stress is less simply defined; it is like pressure in that it is measured in units of force per unit area. However, where pressure acts perpendicular to a surface, shear stress acts parallel to a surface. An example of shear stress is the pressure exerted by streamflow on the streambed. The motion of water is parallel to the streambed and although the direction of force is mostly downstream, a force is also exerted on the streambed. The effects of shear stress are manifest at multiple spatial scales as defined by Frissell et al. (1986); these range from macro-processes such as bank erosion at river segment level, through to the evolution of hydrodynamic shapes of micro-organisms at microhabitat level.

Since macro-processes related to hydraulics are more accurately dealt with in a section pertaining to geomorphological components of the river, only the effects of instream hydraulics at a finer scale will be examined here. Flow velocity is a function of discharge over an area, and is also dependent on factors in the stream such as the slope and the roughness of the stream bed (Gordon et al. 2004). As slope increases, so does the velocity of the water in the stream. The converse is true for the streambed roughness; higher roughness coefficients reduce stream velocity. It is the mosaic of varying discharge, area slope and roughness along a stream's length that provide varied velocities and consequent microhabitats for biota to exploit (Gippel and Stewardson 1998). A streams ability to move sediments is partially dependent on its velocity. The parts of the stream that have the highest velocity are capable of moving both the largest volumes of sediment as well as the largest sediment particles (Allan and Castillo 2007). The slow flowing parts of the stream either deposit sediments, or carry only the smallest particles in solution or suspension in the water column (Allan and Castillo 2007).

The relationship between discharge and a river's structure and function is the undoubtedly the most important aspect of riverine hydraulics. It is the feature that underpins other hydraulic features in the stream, such as shear stress. A concise technique used to summarize the discharge of a stream is the hydrograph (see Figure 1.13). The shape of the hydrograph tells us much about the catchment of the Sabie-Sand River, such as the approximate shape and gradient of the river profile as well as the contribution of baseflow to the discharge (Gordon et al. 2004). Rivers such as the Sabie-Sand that show a strong baseflow component will present a hydrograph with a large proportion of the flow represented as baseflow, particularly in the winter months with little rainfall (Hughes 2010). Over and above this baseflow component it is possible to see how the catchment of the stream reacts to runoff after precipitation events. Some of the precipitation that falls on the catchment will be caught in depressions on the land surface. This water infiltrates the substrate and becomes part of the baseflow of the stream after some lag period. All the water that is not intercepted is termed runoff and reaches the streambed overland at a faster rate than the baseflow. After large rainfall events, greater discharges are experienced, and the stream carries more water. During these periods of high discharge there is often a net loss of water from the streambed to the banks of the stream. This process elevates the groundwater component of the soil adjacent to the river; ie. the runoff adds in turn to the baseflow component. This is however returned to the stream once discharge in the river drops again. This process is hydrologically important because it affects the ability of the stream to retain water in the catchment, and this has secondary effects that are important for the ecology of the river (Gordon et al. 2004). For example, rivers that maintain water as bank storage for long periods may provide enhanced conditions for riparian plants. This may be offset by slumping of the river banks in cases where soils become overly saturated (Gordon et al. 2004). Another important aspect of bank storage in rivers is the mobilisation of various ions “locked” into the desiccated banks once they are inundated (Salama et al. 1994). Some of these ions may be critical for the growth of biota in the riparian and aquatic zones of the stream, but many others may be harmful (Naiman and Rogers 1997). For instance, historical gold mining effluents from the amalgamation process and MacArthur-Forrest Process may still be present in the soils of the catchment and could be mobilised by inundation and subsequent erosion (Kalbitz and Wennrich 1998; Durand 2012).

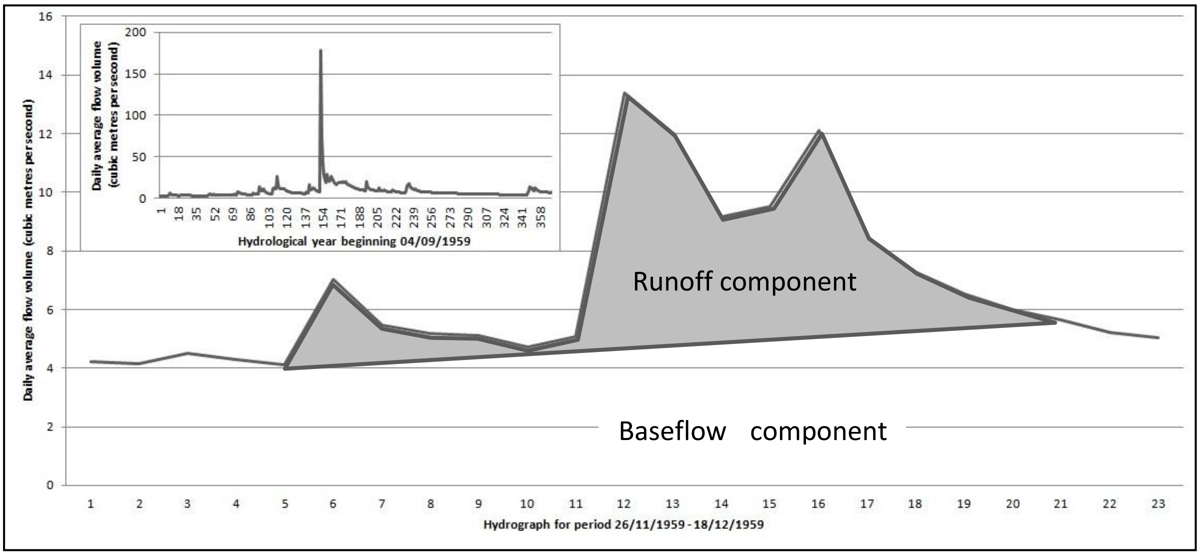

Figure 1.13. Graph showing the hydrograph for Sabie River at flow gauge X3H006 for a 23 day period, illustrating baseflow and runoff flow components. Inset shows a hydrograph for the Sabie River for a complete hydrological year.

The most notable effect of shear stress on a stream is its ability to erode the riverbed and transport sediment. I will concentrate here on sediment transport and deal with erosion as a macro-scale process affecting the geomorphological characteristics of the stream. Although not the only factor affecting erosion and sediment transport, shear stress is the primary force responsible for movement of sediment in a stream system (Roberts et al. 2003). Generally, a gradient of shear stress exists in any stream from the headwaters to a point where the stream enters either another larger stream or the ocean (Rice et al. 2001; Gordon et al. 2004). This gradient of shear stress imparts characteristics to the stream evident to any observer; namely that mountain or upland stream are usually turbulent, often with white water and carry very little sediment except for organic matter such as leaf-fall. Lower reaches of the stream usually carry more sediment compared with uplands. Shear stress is stronger at high flow velocity and discharge over the same area since it is a unit of force over an area and greater flow volumes at greater flow velocities will impart greater shear stress to the stream bed. From the characteristics of the upland and lowland portions of a stream, we can see that shear stress is highest in upland stream where the force imparted by streamflow acts over a smaller area and is given impetus by steeper gradient. The proportion of flow in contact with the stream edge is greater in upland streams and so is the shear stress, hence the relative absence of smaller sediment particles from mountain streams. This proportion is much lower in larger streams since the stream carries much more water lower down the catchment, with less of the flow volume in contact with the stream channel. This means that shear stress will be minimal lower down the river, but the river is capable of carrying a large amount of sediment mobilised from elsewhere in its lower reaches (Philips 2012).

A Hjulström diagram is a summary of whether erosion, transport or deposition processes might occur under different flow conditions (see Figure 1.14). One can see that the curves on the diagram are functions of the relationship between flow velocity and sediment size. It is a generalised relationship, so the values from Figure 1.14 could be used to extrapolate sediment transport and deposition for the Sabie-Sand River. However, this relationship takes no heed of sediment density and in places where the geology yields particularly light or dense material from the substrate, the limiting flow velocities will vary.

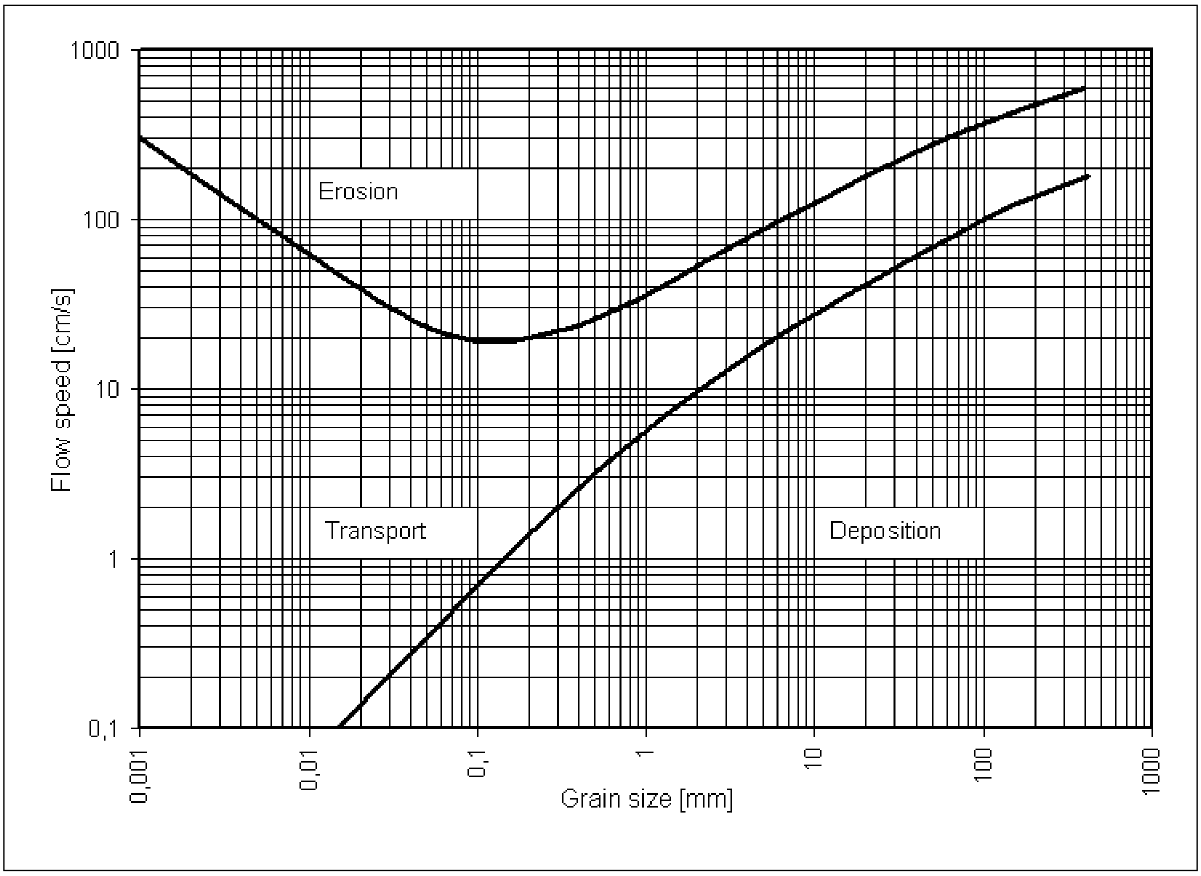

Figure 1.14. A Hjulström diagram showing the continuum of sediment motion dependent on current velocity and particle size (used under the WikiCommons agreement).

The effect on stream hydraulics should IFR's not be met would be a reduction in shear stress, and consequently a reduction in the rivers ability to transport sediments. As explored in Section 1.3.4.2 of this Chapter, different stream reaches react differently to changes in the shear stress profile. However, the overall trend in all stream reaches would be for enhanced sedimentation should shear stress decrease, as would be the case should stream flow be insufficient to meet IFR's. If IFR's are met and frequently exceeded, then shear stress would increase leading to enhanced erosion of alluvium and bedrock, albeit at different rates. The IFR is designed to ensure that occasional flushing flows are capable of removing sediment build-up. As will be seen in Chapter 3, and explored in Chapter 4, the 1:3 year return interval flood in February at all IFR sites is responsible for this function.

Shear stress has both a direct and an indirect effect on instream biota. This is also the case for riparian biota although the riparian zone will only have direct shear stress interactions during times of flooding when water inundates the riparian zone.

The diversity and distribution of the invertebrate components of a stream are largely determined by the hydraulic aspects of streamflow (Statzner and Higler 1986). Fish and other macro-biota appear to show a similar response as invertebrates to instream hydraulic forces (Statzner and Higler 1986). The velocity of a stream affects the respiration rate and other metabolic function of biota, although the mechanics of these processes are not clear since velocity is autocorrelated with other factors such as water temperature and the accumulation of organic matter in the stream (Statzner and Higler 1986; Allan and Castillo 2007). This is the case for microscopic phytoplankton, zooplankton, micro- and macroinvertebrates, and even fish (Statzner and Higler 1986). Some organisms require less oxygen than others, and so those with a lower requirement for dissolved oxygen will dominate those parts of the stream where low oxygen conditions prevail (eg: pools), and those requiring much oxygen will utilise portions of the stream with more highly oxygenated waters (eg: riffles and other fast-flowing stream units). Another important effect that flow velocity has on instream biota is that it influences the feeding biology of many animal taxa, particularly any filter feeders present in the river (Mérigoux and Dolédec 2004). If flow volumes are reduced significantly from those required by the IFR, then we will see a simultaneous reduction in flow velocity. This could result directly in insufficient nutrition for filter feeders in particular, but many other secondary effects may arise from a reduced flow velocity that could harm all riverine taxa, such as habitat loss, concentration of pollutants and sedimentation (Wallace and Merritt 1980). Increases in water temperature and/or a reduction in oxygen content could disturb metabolic functions of these species, and depending on the stability of the individual species to these changes, there will be shifts in community structures and dynamics should stream velocities and volumes decrease (Holling 1973; Power and Dietrich 2002).

While fluctuations in discharge are natural and an inherent part of most riverine systems, and more so the Sabie-Sand River, unnatural fluctuations have negative effects on the biota of a stream (Poff et al. 1997). Unnatural fluctuations may be caused by extraordinary dam releases or unusually large abstraction events. During winter months when low flow conditions prevail, dam releases or river abstractions will have the greatest effect because they represent a massive proportional change in discharge. Events such as these present instream and riparian biota with significant physiological stress and have been found to significantly reduce biomass and energy in these communities (Blinn et al. 1995). Blinn et al. (1995) also found that most instream biota (including algae, invertebrates and fish) are more stable under flash flood conditions than sudden reductions in discharge. A caveat regarding these findings is that the study was conducted with the explicit goal of determining changes in structure and function of benthos below a hydroelectric power assembly on the Colorado River, USA. No hydroelectric power facilities exist in the Sabie-Sand Catchment, but my investigations have revealed that large flow fluctuations do occur in the Sabie-Sand River (see inset of Figure 1.13 above). From the hydrograph in Figure 1.13, one can see one very large flow dominates the hydrological year. The time period used in the example is arbitrary, simply an example of flows in the Sabie-Sand River. The average flow volume on day 151 was measured at flow gauge X3H006 as 7.763 m^3/s, but rose to 177.748 m^3 /s on day 152; a flood of magnitude approximately 23 times larger than the flow volume measured the previous day. This flow volume receded quickly, and on day 157 flow was recorded at 19.405 m^3/s. The source of these fluctuations in the Sabie-Sand River is mainly rainfall and dam-release related.

Since shear stress is a determinant of what types of sediment are present in different portions of the stream, it follows that organisms that favour particular substrate types will seek out shear stress environments that create conditions in which they will thrive (Power et. 1988; Rice et al. 2001). For example, the Lowveld Largemouth (*Serranochromis meridianus)* is a rare fish that favours large open pools (ie: low shear stress environments) with well vegetated banks (Skelton 1987). A situation in which the long-term discharge of the Sabie-Sand River drops could result in pool formation due to the reduction in shear stress associated with drops in discharge. This could favour this rare species and the population will thrive if other factors such as food availability and limited predation allow. This is an example of the indirect effects that shear stress has on the biota of the river. A direct example would be the evolution of streamlined shapes of the organisms in the river that are dependent on the shear stress profile they inhabit (Leavy and Bonner 2009). Organisms that dwell in zones of high shear stress will show extremely hydrodynamic shapes while those that live in low shear stress environments such as pools will be less streamlined.

As regards the riparian vegetation, it is only during flood events that these plants will have shear stress contact with flow from the river. In times of greater discharge when the wetted perimeter of the streambed grows into the riparian zone, it follows that shear stress is immense (Gergel et al. 2002). The resultant effects of this inundation are anaerobic soil conditions and erosion leading to the large-scale removal or death of riparian plants (Bendix 1997). Plants that are capable of withstanding inundation occur lower down the macrochannel banks of the riparian area, but those high up the riparian bank will not be as well equipped to deal with inundation (van Coller et al. 2000).

1.3.4.5. The role of geomorphology in river structure and function:

The Sabie-Sand River has a continuum of geomorphological features from bare bedrock to sections of streambed dominated entirely by alluvium. Within this continuum Heritage et al. (1997) identified ten possible channel types with five of these dominating in the Sabie-Sand River. These five channel types are: bedrock anastomosing, mixed pool-rapid, mixed anastomosing, alluvial single thread, and alluvial braided. These different channel types react differently to variations in flow characteristics. I will use the structure as set out by Heritage et al. (1997) to explore how changes in flow linked to the failure to comply with IFR's affects the geomorphological template in the Sabie-Sand River.

Progressive siltation of the Sabie-Sand River has prevailed over a number of decades (Heritage et al. 1997). This is attributed to the change in land cover within the catchment yielding ever larger amounts of sediment, as well as reductions in flow volume and flood frequency that have subsequently reduced the rivers ability to transport sediment downstream (Moon et al. 1997).

An oscillatory mechanism of change in geomorphological templates has been proposed, beginning with a bedrock dominated stream as a result of a large infrequent flood event (Moon et al. 1997). Progressive siltation of this streambed occurs, leading from bedrock and mixed pool-rapid channel types to anastomosing channel types (Heritage et al. 2001). As bedrock elements undergo sedimentation, a representative portion of the channel progresses along the continuum to mixed anastomosing and then a single thread alluvial channel (Heritage et al. 2001). Once the alluvium is well-established, the alluvium branches and rejoins forming a braided alluvial section (Heritage et al. 2001). The template is reset by large infrequent disturbances such as the floods of February 2000, but not all parts of the river will be reset to a bedrock dominated template (Parsons et al. 2006). Rather, there is a redistribution of sediment of various sizes with a shift from a mostly biotic-dominated (trees and shrubs) state to a template dominated by abiotic features (bedrock, and a range of sediment types) soon after a large flood.

Changes in discharge will have different effects on each of the five templates identified by Heritage et al. (1997). Bedrock dominated channels such as the Sabie-Sand River often exhibit high energy since less of the energy "budget" is spent moving sediment. However, as land use changes have occurred in the catchment, the rate of sediment introduced to the stream has increased and we currently see a mosaic of morphological units with less bedrock influence (Broadhurst and Heritage 1998). This trajectory is mitigated by larger flows that remove sediment buildup; conversely it is enhanced by reductions in stream discharge (Parsons et al. 2005). A scenario in which actual flows are lower than IFR specifications will amplify sedimentation rates. Bedrock dominated channels are most suitable for trees such as *Breonadia salicina* and S*yzygium guineense* (van Coller et al. 1997). van Coller et al. (1997) attempted to link certain plant species to the different geomorphological templates present in the Sabie-Sand River. *Breonadia salicina* and *S. guineense* were identified as species that prefer bedrock dominated habitat, and van Coller et al. (1997) speculate that the fluctuation in the relative proportion of these species to others in the riparian zone are indicative of the position of the system state along the continuum from a bedrock to an alluvial dominated stream. If IFR's are consistently not met, we would see a lower proportion of *B. salicina* and *S.*

guineense present compared to other species, since enhanced sedimentation would render conditions that are unfavourable to these species. Another bedrock dominated channel type is the pool-rapid complex, but large infrequent floods may cause the formation of rapid-like obstructions in the stream through the deposition of large woody debris as flood waters recede (Parsons et al. 2005). Our predictive capacity regarding alluviation of pool-rapids is not as strong as for other channel types. The turbulent dynamics associated with streamflow in a pool-rapid complex only allows us to describe the motion of water in the rapid using a statistical approach (Gordon et al. 2004). Accurate measurement of discharge cannot be conducted with any confidence in these channel types and may only be described using probabilities. Consequently, the manner in which a pool-rapid reacts to changes in flow is a point of speculation even for professionals. Using the Hjulström diagram from Figure 1.14 in this chapter, we can see that a sudden reduction in flow velocity within the rapid could take a hypothetical sediment particle directly from the erosion portion of the Hjulström curve beyond the deposition section of the Hjulström curve. If entrainment of this process occurs beyond a threshold required to maintain a body of sediment in the pool-rapid, then a new stable state, a mixed pool-rapid channel type is formed (Thompson and Wohl 2009). The corollary of this is true and the sudden fluctuation in flow velocity and shear stress that is typical in pool-rapids could result in the reversal of this process without difficulty. The plant species that favour this phase of the channel type on the continuum include the reed *Phragmites mauritianus*, the shrub *Phyllanthus reticulatus* and to a lesser extent the tree *Combretum erythrophyllum* (van Coller et al. 1997). This has been attributed to the increasing influence of alluvium on the channel (van Coller et al. 1997). This alluviation would be enhanced at sites where IFR's are not met, and *Phragmites mauritianus* and *Phyllanthus reticulatus* would be the dominant plant forms there.

As the process of alluviation occurs along the continuum from bedrock to sediment dominated channel types, bedrock channels become progressively more submerged creating a mixed anastomosing channel. This channel type is underlain by bedrock at some depth and also comprises varying proportions of sediment (Broadhurst and Heritage 1998). The time elapsed since a large infrequent disturbance is a strong predictor of the proportion of sediment in the channel (Rountree et al. 2000). As more sediment enters the stream channel, we see a shift from *B. salicina* dominated vegetation types to a vegetation type where *P. mauritianus* and *P. reticulatus* are relatively common. Once alluviation begins the genesis of a mixed anastomosing channel type, a marked positive feedback loop occurs in sedimentation and so sandbar growth in these channel types occurs more quickly than others (Zeigler 1976; Heritage et al. 1997). In periods where a number of months of consecutive IFR's have not been met this positive feedback system would prevail. This has implications for a host of processes such as recruitment of plants in those reaches as well as rapid change of habitat for instream biota in those river reaches. An example of this is the recruitment of the reed *P. mauritianus* in these channel types, which occurs soon after sediment accumulation begins. The *P. mauritianus* reedbeds growth also amplifies the accumulation of sediments by increasing the channel resistance to flow as sandbars increase in size (Heritage et al. 1997).

As more alluvium enters the channel, there is a progression to a channel type dominated by sediments as opposed to those dominated by bedrock or mixed type channels. These channel types are characterised by lower energy levels, hence the deposition of sediments (Heritage et al. 2001). The accumulation of sediments in the channel can be attributed mainly to infrequent flows of relatively large magnitude because flows such as these are capable of carrying more sediment than flows of small magnitude. As these larger magnitude flows enter channel types or morphologies that reduce their energy, the sediment is laid down. Mixed anastomosing channels are an example of a channel type with morphological characteristics that reduce discharge energy, because they usually possess wide channels (Parsons et al. 2006). As siltation occurs in mixed anastomosing channels they progress to alluvial channels of either the single thread or braided variety. Single thread alluvial channels are the least common of the channel types discussed here. They usually occur as a result of reductions in discharge over a braided alluvial channel type and are therefore more common and ubiquitous in the low flow season, when the active braided channel is reduced to a single active channel (Heritage et al. 1997). Since the alluvial deposits within these channel types are relatively fine (comprised of sand), the streambed is unstable and responds quickly to changes in streamflow, moving interchangeably between single and braided flow patterns (Gordon et al. 2004). Upon examination of a series of aerial photographs of the Sabie-Sand River, Heritage et al. (1997) noticed an alternation of dominance between single and braided alluvial channels. They propose that this pattern may be dependent on the alternative drier and wetter patches over southern Africa due to the El Niño-Southern Oscillation climate pattern (Heritage et al. 1997; Reason and Roualt 2002). van Coller et al. (1997) found that *C. erythrophyllum* favours channel types dominated by alluvium. If we recall the continuum of progressive alluviation of the stream and that *C. erythrophyllum* proliferates in alluvium, we see that *C. erythrophyllum* is a climax species in the Sabie-Sand River, as first defined by Clements (1916). *Combretum erythrophyllum* is known to coppice in response to inundation of the bole by sediment and this may provide it with a competitive advantage over other trees in the macro-channel (van Coller et al. 1997). In periods of lower flow and amplified sedimentation, *C. erythrophyllum* are likely to undergo large-scale recruiting from coppice-type growth. This means that the biota associated with alluvium will dominate the system state until a major perturbation occurs. In the case of the Sabie-Sand River, a flood such as the one in February of 2000 would be a sufficient perturbation to remove many established stands of *C. erythrophyllum*, and this would induce the return to a bedrock dominated stream.

1.3.4.6. The role of vegetation in river structure and function:

The geomorphological template of the river is usually seen as the controlling mechanism in river structure and function, with biotic processes occurring as a result of conditions produced by this template. Less consideration is given to the effect of the biota on the function and geomorphological characteristics of the river, but as demonstrated above the biotic components of a river increase in importance as time progresses since the last large infrequent disturbance (Parsons et al. 2006). A number of important roles fulfilled by vegetation in the river and riparian zones include stabilisation of river channels and attenuation of floods (King et al. 2008). Recently, the value of riparian zones and the plants found in them has come to the fore because they function as sinks for anthropogenically derived pollutants (eg: fertilizers) that would otherwise harm ecologically sensitive streams (Jacobs et al. 2007). Through shading and leaf fall, vegetation also influences water temperature and quality (King et al. 2008). Plants provide food and habitat for many plant and animal species in both the riparian and instream environments.

The type and structure of vegetation is both a product of and an agent of change in rivers and riparian zones (Dollar et al. 2007). As can be seen from the examples in Section 1.3.4.5 above, this manifests in species colonising different substrates preferentially, and once this has occurred these plants then have a secondary effect on geomorphological and hydraulic aspects of the river (van Coller et al. 1997; Dollar et al. 2007). An example of this is the colonisation of a sandbar by the reed *P. mauritianus.* As sediment accumulates the seeds of *P. mauritianus* take root in the sand and begin colonising the sandbar on which they landed, and in time the well-developed dense reedbeds trap sediments and amplify the sedimentation rate (Dollar et al. 2007).

If we recall that after large infrequent floods the geomorphological template is reset to a more bedrock influenced state, the presence of dense stands of the reed *P. mauritianus* shows that the river has experienced widespread sedimentation with minimal flooding for an extended period, and we can thus infer much about land-use and/or climatic conditions upstream in the catchment as well as the trajectory of change over time, and that it is likely that IFR specifications have not been regularly met or exceeded. Land cover change has led to increased rates of sedimentation in the catchment (Heritage et al. 1997). As land becomes more urbanised, the roughness coefficient (a measure of how quickly water passes over or through a particular space) of the catchment is reduced (Hernandez et al. 2000). This means that water passes more quickly over the land, and also retains a greater amount of energy that is then capable of mobilising and transporting sediments.

If this effect is coupled with circumstances in which large tracts of land in the catchment are less vegetated than in the past then larger amounts of sediment are mobilised and land is eroded, leading to greater amounts of sediment transport in rivers. This in turn hastens the rate at which species that prefer alluvial substrata colonise the river and riparian zone (Hood and Naiman 2000). This effect may be mitigated to some extent by the presence of large dams in the catchment, and the position of these dams. Large dams trap sediments causing reduced instream alluvial loading below the dam wall and thereby reduce colonisation rates of species such as *P. mauritianus* (Baxter 1977). Both the Inyaka and Da Gama Dams are situated in the upper reaches of a high sediment yield zone of the Sabie-Sand Catchment, and so these dams have resulted in a reduction in sediment transport in comparison with what would have occurred in the catchment if no large dams had been built on the existing template of landcover change (Coetzer et al. 2010). In a case where the catchment or sub-catchment cover is largely natural or has remained in a similar state for a long time period and we notice widespread sedimentation and plant communities associated with alluvial geomorphology, we might infer that rainfall and runoff has been low in the intervening few seasons. An example of sub-catchment that might allow us to detect changes like this is the Nwaswitshaka River; this stream and its sub-catchment are situated entirely within the KNP and will be explored in greater detail in Chapter 4 of this thesis.

Another important functional aspect of vegetation in rivers is that of habitat maintenance for both other plants and animals dwelling in riparian and riverine zones. The changing mosaic of vegetation patterns occurring in the Sabie-Sand River riparian zone is highly dependent on the retention of a range of species in the macro-channel after a large disturbance such as the floods of February 2000. The loss of an important species in a large infrequent event will eliminate that species from the mosaic in the post-flood system state and in time, could have far-reaching implications for the geomorphological features in the catchment (Parsons et al. 2005). If we use the reed *P. mauritianus* as an example again, a mosaic of vegetation with none or very little *P. mauritianus* in its composition will also show higher rates of sediment transport than if stands of *P. mauritianus* dominated that section. The retention of species-heterogenous patches in post-flood conditions is extremely important since they are the source of seeds and other propagules (Parsons et al. 2005).

Although the examples above show how vegetation may affect the geomorphological character of the river and riparian zone, numerous other structural and functional effects can be attributed to vegetation. These effects are caused by the relationship of a multitude of factors that interact in a very complex manner. These factors include the abundance and type of organisms that remain post-disturbance, the spatial arrangement of these organisms in the landscape and their life-history traits, as well as the spatio-temporal arrangement of subsequent disturbance effects (Parsons et al. 2005). Outcomes of the interplay of these factors are therefore extremely variable and the resulting geomorphological state is context-specific and localised.

Vegetation is also linked to reductions in rainfall runoff and thus streamflow is also reduced (Moon et al. 1997; le Maitre 2002). It has been established that in South Africa, water use by alien invasive plant species is much higher than that of indigenous species (Görgens and van Wilgen 2004). The upper reaches of the Sabie-Sand River is heavily vegetated with economically important plantation species, mostly *Pinus patula* and *Eucalyptus saligna* (Shackleton 2000). These plantations are responsible for flow reductions in the Sabie-Sand River in the range of 17 – 45% of pre-forestry flows (Moon et al. 1997; le Maitre et al. 2002). This effect is pronounced in the dry season and drought periods when plantations are responsible for consuming a greater proportion of the share of water in the catchment as compared to wet season flows (le Maitre 2002).

Shading and leaf fall in the river has a significant effect on the hydrological function of the river as well as water quality. A general observation for most streams including the Sabie-Sand River is that organic inputs (as leaf fall) to the stream diminish from the headwaters to the river mouth (Walters and Post 2011). This can be attributed to the gradual change from incised, smaller channels where overhanging vegetation contributes significantly to the organic component of the stream, to a channel of greater width where photosynthetic processes dominate and overhanging vegetation contributes proportionally less energy to the system (Gordon et al. 2004). This leaf fall is also known as particulate organic matter (POM) after the River Continuum Concept (RCC) as outlined by Vannote et al. (1980). The balance of energy introduced into the stream, and where this energy is derived plays a very important role in the composition of the lotic community, and how that community changes along the longitudinal profile of a stream (Power and Dietrich 2002).

The pattern of greater influence of vegetation in narrow streams also prevails with regard to shading, where incised and narrow channels are often completely over-shaded in the Sabie-Sand River while the wider portion of the stream lower down the longitudinal profile are less likely to be completely shaded (Gordon et al. 2004). Shading plays an important role in energy production in rivers; heavily shaded areas are reliant on mainly allochthonous and some autochthonous material introduced into the river as the base of food webs since shaded reaches do not provide suitable conditions for primary producers (Lake et al. 2007). In less shaded portions of the stream, primary producers are the principal sources of basal energy in the system (Power et al. 1996). Shading can also provide camouflage for fish and other aquatic organisms such as terrapins and invertebrates.

Aquatic macrophyta are an often undervalued component of a healthy river, and unfortunately very little research regarding these plants in the Sabie-Sand Rivers has been undertaken or published. Since the Sabie-Sand River is well-studied I believe that this omission is due to aquatic macrophyta not playing a large role in the Sabie-Sand River, but the possibility that this feature of the Sabie-Sand River's ecology has not been investigated is also realistic. For this reason, no specific examples of how macrophyta interact with structural and functional aspects of the Sabie-Sand River can be given. Some generalised relationships may hold true, and these shall be briefly explored. Power et al. (1996) noted in their research that flow reductions and the associated effects on hydrological regime (eg: slower flow) often lead to encroachment of vegetation in the channel and reduced ability to convey floods and higher flows. Moribund macrophytic material also causes anoxic conditions when it begins to decompose, and this is detrimental to many aquatic organisms. This may occur during either low flow or prolonged high flow condition (Brock and Cassanova 1991). Low flow conditions often lead to high water temperature conditions coupled with lower oxygen content of water, while prolonged flood conditions are accompanied by turbid conditions which hinder autotrophic processes in macrophyta (Brock and Cassanova 1991). This situation is more likely to occur in the Sabie-Sand River if the IFR specifications are not met. Experiments undertaken by Prosser and Slade (1994) on shear stress in degraded and undegraded catchments showed that those with aquatic macrophytes showed a greater resistance to scour and were therefore less likely to erode, or erode at a slower rate than degraded streams. Aquatic macrophytes also act as a food source, provide habitat and refugia for fish, aquatic invertebrates and other organisms (Gordon et al. 2004).

Vegetation influences the geomorphological and other structural features of the river as well as being influenced by these structural characteristics. Vegetation is also responsible for many functional aspects of the river. As with all of the other facets discussed here, the vegetation of the catchment and especially the riparian and riverine features of the landscape will respond to spatio-temporal changes in flow. Failure to meet IFR's results in shift in plant communities in response to decreasing flows. With the knowledge of which plant species favour different localised climatic and geomorphological conditions within the catchment, we can hypothesize a trajectory of shifts in community structure and therefore function in the river in the future. A scenario in which flow volumes are insufficient when compared to IFR's would in all likelihood lead to greater sediment deposition. Plant species that favour such conditions would come to dominate the river and riparian zone, and thereby change the structure of the river. Flow volumes that mobilise sediments would enhance recruitment of plants that favour a more bedrock dominated template. If the scenario that we envision is not desirable then we must ensure that IFR's are met so as to avoid a scenario in which the river and its functions are compromised.

1.3.4.7. The role of aquatic invertebrates in river structure and function:

Aquatic invertebrates are a crucial component of river systems. Less research regarding their effect on structural facets of the river has been done when compared with the functional components, but there is little doubt as to the critical role played by these organisms in rivers. For the purposes of this investigation, the aquatic invertebrates considered include the worms, molluscs, crustaceans and insects and their larvae found in the instream environment (King et al. 2008).

A study of this nature and resolution does not require any specific detail regarding aquatic invertebrates. For this reason the examination of their effect on the structure and function of the riverine and riparian zones of the river will be undertaken at the feeding guild or order level, with particular attention paid to a group if they are deemed to perform an important role in a particularly pertinent structural or functional aspect of the river. The feeding guilds that will be dealt with in this section are so named because they utilise different means of obtaining nutrition and in doing so are key components for nutrient cycling in the system (Vanni 2002). The guilds as outlined by Vannote et al. (1980) include shredders, collectors, grazers and predators.

Shredders consume the coarser fraction of particulate organic matter (POM) such as leaf fall, along with a significant amount of micro-organisms and fungi present on leaves (Yoshimura 2012). In doing so, they render smaller particles available for consumption by other organisms through either wastage or defecation (Vanni 2002). As a consequence of their diet, shredders dominate in the upper reaches of rivers or in smaller streams where leaf fall is responsible for the majority of energy introduced into the stream (Vannote et al. 1980). Some examples of shredders include the mayflies (Order: Ephemeroptera), stoneflies (Order: Plecoptera), caddisflies (Order: Trichoptera), alderflies (Order: Megaloptera), some damselflies and dragonflies (Order: Odonata), some chironomids and simuliids (Order: Diptera), some adult and larval beetles (Order: Coleoptera) and freshwater crabs (Phylum: Crustacea). But for the crabs, all of these organisms belong to the Class Insecta and comprise the majority of the shredders found in aquatic environments along with crabs (Davies and Day 1998). Other important organisms that can be found in areas of allochthonous reaches of the stream are the flatworms, roundworms, aquatic annelid worms and snails (Davies and Day 1998). The habitat preference for these organisms is generally free of sediment, and so they would dominate in bedrock and to some degree the mixed anastomosing sections of the river. It follows that if IFR compliance does not occur and sedimentation occurs due to lower flows than required, progressively less habitat would be available for the shredder guild.

Collectors, comprising both filter feeders and gatherers consume fine particulate organic matter. They are referred to as such since they re-aggregate minute particles of POM for ingestion (Cummins 1974). This is derived from the shredded coarse POM and other nutrients present in the water. Similar to shredders, collectors also utilise the microbial and fungal associate organisms on leaf particles for nutritive purposes (Yoshimura 2012). This feeding guild comprises a greater proportion of the aquatic invertebrate biomass further downstream, eventually coming to dominate the mix of instream biota in the lower reaches of streams. Examples of biota in this feeding guild include some filter feeding larval stages of the caddisflies (Order: Trichoptera), simuliid flies (Order: Diptera), members of the mayflies (Order: Ephemeroptera) as well as some molluscs and nematodes (Vannote et al. 1980). Some of the members of this guild are reliant on alluvium for part of their life cycle and are capable of coping with increased rates of sedimentation. If IFR's are not met, a sedimentation situation in which greater alluvium is deposited would occur. This would likely result in the proliferation of collectors in the river until such a time as those sediments are removed by a large flood.

Grazers (sometimes referred to as scrapers) are dominant in the portions of the stream where photosynthesis is greatest (Vannote et al. 1980). This is because grazers rely on the energy created by primary producers and are therefore most prevalent wherever aquatic plants are most common. Where the RCC states that grazers occur in the middle reaches of the river, South African systems are quite different and grazers are most likely to occur in reaches of the stream where sediment transport is low even if substantial amounts of alluvium is present, and suitable substrata for attachment by aquatic macrophyta is available. Grazers are comprised of a varied group of organisms; some common groups include gastropods such as snails, a number of Baetid species (Order: Ephemeroptera), adults insects of the family Corixidae (Order: Hemiptera) and some larval stages of caddisflies (Order: Trichoptera) (Picker et al. 2004). Due to the requirements of grazers in terms of life cycle and feeding, they are common in places where there is mixed alluvium and bedrock, such as the habitat found in bedrock anastomosing channels. This has imparted most with a degree of hardiness to dwelling in an environment that oscillates around the mixed bedrock and alluvium template. However, a consistent unidirectional shift towards either bedrock or alluvium is likely to have a negative effect on the grazer population in the river.

Predators feed on all other guilds they subsist in all reaches of streams where suitable food sources are available (Power et al. 1996). Predators include a range of animals, from larval to adult insects and other arthropod and non-arthropod species from the amphibians, fish, birds, mammals and others. Some of the important invertebrate predator include a range of either larval/young or adult phases of the orders Plecopotera, Hemiptera, Odonata, Megaloptera, and within the Coleoptera, genera of the families Dytiscidae, Gyrinidae and the Hydrophilidae (Picker et al. 2004). Predators occur in all reaches of the stream, only differing in their composition and proportion from headwaters to river mouth depending on the prevalence and abundance of their food source. In streams and rivers, the number of trophic levels exceeds most of those in terrestrial environments and many predators, especially invertebrates are themselves predated by larger invertebrates and other non arthropods (Arim et al. 2010). Along with other determinant factors explored above, invertebrate predators are partially responsible for the variety and composition of the biota in the stream and exert both top-down and bottom-up influences since many occur at intermediate trophic levels (McHugh et al. 2010). As outlined above, the fact that predators feed on all other guilds means that even progressive alluviation of the Sabie-Sand River would not eliminate them from the stream since a food source would always be available. However, the composition of the guild would change depending on whether some predators have a preference for consuming members of any particular guild. A predator that consumed only shredders would decline in numbers should the river undergo siltation. This would be the scenario if streamflow is too low to meet IFR's. Conversely, should flows be consistently greater than IFR's, and the river become dominated by the underlying bedrock template then predators that feed on collectors would increase in number.

The composition of instream biota also plays a role in the structural and functional aspects on the stream. These organisms are responsible for a large proportion of nutrient cycling and translocation in the stream, and influence primary production and decomposition processes (Wallace and Webster 1996). Many invertebrate organisms are not well understood and described. Consequently their functional roles in streams may not be evident until they are lost from the system. However the relationship among instream organisms is complex and may mask the effects of any one species on the ecosystem, meaning that the ecosystem function may be maintained even in a situation where a species is lost (Wallace et al. 1986). In the context of this study it is important to acknowledge that many species among the shredders, collectors, grazers and predators are sensitive to flow reductions (Dewson et al. 2007). Decreases in flow volume are almost always accompanied by reductions in flow velocity, reductions in wetted perimeter of the streambed, increased temperature and alluviation. These factors alter instream habitat conditions, thereby shifting habitat suitability for many species and consequently changing the suite of aquatic invertebrates (Bunn and Arthington 2002).

1.3.4.8. The relationship between fish community structure and river structure and function:

The Sabie-Sand River is known to be the most fish species rich system in South Africa (Rivers-Moore and Jewitt 2007). Forty nine species have been described in the river, making it a priority for conservation (Rivers-Moore and Jewitt 2007). Fish are an important facet of river ecosystems since they occupy most feeding niches; in the Sabie-Sand River the omnivore, herbivore and carnivore groups are represented. Many species even occupy multiple niches from the larval stage through to adulthood. An example of this is the widespread *Labeobarbus marequensis*, which has been found throughout most of the Sabie-Sand River system (Rivers-Moore et al. 2004). This species is known to feed on insects, molluscs, crabs and other fish in the adult stage, and favours plant detritus, midge larvae and mayflies when not fully grown and microscopic phytoplankton during its larval stage (Pienaar 1978; Skelton 2001).

Other important species include two of the genus *Chiloglanis*, namely *C. anoterus* and *C. paratus*. The significance of these species relates to the fact that their presence or absence is an indicator of water temperature, and therefore an aspect of water quality (Rivers-Moore et al. 2004). In the outline of the BBM, King et al. (2008) also assert that knowledge of the environmental conditions required by fish to complete lifecycles can provide important information about functional aspects of a river. The work conducted by Rivers-Moore et al. (2004) on the two above-mentioned species of *Chiloglanis* linked the relative abundance of the two species to temperature. *C. anoterus* and *C. paratus* have very similar habitat requirements in terms of water depth, flow velocity and cover, but differ markedly in their water temperature preferences. *C. anoterus* prefers cooler water, while *C. paratus* thrives in warmer water. From this relationship we can see that changes in the relative abundance of the two species point towards changing water quality in the river. The species of fish selected by Rivers-Moore et al. (2004) for their study are ubiquitous and common, and as such can be used as indicators of environmental health and conditions for the river since they show deterioration of their metabolism and general health when they are exposed to temperature fluctuations and sub-optimal temperature regimes (Magnuson et al. 1979). Other linkages between water quality and fish health are not well established in South Africa, although research in the field is ongoing (Rivers-Moore et al. 2005). Reductions in flow volume (ie: IFR non-compliant flows) in the Sabie-Sand River over the long-term will lead to warming of the stream. The relative abundance of the two *Chiloglanis* species should mirror this change and provide us with a yardstick for how much water quality in the Sabie-Sand is changing, and at what rate. Conversely, if IFR's are consistently met and the stream sees cooler water further down the catchment than usual, there will also be a greater numbers of *C. anoterus* per *C. paratus* individual further downstream.

Numerous aquatic taxa and species have been used for biological monitoring and evaluation in the past, mostly diatoms and invertebrate fauna depending on monitoring skills and local conditions (Karr et al. 1986). The use of aquatic invertebrates for monitoring river health has a long history in South African streams (Dickens and Graham 2002). The BBM advocates for a holistic approach to river management, and so uses vegetation and invertebrate information as well as fish data in the assessment of biological integrity (King et al. 2008). Because fish are easily caught and indentified, their health and community dynamics can be useful in determination of flow specifications that ensure good ecological maintenance of streams (King et al. 2008). Once initial flow specifications are established and the ichthyofaunal benchmarks set, the health of fish can be monitored. Consequently, stream health can also be ascertained against the health of fish populations and individuals in the stream. In addition data regarding flow requirements for healthy fish populations can be refined.

Fish response to variations in flow differs depends on the species. It is therefore difficult to manage for a flow regime beneficial to all species; in fact, many species may have conflicting requirements and so a regime that mimics the natural flow regime as far as possible is recommended. The reasoning for this states that the historical flow regime created conditions for all the species currently recognised to evolve and thrive, and is therefore assumed to be suitable for their perpetuation (King et al. 2010). If the historical flow regime was perennial, as is the case with the Sabie-Sand River, the biota have evolved under these conditions and we can expect that if flows had to cease, this would have a very detrimental effect on the biota. Data retrieved from the flow gauge X3H006, chosen for it has the longest dataset for a larger reach of the main stem of the Sabie River show that flows have never ceased in the Sabie River and this is corroborated for the rest of the river in the literature (Pringle 2001; van Wilgen and Biggs 2011). However, the trend of daily mean flow has diminished from over 7 m^3/s in April 1978, to just over 6 m^3/s in January of the year 2000 when the flow gauge was broken by the floods a month later (see Figure 1.6 above). The effect of changes in flow regime on sedimentation and other geomorphological aspects of the river that would affect fish habitat have been explored above and it is known that reductions in flow results in alluviation of the stream. We can expect that such a scenario will provide conditions that support a shift in ichthyological communities towards those species that favour sandy substrates. The long-term change towards a sandier substrate may however not benefit even those fish that dwell on sandy substrates as adults since many are dependent on gravel beds for breeding and these will be less prevalent if flows are reduced (King et al. 2008).

Studies on fish spawning have mostly been undertaken in North America on the salmonids, but much of the information that has been discovered regarding photoreception and streamflow cues to begin spawning is applicable to the freshwater fish of South Africa. Many developmental aspects of fish physiology are also reliant on various cues related to timing of flows and sunlight hours per day (Sloman et al. 2005). Gonadogenesis and sexual maturation are examples of flow and light sensitive processes, and can be affected by changes in flow regime (Penman and Piferrer 2008). Water temperature is partially dependent on flow; this has been explored above. The link between water temperature and sex ratios in fish is well-established and fluctuations in temperature mediate hormones responsible for sex-determination in many species (Baroiller et al. 1995). Direct anthropogenic influence on water temperature in streams has the potential to change stream temperature beyond the regular variation that fish may be accustomed to (Burt et al. 2011). Besides this, the effect of reduction in flow volume will cause increases in water temperature and in conjunction with the increased temperature oscillations that may occur as a result of climate change may cause severe disruption to fish life cycles and communities (Baroiller et al. 1995). Thermal regime has also been shown to influence larval size and deformities, yolk utilisation and physiological ontogeny (Burt et al. 2011).

Ichthyofaunal diversity and function will be disrupted by changes to quality and quantity of flow in the Sabie-Sand River under a changing flow regime. This may manifest in the loss of some species of fish from the ecosystem, and in some cases disruption to functional components of the ecosystem. In an IFR context, management would aim for maintaining an appropriate diversity of habitat types, with the associated variation in fish community structure as a response variable to inform IFR adjustment, or research into fish-habitat relationships.

1.3.4.9. The role of groundwater in river structure and function:

The groundwater component of the stream is a crucial aspect of the character of a river. While the focus of this section will be the contribution of groundwater to the baseflow of the Sabie-Sand River, other vital functions fulfilled by groundwater include the supply of water to plants in upland regions of the catchment, maintenance of crucial instream habitats such as pools and riffles in most dry periods, and water storage for a range of human and ecological uses (King et al. 2008).

Importantly, groundwater is responsible for the baseflow element of the volume of water in a stream (see Figure 1.13 of this chapter). In regions where baseflow contributions occur, the baseflow of a river is most easily detected in the dry season. For the Sabie-Sand River, baseflow is most evident between May and September as well as the periods between precipitation events during the wet season. Baseflow is detectable during these periods because it is considered to be indirect discharge; ie: streamflow of subterranean derivation as opposed to overland flow from precipitation, and is evident when the direct effects of precipitation are removed (Seiler and Gat 2007).

Baseflow is the most stable component of streamflow since it is infiltrates the soil and aquifers before entering the stream and moves slowly into the stream channel, whereas runoff is the “flashy” aspect of streamflow as illustrated in Figure 1.13 of this chapter (Ward 1984). The linkage of baseflow to river structure and function is particularly important for the Sabie-Sand River for numerous functional reasons (Smakhtin et al. 1998a). The primary reason for the importance of baseflow in the Sabie-Sand River is due to the underlying geology of the upper portions of the catchment. The headwaters of the catchment are underlain by dolomitic rock, a permeable rock that holds water well meaning that baseflows for the Sabie-Sand River approach 20% of rainfall volume and almost half of the total runoff volume (Xu and Beekman 2003). The drainage region in which the Sabie-Sand Catchment is found shows the highest proportion of mean annual runoff as baseflow of any region in the country (Xu and Beekman 2003). As will be explored in Chapter 2, the extreme unpredictability of the Sabie-Sand River’s flow regime is mitigated somewhat by a strong baseflow component that dampens fluctuations at the lower end of the scale of flow volumes. It is due in large part to these baseflow characteristics that the Sabie River has never run dry. During the meteorological drought of 1992, voluntary restrictions by irrigators meant that water was available for ecological maintenance downstream in KNP, thereby attenuating the effects of the hydrological drought, where the Sabie River might have run dry if not for this intervention (van Wilgen and Biggs 2011). The contribution of baseflow to the stream buffers the ecological functions of the river against xeric conditions in the dry season, and is therefore crucial in particular to the base or low flow components of the IFR (Xu et al. 2002). The proportion of streamflow that can be attributed to the groundwater varies in time; in a hydrological year the dry season streamflows are dominated by groundwater baseflow while overland flow is responsible for a greater part of the flow in the wet season (Boulton and Hancock 2006). The contribution to streamflow of groundwater is also spatially dependent. Upper courses of the river generally do not show great hydraulic connectivity with groundwater; the middle reaches often show interchangeable interaction with water moving between the river banks and the stream, and the lower reaches of a river usually gains water from subterranean sources (Xu et al. 2002). This is due to changes in hydraulic connectivity to aquifers and permeability of rock underlying the stream coupled with greater availability of water lower down slopes as the stream passed through the landscape and catchment area increases (Boulton and Hancock 2006). However, due to the spatial arrangement and climate of the Sabie-Sand River catchment, the river rarely gains water from subterranean sources in the reaches after it enters the KNP and most often loses water to bank storage after the confluence of the Sand and Sabie Rivers

(Smakhtin et al. 1998b). Figure 1.1 of this chapter shows how the rainfall diminishes significantly in an easterly direction in the catchment. In Figure 1.2 and Figure 1.3 of this Chapter, it can be seen that the density of tributaries is lower after the confluence of the Sand and Sabie Rivers. These tributaries are ephemeral in nature, and even the largest of these, the Nwaswitshaka, does not flow during the dry season and is often dry even in the wet season under drought conditions. This means that less water is present in that part of the catchment as either rainfall or streamflow as compared with the upland catchment areas, highlighting the importance of meeting the IFR flow objectives that enter the KNP, for purposes of ecological maintenance.

In Section 1.3.4.8 it was noted that the average streamflow rate in the river has decreased over the period 1978 to 2000 (see Figure 1.6). This trend evident at flow gauge X3H006 is long-term, and the moving average on which it is based gives us strong reason to believe that this trend has continued and is ongoing. The effects of flow reductions on instream structure and function are easily quantified since flows can be measured directly and in almost real-time with flow gauges. However, the mechanism of these flows requires attention. The nature of hyporheic flows and aquifer dynamics means that the effects of long-term reductions in baseflows are not simple to quantify; the causal source of change in the features of the stream may have occurred many years previous to the manifestation of their effects. Using hydrograph separation methods, we may be able to better understand the mechanism of changing flows by separating the baseflow and runoff components of long-term average annual streamflow. If wet season streamflow is similar or even higher than previously experienced but larger than expected drops in water availability during the dry season occur, this points toward depletion of groundwater resources and therefore a smaller volume and proportion of streamflow as baseflow occurs.

Climate change research has shown that the Lowveld region is becoming wetter (Knoesen et al. 2009). This means there should be greater water availability due to an increase in rainfall in the wet season, and we should expect more water in the catchment, initially as runoff and then after some lag, baseflow from groundwater. If however, we notice the continued trend of reductions in flow in the river, we might assume that some has been intercepted for anthropogenic use, but also that the baseflow component has been depleted. The nature of the rainfall will also impact on the proportion that enters the stream as runoff versus groundwater-derived flow. High intensity thunderstorms will not allow time for infiltration of rain into the soil, thereby reducing the volume of water in the catchment as groundwater, and enhancing the volume of water experienced as runoff (Burt and Butcher 1985).

The National Water Resource Strategy (NWRS) has recognised the need to undertake comprehensive studies of the subterranean water resources of the country since water resources from most rivers are over-exploited or nearing over-exploitation (DWA 2013). The recent NWRS 2 identifies groundwater as an under-exploited resource, and DWA is looking to quantify and utilise the resource for service provisioning in the future. For an area like the Sabie-Sand River, this could have serious and detrimental consequences since preliminary work suggests that groundwater recharge potential in the catchment is low and groundwater in the region has medium to high electrical conductivity, and therefore not of very good quality for human consumption (Murray et al. 2012). Long-term desiccation of the catchment could occur if groundwater is over-burdened and a number of system services reliant on groundwater could fail, such as water supply to plants in upland regions and maintenance in the dry season of important habitat like pools and riffles (Moon et al. 1997). However, Hughes (2010) argues that the majority of groundwater abstractions occur from regional aquifers below the water table, which is the portion of groundwater that intersects with the stream channel. As a result, Hughes (2010) believes that groundwater abstraction should not affect the baseflow regime of streams unless the groundwater abstraction is so substantial that it influences the water table. This view on subterranean water dynamics is not a widely held one but nevertheless may prove to influence hydrological processes with further investigation.

1.4. Dissertation outline and chapter contents:

This dissertation is comprised of four chapters, the content of which will be outlined briefly below. The contents of this chapter (Chapter 1) are also briefly presented to show the conceptual development of the dissertation. Chapters were written in a manner that will facilitate publication, so there may be some overlap of references and introductory material.

1.4.1. Chapter 1:

Chapter 1 (this chapter) outlines the rationale for the study, as well as the aims and objectives (particularly Objective 1) of this investigation. The aims and objectives are followed by the literature review in which the characteristics of the Sabie-Sand River Catchment are outlined. These include the prevailing climatic conditions, makeup of stakeholder in the catchment, water-related infrastructure such as dams, and the nature of the streams in the catchment. This is followed by an outline of the potential trajectories of change in water use in the catchment and estimated water use volumes of the water user sectors. The IFR's of the Sabie-Sand River follows this section. Here we outline the method used to determine the IFR's for the Sabie-Sand River, and highlight the role and importance of strategic adaptive management in successful maintenance of IFR's. The dimensions of the IFR for the IFR sites in this study are presented.

Most importantly, the factors affecting the ecological health, structure and functions of the Sabie-Sand Catchment follows this section and forms the outline against which we will explore the potential ecological changes that may occur should actual flows not meet the IFR specifications that have been set for the Sabie-Sand River (Chapter 4).

1.4.2. Chapter 2:

Chapter 2 addresses Objective 2, and is a concise investigation into the potential sources of pressure on the water resources of the Sabie-Sand River, and how that pressure may be changing. The likely contributions to water use by irrigation and forestry are dealt with in Section 2.1.4, and in this chapter, I hypothesize that growing populations and affluence are the most likely as well as the largest potential cause of pressure on water resources, and will continue to create difficulty in ensuring effective water resource management in the future. I explore trends in population growth and affluence and assess the potential consequences for IFR compliance.

1.4.3. Chapter 3:

Chapter 3 deals with Objective 3, and so examines the actual flow volumes experienced at the four IFR sites in the Sabie-Sand River Catchment against the IFR, between 1978 to present, depending on data availability per site. I also quantify long term trends in measured flows, and the compliance of these flows with the relevant IFRs.

1.4.4. Chapter 4:

Chapter 4 addresses Objective 4. This chapter is an exploration of the inferred ecological changes that the river is likely to experience as a result of IFR non-compliant flows at the IFR sites. These changes are inferred using the extensive literature review outlined in Chapter 1. The yardstick against which this comparison is made is described in Section 1.3.4. of Chapter 1. Each of the features of the river as outlined in Section 1.3.4 was scrutinized for each IFR site and a scenario of the current ecological status of the river is made. Chapter 4 concludes the dissertation with a synthesis on the potential consequences of non-compliance, and recommendations to improve the implementation of IFRs in the study area. Towards the end of the period in which this dissertation was conducted, there was a major change in the management of the Sabie-Sand River; the IFR method was replaced by a different, real-time approach, and the value for IFRs were now not only determined in real-time, but also substantially adjusted downward. This presented an unplanned opportunity to compare the recommendations from my own study, with the reasoning behind and method of this new system.

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2. Chapter 2 – Water use in the Sabie-Sand River - Potential sources of Instream Flow Requirement non-compliance

2.1. Introduction

This chapter is a concise investigation into the potential sources of pressure on the water resources of the Sabie-Sand River Catchment, and how these pressures may be changing. I hypothesize that growing human populations and affluence are the most likely as well as the largest potential cause of pressure on water resources in the Sabie-Sand Catchment, and will continue to create difficulty in effectively managing the water resource of the Sabie-Sand River in the future. The reason for the choice of water use for sanitation as a primary driver of IFR non-compliance is due to the fact that other sectoral users in the Sabie-Sand River Catchment have seen stabilisation or diminishing influence of their water use since the advent of the National Water Act of 1998 (No. 36 of 1998) (DWAF 1998). In addition to this, the National Water Act of 1998 (No. 36 of 1998) is designed to aid government to rectify the past inadequate access to water (and by extension sanitation) by the poor and this chapter highlights the spatial component of low levels of access to improved sanitation.

Section 1.3.2 of the previous chapter was a comprehensive treatment of sectoral water users and uses in the Sabie-Sand River Catchment. As described in that section as well as this one, forestry is a major subterranean water user in the catchment. During the expansion of forestry in the Sabie-Sand River catchment during the 1950's, a significant drop in the subterranean water levels was noted in the catchment, leading to diminished flows in the Sabie-Sand River, particularly those contributing to base flow (le Maitre et al. 2002). This gradually increased to current levels; around 17 – 45% for the Sabie and 31% for the Sand River (le Maitre et al. 2002). The Department of Water Affairs and Forestry realised that water use by plantation forestry was vast; forestry was therefore classed as a Streamflow Reduction Activity (SFRA) in "Part 4; Stream Flow Reduction Activities" of the National Water Act of 1998 (No. 36 of 1998), meaning that future expansion of the industry was unlikely to occur and would be highly regulated thenceforth (DWAF 1998). Large-scale irrigated agriculture has also seen a stabilisation and gradual decrease in usage volume after the National Water Act of 1998 (No. 36 of 1998) was signed into law (DWA 2013). The National Water Act of 1998 (No. 36 of 1998) removed the bias of the access to water from the established commercial farmers, giving more opportunity to emerging and small-scale agriculture (Perret 2002). These factors (reductions in water usage in forestry and commercial agriculture) in conjunction with the government's greater focus on providing adequate access to water for impoverished people under the democratic dispensation provides a strong indication that human consumption of water is where the greatest increase in water demand is likely to be sourced. Of the variety of domestic water uses, sanitation uses the most water, hence it was chosen for this study. The Internal Strategic Perspective document published in 2004 by the then DWAF also indicated that the department was aware at that early stage that water for domestic use and sanitation was likely to grow at a faster rate than other use sectors since much of the catchment was and is under-serviced (DWAF 2004).

Since this is a catchment level assessment, the real water volume used for sanitation was deemed less relevant than the pattern and trajectory of sanitation. Several disparate datasets exist for the flow gauge network, human population trends, and sanitation data in the Sabie-Sand Catchment but a geographically explicit investigation detailing these relationships has not been presented in this manner before (to the author's knowledge).

The results of the access to sanitation investigation are presented in this chapter, and the method employed to discover these relationships is set out in the relevant sections. It is first necessary to describe general characteristics of the flow regime of the Sabie-Sand River so as to contextualise the findings of the sanitation investigation against how they might affect flows in the Sabie-Sand River and thereby IFR compliance. For this reason a brief investigation into the measurement of flows in the Sabie-Sand River is outlined, and the means by which we measure these flows is also described followed by a description of the Sabie-Sand River's flow regime. Water use in the sanitation sector is used here as a case study in response to Objective 2 ("Explore potential future pressure on Instream Flow Requirement compliance using domestic sanitation as a case study"), since it appears that this sector has the largest growth potential of all the sectors outlined in Section 1.3.2 in the previous chapter as water users in the Sabie-Sand River Catchment. A number of important facets must be explored to gain an understanding of the changes to domestic sanitation in the catchment, and these include:

- What is considered adequate access to sanitation?
- What are the spatial patterns in population changes over the period of the study?
- What are the spatial patterns in access to sanitation?
- What is the relationship between change in population and change in sanitation and what are the implications for IFR compliance?

2.1.1. Description of the Sabie-Sand River flow gauge network:

For the Sabie-Sand River, nineteen flow gauges have at some stage been operational in the catchment (see Figure 2.1).

Table 2-1. Flow gauges for catchment X3 Sabie-Sand catchment. The numbers on Figure 2.1 match those in the left column of

Gauge Number	Description of Site	Gauge Name	Start date	End Date
1	Sabie River @ Sabie	X3H001	1948-03-15	Present
2	Klein Sabie River @ Sabie	X3H002	1963-11-08	Present
3	Mac-Mac River @ Geelhoutboom	X3H003	1948-03-16	Present
4	Noordsand River @ De Rust	X3H004	1948-02-21	Present
5	Mnondozi River @ Kruger National Park	X3H005	1952-10-01	1960-02-29
6	Sabie River @ Perry's Farm	X3H006	1958-09-04	2000-01-19
7	White Waters River @ Etna	X3H007	1963-11-12	1991-09-16
8	Sand River @ Exeter	X3H008	1967-09-01	Present
9	Ngwaritsana River @ Injaka	X3H009	1976-07-01	1978-11-30
10	Ngwaritsana River @ Beestekraal Spruit	X3H010	1976-07-01	1976-11-30
11	Marite River @ Injaka	X3H011	1978-11-28	Present
12	Sabie River @ Lower Sabie Rest Camp	X3H015	1986-12-09	Present
13	Golden Valley Creek @ Sabie	X3H016	1960-07-27	1967-10-01
14	Right Canal From Dam @ Etna	X3H019	1977-07-01	Present
15	White Waters River @ Etna	X3H020	1973-05-17	Present
16	Sabie River @ Kruger Gate	X3H021	1990-11-15	Present
17	Pipeline From Injaka Dam @ Dwarsloop	X3H022	1997-10-29	Present
18	Sabie River @ Emmet	X3H023	2002-04-17	Present
19	Tevrede Canal @ Emmet	X3H024	2002-05-02	Present

Table 2-1 shows the period in which data for these gauges is available. Many of these gauges are no longer in existence. A number were washed away in flood flows, others have fallen into a state of disrepair or not been maintained by DWA in an effort to reduce the costs associated with maintaining the network. Many flow gauges were not retained because they had not produced good quality data as a result of inadequate build quality.

Flow gauge infrastructure is in general initially constructed as a means to measure the quantity of surface water available and create an inventory of water resources in a region (Wessels and Rooseboom 2009a). Most often the data are used to provide baseline information on the land potential of an area (Benson and Carter 1973). Thereafter, flow gauges are used for a range of purposes that require streamflow data. These could range from mining and industrial requirements, scoping studies for dam potential and water quality monitoring. The spatial organisation of the flow gauges in the Sabie-Sand Catchment show a bias towards the gathering of information in the areas formerly reserved for white South Africans, where the majority of revenue was and is generated. The flow gauge numbered 17 (X3H022) in Figure 2.1 is in the former Lebowa homeland but was only built in 1997, a number of years after the dissolution of the homeland state. Flow gauge 17 (X3H022) is used to measure the outflow from a pipeline connected to the Inyaka Dam (see Figure 1.3 in Chapter 1). The pipeline terminates in the village of Dwarsloop and is used for the provisioning of water services to the communities around the Dwarsloop and Ndlebesuthu villages.

The pattern of flow gauge distribution for the Sabie-Sand River reflects the historical pattern of infrastructure development, and DWA believes the network of flow gauges to be optimal at present (Wessels and Rooseboom 2009a). This means that future planning will include further optimisation rather than extension of the flow gauge network, with the possible closure of some flow gauges and the maintenance of current infrastructure.

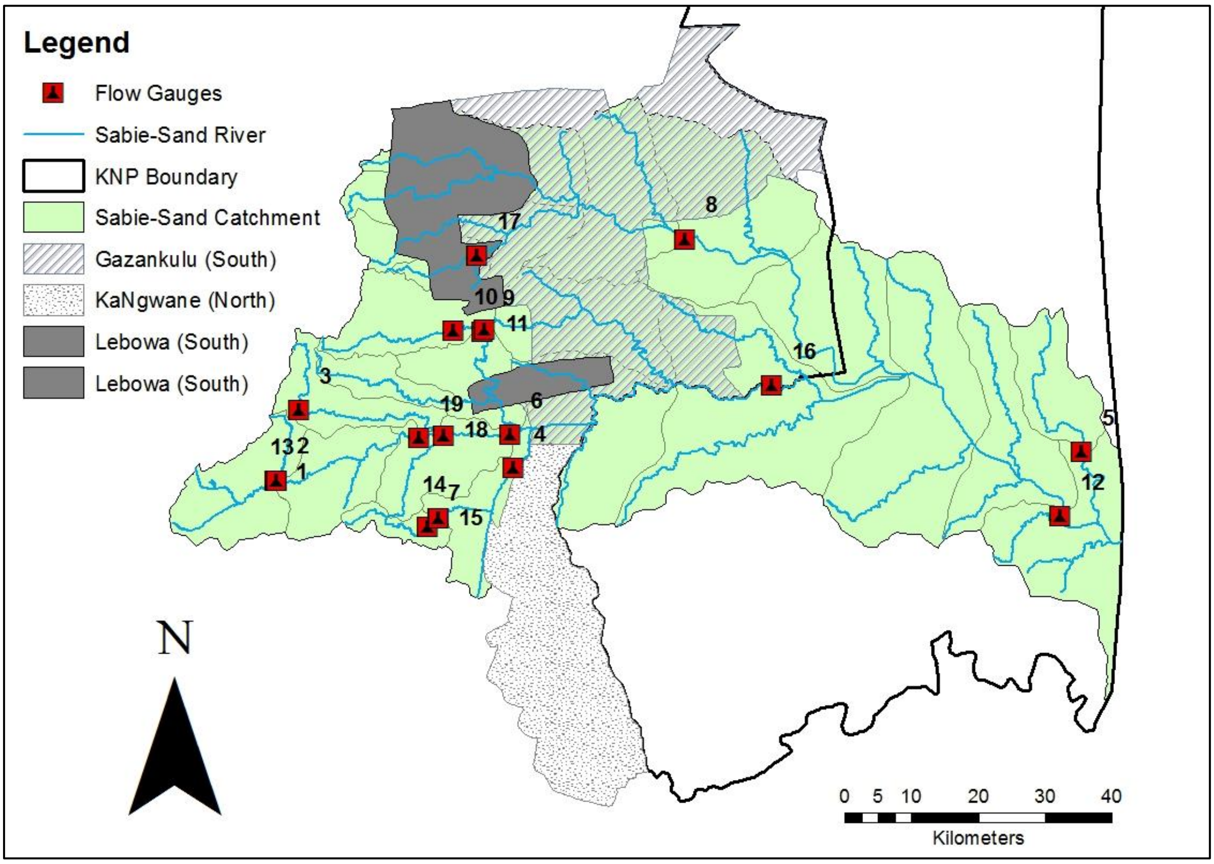

Figure 2.1. Map showing geographical location of the 19 flow gauges in the Sabie-Sand River catchment (X3). The numbers on Figure 2.1 match those in the left column of Table 2.1.

2.1.2. General description of flow gauges:

Flow gauges are artificial structures created for measuring the discharge of a stream (Wessels and Rooseboom 2009a). The placement and type of gauge is important. Gauges must be organised in a manner that maximises their utility in terms of recording as much data as possible for catchment managers while simultaneously being cost-effective to build and maintain (Wessels and Rooseboom 2009b). V-notch gauges (a variety of sharp-crested gauge) measure small flow discharges accurately and so find favour on smaller tributaries, while larger streams such as the Sabie-Sand have been fitted with long-base gauges, mostly of the crump variety because they are able to handle the measurement of non-modular flows accurately (Rabie 1960; Rossouw et al. 1998).

Data from flow gauges are managed and controlled by DWA. DWA provides hydrologists, catchment managers and other stakeholders with the means to understand many aspects of hydrology, legal aspects of water-use, riparian ecology and much more through the data they provide. The data are available on the DWA website, and are presented as daily flow rates and monthly flow volumes for each flow gauge. I obtained the data for all gauges in the catchment from the DWA Hydrological Services Database website (URL: http://www.dwaf.gov.za/Hydrology/), for the entire period that each gauge has been functional. To better understand the flow regimes of the tributaries as well as both the Sabie and Sand rivers, I will expand upon the data from some of these gauges.

2.1.3. Use of flow gauges in the description of the Sabie-Sand River flow regime:

For the purpose of this dissertation, some descriptive statistics for three gauges are presented here. Not all gauges are important here since they are far from monitoring sites, obsolete, or used to measure peripheral tributaries. Obsolete gauges include those with very short datasets (eg: flow gauge 9 - X3H009 and flow gauge 10 - X3H010), those on tributaries that join the main Sabie River and are gauged downstream (eg: flow gauge 3 - X3H003 and flow gauge 18 - X3H023), and those that are on tributaries with no effect on monitoring sites (eg: flow gauge 5 - X3H005). The three gauges with the longest data sets and in close proximity to monitoring sites are gauges X3H001, X3H006 and X3H008 and so have been chosen since they most accurately characterize the nature of flow in the Sabie-Sand River.

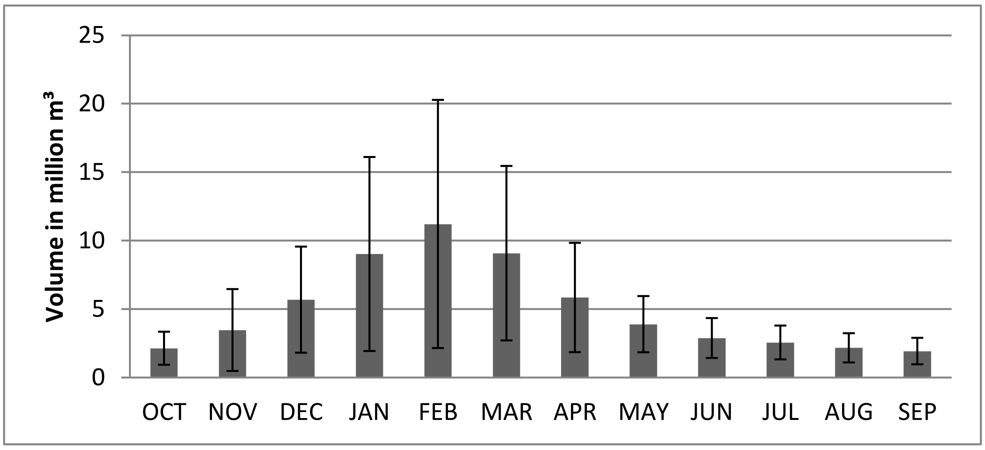

Figure 2.2. Average of monthly flows for the period 1948-2012. Error bars show standard deviation of flow per month at Gauge X3H001 Sabie River at the town of Sabie.

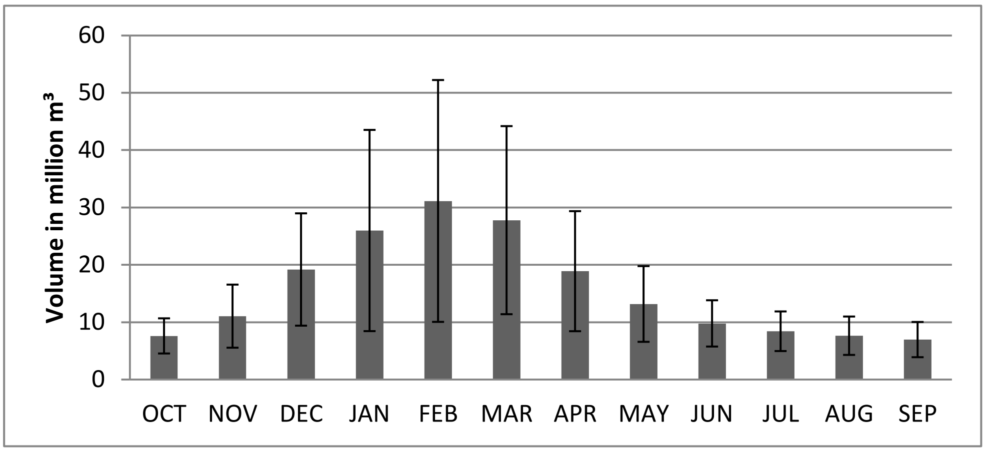

Figure 2.3. Average of monthly flows for the period 1958-2000. Error bars show standard deviation of flow per month at Gauge X3H006 Sabie River at Perry's Farm.

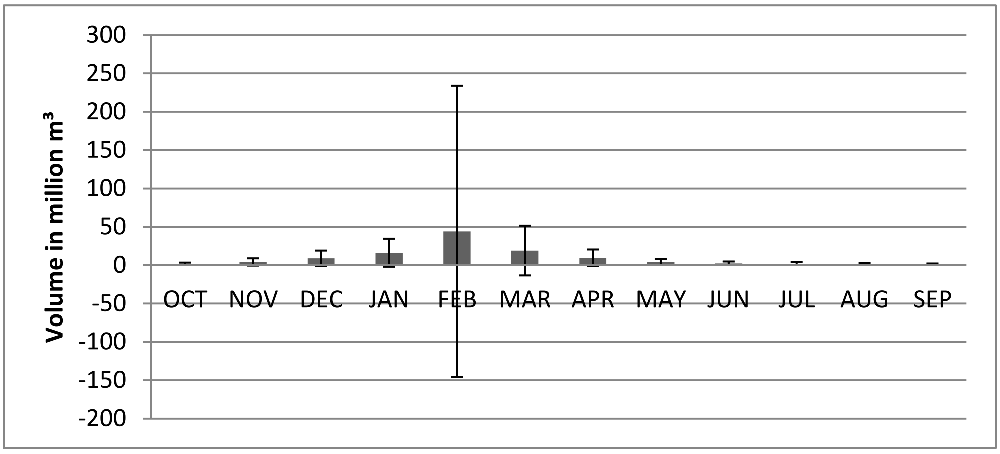

Figure 2.4. Average of monthly flows for the period 1967-2012. Error bars show standard deviation of flow per month at Gauge X3H008 Sand River at Exeter.

Much information can be drawn from Figure 2.2 - Figure 2.4 that tells us much about flow conditions in the catchment. Firstly, we can see that monthly flow values vary in a similar pattern of annual flow for the entire catchment, although the flow volumes are different across the flow gauges. From this we can infer that similar precipitation, geology, and evapotransporation characteristics occur across the gauging sites in question. Although the precipitation in the catchment decreases in an easterly direction, the evapotranspiration increases in an easterly direction, and the geology is dominated by basalts in the east of the KNP and granites in the west of the catchment, the above-mentioned factors are all similar where most of the flow gauges are situated (Sweeney 1986; Schulze and South Africa 2008). Since most of the flow gauges are found in the western half of the catchment, granites of the Nelspruit type underlie the majority of the flow gauges, including those represented in Figure 2.2 to Figure 2.4 (Barton et al. 1986). The largest flow volumes occur in February at all gauge sites (this is a crucial aspect of the IFR and will be explored in greater depth in Chapter 3). For both flow gauge sites in the Sabie River (X3H001 and X3H006) flows are perennial, where periods of no flow have never occurred at the monthly time-scale as corroborated by Pringle (2001) as well as van Wilgen and Biggs (2011). The Sand River at Exeter (X3H008) has a lower comparative average discharge with extreme variability and has experienced periods of no flow in the drier months of the year, from June through to September (albeit infrequently).

Data for each of the graphs represent a long time series, yet we notice a large difference across months at each site, particularly at Gauge X3H008, where on average February flows are almost 50 times higher than the average for September flows. From this we can conclude that flows are highly variable intra-annually. In addition, we see a large standard deviation across all months in the dataset and this points towards large inter-annual variability of flow compared to Northern Hemisphere streams and rivers (Grenfell and Ellery 2009). The standard deviation that we see for Gauge X3H008 in February may seem anomalous in that is it very large. The reason for this very large standard deviation is mainly because of a single month in the year 2000. That month was characterised by a massive cyclonic intrusion bringing in rainfall more than three times the normal amount for February (measured at Nelspruit; largest proximal weather station), and the runoff created from this unusual event led to the large flow volume measured during that month at flow gauge X3H008. This volume was in fact not the maximum flow through that portion of the Sand River, but rather the largest possible discharge that could be measured by the gauge before it was outflanked. Some gauges in the catchment were incapable of measuring discharge at such volumes and were either inundated or destroyed in this period and thus rendered incapable of measuring the large flows of February 2000. These therefore do not exhibit the large standard deviation in flows for February (see Figure 2.2 and Figure 2.3 above). The smaller standard deviation in February flows for Gauges X3H001 is explained by the fact that flow gauge X3H001 is high up in the catchment and therefore would experience less runoff entering the stream at or before that point, although the volume for that month, at 49.6 million m^3, is more than one and a half times the average flow experienced further downstream in the larger catchment area of flow gauge X3H006 for February, illustrating the magnitude of flooding over that period. As one can see from Figure 2.1, flow gauge X3H006 measures a section of the river that drains a much larger area and so a flow volume of 49.6 million m^3 at Gauge X3H001 is extraordinarily large. The highest monthly flow on record for flow gauge X3H001 is in the February of 2000.

For flow gauge X3H006, the data record stops in December 1999 and this was most likely because the last data collection by DWA officials took place in that month before the flow gauge was no longer functional. In the floods of February 2000, flow gauge X3H006 was outflanked thereby compromising its ability to measure flows, and the recorder hut was also destroyed (see Figure 2.5 below). The gauge structure and recorder hut has not been repaired. According to the Senior Control Technician in Mpumalanga's Hydrological Services, the costs of fixing the outflanked portions of the gauge structure or replacing the gauge entirely are prohibitive. This gauge does not show the large standard deviation as shown by Gauge X3H008 because of the fact that the gauge was destroyed in the floods February of 2000 and no data are available for that period and the period thereafter.

Figure 2.5. Recorder hut for Gauge X3H006 destroyed in the floods February 2000 on the left and vestiges of weir on the right, also showing eroded banks where outflanking occurred.

The data as presented in Figure 2.2 to Figure 2.4 support the perception that the Sabie-Sand River has a highly variable flow regime (Heritage et al. 1997). The variability results in a complex set of physical habitat components and these make for a distinctive riverine ecology (Newson and Newson 2000). If we observe the long-term trends for the same flow gauges (Figure 2.6 to Figure 2.8), further evidence for high flow variability can be found. Highly variable flow regimes are characterised by longer periods of low flow interspersed with short periods of large flow discharge at unpredictable time intervals (Hughes and Hannart 2003). This is important because in catchments characterised by variability and longer periods of low or even no flow, biota are assumed to have evolved to withstand low flow conditions for lengthy periods, but are also likely to be reliant on periodic larger flood flows for some aspects of their lifecycle (Bunn and Arthington 2002).

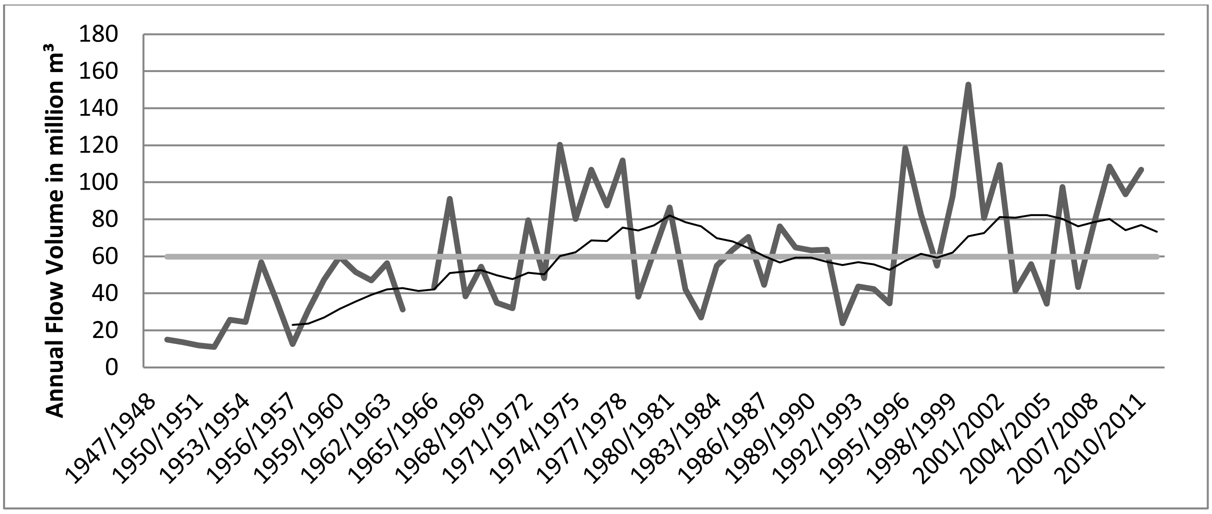

Figure 2.6. Variation of annual flow for the period 1948-2012 at flow gauge X3H001 Sabie River at the town of Sabie. Line in light grey shows average for 1948-2012 (59.8 million m³/annum), thin black line indicates the moving average using a 10-year window.

In Figure 2.6 we can see that annual flows are extremely variable around the mean flow throughout the entire period for which data are available. Four distinct trend-periods (as highlighted by the thin black moving average line) can be seen for flow gauge X3H001. From 1948-1966 flows were below the long-term annual average, followed by a period of higher annual flow volumes from 1966-1982, and a marked increase within that period between 1974-1978. Between 1982 and 1994 flows oscillated closely around the mean annual average and then rose again with distinct flood periods during 1996 and 2000 in particular. The idea that precipitation and discharge is linked is intuitive and correct, but this association often has many intermediary processes that complicate the association (Hernandez et al. 2000). Impoundments, land cover, the type and intensity of precipitation, geological and pedological features of a region all influence the rate and volume of precipitation that ends up as runoff in a river (Hernandez et al. 2000; Poff and Zimmerman 2010).

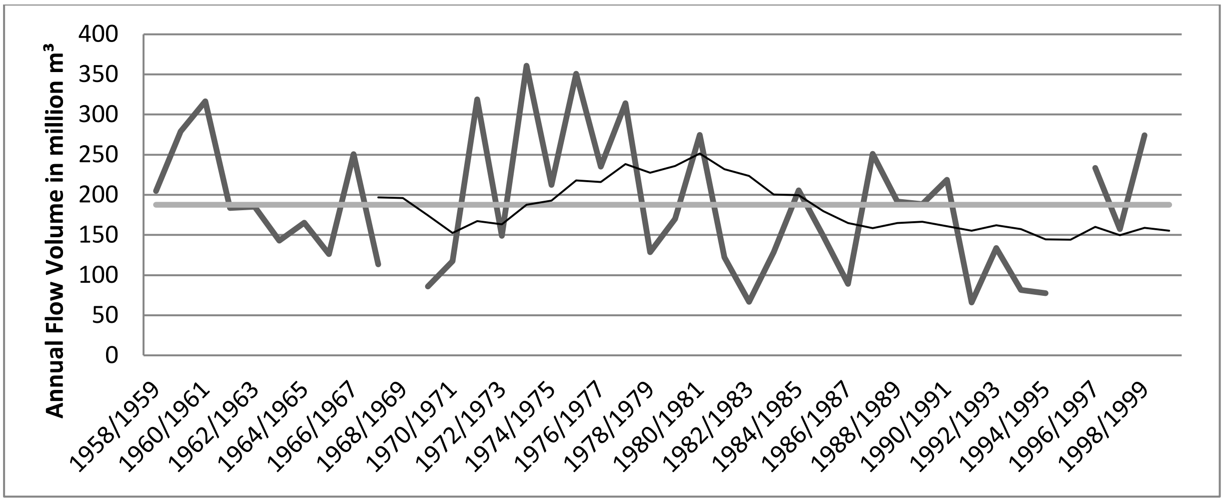

Figure 2.7. Variation of annual flow for the period 1958-2000 at flow gauge X3H006 Sabie River at Perry's Farm. Line in light grey shows average for 1958-2000 (187.7 million m³/annum), thin black line indicates the moving average using a 10-year window.

A similar pattern emerges again with annual flow volume at flow gauge X3H008 as compared with the monthly flow volume, in that it has a large anomalous value during the year 2000. The discharge in that year was so large that if one includes it in the calculation of the long-term mean for annual flows, the average is 125 million m³/annum (n=31). If it is omitted, the annual average discharge is much lower, at 76 million m³/annum (n=30). This serves to demonstrate the magnitude of the floods of the year 2000 and also the highly variable nature of the Sabie-Sand Rivers flow.

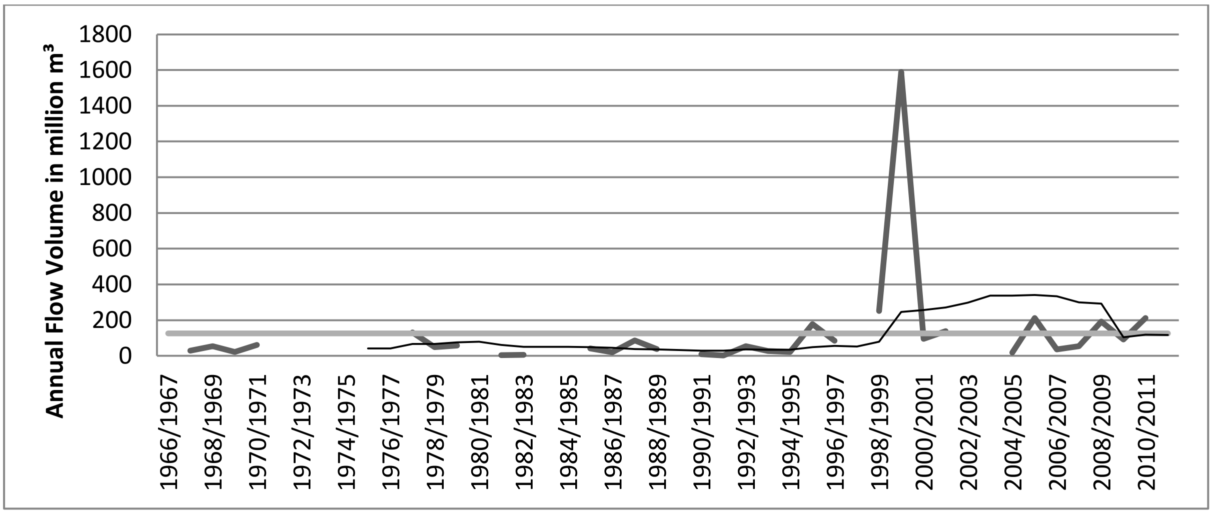

Figure 2.8. Variation of annual flow for the period 1967-2012 at flow gauge X3H008 Sand River at Exeter. Line in light grey shows average for 1967-2012 (124.9 million m³/annum), thin black line indicates the moving average using a 10-year window.

2.1.4. Water Balance for the Sabie-Sand Catchment:

Due in some part to the highly variable and seasonal flow in the Sabie River, and more so the Sand River, an accurate water balance for the catchment has proven difficult to compile despite relatively comprehensive flow gauge networks and data availability. Since SFRA water use in forestry is derived from subterranean water, it is not as easily measured as water uses that utilise surface water, although through subsequent investigations it appears that robust evidence of actual water volume uses is not apparent for any water use sector in the catchment. This issue is compounded by the fact that different authors have used different years and levels of assurance of supply to quote water demand and utilisation figures, making for very disparate water use volumes across the various documents that deal with this subject.

Some of the early work on water budgeting undertaken by the then Department of Water Affairs and Forestry stated a total water availability of 293 million m³ in the Sabie River for the year of 2003 (Figure 2.9 below). It is interesting to note that the document from which these data are derived pointed out that the major sectoral water users in the catchment at the time were irrigated agriculture and forestry, but that urban water requirements were becoming increasingly significant as early as 2003 (DWAF, 2004).

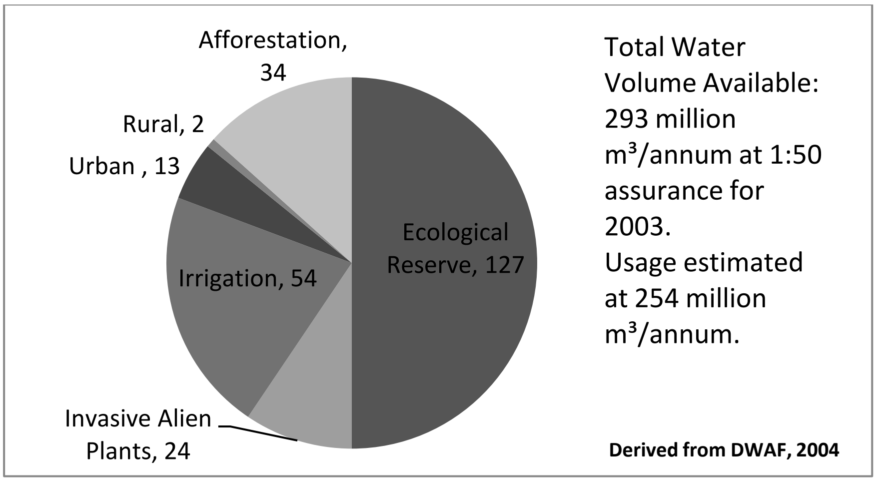

Figure 2.9. DWAF water resource and usage estimate for 2003 - Sabie River (DWAF, 2004)

Pollard and du Toit (2011), using data from a more recent DWA report, showed that the flows in the Sabie-Sand Catchment were in fact substantially lower than the volume estimated by DWAF in 2004 (see Figure 2.9). To compound the difficulty facing IUCMA managers, Pollard and du Toit (2011) outline values for a much larger ecological reserve value, as well as substantially higher water demand from forestry and irrigated agriculture. These values were revised from the 2004 figure, and do not indicate that these sectors are growing but rather that the 2004 volumes were not accurate.

Further complicating the comparative estimates of water volume available in the Sabie-Sand River is the fact that both the DWAF (2004) and Pollard and du Toit (2011) values use “available water” as the baseline rather than the virgin mean annual runoff (MAR) volume. A clear definition of “available water” is not provided in either document, but it is likely that this volume does not include water unavailable through the current delivery infrastructure (ie: deep aquifer water and water used by forestry).

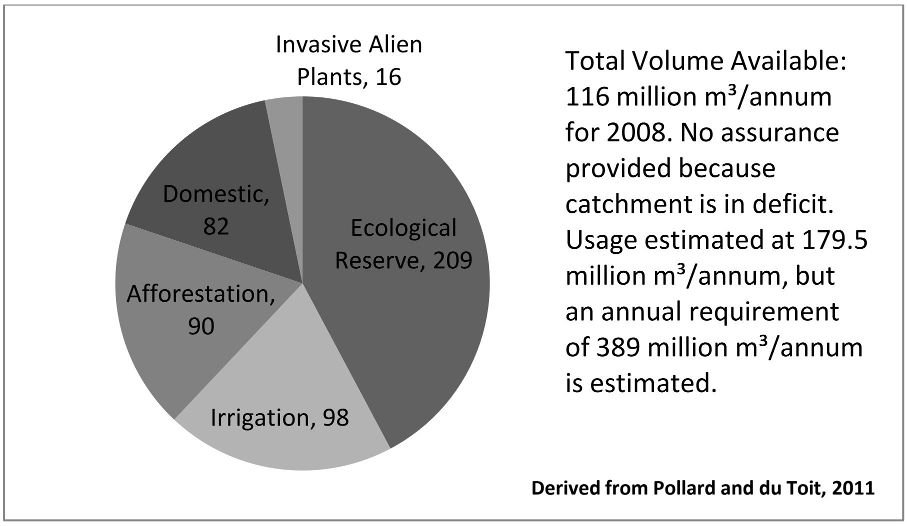

Figure 2.10. DWA water resource and usage estimate for 2008 - Sabie River (Pollard and du Toit 2011)

Drawing on an extensive and wide pool of literature and other information sourced from managers, technicians, forestry and agricultural reports and documents, I have compiled two water use balance scenarios for the Sabie River including the Sand River. The baseline value for virgin MAR utilised for this exercise was derived from a value quoted in multiple sources (albeit with slight differences) as modelled by Chunnet et al. in 1990 (le Maitre et al. 2002; Rivers-Moore and Jewitt, 2007). Due to the highly incongruent water use values associated with the other water use sectors as reported in the literature, the decision was taken to include the lowest available values in the literature to compile the best case scenario, and the highest useage values for the worst case scenario. This approach has however still not yielded clarity in water use volumes for the Sabie-Sand River, since some reports record that the Sabie-Sand River is in water deficit (specifically Pollard and du Toit, 2011). Juxtaposed to this, the sum of the largest sectoral water use values used for the worst case scenario still falls below the MAR value for the Sabie-Sand River. This points towards substantial uncertainty in knowledge of water use volumes for the river despite good quality flow gauge data.

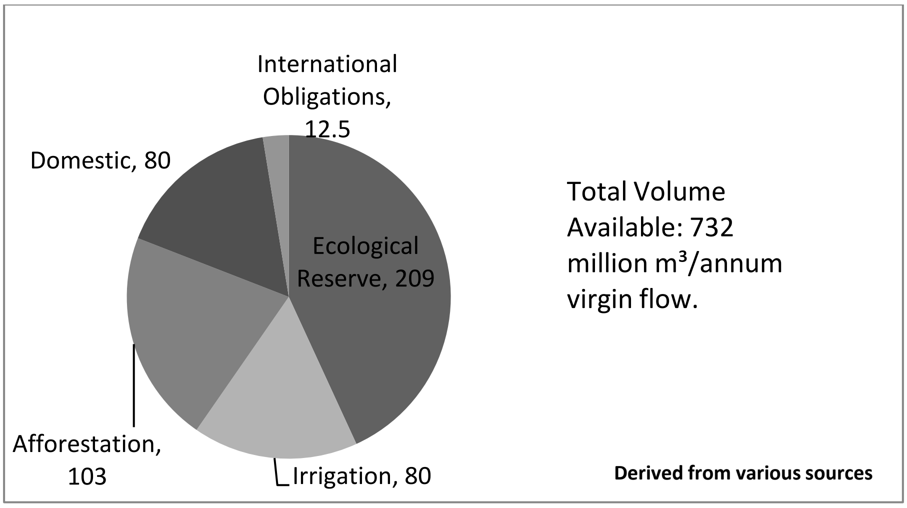

Figure 2.11. Sabie River Water Balance - Best Case Scenario

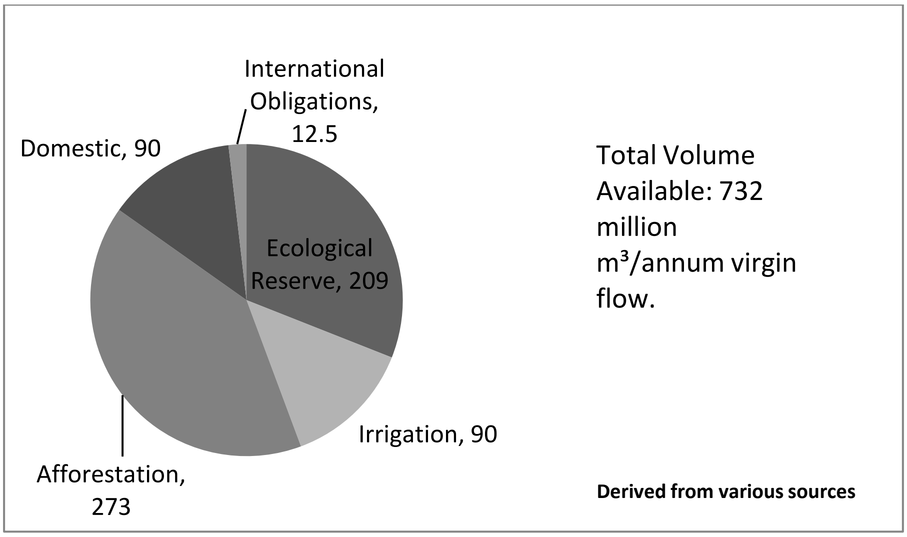

Figure 2.12. Sabie River Water Balance - Worst Case Scenario

The preceding sections of this Chapter (Section 2.1.1 – Section 2.1.4) indicate that managers of water resources in the Sabie-Sand Catchment deal with highly variable water availability. This in itself is not as problematic as the issue of having poor data and information on the volume of water that managers must manage. The Sabie-Sand River is not as water-stressed as the Olifants Catchment to the north (Pollard and du Toit 2011), meaning that there is not as much pressure to obtain a comprehensive idea of available water versus the volumes used. This will change should water use volumes increase in the future.

Section 1.3.2 in Chapter 1 outlines the rationale of using water use for sanitation as a major pressure source on the water resources of the Sabie-Sand Catchment. In summary, it appears that water use in the forestry and irrigated agriculture sectors is stable or diminishing in the catchment, but that water use for domestic and sanitation purposes will likely rise as populations grow and become more affluent in the catchment. Additionally, it is important to note that the preceding sections of this chapter highlight the uncertainty in the volume of water available for use in the Sabie-Sand Catchment.

2.2. Study Methods:

The methods for this portion of the study entailed measuring the change in population for each ward between the census in 1996 and that of 2001. A similar method was employed in deriving the change in sanitation over the same time period.

2.2.1. Human population of the Sabie-Sand Catchment:

In line with my objective to obtain and collate population and sanitation data for the Sabie-Sand Catchment for both the 1996 and 2001 censi, I downloaded the population data for all wards completely and partially contained by the catchment boundary for both censi at http://www.statssa.gov.za/census2001/atlas_ward/index.html. As explored above, the reason that this water use sector was chosen for further analysis against others such as forestry, irrigation, industrial, power generation and mining uses is that it is expected to show the largest growth in the future in the Sabie-Sand Catchment (DWA 2013). The recent reconciliation report for the region expects the demand from forestry and irrigation to remain stable and even decline in the future (DWA 2013). Industrial growth in the Sabie-Sand Catchment is stable but growing further south in the Nelspruit-Hazyview corridor. Demand from the industrial sector is not expected to put pressure on the water resources of the Sabie-Sand River since the majority of the sector derives water from the Crocodile River (DWA 2013).

The population density figures for each of the wards were compared across the two census years, and a percentage change in population between 1996 and 2001 was calculated. Using GIS, shapefiles of the wards in the Sabie-Sand Catchment were created and the attributes of these shapefiles were populated with the relevant population information for both Censi 1996 and 2001 to obtain a change in population between the two time periods, represented geographically. This was the primary step related to population, and was necessary to understand the human population dynamics of the Sabie-Sand River Catchment.

2.2.2. Calculating levels of sanitation in the Sabie-Sand Catchment:

The manner in which sanitation levels were calculated is a simple proportional relationship between the number of households with sanitation facilities compared to those with no facilities or bucket latrines. According to StatsSA (the organisation responsible for conducting censi in South Africa), improved sanitation includes the following classes: pit latrine; ventilated improved pit (VIP) toilet; chemical toilet; flush septic tank toilet and flush toilet. Unimproved sanitation is no access to any of the above classes, or the use of bucket latrines.

For Census 1996, the number of households with access to improved sanitation was divided by the total number of households counted in the census, per ward. This was repeated for Census 2001 data. The resultant percentage for each ward in Census 1996 was then compared with the corresponding percentage calculated from the identical ward in the Census 2001 dataset, giving an idea of the trajectory of sanitation level (and therefore water use) per ward, and overall for the catchment.

2.3. Results and Discussion:

2.3.1. Human population numbers of the Sabie-Sand Catchment:

The results of the population data analysis are presented in Table 2-2, and show a slight decline at catchment level from 690 709 people accounted for in 1996 compared with 677 367 people in 2001. Data for Census 2011 were unfortunately not available at ward level at the time of this study, and were likely to have been omitted even if available since the time period for Censi 1996 and 2001 matches the flow data. Once again, the need for scale-sensitive analyses in sanitation planning is highlighted by the fact that while the total population is relatively stable, people are moving around within the catchment.

The percentages expressed in the last column of Table 2-2 show us that populations are shifting around the catchment, or perhaps that the catchment is experiencing high levels of both emigration and immigration, but to different parts of the catchment. Figure 2.13 shows two maps of the catchment, one with the population density of the catchment's population in 2001 and the other a map of the population change over the period between Census 1996 and the census of 2001.Two wards in the catchment, namely Bushbuckridge Wards 29 and 33 shows very large population increases in excess of 2000% and 1400% respectively. This is attributed to the urbanisation and development of new infrastructure in these wards including roads and schools, making it attractive to people in neighbouring wards as a new area to settle in. These wards are also adjacent to very densely populated wards, which act as push factors towards the new areas.

Table 2-2. Population for all wards in Sabie-Sand Catchment in 1996, 2001 and the change over the period 1996-2001.

Municipality Name	Ward Number	Census 1996	Census 2001	Population Change (%)
Bushbuckridge	1	7449	15299	105.38
Bushbuckridge	2	13576	10242	-24.56
Bushbuckridge	3	30786	9849	-68.01
Bushbuckridge	4	13331	8312	-37.65
Bushbuckridge	5	18465	11582	-37.28
Bushbuckridge	6	18177	12297	-32.35
Bushbuckridge	7	21882	16947	-22.55
Bushbuckridge	8	14928	15579	4.36
Bushbuckridge	9	15696	3002	-80.87
Bushbuckridge	10	12672	14349	13.23
Bushbuckridge	11	11103	7358	-33.73
Bushbuckridge	12	15855	17694	11.60
Bushbuckridge	13	10476	29463	181.24
Bushbuckridge	14	22241	9204	-58.62
Bushbuckridge	15	27531	20757	-24.60
Bushbuckridge	16	15390	15544	1.00
Bushbuckridge	17	19882	21106	6.16
Bushbuckridge	18	13329	25789	93.48
Bushbuckridge	19	12569	12837	2.13
Bushbuckridge	20	20700	15661	-24.34
Bushbuckridge	21	8592	7412	-13.73
Bushbuckridge	22	15234	15159	-0.49
Bushbuckridge	23	17731	13424	-24.29
Bushbuckridge	24	16902	17981	6.38
Bushbuckridge	25	16467	22334	35.63
Bushbuckridge	26	14027	15249	8.71
Bushbuckridge	27	13514	10117	-25.14
Bushbuckridge	28	25285	11781	-53.41
Bushbuckridge	29	33	774	2245.45
Bushbuckridge	30	17622	17283	-1.92
Bushbuckridge	31	20687	16130	-22.03
Bushbuckridge	32	15711	17663	12.42
Bushbuckridge	33	1665	25342	1422.04
Bushbuckridge	34	20955	16176	-22.81
Mbombela	1	12181	15160	24.46
Mbombela	3	14951	20703	38.47
Mbombela	5	9094	11540	26.90
Mbombela	6	5721	9088	58.85
Mbombela	7	16232	17693	9.00
Mbombela	8	15243	14873	-2.43
Mbombela	9	16863	16178	-4.06
Mbombela	25	12814	13259	3.47
Mbombela	34	10621	12600	18.63
Thaba Chweu	4	6226	9719	56.10
Thaba Chweu	5	7098	6675	-5.96
Thaba Chweu	6	3298	5486	66.34
Thaba Chweu	7	1970	1916	-2.74
Thaba Chweu	9	7521	8614	14.53
Thaba Chweu	10	4528	6348	40.19
Thaba Chweu	11	5885	7819	32.86
Total Population		690709	677367	

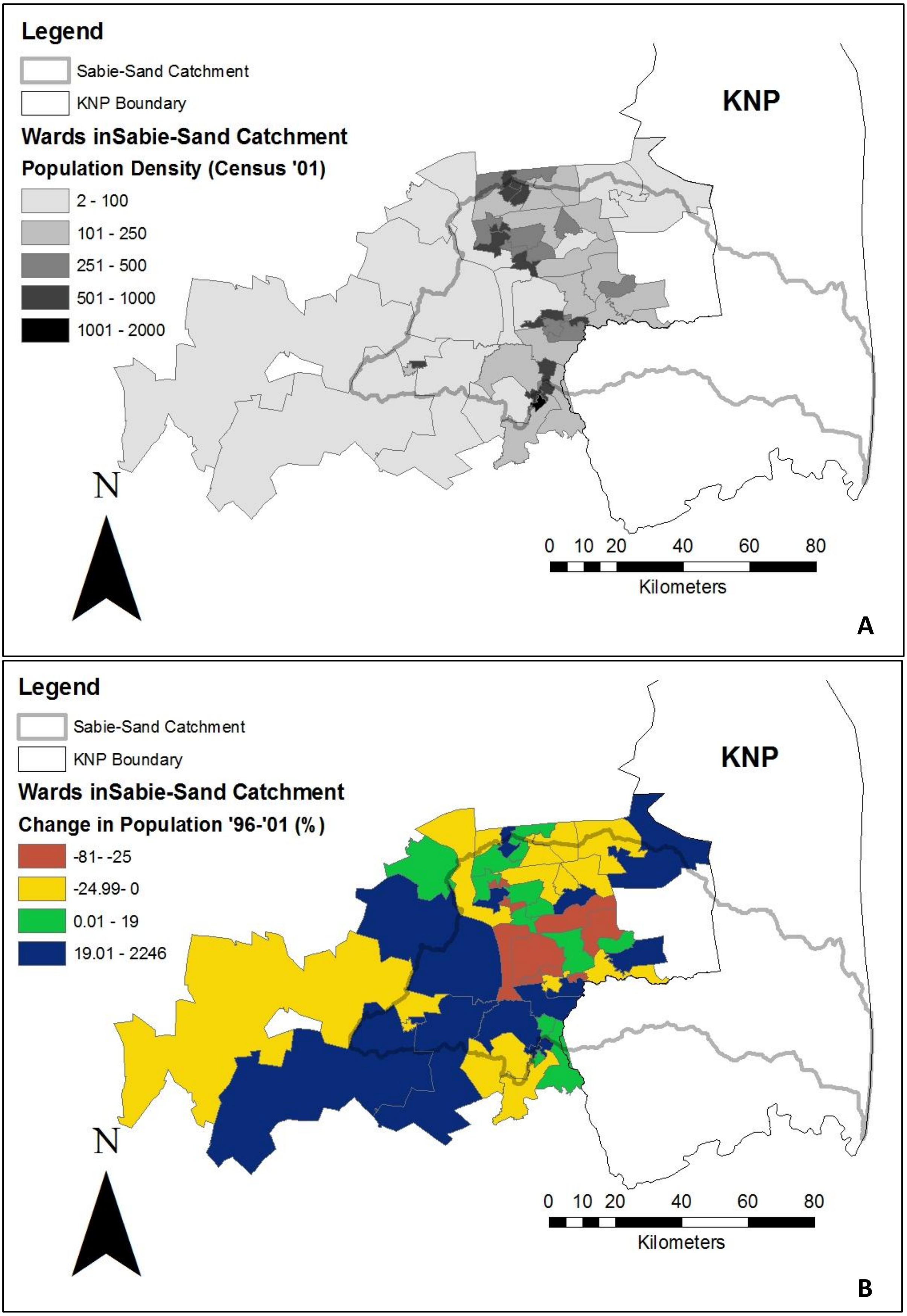

Figure 2.13.A Shows the ward population density for the 2001 Census (people/km²); B shows how the population changes in each ward between Census 1996 and Census 2001.

As one can see in Figure 2.13A, the regions adjacent to the border of the Kruger National Park and north-western portion of the catchment are the most densely populated. These regions coincide approximately with the border of the old homelands of Gazankulu and kaNgwane. The region west of those highly populated wards in the catchment were designated for white citizens under apartheid, and less densely populated. The portions of the catchment with no data are protected areas (either the KNP or the private Sabi-Sand Private Game Reserve) and very few people reside in these areas.

Figure 2.13B shows how population density changed in the catchment between 1996 and 2001. It appears that the density of people is decreasing mostly in what used to be the core of the homeland of Gazankulu and to a lesser extent Lebowa, and increasing in areas that were formerly reserved for whites under apartheid and the peripheral areas of the old homelands. This is partially consistent with the trend in urbanisation in South Africa, since most large cities and job opportunities are in former white areas (Todes et al. 2010). Where people have moved to peripheral areas of the old homelands, this is most likely in response to over-crowding in the core zones, and movement is mostly to places where pressure on resource harvesting for subsistence is not as intense (Christopher 1994).

This analysis has revealed the spatial changes in density of the population in each ward of the Sabie-Sand River Catchment. This information aids catchment managers and sanitation planners with information about where to expect greater pressure on water resources in the future. In the case of catchment managers this information also provides an indication of where to expect the greatest pressure on IFR compliance moving forward, while sanitation planners would be interested in finding out where large increases in population have rendered the existing sanitation infrastructure insufficient. Population growth in the wards of the upper southern reaches of the Sabie River is generally the largest in the catchment, and the geographical location of this change in population is likely to place the greatest pressure on IFR compliance on the Marite-Sabie IFR site in the future. However, it must also be noted that because this population growth is higher up the catchment and therefore within the source area for much of the Sabie-Sand Rivers water, IFR compliance could be reduced throughout the river if large proportions of the water at source is diverted for uses other than the ecological Reserve. Catchment managers would do well to ensure resources are available for the maintenance of the flow gauges in particularly the upper reaches of the Sabie so that any significant negative changes in flow volume are captured and dealt with as early as possible to mitigate against ecological damage to the river. Of particular strategic importance in this regard would be gauges X3H011 and X3H021.

2.3.2. The trajectory of sanitation provisioning in the Sabie-Sand Catchment:

Levels of sanitation in the catchment vary quite widely, again most often as a result of the policies of the apartheid system of governance. Favour was given to white areas while lack of services is commonplace in the ex-homelands. Figure 2.14 shows the percentage of households per ward with access to improved sanitation facilities for both censi 1996 and 2001.

The number of wards present in the Sabie-Sand River Catchment preclude a thorough examination of each ward, and so such information cannot be presented in this succinct assessment of population and sanitation change for the catchment. However, two divergent examples are illustrated by Bushbuckridge Wards 1 and 2 and these adequately exemplify issues facing both managers of ecological resources, and also sanitation provisioning in the Sabie-Sand Catchment.

The finest level of data on sanitation is resolved at the household level; the maps below therefore present the data at the household level. If we take Ward 1 of Bushbuckridge as an example, we see that in 1996, 1 369 households out of a total of 1 479 had access to sanitation facilities above that of a bucket latrine. This gives a percentage of 92.56% of households with access to improved sanitation facilities. Data for the same ward in the year of 2001 showed that 2 490 out of 3186 households had access to sanitation above bucket latrines giving a percentage of 78.15% of households with improved sanitation. This is a substantial drop in sanitation level for the ward, and even in the face of apparent large-scale migration (when viewed in conjunction with the population data presented in Table 2-2) is poor if government wishes to keep pace with growing populations.

The above example (Bushbuckridge Ward 1) illustrates a scenario in which the provision of sanitation has not kept pace with a growing local human population. While this is inadequate, it is an understandable state of affairs especially if the population growth is recent and occurred rapidly, since government may have already planned for sanitation infrastructure roll-out and plans simply need to be implemented. But an example of a ward in which a different scenario has occurred is apparent in Bushbuckridge Ward 2. Here, the number of households has decreased and sanitation infrastructure has undergone simultaneous attrition. The 1996 census measured 2 460 households out of 2 607 as having improved sanitation (94.36%). By 2001, the ward had significantly fewer households at 2169, with only 1 698 having improved sanitation access (78.28%). In established urban suburbs, such a scenario would be rare but rural areas exhibit an entirely different phenomenon. Rural dwellers rarely hold title deeds on their land, and as such have much more tenuous economic links to rural areas. This means that they are more likely to leave their rural dwellings in search of better opportunities for employment elsewhere. This can lead to large fluctuations in rural populations, and this is likely what has occurred in Bushbuckridge Ward 2, leading to the progressive ruin of existing infrastructure. In light of the fact that not all people in the ward had sufficient access to improved sanitation in the first place, this is unacceptable. The relevant authorities should ensure that money already spent on sanitation infrastructure is maintained so as to avoid costly replacement programmes in the future.

Although Figure 2.14 is useful as a spatial representation of where people in the catchment have seen improved or worsening access to sanitation at ward-level across the two censi, it is less useful to find out if government is showing overall improvements in bringing sanitation to the people of the Sabie-Sand Catchment. If we take a look at the changes in availability of sanitation for each ward and average them we find that there is an overall reduction in the sanitation per household in the catchment of approximately 7% per ward between the two censi. This shows that government and the residents of catchment X3 (Sabie-Sand River) are failing to maintain the sanitation facilities in their regions. If expansion of sanitation facilities failed to keep pace with a growing population, this would show that while more sanitation facilities were being provided, the rate at which this is occurring needs to increase. Such a pattern does mean that water use for the domestic sanitation sector is showing reduced pressure on the water resources in the catchment. This is at odds with information contained in the recent DWA Reconciliation Strategy, which claims an annual increase in domestic water demand for sanitation and that this pattern is set to continue (DWA 2013). Unfortunately, the document does not contain information for the Sand River portion of the catchment and no other information for the Sand River was available in this regard. This could be the reason for the contrasting findings between the Reconciliation Strategy and the results presented here.

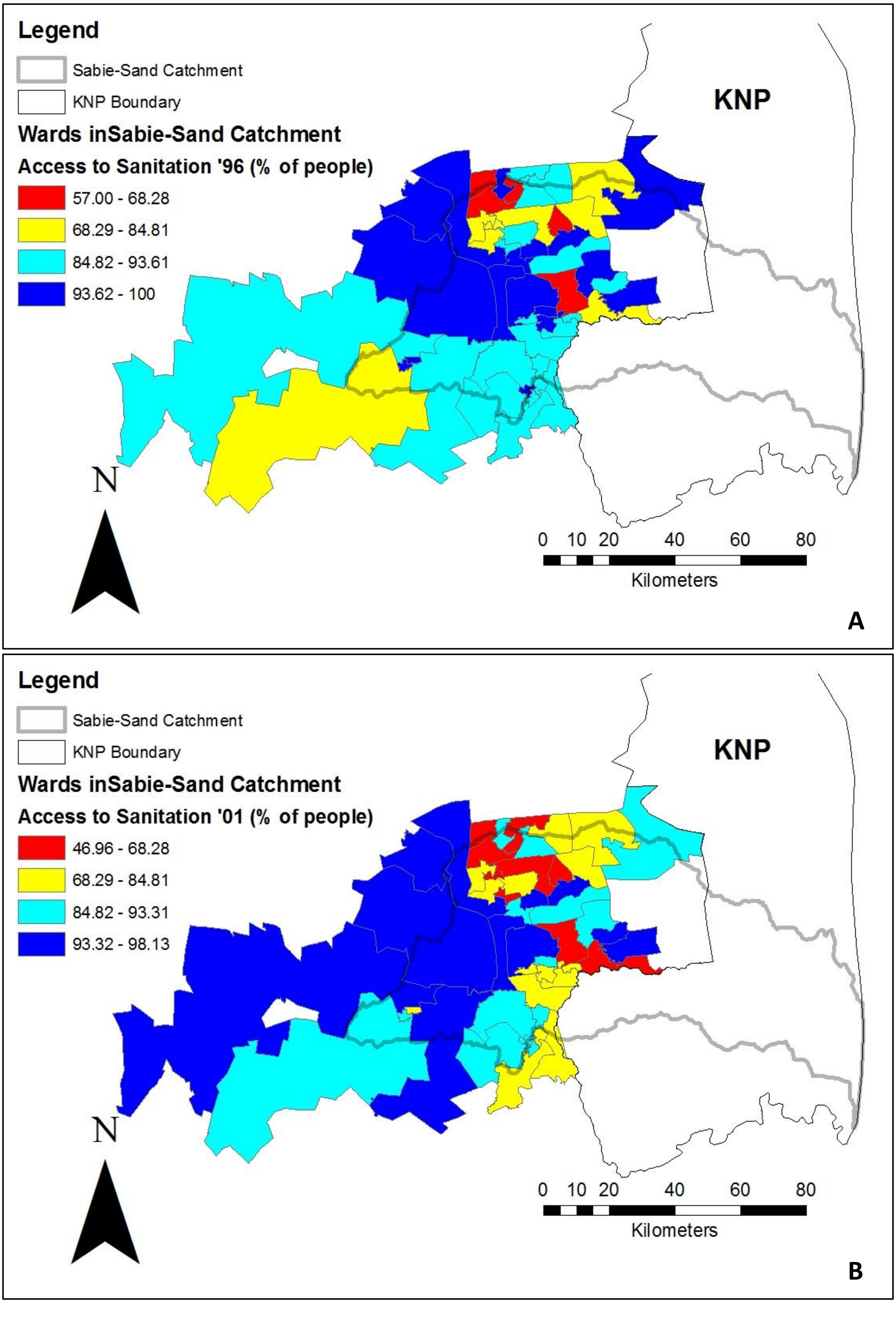

Figure 2.14.A Shows the percentage of population per ward with access to any form of sanitation at Census 1996; B shows percentage of population per ward with access to sanitation at Census 2001.

2.3.3. Patterns of change in population versus change in sanitation for the Sabie-Sand Catchment:

The potential scenarios of changes to population and sanitation in the Sabie-Sand Catchment as outlined towards the end of Section 1.3.2 of Chapter 1 were as follows:

- Increasing population and increasing levels of sanitation
- Increasing population and decreasing levels of sanitation
- Decreasing population and increasing levels of sanitation
- Decreasing population and decreasing levels of sanitation

If we plot this relationship we see that there is no clear-cut scenario prevailing in the catchment, but rather a mosaic of all of the above scenarios, as demonstrated in Figure 2.15 below.

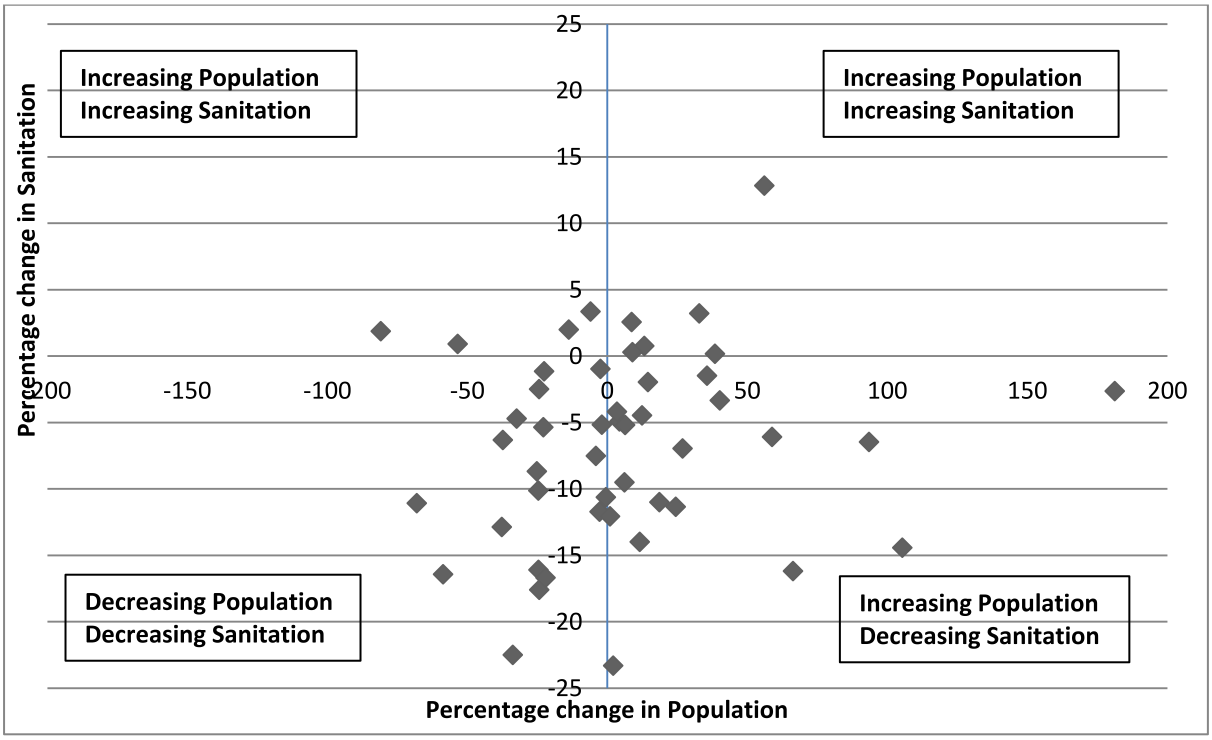

Figure 2.15. Graph showing the relationship between population growth and sanitation levels for wards in the Sabie-Sand Catchment. Note that Bushbuckridge Wards 29 and 33 are omitted for ease of representation.

The aspect that is most noticeable in the graph is the preponderance of wards showing a decline in sanitation. More wards show an increase in population than a decrease in population, but as demonstrated in Section 2.3.1 there is an overall slight decrease in the number of people residing in these wards when comparing 2001 data to 1996 data. It is necessary to note that Wards 29 and 33 of Bushbuckridge have been left off the graph for ease of representation since their enormous population growth would mask the detail of all the other wards. Bushbuckridge Ward 29 grew by 2245% and saw a simultaneous decline in sanitation of approximately 5%. Ward 33 grew by 1422%

in population with a decline of roughly 4%. The fact that there is less serviceable sanitation infrastructure in 2001 compared with 1996 for vastly more people residing in these two wards is cause for concern.

2.4. Conclusion:

2.4.1. Resultant effect of changes in sanitation provisioning on Instream Flow Requirements of the Sabie-Sand River:

This investigation has led to the discovery that the trajectory of water use for sanitation is likely to follow the decline in sanitation provisioning in the Sabie-Sand River. If we use the percentage decline in sanitation of approximately 7% between 1996 and 2001, we could posit an annual decline in water use for sanitation of around 1.4% for the same time period. Coupled with the best case scenario of domestic water use from Section 2.1.4 (80 million m^3/annum for domestic use), we can expect an annual decline in water use of around 1.12 million m^3 and a total of around 5.6 million m^3 between 1996 and 2001. The worst case scenario (90 million m^3/annum water use for domestic purposes) would yield 1.26 million m^3 per annum of water in the river over the same period, and a total of 6.3 million m^3 between 1996 and 2001. Not all the water used in domestic consumption would be used for sanitation purposes, so the volumes above may not be accurate, although it is likely that if infrastructure for sanitation purposes is no longer functional then other water delivery infrastructure is also not working. This trend might have changed in the years subsequent to this analysis, but it is evident for the period between 1996 and 2001. In addition, the stable or diminishing volumes of water used in the forestry and irrigated agriculture sectors appears to not be of concern with regard to IFR compliance, and other sectoral users (power generation and industry) are also not significant users in the Sabie-Sand River Catchment. We can therefore conclude that while sanitation and human use of water in the catchment places a burden on managers in the Sabie-Sand River in terms of meeting the IFR, this burden was declining in influence between 1996 and 2001.

The decline in water use for sanitation between 1996 and 2001 is a small proportion of the volume required for IFR maintenance and should therefore not have a significant impact on maintenance or transgression of IFRs. The recent work by Pollard and du Toit (2011) states that approximately 209 million m^3 is required for ecological maintenance in the Sabie-Sand River annually. The additional water from declining sanitation water use represents between 0.5% and 0.6% of the ecological water requirements annually, and we can therefore conclude that the effect of declining water use for sanitation is negligible with respect to IFR maintenance. Managers of the catchment should keep in mind that if the population does grow and become more affluent in the future, the state of affairs described above will cease to be favourable towards IFR compliance. A large increase in water for domestic use and sanitation would seriously jeopardise the prevailing state of affairs in which managers do not have the added pressure of trying to meet IFR's while a burgeoning population requires ever-growing volumes of water. Cognisance should also be taken of the patterns of migration undertaken by the population of the Sabie-Sand River Catchment, as this is relevant to managers of sanitation infrastructure as well as those managing ecological aspects of the river. Localised growth in populations could have a harmful effect on meeting ecological water requirements of certain parts of the river.

This investigation served as a proximate analysis used to garner a better understanding of any processes that may affect IFR compliance rates, the quantification of which was the major aim of this dissertation. Whether this pattern will be reflected in the compliance rates over this period will be quantified in the following chapter (Chapter 3), and explored in greater detail in the fourth chapter.

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3. Chapter 3 - Spatio-temporal compliance of Instream Flow Requirements in the Sabie-Sand River: do we meet ecological management objectives?

3.1. Introduction:

Preliminary work on the Sabie-Sand River suggests that actual flow volumes in the Sabie-Sand River are often inadequate in comparison with the flow volumes required to fulfill the Instream Flow Requirement (IFR) specifications meant to preserve ecological processes and services in the river system. The paradigm shift in the management of South African water resources, as discussed in the previous two chapters, requires an explicit monitoring and feedback component. This is the standard procedure when using a strategic adaptive management policy (see Figure 3.1). This feedback is then used in the decision-making process for changes to management plans, the redefinition of goals and key objectives, and the identification of performance indicators, among other management actions (Holling et al. 1978).

Instream Flow Requirements function as the operational aspect of the ecological portion of the Reserve, as outlined in "Part 3: The Reserve" of the National Water Act of 1998 (No. 36 of 1998). The history, theory and the specifications of the IFR's have been described and discussed in Chapter 1 (starting at Section 1.3.3.1). As outlined in the Rationale section of Chapter 1 (Section 1.1), the National Water Act of 1998 (No. 36 of 1998) replaced the Water Act of 1956 (No. 54 of 1956) and in doing so created a very different environment for the management of water resources in South Africa. Under the new dispensation, greater focus has been placed on maintaining freshwater resources in a state that preserves or enhances the ecological integrity of these resources (DWAF 1998). The IFR was put forward as a potential method by which to achieve sustainable water resource utilisation and maintenance of ecological systems even before the enactment of the current water legislation. However, impetus was given to the IFR system once the new legislation came into effect. Much of the research completed towards defining minimum flow requirements for rivers in South Africa was drawn on during the determination of IFR's for South African rivers. The IFR method has been used in the determination of minimum flow requirements for all the major rivers in the north-east of South Africa, which includes the Sabie-Sand River. The proportion of the virgin mean annual runoff which the IFR aims to protect ranges from 68% on the main Sabie River to 82% of the flow in the Marite tributary below the Inyaka Dam.

An explicit requirement in the IFR management regime is to review both the flow volumes required for IFR, and even the IFR system at regular intervals (King et al. 2008). The findings of this review would then be used to specify changes to the IFR volumes or method of managing river flows, so as to obtain maximum sustainable benefit from the water resources of the country. This style of management requires a hands-off approach in which less manipulation of ecological systems occurs than the command and control style favoured in the past (Jewitt 2002). However, a strong monitoring component must be adhered to so as to understand causal mechanisms of change in the characteristics of the ecological system for which the IFR has been specified (Hughes et al. 1997; King et al. 2010). The findings of the monitoring programme should be integrated and used to at minimum, review, and where necessary, adjust the IFR's. This is called Strategic Adaptive Management (Holling et al. 1978); an illustration of the strategic adaptive management cycle can be seen in Figure 3.1 below.

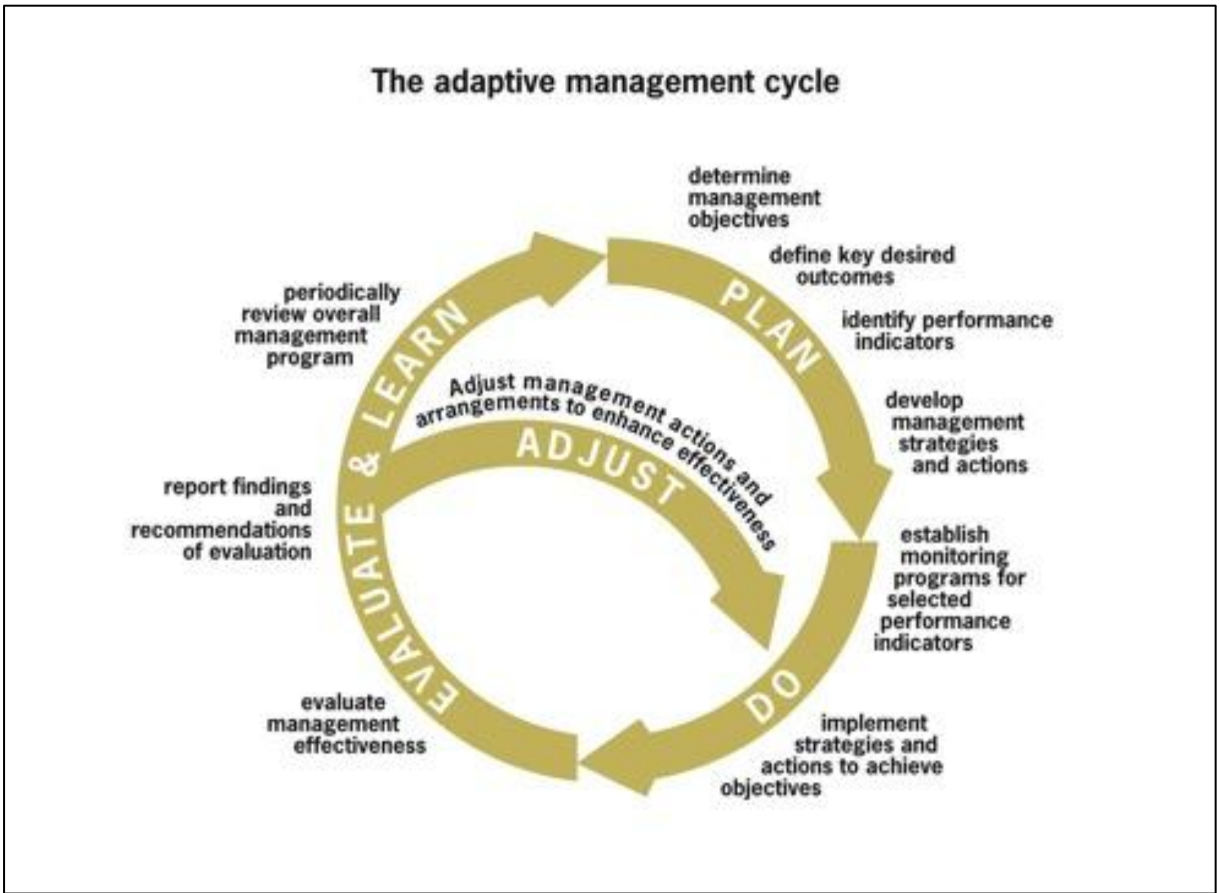

Figure 3.1. An illustration of the adaptive management cycle (Image courtesy Jones 2005).

After undertaking an intensive and rigorous literature search (Chapter 1), it is apparent that the monitoring of the flow dimensions of the Sabie-Sand River against the IFR has not yet been undertaken by the authorities tasked with managing the river, or that very little action has resulted from the monitoring operation if monitoring has occurred. Literature on IFR's concerns only pre-introduction groundwork and supporting documentation but very little to no critical evaluation of the performance of the system in South Africa, even after it has been the incumbent management tool for a number of years in the Sabie-Sand River Catchment. SAM calls for findings and recommendations of evaluation to be clearly and precisely reported and then periodically reviewed. The dearth of such information is an indication that SAM has not been adequately embraced as a management framework.

This portion of the study aims to assess compliance with IFR's for sites at which IFR's have been specified for the Sabie-Sand River.This chapter will expose the spatio-temporal dimensions of actual flows in the Sabie-Sand River compared with the IFR for each of the four sites for which these flows have been specified. Specifically, I calculate the frequency of annual monthly compliance and compare the trends in compliance between different IFR sites. The period over which the investigation is made varies per site depending on the availability of flow data from proximal flow gauges. It is notable that both drought (in the year of 1992) and flooding (in the years of 1996 and 2000) occurred and was measured by the gauges that were functional during the occurrence of these phenomena (see Figure 3.2).

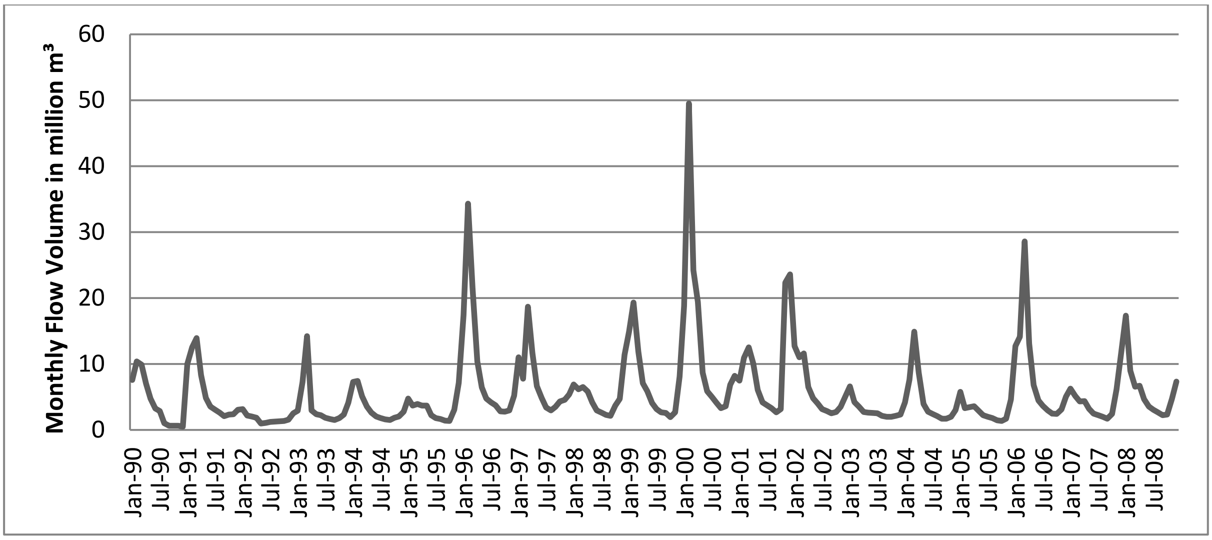

Figure 3.2. Variation of annual flow for the period 1990-2008 at Gauge X3H001 Sabie River at the town of Sabie. Note the drought season between July 1991 and July 1992 and the flood season between July 1999 and July 2000.

3.2. Study Methods:

This section details the means by which the total flow volumes were calculated for each IFR site. This includes the method for the calculating base flows for drought and maintenance specifications as well as the method for flow volumes relating to higher specifications of the IFR for drought and maintenance IFR conditions. The method by which the trends in compliance are evaluated is also presented.

3.2.1. Flow Gauging Structures and IFR Sites:

3.2.1.1. Flow Data:

Daily and monthly flow data from all the functional and obsolete flow gauges present in the Sabie-Sand River catchment were obtained from the Department of Water and Sanitation (DWS) Hydstra Database (URL: http://www.dwaf.gov.za/hydrology/cgi-bin/his/cgihis.exe/station). A list of all flow gauges in the Sabie-Sand River Catchment can be found below in Table 3-1. The numbers adjacent to flow gauges in Table 3-1 correspond with the numbers in Figure 3.3. Figure 3.3 shows all the flow gauges in the Sabie-Sand River; for the purpose set out at the start of this chapter we will focus on the flow gauges closest to the IFR monitoring sites. Although nineteen flow gauges are on DWA records for the Sabie-Sand River and tributaries, many have only functioned intermittently, and at the scale that this portion of the study took place all relevant flow is captured by the five gauges described in Table 3-2, since they are adjacent to the IFR sites and comprise the closest means by which to remotely measure flows at the IFR sites. A short descriptive summary of the pertinent flow gauges can be found below Table 3-2, and daily and monthly data from these gauges were used in evaluating compliance with IFR specifications at all IFR sites.

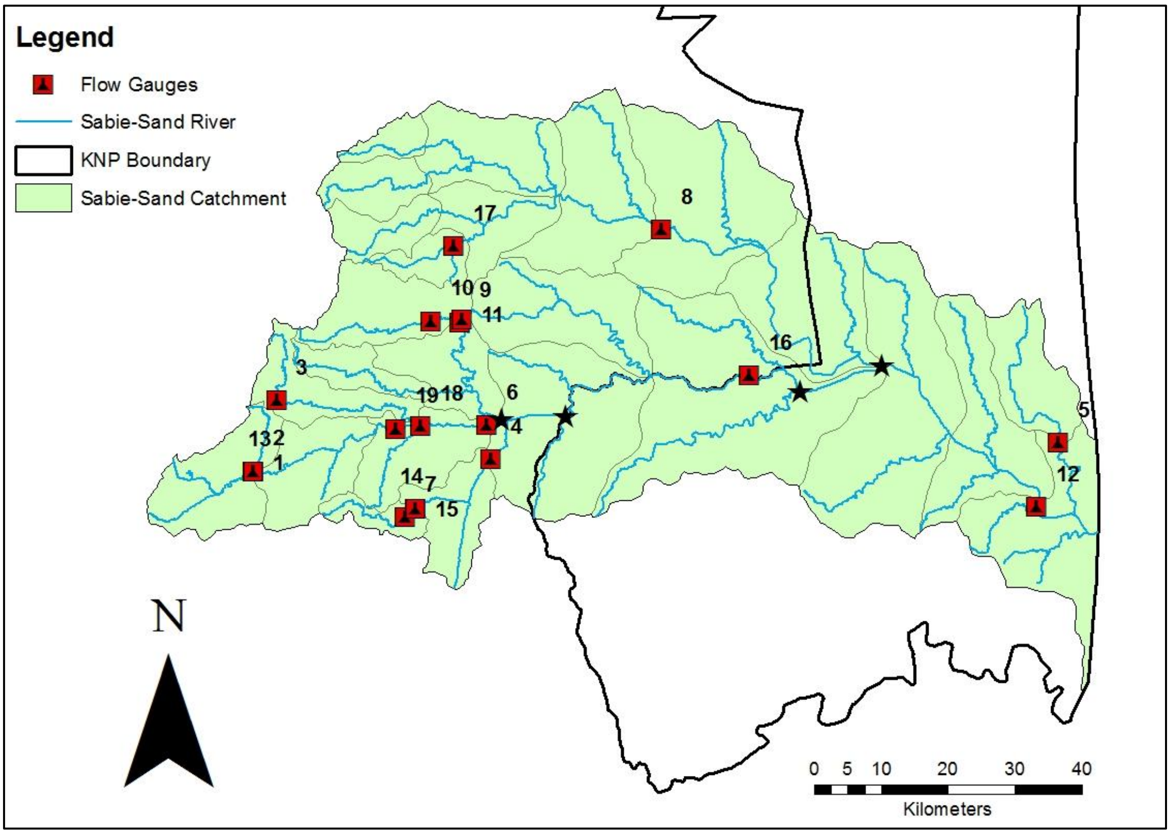

Figure 3.3. A map of the study region with all flow gauges and IFR monitoring sites (details provided in Table 3.1)

Table 3-1. List of all flow gauges and data availability in the Sabie-Sand River catchment.

Gauge Number	Gauge Name	Start date	End Date
1	X3H001	1948-03-15	Present
2	X3H002	1963-11-08	Present
3	X3H003	1948-03-16	Present
4	X3H004	1948-02-21	Present
5	X3H005	1952-10-01	1960-02-29
6	X3H006	1958-09-04	2000-01-19
7	X3H007	1963-11-12	1991-09-16
8	X3H008	1967-09-01	Present
9	X3H009	1976-07-01	1978-11-30
10	X3H010	1976-07-01	1976-11-30
11	X3H011	1978-11-28	Present
12	X3H015	1986-12-09	Present
13	X3H016	1960-07-27	1967-10-01
14	X3H019	1977-07-01	Present
15	X3H020	1973-05-17	Present
16	X3H021	1990-11-15	Present
17	X3H022	1997-10-29	Present
18	X3H023	2002-04-17	Present
19	X3H024	2002-05-02	Present

3.2.1.2. Description of flow gauges relevant to the study:

Not all flow gauges proved useful in the evaluation of IFR compliance in the study. Of the nineteen flow gauges with data records, many were not considered for this evaluation for various reasons. Some flow gauges are situated on tributaries or along the Sabie River at places that are not in close proximity to the IFR sites (e.g. X3H003). Other flow gauges have very short data sets and therefore do not incorporate a large enough data set with a range of flow conditions against which to observe potential ecological changes in the catchment (eg: X3H009). Yet other flow gauges are situated in places that are not useful to measure ecological changes relative to the IFR sites; for instance those that occur further away from an IFR site than another flow gauge (eg: X3H023). In some instances a combination of these factors renders a particular flow gauge extraneous to the requirement of this analysis (eg: X3H010 which is both far from an IFR site and has a very short dataset).

Below is a brief description of the flow gauges that were chosen for the study. Table 3-2 shows a summary of the gauges that are pertinent for analyses at the various IFR sites, followed by a map (Figure 3.4) showing the position of all of the relevant flow gauges relative to the IFR sites.

Table 3-2. IFR Sites and the corresponding flow gauges in the Sabie-Sand Catchment.

IFR Site Name:	Pertinent Flow Gauges:
MariteSabie Site:	X3H006
	X3H011
InsideKNP Site:	X3H004
	X3H006
	X3H011
Skukuza Site	X3H021
SabieSand Site	X3H015

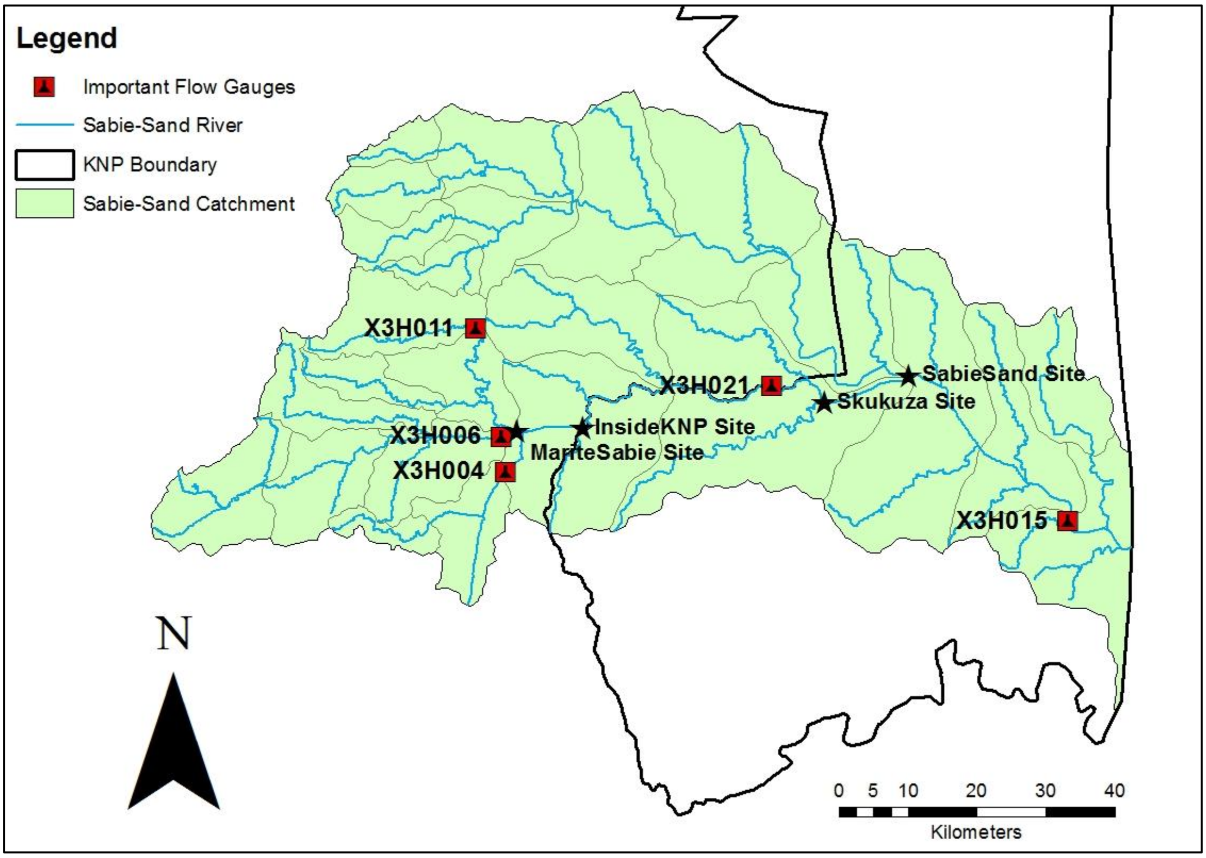

Figure 3.4. A map of the study region highlighting important flow gauges and the IFR sites.

3.2.1.2.1. Flow Gauge X3H004 (Number 4):

Flow gauge X3H004 has the longest data record in sub-catchment X3, and is still in operation. Like other long-running and currently operational gauges in the catchment, X3H004 was built in response to requirements from irrigation societies (and later, the irrigation boards formalised under the 1956 Water Act (No. 54 of 1956) to measure water quotas used for crop production and bulk distribution (Woodhouse 1997). The data record for X3H004 is both extensive and good with very few missing data points (operational period: 1948 – present). Unfortunately, the full dataset could not be put to use in this analysis since the flows passing the InsideKNP site are the combination of the flows measured at gauges X3H004, X3H006 and X3H011. As a result, only data from flow gauges functioning contemporaneously could be used. The trend in the long-term data for the flow rate of gauge X3H004 shows that the daily average flow rate is slowly declining and quite variable (equation of trendline: $y = -0.00001115x + 1.30$, $R^2 = 0.08$, $n = 21\ 401$).

The gauge is situated on the NoordSand River (not to be confused with the larger but ephemeral Sand River), and as can be seen from Figure 3.5, joins the main stem of the Sabie River just below the MariteSabie Site. As such, and in conjunction with flows from gauges X3H006 and X3H011, flow gauge X3H004 plays an important role in determining flow characteristics at the InsideKNP site.

3.2.1.2.2. Flow Gauge X3H006 (Number 6)

Flow gauge X3H006 was commissioned in 1958, in all likelihood to cater for the expanding irrigated agriculture requirements of the citrus industry in the area at that time (Woodhouse 1997). The data record for gauge X3H006 is very good, with the only significant period of non-function occurring between February and July of 1996. The entire data record shows a gap of 155 days out of a period of 3 670 days of data collection, evidence for the utility of the dataset in both daily and monthly IFR evaluations. Daily average flow rates also show a decline for gauge X3H006 over the period of analysis but much less variability (equation of trendline: $y = -0.00008895x + 7.26$, $R^2 = 0.39$, $n = 14\ 692$). Failure of the gauge during 1996 was most likely as a result of the river outflanking the gauge structure during an extraordinary flood period. Subsequent repairs restored the flow gauge and flow continued to be measured thereafter until the 18th of January 2000. Figure 2.5 in Chapter 2 shows the remnant structures after the flow gauge and recorder hut were outflanked and destroyed in the floods of February 2000. The cost of replacement of the gauge and recorder hut structures were considered too expensive to recommission the X3H006 site, and so this flow gauge was not repaired. However, a new gauge approximately 6km upstream of X3H006 was completed in April 2002 at Emmet on the Sabie River, effectively replacing X3H006.

Flow gauge X3H006 plays an important role in verifying IFR compliance at both the MariteSabie and the InsideKNP sites.

3.2.1.2.3. Flow Gauge X3H011 (Number 11)

Flow gauge X3H011 is situated less than 1km from the outlet of the Inyaka Dam (described in Chapter 1), although its existence pre-dates the construction of the dam which was completed in 2002. The flow gauge may have played a role in the site selection for Inyaka Dam as it was commissioned during November 1978 and has continued to function to the present day. The data record for X3H011 is far patchier than either X3H004 and X3H006, but it is nevertheless an integral component in measuring the total flow occurring at both the MariteSabie and InsideKNP sites. Like the two flow gauges described above, daily average flow rates also show a decline for gauge X3H011 over the period of analysis but with less variability, likely a result of the attenuation effect of the dam upstream (equation of trendline: $y = -0.00007791x + 2.29$, $R^2 = 0.52$, $n = 9\ 507$). Since this flow gauge is the newest of the three described so far, it provides the baseline for the temporal component of the evaluation from which to measure flow compliance at the proximal IFR sites. As it is necessary to combine data from gauges X3H006 and X3H011 to obtain a representation of flows at the MariteSabie IFR Site, flows from X3H004, X3H006 and X3H011 are used for the InsideKNP IFR Site. Consequently the first complete month of flow records for which the analysis was done was December 1978.

3.2.1.2.4. Flow Gauge X3H015 (Number 12)

Flow gauge X3H015 is situated on the main stem of the Sabie River after confluence with the Sand River in the KNP and began recording data in December of 1986. It is the 12th gauge that is currently operational in the catchment, but three others were built before it and failed, hence the gauge number X3H015. Flow gauge X3H015 has presented a number of problems, having failed no less than nine times over the period of investigation in this study. While such failures might ordinarily provoke DWA to close the flow gauge, it is assumed that the strategic importance of X3H015 prevents DWA from taking such action. South Africa has an international obligation to Mozambique for a certain volume of water from the Inkomati Water Management area and X3H015 is the last flow gauge on the Sabie River before it enters Mozambique, and therefore is the most accurate flow measuring structure in terms of South Africa's ability to measure compliance with its obligations to Mozambique.

Besides some early relatively minor failures, as noted for flow gauge X3H006, flow gauge X3H015 also ceased to function during the flood period during February 2000, with the last daily data record occurring on the 18th of January 2000. However, DWA chose to repair flow gauge X3H015 and it became functional once more on the 10th of August 2000. Two months later on the 10th of October, the gauge ceased to function again and only became operational again on the 31st of August 2001, a period of 324 days without transmitting data. The reasons for this extended failure are not known, but a pattern of prolonged malfunction or breakdown after initial failure has been noted for X3H015, probably due to its distance from the network of technicians based higher up in the catchment.

The high flows measured in the days leading up to 27th of November 2001 may have been the cause of the gauges failure to function from that date. It was repaired and began to work again on the 31st of January 2002, from where it worked successfully until the end of the analysis period in 2013.

The accurate assessment of flows at the site known as SabieSand proved to be quite difficult, in that it is not in close proximity to any flow gauges. However, it was decided that flow gauge X3H015 would be used, even though many tributaries enter the river between the SabieSand site and flow gauge. Upon visual exploration of the area on numerous occasions and consultation of the literature, all of the tributaries of the Sabie River after confluence with the Sand River very rarely carry water. As a result, flows in most seasons as measured at flow gauge X3H015 will in all likelihood be an accurate reflection of the flows experienced at the SabieSand site. It is acknowledged that in flood periods when these tributaries carry water, the flow gauge will not show an accurate reflection of the flows experienced at the IFR site SabieSand, but it is assumed that the IFR would be exceeded in these instances anyway due to higher rainfall and additions from groundwater and overland flow. Flows in the Sabie-Sand River measured at flow guage X3H015 have shown an increase over the time (1987 – 2008 for this dataset, and the gauge is still functional) for which flow data are available (equation of trendline: $y = 0.00004x + 12.46$, $R^2 = 0.16$, $n = 6\,961$). The lower R^2 value can be attributed to the fact that the flow dataset is not as long as the flow gauges above, and the gauge was installed just before a period of high flow variablility, with the hydrological drought of 1992 and the floods of 1996.

3.2.1.2.5. Flow Gauge X3H021 (Number 16)

One of the newer flow gauges on the Sabie River, gauge X3H021 was commissioned in November of 1990. As noted for flow gauge X3H0015, flow gauge X3H021 is also prone to failure having ten data gaps over the period of analysis. Also similar to gauge X3H015, the flow gauge is situated within the KNP but its proximity to the border of the KNP has meant that failures have resulted in fairly quick repair in most cases. However, a failure period of 72 days occurred in mid-1991. Reasons for the failure have not been given by DWA and literature surveys have not revealed reasons for failure.

On the 7th of February 2000, flow gauge X3H021 failed as a result of intense flooding. This occurred earlier than other flow gauges in the catchment. The flow gauge was outflanked on both sides, causing much damage to the concrete structures of the flow gauge. As a result, the flow gauge was rendered inactive for a period of 101 days until the 18th of May 2000. DWA also sees flow gauge X3H021 as one of strategic importance due to its proximity to Mozambique and as such always attempts to maintain the gauge in working order, repairing it shortly after malfunction from any cause.

For the purpose of this investigation, data from gauge X3H021 was used to evaluate IFR compliance at the Skukuza IFR site. Potential error in flow magnitude could be sourced from the fact that both the Musutlu and Nwaswitshaka streams make confluence with the Sabie River below the flow gauge but before the Skukuza IFR site. However, as is the case with tributaries in close proximity to the SabieSand IFR Site and flow gauge X3H015, both the Musutlu and Nwaswitshaka streams are non-perennial, so it can be assumed that flow volumes at the IFR site would be compliant during periods in which these streams are flowing. Daily flows have been measured at gauge X3H021 since 1990, and like X3H015 also appear to getting larger (equation of trendline: $y = 0.001x + 7.54$, $R^2 = 0.33$, $n = 5\ 535$).

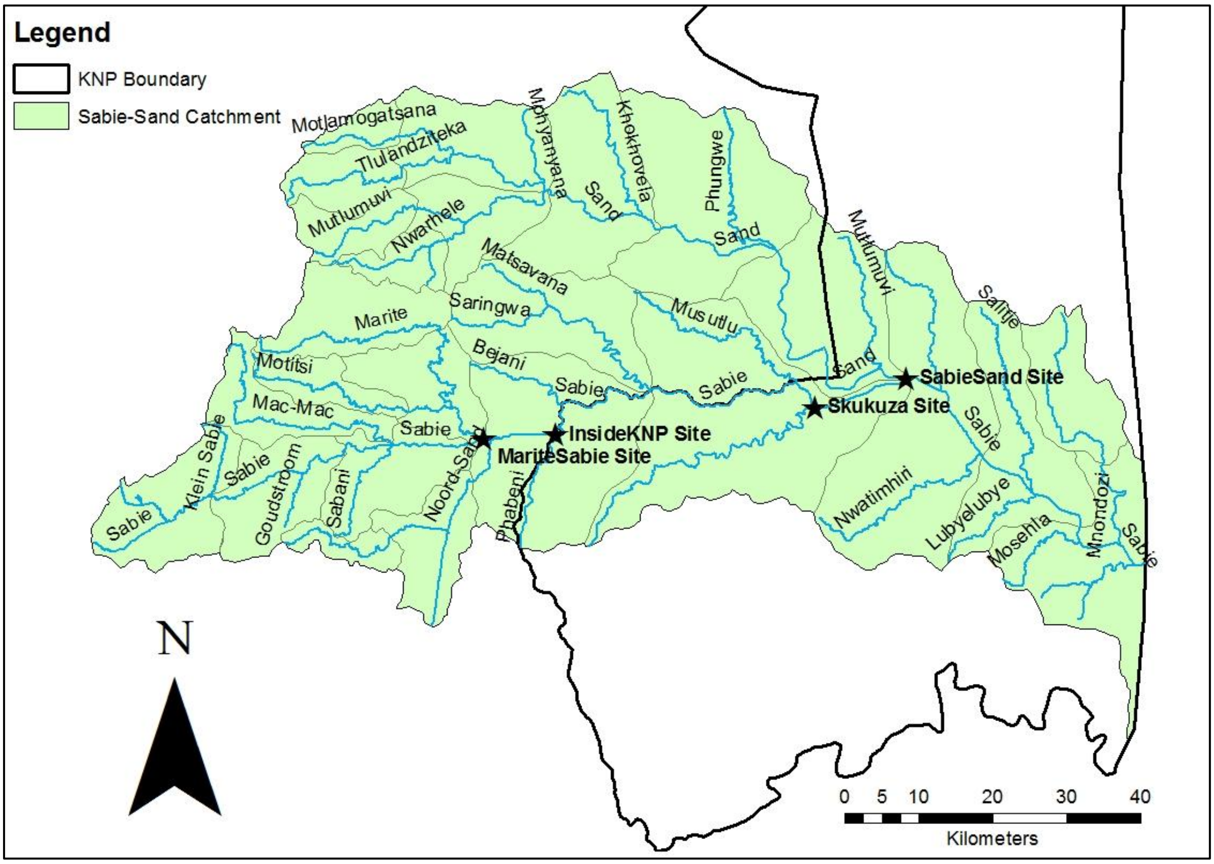

Figure 3.5. A map of the Sabie-Sand River catchment showing IFR sites and names of all tributaries in the catchment.

3.2.2. Evaluating IFR compliance:

High flow and base flow IFR compliance were assessed with different data sets. Daily flow data from the pertinent flow gauges were used in the evaluation of compliance with higher flows for both the maintenance and drought IFR scenarios at all sites. Monthly flow data from the flow gauges were used to evaluate whether IFR flow specifications at all sites were realised, for base flows in both the maintenance and drought IFR scenarios. The method employed for the evaluation of IFR compliance differed for base flow compliance and that of higher flow compliance. It is important to note that the method used to evaluate compliance with Maintenance and Drought IFR scenarios is identical, but within each scenario, the method by which we evaluate compliance with base flows and higher flows differs. Each will be described separately below.

The example in Table 3-3 points out important aspects of the IFR that must be met to ensure compliance. The black box in the base flow specification highlights the volume component. The units of volume are million cubic metres (MCM) per month; hence the analysis was undertaken at the monthly timescale. In the higher flow specification, the grey box aims to highlight specifically the flow volume (in million cubic metres), but a flow of this volume must occur cumulatively over the period specified in the duration column, in units of days. The return period specifies how frequently flows of this magnitude should occur. Accordingly, if we use October as the example, a 1:1 return period means that a cumulative flow of 0.9 MCM should occur in some consecutive 3 day period in October of every year. The 1:3 year return period specified in February should occur once every third February. As we can see in Table 3-3, this means that the cumulative flow of 100 MCM needs to occur in a 14 day period in February to fulfil requirements at the 1:3 year return interval.

Table 3-3. Table showing important components of the IFR specification.

BUILDING BLOCKS		OCT	NOV	DEC	JAN	FEB	
Maintenance IFR	Magnitude (m^3/s)	2	3	5	6	6	
	Depth (m)						
Base flows	Volume (MCM)	5.3	7.8	13.4	16.1	14.5	
	FDC % V	100	100	100	100	100	
	FDC % V	79	87	86	76	85	
	Magnitude (m^3/s)	9	12	30	17	50	190
	Depth (m)						
	Duration (d)	3	3	7	5	10	14
Higher flows	Return period (y)	1:1	1:1	1:1	1:1	1:1	1:3
	Volume (MCM)	0.9	1.2	7.6	2.4	19	100
	FDC % V	67	46	10	26	4	0.4
	FDC % V	33	23	6	15	3	0.3
DROUGHT IFR	Magnitude (m^3/s)	1.5	1.9	2.3	2.6	3	
	Depth (m)						
Base flows	Volume (MCM)	4	4.9	6.2	7	7.2	
	FDC % V	100	100	100	100	100	
	FDC % V	90	95	97	99	98	
	Magnitude (m^3/s)		3.8	4.6	5.2	6	
	Depth (m)						
	Duration (d)		3	3	3	3	
Higher flows	Return period (y)		1:1	1:1	1:1	1:1	
	Volume (MCM)		0.25	0.3	0.34	0.39	
	FDC % V		99	98	96	92	
	FDC % V		78	69	63	54	

3.2.2.1. Method used to evaluate base flow compliance:

The evaluation of the actual flows against those required to fulfil IFR base flows is fairly straightforward, particularly for the sites in which data from one flow gauge could be used (Skukuza and SabieSand IFR sites). However, in cases where data from more than one flow gauge could be used to enhance the accuracy of assessment, the flow volume data from the matching months of the pertinent flow gauges were added together to obtain a more robust and accurate representation of the flow volume passing the IFR site (MariteSabie and InsideKNP IFR sites). In the case of the MariteSabie IFR site, data from flow gauges X3H006 and X3H011 were added together for the period spanning December 1978 (when X3H011 began to transmit data) until the last full month of data prior to the permanent failure of flow gauge X3H006, which was December 1999.

For evaluating flows at the InsideKNP IFR site, data from the concurrent period from flow gauge X3H004 was added to the combined volumes passing through X3H006 and X3H011, also between December 1978 and December 1999. These sites will be dealt with separately to both the Skukuza and SabieSand IFR sites, since the method of flow comparison and evaluation were slightly different where multiple flow gauges were used.

3.2.2.1.1. Evaluation method for base flows at sites incorporating flows from multiple flow gauges:

Firstly, the flow gauge network was appraised and the flow gauges that would provide the best data for the evaluation of IFR compliance were selected. The criteria for selection included: distance from corresponding IFR site; the effect of ungauged tributaries between gauging station and IFR site; length of flow gauge data record (or records in the cases where multiple gauges were used); and data quality (ie: gaps and no records) for each flow gauge.

For the evaluation of IFR compliance specifically at the MariteSabie IFR site, monthly flow data for flow gauges X3H006 and X3H011 were downloaded from DWA's Hydstra database. Data are downloaded in *.txt format and converted to *.xlsx to render them more tractable for analysis.

Once the data for both flow gauges X3H006 and X3H011 were added to the Microsoft Excel workbook, the flows for the same months of the same year were added together in order to get a more representative flow volume as it would occur at the MariteSabie IFR site. The flaw in such a method is that it ignores any overland flows and various inputs from any source between the flow gauges and the IFR site. Perhaps even more importantly due to the probability of occurrence, the method I have used to evaluate IFR compliance is not sensitive to abstraction and evaporation in the length of stream between the gauging structure and the IFR site. Although these factors play a role in changing the actual flow volume in the river between the flow gauges and the IFR site, a study of this nature in which the remote determination of IFR compliance is inextricably linked to the aim, we cannot easily account for such changes in actual flow volume between gauge site and IFR site. The value that a remote analysis adds is that it has the potential to quickly and cost-effectively identify latent reasons for IFR non-compliance which might then be followed up on the ground at finer scale should such action be deemed necessary.

The monthly flow data from the DWA Hydstra database are downloaded in units of million cubic metres (MCM), and so are already directly comparable with the flow specifications from the IFR tables for each IFR site (see Table 1-1 - Table 1-4 in Chapter 1). Once the flow data from the various flow gauges are added together to give a representative total at the IFR site, this volume can be compared with the monthly IFR requirement. The manner in which this analysis was conducted was to tabulate the data and arrange the monthly column from largest to smallest monthly flow volume for each month and for all years between 1978 and 1999. The flow volumes for each month that fell below the threshold for drought base flows were colour-coded red, and those falling between the non-compliant drought base flows and the compliance level-flows were colour-coded orange. Once all months for all years were analysed, the data were re-arranged in chronological order.

The same method was applied in calculating total flows at the InsideKNP IFR site, except that the flows occurring there are an accumulation of synchronous data from three flows gauges; X3H004, X3H006 and X3H011. The same analysis period was used for the InsideKNP IFR site as the MariteSabie IFR site.

3.2.2.1.2. Evaluation method for base flows at sites incorporating flows from a single flow gauge:

As in the method applied above, monthly flow volume data from the relevant flow gauge were downloaded from the DWA Hydstra database, in units of MCM. Unlike the above method, the monthly flow volume data from the single flow gauge are compared directly to the IFR specifications and not added to flow data from any other gauging station. Otherwise, the same analysis method was used. The monthly flow data are tabulated for the relevant years, and flow data for each month are sorted smallest to largest and designated non-compliant for either drought base or maintenance base flows and colour co-ordinated accordingly.

For the Skukuza IFR site, data from flow gauge X3H021 were used and the entire data record of the flow gauge was utilized, spanning December 1990 to the last audited monthly dataset in April of 2013. The SabieSand IFR site compliance was conducted using flow data from flow gauge X3H015 downstream of the site. Here again, the entire monthly flow volume dataset from X3H015 was used. The flow gauge transmitted its first full month of data in March 1987, and is currently still functional with the last audited flow volume data available for April 2013.

3.2.2.2. *Method used to evaluate higher flow compliance:*

As can be seen in Table 3-3, higher flows for both maintenance and drought scenarios are more precise flows occurring over shorter time intervals, specified in days and varying across months. Only wet season months have higher flow specifications. Higher flow specifications of the IFR are intended to fulfil explicit functions. These include the flushing of sediment build-up, spawning cues for fish and invertebrates among many functions as outlined in Chapter 1.

As with the monthly flow volumes, daily flow data for the daily analysis exercise were obtained from the DWA Hydstra database for the same flow gauges used in the base flow analysis. However, unlike the monthly flow data which is published in million cubic metres per month (MCM), daily flow data is published as an average instantaneous flow rate per day in m^3/s. The higher flow IFR's stipulate a flow requirement in million cubic metres over a certain number of days, and the volume and period vary depending on the month. The daily flow rate data needs to be transformed from an instantaneous flow rate into a total flow volume per day. This is carried out using the following formula:

$$TOTAL\ DAILY\ DISCHARGE\ (MCM) = \frac{x\ m^3/s\ \times 60\ s\ \times 60\ m\ \times 24\ h}{1\ 000\ 000}$$

where total daily discharge is measured in million cubic metres, and is a product of the average daily flow rate in m^3/s multiplied by the number of seconds in a minute, and then the number of minutes in an hour and then the number of hours in a day. This gives the number of cubic metres (m^3) of flow volume in a day. To render the resultant volume comparable to the IFR specification in units of million cubic metres (MCM) per day, we divide that number by 1 000 000, thereby obtaining a flow volume in units of MCM per day. However, the IFR tables specify a cumulative flow of a number of days ranging from 3 (in Table 3-3 we see that October and November maintenance high flows are an example of this) to 10 (1:1 year return interval) or 14 (1:3 year return interval) days worth of cumulative flow in the month of February. Once we have obtained the daily flow volume figures (using the equation above) for all flow gauges and added the synchronous data together where more than one flow gauge is needed for the analysis, we perform a running cumulative total of flow volume for the number of days as per requirement for that month.

Let us use Table 3-3 once more as an example. Maintenance IFR higher flow specifications for October state that a flow of 0.9 MCM over any 3 day period in that month must occur for maintenance IFR compliance targets to be met. We start the analysis by adding the respective flow volumes on the 29th and 30th of September to the flow volume on the 1st of October. This is because flow volumes are measured in batches of 3 days for October and the two days from the previous month need to be used to measure compliance on the 1st of October. If the flow volume was 0.1 MCM on the 29th of September, 0.1 MCM on the 30th of September and 0.3 MCM on the 1st of October, the total flow volume for the three days up to and including the 1st of October would equal 0.5 MCM. This is well below the maintenance higher IFR specification for October, which is 0.9 MCM. However, if the flow volume on the 2nd of October was 0.5 MCM, and we add to it the flow volumes from the 30th of September (0.1 MCM) and the 1st of October (0.3 MCM), we see the sum equals 0.9 MCM for the 3 days up to and including the 2nd of October. This volume equals the IFR requirement for October, and we would designate that particular October an IFR compliant month. Any 3-day period throughout October in which a 3-day cumulative flow volume of 0.9 MCM occurs, even if only occurring once, would be judged compliant for October in this example.

If we consult the IFR specification table, we can see that higher flows have two fundamental components, namely duration of flow and volume of flow. This is similar to base flow specifications. However, the difference between base flows and higher flows is that base flows are always specified for the entire time period in a month (ie: 31 days for January, 28 days for February, etc.), while higher flows are specified for a number of days within a month (ie: maintenance higher flows in Table 3-3 show a period of 3 days for October, 3 days for November, 7 days for December, etc.) and not for all months. As we see from Table 3-3, maintenance higher flows for October are specified at a level of 0.9 MCM of flow within a three day period. For November, a requirement of 1.2 MCM of flow in 3 days is required to meet the maintenance higher flow specification for that month. An annual return period is specified for all months with a higher flow requirement, except for the month of February. Unlike the other months possessing flow specifications (maintenance or drought higher flows), we see that February has two specification options. The difference between the two is the return interval; the first specification is for the 1:1 year return interval. In Table 3-3, this specification shows that a flow of 19 MCM must occur annually in February over a period of 10 days. To the right of this annual specification but still within the February column, we see a flow requirement with a 1:3 year return interval. This specification is for a flow that must equal (or exceed) 100 MCM within a 14 day period every third February. It must be noted here that there is no rigid stipulation that every third year such a flow should occur. Rather, over the longer term (such as the study undertaken here), we should expect a flood of 100 MCM or greater in roughly 33% of the number of "February's" that we scrutinize. Since each site has approximately a 20-22 year data record, we could expect that for each site we see seven floods of such a magnitude over the analysis period.

The process described above using Table 3-3, in which compliance testing for October was outlined, was employed for all four IFR sites. A summary of the details of the maintenance and drought higher flows for each of these sites is outlined in sections 3.2.2.2.1 and 3.2.2.2.2 below. For each site, compliance was tested in all months for both maintenance and drought higher flows, as well as the 1:3 year return interval February floods for the entire analysis period.

3.2.2.2.1. Evaluation method for higher flows at sites incorporating flows from multiple flow gauges:

As is the case in the base flow analysis where multiple flow gauge data are used together for analysis of IFR site compliance (MariteSabie and InsideKNP IFR sites), the flow volumes from multiple sources must be summed (see Table 3-2 for flow gauges and matching IFR sites). In the case of the MariteSabie IFR site, the flow volumes as obtained from data recorded at flow gauges X3H006 and X3H011 are made use of in evaluating compliance. Compliance at the InsideKNP IFR site is measured against the combined flow volume at flow gauges X3H004, X3H006 and X3H011.

The flow volumes and time periods of the IFR specifications differ across the IFR sites. As mentioned above, the higher flow specifications are more precise than base flows and therefore differ at even one site between maintenance and drought flows, as well as across months. Neverthless, the notion that a certain flow volume must occur in a certain number of days in each month at each site is a universal concept across IFR sites and maintenance and base scenarios. It is only the flow volume and flow duration that differs. A summary of the specifications at each site can be found below.

Table 3-4 through Table 3-7 focus on only the flow volumes and durations over which higher flows must occur. The IFR's for higher flows are summarised below so as to avoid confusion with extraneous higher flow information in Table 1-1 - Table 1-4, as well as the base flow requirement information.

3.2.2.2.1.1. MariteSabie IFR higher flow summary:

Maintenance higher flows at the MariteSabie IFR site are specified for the wet season, namely from October until April of the following year. Drought higher IFR specifications are applicable for November through April but no 1:3 year specification is given since a drought year cannot simultaneously be designated a flood year.

Table 3-4 below shows a summary of the flow volume and duration requirements for both the maintenance and drought higher flows at the MariteSabie IFR site.

Table 3-4. Summary of flow volume and duration specifications for maintenance and drought higher flows at the MariteSabie IFR site.

<table>
<tr><th>MariteSabie IFR specifications</th><th>MONTH</th><th>OCT</th><th>NOV</th><th>DEC</th><th>JAN</th><th colspan="2">FEB</th><th>MAR</th><th>APR</th></tr>
<tr><td rowspan="3">MAINTENANCE IFR</td><td rowspan="2">Return Period (days)</td><td rowspan="2">3</td><td rowspan="2">3</td><td rowspan="2">7</td><td rowspan="2">5</td><td>1:1</td><td>1:3</td><td rowspan="2">5</td><td rowspan="2">5</td></tr>
<tr><td>10</td><td>14</td></tr>
<tr><td>Flow Volume (MCM)</td><td>0.9</td><td>1.2</td><td>7.6</td><td>2.4</td><td>19</td><td>100</td><td>2.1</td><td>3</td></tr>
<tr><td rowspan="2">DROUGHT IFR</td><td>Return Period (days)</td><td>N/A</td><td>3</td><td>3</td><td>3</td><td>3</td><td>N/A</td><td>3</td><td>3</td></tr>
<tr><td>Flow Volume (MCM)</td><td>N/A</td><td>0.25</td><td>0.3</td><td>0.34</td><td>0.39</td><td>N/A</td><td>0.36</td><td>0.32</td></tr>
</table>

3.2.2.2.1.2. InsideKNP IFR site higher flow summary:

Maintenance higher flows at the InsideKNP IFR site are specified for the wet season, namely from October until April of following year. Drought higher IFR specifications are applicable only in November and February but no 1:3 year specification is given since a drought year cannot simultaneously be designated a flood year. Table 3-5 below shows a summary of the flow volume and duration requirements for both the maintenance and drought higher flows at the InsideKNP site.

Table 3-5. Summary of flow volume and duration specifications for maintenance and drought higher flows at the InsideKNP IFR site.

<table>
<tr><th>InsideKNP IFR specifications</th><th>MONTH</th><th>OCT</th><th>NOV</th><th>DEC</th><th>JAN</th><th colspan="2">FEB</th><th>MAR</th><th>APR</th></tr>
<tr><td rowspan="3">MAINTENANCE IFR</td><td rowspan="2">Return Period (days)</td><td rowspan="2">3</td><td rowspan="2">3</td><td rowspan="2">7</td><td rowspan="2">5</td><td>1:1</td><td>1:3</td><td rowspan="2">5</td><td rowspan="2">5</td></tr>
<tr><td>10</td><td>14</td></tr>
<tr><td>Flow Volume (MCM)</td><td>0.6</td><td>0.8</td><td>6.3</td><td>1.5</td><td>16.4</td><td>100</td><td>1.1</td><td>0.9</td></tr>
<tr><td rowspan="2">DROUGHT IFR</td><td>Return Period (days)</td><td>N/A</td><td>3</td><td>N/A</td><td>N/A</td><td>5</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Flow Volume (MCM)</td><td>N/A</td><td>0.4</td><td>N/A</td><td>N/A</td><td>0.9</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
</table>

3.2.2.2.2. Evaluation method for higher flows at sites incorporating flows from a single flow gauge:

As is the case in the base flow analysis where single flow gauge data are used for analysis of IFR site compliance (Skukuza and SabieSand IFR sites), the flow volumes derived from a single flow gauge is compared directly against the IFR at that particular site (see Table 3-2 for flow gauges and matching IFR sites). Once the flow volume is acquired from the instantaneous flow data, then comparison with the corresponding IFR specification table can begin. In the case of the Skukuza IFR site, the flow volume as obtained from data recorded at flow gauges X3H021 are made use of in evaluating compliance. Compliance at the SabieSand IFR site is measured against the flow volume occurring at flow gauge X3H015.

3.2.2.2.2.1. Skukuza IFR site higher flow summary:

Maintenance higher flows at the Skukuza IFR site are specified for the wet season, from October until April of the following year. Drought higher IFR specifications are applicable for November through to April but no 1:3 year specification is given since a drought year cannot simultaneously be designated a flood year. Table 3-6 below shows a summary of the flow volume and duration requirements for both the maintenance and drought higher flows at the MariteSabie IFR site.

Table 3-6. Summary of flow volume and duration specifications for maintenance and drought higher flows at the Skukuza IFR site.

<table>
<tr><th>Skukuza IFR specifications</th><th>MONTH</th><th>OCT</th><th>NOV</th><th>DEC</th><th>JAN</th><th colspan="2">FEB</th><th>MAR</th><th>APR</th></tr>
<tr><td rowspan="3">MAINTENANCE IFR</td><td rowspan="2">Return Period (days)</td><td rowspan="2">3</td><td rowspan="2">3</td><td rowspan="2">7</td><td rowspan="2">5</td><td>1:1</td><td>1:3</td><td rowspan="2">5</td><td rowspan="2">5</td></tr>
<tr><td>10</td><td>14</td></tr>
<tr><td>Flow Volume (MCM)</td><td>0.8</td><td>1</td><td>7.6</td><td>3</td><td>17.7</td><td>100</td><td>2.8</td><td>2.4</td></tr>
<tr><td rowspan="2">DROUGHT IFR</td><td>Return Period (days)</td><td>N/A</td><td>3</td><td>3</td><td>3</td><td>3</td><td>N/A</td><td>3</td><td>3</td></tr>
<tr><td>Flow Volume (MCM)</td><td>N/A</td><td>0.3</td><td>0.4</td><td>0.4</td><td>0.5</td><td>N/A</td><td>0.4</td><td>0.3</td></tr>
</table>

3.2.2.2.2.2. SabieSand IFR site higher flow summary:

Maintenance higher flows at the SabieSand IFR site are specified for the wet season, from October until April of following year. Drought higher IFR specifications are applicable only in November and February but no 1:3 year specification is given for the reason given above. Table 3-7 below shows a summary of the flow volume and duration requirements for both the maintenance and drought higher flows at the SabieSand IFR site.

Table 3-7. Summary of flow volume and duration specifications for maintenance and drought higher flows at the SabieSand IFR site.

<table>
<tr><th>SabieSand IFR specifications</th><th>MONTH</th><th>OCT</th><th>NOV</th><th>DEC</th><th>JAN</th><th colspan="2">FEB</th><th>MAR</th><th>APR</th></tr>
<tr><td rowspan="3">MAINTENANCE IFR</td><td rowspan="2">Return Period (days)</td><td rowspan="2">3</td><td rowspan="2">3</td><td rowspan="2">7</td><td rowspan="2">5</td><td>1:1</td><td>1:3</td><td rowspan="2">5</td><td rowspan="2">5</td></tr>
<tr><td>10</td><td>14</td></tr>
<tr><td>Flow Volume (MCM)</td><td>0.5</td><td>0.5</td><td>6</td><td>3.7</td><td>11.7</td><td>96</td><td>1.5</td><td>1.7</td></tr>
<tr><td rowspan="2">DROUGHT IFR</td><td>Return Period (days)</td><td>N/A</td><td>N/A</td><td>3</td><td>N/A</td><td>3</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Flow Volume (MCM)</td><td>N/A</td><td>N/A</td><td>1</td><td>N/A</td><td>0.6</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
</table>

3.2.3. Method for the analysis of trends in compliance

The pattern of IFR compliance for all sites was compared using a Theil-Sen trend estimator (Sen 1968), which is a pair-wise regression analysis of the trend in compliance for the time-series of the IFR sites. For each of the the four IFR sites, the number of compliant months in every year was added to give a number of between 0 and 12 for the base flow analysis, and 0 and 7 for the higher flow compliance analysis. This is because base flows are specified for all months of the year, while higher flows are only specified for 7 months of the year. This is the case for all IFR sites.

The Theil-Sen trend estimator was used for this purpose because it is appropriate for ordinal data sets such as monthly compliance data, and has been applied on small (9 pairs) data-sets (Parmentier and Eastman 2014). The technique is proven to be robust to short-term inter-annual variability (Parmentier and Eastman 2014). Although less relevant here, the method is robust to the impact of outliers and could therefore prove useful in future analyses of flow volume data for the Sabie-Sand River, because of the river's highly variable flow regime and the substantial absence of data during flow gauge failure events. The method is a nonparametric linear regression in which the slopes of two time-series data-sets are compared. The same data from the time-series is used for the significance test, which is the Kendall's Tau Rank Order in this case (Sen 1968).

Four IFR sites are the subject of this study, therefore six possible time series permutations are evaluated so that all sites are compared with one another. Only concurrent periods can be compared for the two regression slopes of any permutation, meaning that the base flow compliance data presented below in Table 3-9 to Table 3-12 were sub-selected for only the periods in which data were available for the two sites being compared. This process was repeated for the higher flow compliance information found in Table 3-13 to Table 3-16. A summary of the permutations and length of data record for each permutation is found below in Table 3-8.

Table 3-8. Summary of permutations and data record for Theil-Sen analysis

COMPARISON		CONCURRENT DATA PERIOD – FULL YEARS
MariteSabie IFR Site	InsideKNP IFR Site	1978 - 1999
MariteSabie IFR Site	Skukuza IFR Site	1991 – 1999
MariteSabie IFR Site	SabieSand IFR Site	1988 – 1999
InsideKNP IFR Site	Skukuza IFR Site	1991 – 1999
InsideKNP IFR Site	SabieSand IFR Site	1988 – 1999
Skukuza IFR Site	SabieSand IFR Site	1991 - 2012

From the Theil-Sen test, the p-value will allow us to state whether the trend lines of any of the permutations described in Table 3-8 is distinguishable as statistically significantly different from its pair, and therefore whether there is a divergent trend in the compliance rates among the IFR sites. If the trend line is seen to be significantly different from its pair, this would help in revealing potential reasons for disparity in compliance beyond obvious intra-annual seasonal differences in IFR compliance and similar compliance patterns for all sites across dry or wet inter-seasonal periods.

3.3. Results:

3.3.1. Results of base flow compliance analysis:

Below follows the results of the base flow compliance analysis. Base flow analysis occurs for all months of the year.

3.3.1.1. MariteSabie IFR site:

The period of analysis at this site was December 1978 – December 1999 for reasons of data availability, as explained in Section 3.2.1 of this chapter. Monthly flow volumes that fall below the drought requirement stipulated in the IFR lookup table have been coloured red, and those between the drought IFR but below the maintenance IFR are in orange. All other cells contain IFR compliant flow volumes. A summary of monthly compliance results can be found below in Figure 3.6, while Table 3-9 shows the comprehensive results of the analysis for the MariteSabie IFR site.

Table 3-9. Comprehensive results of base flow compliance at MariteSabie IFR site (1978 – 1999).

	MONTHS											
DROUGHT IFR SPEC.	**7.0**	**7.2**	**7.5**	**6.5**	**6.2**	**5.4**	**5.1**	**4.5**	**4.1**	**4.0**	**4.9**	**6.2**
MAINTENANCE IFR SPEC.	**16.1**	**14.5**	**16.1**	**13.0**	**10.7**	**9.1**	**8.0**	**7.0**	**6.0**	**5.3**	**7.8**	**13.4**
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
1978												24.29
1979	19.8	16.54	31.3	14.85	13.07	10.3	9.92	9.24	9.5	9.85	16.97	23.63
1980	25.67	46	51.9	22.46	14.04	10.57	9.1	9	9.34	8.55	23.54	36.6
1981	48.3	99.1	54.3	28.58	23.24	16.12	13.68	11.76	12.56	13.95	12.72	17.65
1982	27.16	20.36	14.23	16.23	12.87	8.99	8.65	7.54	6.14	5.69	7.35	7.9
1983	11.52	7.64	11.36	9.12	7.78	5.81	4.873	4.751	3.967	5.01	11.93	22.36
1984	21.76	17.56	20.89	20.52	10.32	7.7	13.13	9.29	8.53	8.42	16.61	24.08
1985	27.11	103.9	33.48	19.47	15.92	12.03	9.86	7.66	7.1	7.47	10.56	15.93
1986	25.32	40	21.21	25.36	18.06	10.83	8.82	7.58	6.07	6.31	7.33	9.12
1987	13.85	11.57	20.98	14.81	8.14	6.44	5.33	5.33	8.78	10.55	9.18	37.18
1988	24.88	84.1	68.6	29.41	18.02	12.69	12.22	9.97	11.59	15.78	13.15	21.48
1989	18.89	78.9	38.11	18.42	14.31	14.09	9.72	7.97	6.26	7.45	13.93	27.94
1990	30.28	37.12	35.42	26.68	17.18	11.94	10.54	9.62	7.11	7.35	8.207	24.01
1991	49	51.3	51.3	26.18	15.13	12.559	9.268	7.69	6.79	7.66	8.96	11.5
1992	9.187	7.279	6.175	5.902	4.029	3.443	3.29	3.62	2.711	3.375	5.076	12.68
1993	14.35	18.84	63.35	11.891	10.34	7.02	6.2	5.23	4.033	5.36	7.26	17.06
1994	19.23	17.23	15.09	10.12	6.64	4.579	4.343	3.629	2.871	5.4	6.12	9.96
1995	15.69	13.47	12.64	11.54	11.14	6.08	4.692	4.114	3.284	3.146	15.72	24.42
1996	60.5	60.88	185.8	174.91	172.42	172.29	12.14	14.86	8.47	7.9	8.78	13.91
1997	29.53	24.55	85.3	41.64	24.81	13.32	12.67	10.65	13.53	12.93	10.384	15.008
1998	48.3	28.74	26.08	16.81	12.87	9.18	8.48	6.97	6.74	12.81	21.27	55.8
1999	65.3	88.4	52.6	32.83	26.73	18.47	15	12.36	10.4	10.4	15.21	37.8

KEY:
Drought Base IFR Transgression
Maintenance Base IFR Transgression

The summary in Table 3-9 above shows all months over which I applied the analysis of monthly flow volumes at the MariteSabie IFR site. Drought base flow compliance appears to not to be problematic in most years. However, we see that 1992 was a year in which particularly poor compliance was observed. This was followed by three more years of mostly non-compliant flows.

Inspection of individual months yields an interesting pattern of maintenance IFR compliance compared with results from the drought IFR compliance analysis. The pattern of non-compliance with maintenance specifications shows a peak in the middle of the dry season but universal maintenance flow non-compliance in all months (see Figure 3.6). The pattern for non-compliance with drought IFR specifications peaks later in the season and points towards agricultural off-take when water is scarce as a potential source of non-compliance. This will be explored in greater depth in Chapter 4. The months comprising the wet season, ie: October to March show stronger compliance, in all likelihood due to greater availability of water for all stakeholders and users. This means that stakeholders and users are less likely to rely directly on streamflow for their water needs, but also that the greater volume of water available means that proportionally, offtake does not have the large effect on the river as observed when flows are low in the dry season.

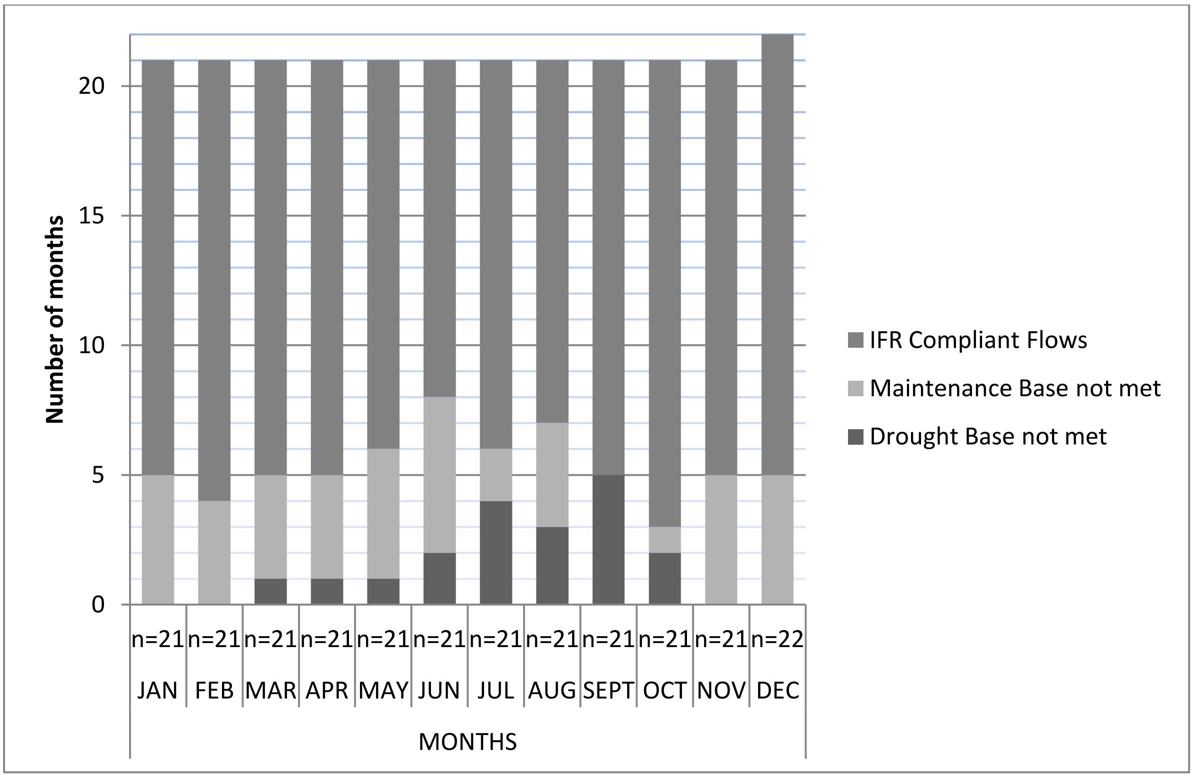

Figure 3.6. Summary bar graph of results of base flow compliance at MariteSabie IFR site.

3.3.1.2. InsideKNP IFR site:

The period of analysis at this site was December 1978 – December 1999 (see Section 3.2.1). Again, monthly flow volumes that fall below the drought requirement stipulated in the IFR lookup table have been coloured red, and those between the drought IFR but below the maintenance IFR are in orange. All other cells contain IFR compliant flow volumes. A summary of monthly compliance results can be found in Figure 3.7, while Table 3-10 shows the comprehensive results of the analysis for the InsideKNP IFR site.

Table 3-10. Comprehensive results of base flow compliance at InsideKNP IFR site (1978 – 1999).

	MONTHS											
DROUGHT IFR SPEC.	13.9	14.5	14.7	11.7	9.4	7.8	6.7	5.3	5.2	6.7	9.1	10.7
MAINTENANCE IFR SPEC.	26.8	29.0	29.5	25.9	21.4	15.4	13.4	12.1	10.4	12.1	15.5	24.1
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1978												25.123
1979	20.604	17.066	32.082	15.171	13.352	10.484	10.095	9.43	9.881	10.316	17.752	24.95
1980	26.97	52.39	55.99	23.48	14.398	10.856	9.371	9.384	9.779	9.113	26.1	48.2
1981	58	117	60.23	30.41	24.65	16.843	14.213	12.412	13.37	14.87	13.711	19.25
1982	29.96	21.105	14.489	16.604	13.093	9.162	8.842	7.709	6.335	5.814	7.474	8.06
1983	11.982	8.035	11.5	9.289	7.885	5.874	4.896	4.795	3.975	5.057	12.584	22.956
1984	22.508	19.49	22.77	22.12	10.646	7.87	13.92	9.5	8.723	9.214	20.14	26.39
1985	28.36	124.2	38.89	20.68	16.761	12.66	10.358	7.881	7.32	8.093	11.465	16.98
1986	26.5	41.21	22.33	28.42	19.31	11.276	9.035	7.705	6.147	6.406	7.461	9.344
1987	14.406	11.739	21.633	15.433	8.198	6.474	5.347	5.332	9.064	11.58	9.328	42.32
1988	27.7	92.79	78.08	32.1	19.09	13.134	12.654	10.229	12.088	17.03	13.603	23.4
1989	20	86.96	43.39	19.335	14.924	14.873	10.029	8.196	6.603	7.931	15.59	36.24
1990	33.28	42.12	40.98	29.17	17.962	12.202	10.808	10.04	7.456	7.799	8.597	25.99
1991	52.12	55.38	54.15	27.19	15.503	13.028	9.554	7.837	6.921	7.946	9.53	12.242
1992	9.451	7.448	6.27	6.008	4.084	3.521	3.341	3.649	2.745	3.397	5.134	15.25
1993	16.12	19.347	69.55	12.62	10.627	7.086	6.275	5.333	4.182	5.487	7.377	17.086
1994	19.295	17.281	15.1	10.154	6.697	4.644	4.415	3.721	2.935	5.426	6.139	9.977
1995	16.42	13.89	12.683	11.586	11.166	6.124	4.743	4.176	3.339	3.185	19.64	27.86
1996	70.49	62.37	185.8	174.91	172.42	172.29	12.14	14.94	8.882	8.151	9.243	15.37
1997	31.51	25.89	93.32	48.13	26.04	13.985	13.055	10.895	14.262	13.624	11.228	18.368
1998	56.06	31.95	27.55	17.571	13.154	9.332	8.719	7.137	6.819	14.11	23.28	66.9
1999	74.68	107.4	62.7	36.26	28.7	19.27	15.432	13.11	10.773	10.9	16.62	40.08

KEY:
Drought Base IFR Transgression
Maintenance Base IFR Transgression

The summary above shows all months over which I applied the analysis of monthly flow volumes at the InsideKNP IFR site. IFR compliance is extremely low at this site, as witnessed by the number of non-compliant monthly flow volumes shown in Table 3-10. Out of 253 months analysed, 173 were found to not meet the level required to comply with maintenance base flows. Of the 173 non-compliant flows, 57 did not meet drought base flows. Drought base flow compliance appears to be problematic in many years, with 9 out of 21 complete years of analysis showing at least one month of drought base flow non-compliance. Keeping with the pattern observed at the MariteSabie IFR site, we see that 1992 was a year in which particularly poor compliance was observed. Only December showed a monthly flow greater than was required to fulfil the drought base IFR, but this flow was still below the maintenance base IFR. This was followed by three more years dominated by months of flows that did not comply with drought IFR specifications.

Inspection of individual months yields a similar pattern to that seen at the MariteSabie IFR site. The pattern of non-compliance with maintenance specifications shows a peak in the middle to late dry season but pervasive non-compliance across all months (see Figure 3.7). The pattern for non-compliance with drought IFR specifications peaks later in the season, most likely for similar reasons as given for the MariteSabie IFR site. This will be explored in Chapter 4. The months comprising the wet season, ie: October to March show stronger overall compliance due to greater availability of water for all stakeholders and users, but at this site the level of compliance requires action from authorities. This IFR site does however present the strongest case for lowering the IFR specifications should no changes in ecological functions at the site locale occur in response to non-compliant flows.

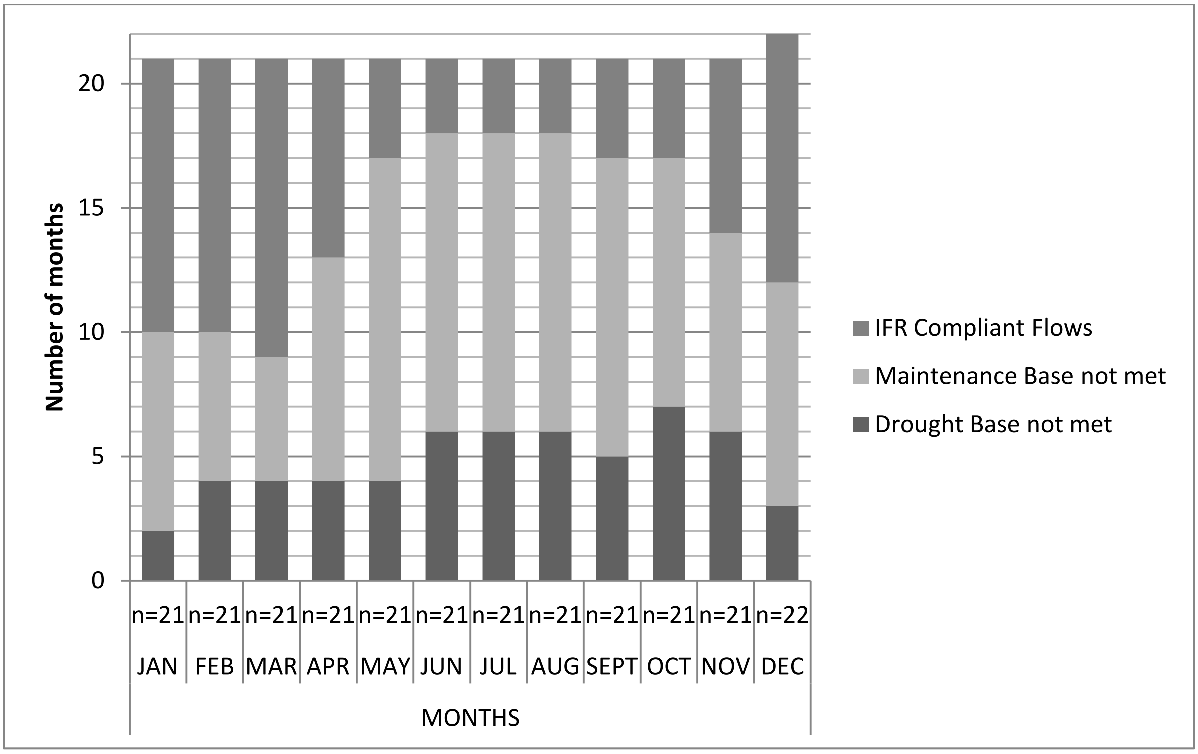

Figure 3.7. Summary bar graph of results of base flow compliance at the InsideKNP IFR site.

3.3.1.3. Skukuza IFR site:

The period of analysis at this site was December 1990 – April 2013 (see Section 3.2.1 for reasons why this is the case). Monthly flow volumes that fall below the drought requirement stipulated in the IFR lookup table have been coloured red, and those between the Drought IFR but below the maintenance IFR are in orange. Where blocks with no data are found, flow gauge failure occurred and no data are available for those periods. All other cells contain IFR compliant flow volumes. A summary of monthly compliance results can be found below in Figure 3.8, while Table 3-11 shows the comprehensive results of the analysis for the Skukuza IFR site.

Table 3-11. Comprehensive results of base flow compliance at the Skukuza IFR site (1990 – 2013). Blacked outed boxes show where flow data are not available.

	MONTHS											
DROUGHT IFR SPEC.	9.4	9.7	9.9	8.6	8.3	7.2	6.7	6.2	5.4	5.3	6.5	8.0
MAINTENANCE IFR SPEC.	16.1	21.8	21.4	18.1	16.1	13.5	12.0	10.7	8.8	8.0	10.4	13.4
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
1990												20.3
1991	50.9	73.9	6.13	170	8.6	16.1	11.7	8.53	6.62	6.48	11.9	14.7
1992	9.67	6.4	5.45	5.29	2.92	2.61	2.55	2.78	1.69	2.14	4.73	29.6
1993	25.1	27.3	121	20.6	13.2	7.41	6.2	4.99	3.11	4.28	6.71	20.2
1994	26.7	21.2	16.7	10.6	6.17	4.46	3.5	2.8	1.8	4.37	6.17	11
1995	24.5	17.5	14.8	12.4	14.2	5.75	2.78	2.99	1.75	1.46	24.1	50.4
1996	92.7	573	176	57.1	45.6	27.6	21.6	16.6	12.6	10.7	12.2	20.4
1997	38.5	35.7	107	55.6	27.5	13.3	15.1	12.3	20.3	17.3	15.8	31.3
1998	70.3	39.3	33.5	25.1	14.7	9.98	9.31	7.3	6.8	20.2	36.2	116
1999	95.2	164	84.2	43.8	33.6	21	16.9	13.7	10.7	10.6	20.2	48.7
2000	199	26.2	255	255	29.4	48.9	40.4	34.9	29.7	27.3	49.2	76.4
2001	64.8	47.9	55.4	57.1	11.5							
2002									5.08	9.47	12.8	15.9
2003	15.9	10.9	10.6	8.36	7.55	7.81	6.83	5.02	7.16	5.6	7.04	6.42
2004	19.7	52.7	57.1	30.9	16.8	10.2	8.25	6.28	5.2	6.51	9.17	13.8
2005	14.8	13.1	14.7	15	10.3	1.56	5.48	4.17	2.71	2.79	5.33	11.2
2006	78.6	64.5	157	92.5	48.2	33.7	21.4	16.1	11.3	11.8	33.5	25.3
2007	50.1	22.3	14.4	28	11.8	9.58	8.82	6.65	6.24	14.6	34	93
2008	85.5	43.2	34.3	40.5	22.5	15	11.5	6.89	4.88	5.82	18.3	74.4
2009	222	466	214	292	314	138	111	19.6	8.97	8.62	27.4	83.3
2010	76	65.7	43.9	24.6	37.1	29.4	26.7	12.1	9.56	12.1	9.52	17.2
2011	80.4	33.8	43.8	48.2	23.9	16.6	15.3	14	11.8	12.7	13.5	42.3
2012	438	116	35.4	21.9	17.2	10.9	8.65	7.02	18.4	17.5	18.3	128
2013	407	232	189	83.1								

KEY:
Drought Base IFR Transgression
Maintenance Base IFR Transgression

The summary above shows all months over which I applied the analysis of monthly flow volumes at the Skukuza IFR site. Although IFR's compliance at this site is the highest of the four IFR sites, with 96 out of 254 months considered non-compliant, it is still low when considering that only 6 full years of maintenance compliant flows occurred out of 20 full years. Even drought base flow compliance appears to be problematic in many years, with 10 years in the dataset showing at least one month of drought base flow non-compliance. Keeping with the pattern observed at the MariteSabie and InsideKNP IFR sites, 1992 was again a year in which particularly poor compliance was observed. Only December showed a monthly flow greater than was required to fulfil the maintenance base IFR, with flow for January failing to meet the maintenance base IFR and all other months falling below the requirement for drought base IFR. Like the two previous IFR sites, flows at the Skukuza IFR site were also observed to have many months of non-compliant flows for the following three years after the 1992 drought, many of which did not meet the drought IFR specifications.

The established pattern of maintenance IFR non-compliance during the middle to late dry season is once again evident at the Skukuza IFR site. The pattern for drought IFR compliance at the Skukuza IFR site also follows the pattern observed at MariteSabie and InsideKNP, with non-compliance peaking in the late dry season to early wet season (Figure 3.8). Levels of compliance at the Skukuza IFR site, while not as poor as those experienced at the InsideKNP IFR site, are still insufficient with dry season compliance occurring in less than half of the months between June and September for all years analysed.

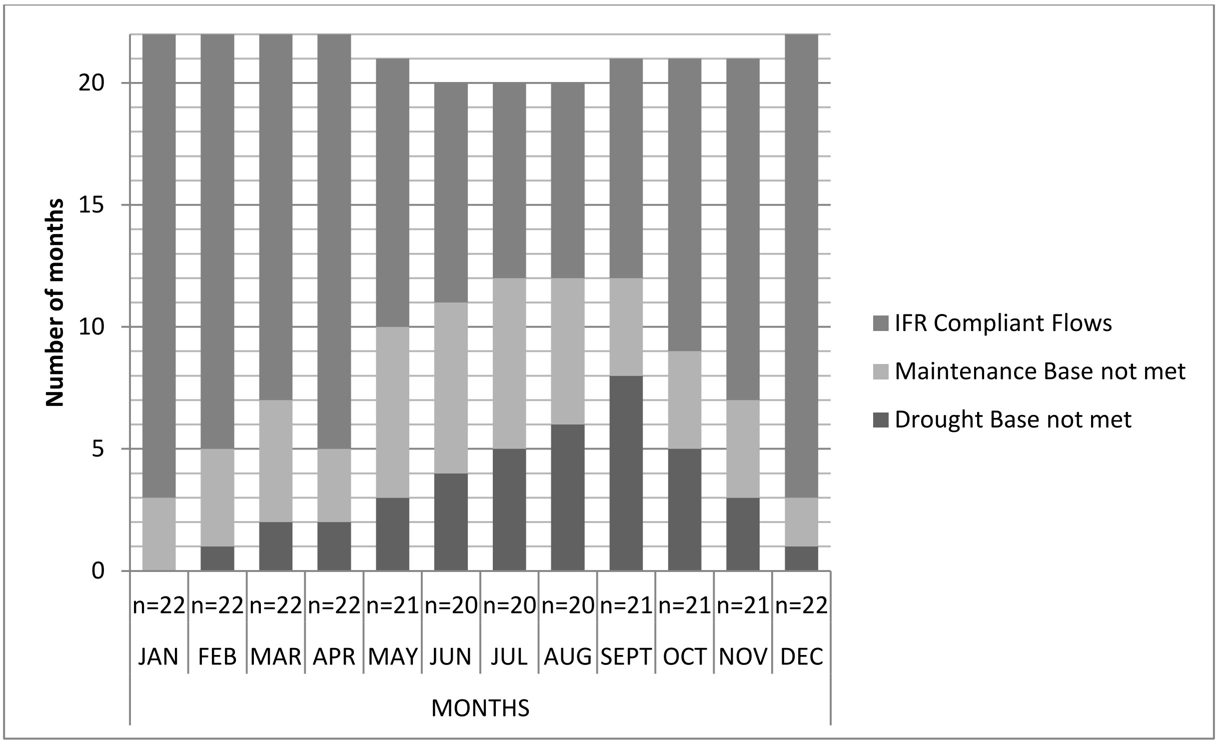

Figure 3.8. Summary bar graph of results of base flow compliance at the Skukuza IFR site.

3.3.1.4. SabieSand IFR site:

The period of analysis at the SabieSand IFR site was March 1987 – April 2013 (see Section 3.2.1 for data record details). Monthly flow volumes that fall below the drought requirement stipulated in the IFR lookup table have been coloured red, and those between the drought IFR but below the maintenance IFR are in orange. Where blocks with no data are found, flow gauge failure occurred and no data are available for those periods. A summary of monthly compliance results can be found below in Figure 3.9, while Table 3-12 shows the comprehensive results of the analysis for the SabieSand IFR site.

Table 3-12. Comprehensive results of base flow compliance at the SabieSand IFR site (1987 – 2013). Blacked outed boxes show where flow data are not available.

	MONTHS											
DROUGHT IFR SPEC.	**12.1**	**12.0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**8.0**	**9.1**	**10.7**
MAINTENANCE IFR SPEC.	**34.8**	**43.5**	**37.5**	**25.9**	**21.4**	**15.5**	**10.7**	**10.7**	**7.8**	**10.7**	**20.7**	**26.8**
YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
1987			37.1	21.2	8.67	6.83	4.46	4.26	7.75	22	8.99	118
1988	56.4	127	142	37.8	18.8	9.18	9.68	10.4	12.3	17.4	14.2	26.5
1989	20.6	139	68.8	20.7	17.3	18.4	10.7	7.89	5.11	5.95	21.1	73.4
1990	46	75.4	57.1	43	20.1	10.6	8.98	8.59	5.35	6.04	6.55	42.4
1991	60	80.4	71.6	38.6	17	15	10.8	7.69	6.58	6.66	12.1	12.2
1992	8.17	4.87	3.78	3.53	1.84	1.55	1.59	1.58	0.714	0.989	16.7	54.3
1993	52.6	29.7	60.3	23.6	13.9	6.51	5.28	3.86	2.16	2.79	4.24	21.2
1994	37.1	22.5	17.9	10.6	5.27	3.23	2.33	1.78	1.05	2.57	4.44	8.33
1995	35.7	19.6	15.3	12.3	16	5.59	3.05	2.27	1.45	0.526	21.9	63.2
1996	158	766	268	79.5	65.8	34	27.1	25.5	14.2	11.7	12.9	24.1
1997	53.5	40.9	137	69.4	30.4	20	14.3	11.6	19.6	15.3	13.2	32.3
1998	63.3	48.8	38.8	27.1	14.2	9	8.78	6.75	5.52	18	48.5	175
1999	150	96.4	86.9	61	46.6	28.8	22.2	17.8	12.3	8.12	14.2	40.1
2000									35.6			
2001								0.601	13.9	18	107	
2002	2.05	117	64.4	46.6	29	24.2	19	9.86	4.49	11.7	17.6	22.9
2003	21	12.9	13.2	9.74	9.63	9.6	9.03	6.35	8.29	5.72	6.9	6.38
2004	35.2	30.3	47.6	60.6	25.1	14.9	12.3	10.4	6.71	7.94	14.1	25.6
2005	30.1	17.9	19.6	19.1	13.1	4.79	8.36	5.74	3.5	3.28	11.6	20.3
2006	112	132	397	129	49.6	28.3	20.8	15.1	9.5	8.97	32.5	18
2007	53.8	19.8	14.1	28.1	11.7	8.53	8.27	5.93	4.11	10.5	21.2	94
2008	82.2	36.1	24.8	29.1	17.6	12.1	10	7.12	4.77	5.42	21.1	58
2009	173	350	195	61.3	39.9	26	20.3	17.2	11.3	9.49	39.4	68.2
2010	67.4	56.7	53.5	132	59.1	27.5	22.8	14	9.98	11.1	25.9	110
2011	156	89.6	91.8	102	57	34.2	28.8	23.6	16.1	18	15.8	37.7
2012	25.8	170	170	23.8	16.4	13.8	12.2	10.4	23.3	22.5	21.2	90.7
2013	34.7	170	33.6	76.1								

KEY:	**Drought Base IFR Transgression**	**Maintenance Base IFR Transgression**

The summary above shows all months over which I applied the analysis of monthly flow volumes at the SabieSand IFR site. IFR compliance is low with only a single full year of maintenance compliant flows occurring out of 23 full years. Drought base flow compliance is not as problematic as at other IFR sites, but non-compliance with maintenance base flows is ubiquitous. As compared with the other IFR sites, the 1992 drought resulted in low compliance at the SabieSand IFR but most flows fell between the compliance criteria for drought and maintenance flows. Only December of that year showed a monthly flow greater than was required to fulfil the maintenance base IFR, with flow for January 1992, February 1992 and October 1992 failing to meet the drought base IFR and all other months in 1992 falling below the requirement for the maintenance base IFR. Like all other IFR sites, flows at the SabieSand IFR site were also observed to have many months of non-compliant flows for the following three years after the 1992 drought. While most of these flows fall below the maintenance base category, all three years after the drought of 1992 show low compliance in and around October. This points towards late rainfall, or that the specialists formulating the IFR interpreted rainfall and/or streamflow records incorrectly for the area. Rainfall data for Skukuza between the years of 1987 and 2013 show that rainfall in October (approx. 26 mm/month; n= 26) more closely resembles that of September (approx. 22mm/month; n = 26) than November (approx. 70mm/per month; n = 26). The climate and precipitation profile for October is closer to that of September than November. This should be reflected in the IFR tables, meaning that IFR requirements for October should be at the same level or lower than the September IFR values since there would be a lag period for rainfall to affect streamflow. This is not the case, so I believe that the interpretation of the rainfall values for October was not used to correctly inform the IFR for this month and it should be revised lower.

The established pattern of maintenance IFR non-compliance during the middle to late dry season is once again evident at the SabieSand IFR site. The pattern for drought IFR compliance at the SabieSand IFR site also follows the pattern observed at all other sites, with non-compliance peaking in the late dry season to early wet season (see Figure 3.9). At the SabieSand IFR site, this is particularly pronounced with 11 out of 25 October data points failing to meet drought IFR specification levels. Compliance levels at the SabieSand IFR site are poor overall; more than half (n=150) of the months in the analysis (n=295) are non-compliant against maintenance base flow requirements.

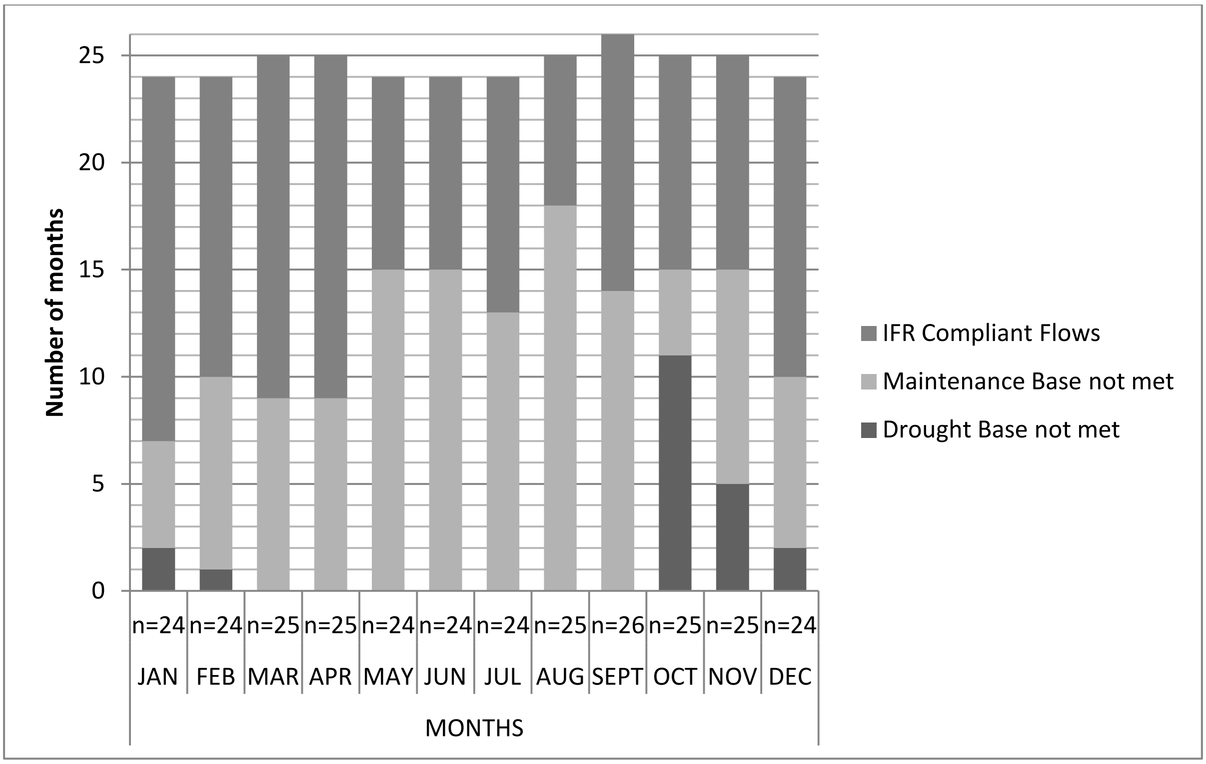

Figure 3.9. Summary of results of base flow compliance at the SabieSand IFR site.

3.3.2. Results of higher flow compliance analysis:

Higher flow IFR's are only specified for some months of the year, and differ between maintenance and drought scenarios. For maintenance specifications, higher flows are indicated for all months of wet season. Drought higher flows specifications are both lower in volume and duration and given for fewer months of the wet season as compared with maintenance higher flows.

Unlike maintenance and drought base flow scenarios, which are specified for the entire duration of the month in all months, higher flows for both maintenance and drought scenarios are specified in days and differ in length across scenarios and months at all sites (see Table 1-1 - Table 1-4 in Chapter 1). Due to the "peaky" nature of higher flow specifications and the fact that they are specified for only the wet season when water is abundant, maintenance higher flow compliance rates are better than those for base flows. Related to this finding, drought higher flow compliance is almost universal; only during December 2003 at the SabieSand IFR site did flows not meet or exceed the IFR requirement.

In some instances flow specifications may be available in particular months for higher maintenance flows but not in the same month under the drought scenario. Moreover, the volume associated with the specification is different for the same period maintenance higher flow. Due to this the maintenance and higher scenarios analysis had to be undertaken separately and will be presented as such below, for each site.

The pattern of compliance is important; several consecutive months as well as years of non-compliance with a higher flow specification may have important ecological effects. An example of this would be the absence for three years of a sediment-flushing flow. Such a situation could curtail the breeding ability of a fish or invertebrates that spawn in cobbles.

As explained in the methods section (Section 3.2.2.2), the analysis of higher flows requires daily data since the specifications are resolved at the levels of days rather than months as is the case with IFR base flow scenarios. Depending on the month, higher flow analysis requires between 3 and 14 days of consecutive data to be summed. As such, the analysis is less resilient than a monthly analysis to relatively few missing days of data in periods of flow gauge failure. It is for this reason that we see more periods of no data in the higher flow analyses than we do with the base flow analyses. Even so, there is a sufficient length of data record for all sites to provide useful outcomes for all four IFR sites.

It is crucial to point out here that the analysis was undertaken using daily data for reasons outlined in the methods section (Section 3.2.2.2). Daily data are used to determine whether the flow for the month in question is compliant or not. For this reason, compliance for higher flows, like base flows is also presented in terms of monthly compliance.

3.3.2.1. MariteSabie IFR site:

The flow data record from the two flow gauges (X3H006 and X3H011) used to measure higher flow compliance at the MariteSabie IFR site were of particularly good quality. No data gaps were found for the entire period of assessment (1st of December 1978 – 31st of December 1999).

Maintenance and drought base flow compliance was most comprehensive at the MariteSabie IFR site when compared with the other sites. Despite this, compliance with maintenance higher flows at MariteSabie is not as good.

3.3.2.1.1. Maintenance Higher Flow compliance at the MariteSabie IFR site:

The summary below shows all months for the period over which I applied the analysis of daily flow volumes at the MariteSabie IFR site. The period between May and September has no information associated with it since higher flow specifications are not prescribed for the dry season flows. The major graph in Figure 3.10 shows compliance against maintenance higher IFR for the entire data period using the specifications for the 1:1 year return interval. The small inset bar graph to the right illustrates the compliance rate with the maintenance higher flows at the 1:3 year return interval specified for February.

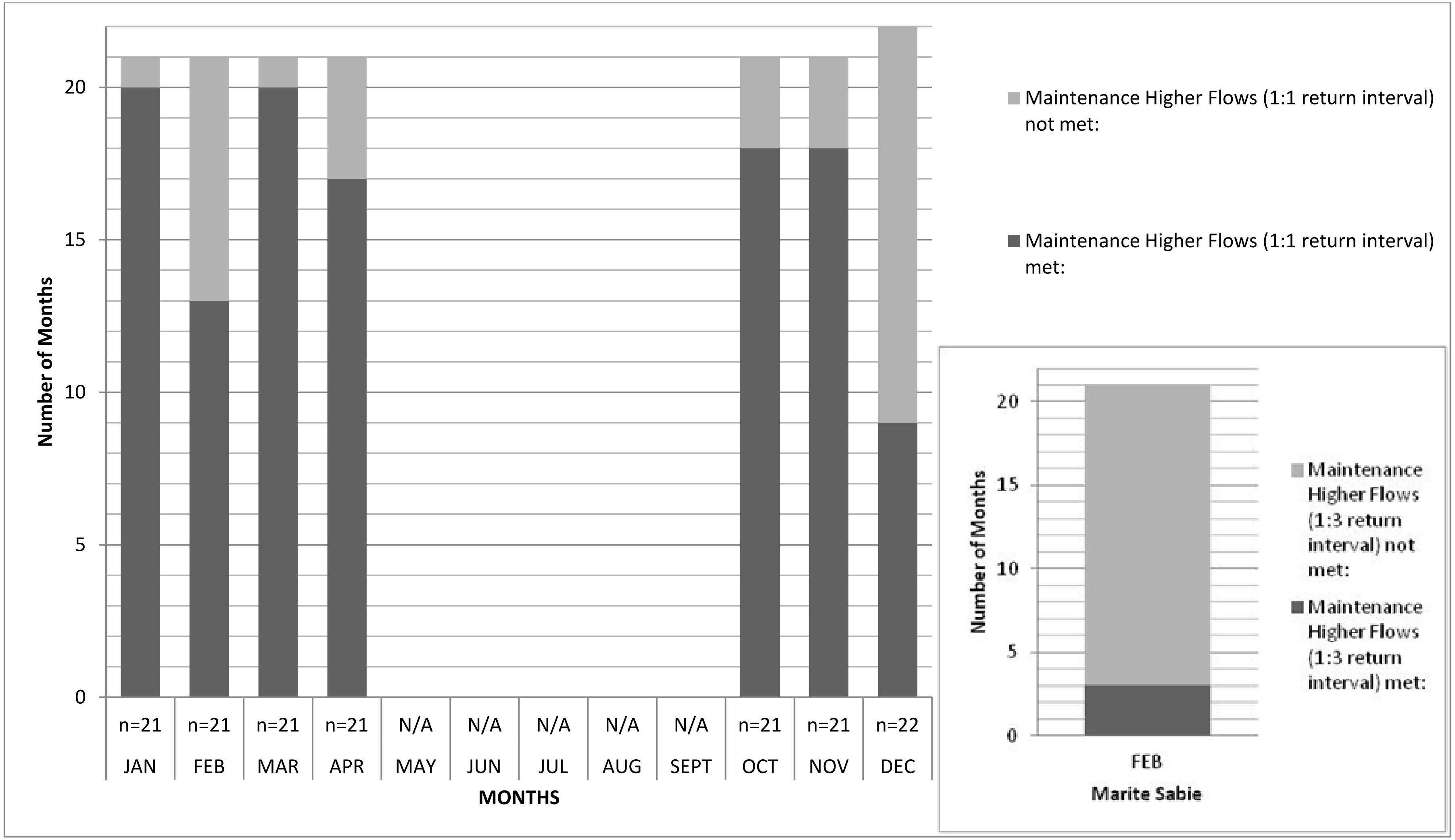

Figure 3.10. Summary of results of maintenance higher flow compliance at MariteSabie IFR site for all months at 1:1 year return interval. Inset illustrates the 1:3 year return interval for February.

Inspection of the bar graph above yields an interesting pattern of maintenance higher IFR compliance. Non-compliance occurs in all months but is highest in both February (for both 1:1 and 1:3 year return intervals) and December. If we consult the IFR table for the MariteSabie site (Table 1-1 in Chapter 1), we see that both February and December have distinctly higher flow volume requirements than the other months. However, these flows are specified to occur over longer periods than other months; 10 days for February (and 14 days for the 1:3 year return interval flow) and 7 days for December. It is therefore apparent that higher flow IFR's are more easily met in months where the requirement is for "peaky" flows, ie: flows that last no longer than 5 days. As explored in Section 1.3.4.3 of Chapter 1, the strong base flow signature that characterises the Sabie-Sand River system means that even a precipitation event in the catchment of small intensity and duration will lead to overland flow of significant enough magnitude to meet short duration, or "peaky" higher IFR specifications. This is the case for both maintenance and drought higher IFR scenarios.

Sequential months of compliance with higher flow specifications are also important for the perpetuation of the full suite of ecological responses to higher flows to occur. Table 3-13 shows the pattern of maintenance higher compliance at the MariteSabie IFR site. Unlike the base flow assessment, no values are present in the cells, because the tables for higher flow assessment are a summary of all the daily data and whether compliant flows occurred in that month. It is impossible to include daily data for all days in that month here. Consecutive months of non-compliance, and "gappy" compliance have a very different ecological effect as compared with missing specific consecutive months inter-annually (eg: consecutive December's from year to year, as we see in this example). The regular non-compliance of monthly higher flows could lead to the attrition of ecological processes for which these particular flows are specified. For instance, with maintenance higher IFR compliance for December being very low at the MariteSabie IFR site, we can expect that the functions associated with December higher flows often do not take place here. An example of this would be fish spawning cues associated with December higher flows. Where historically fish spawning may have occurred at this site, this event would now occur infrequently, occur with fewer fish than before or potentially not at all.

Table 3-13. Pattern of maintenance higher compliance at MariteSabie IFR site (1978 – 1999).

The bar graph in Figure 3.11 shows an annual breakdown of the percentage of monthly maintenance higher IFR targets for the MariteSabie IFR site, that are met inter-annually for the duration of study period dataset (ie: 1979 – 1999). The severe meteorological and hydrological drought of 1992 is shown as the only month in which flows for all seven months of maintenance IFR specifications were not met. Otherwise, it is apparent that in most years at the MariteSabie IFR site we can expect full compliance or compliance for 6 out of seven months, with December being the most likely to not comply. No years occurred in which one, two or three out of seven monthly IFR specifications were met.

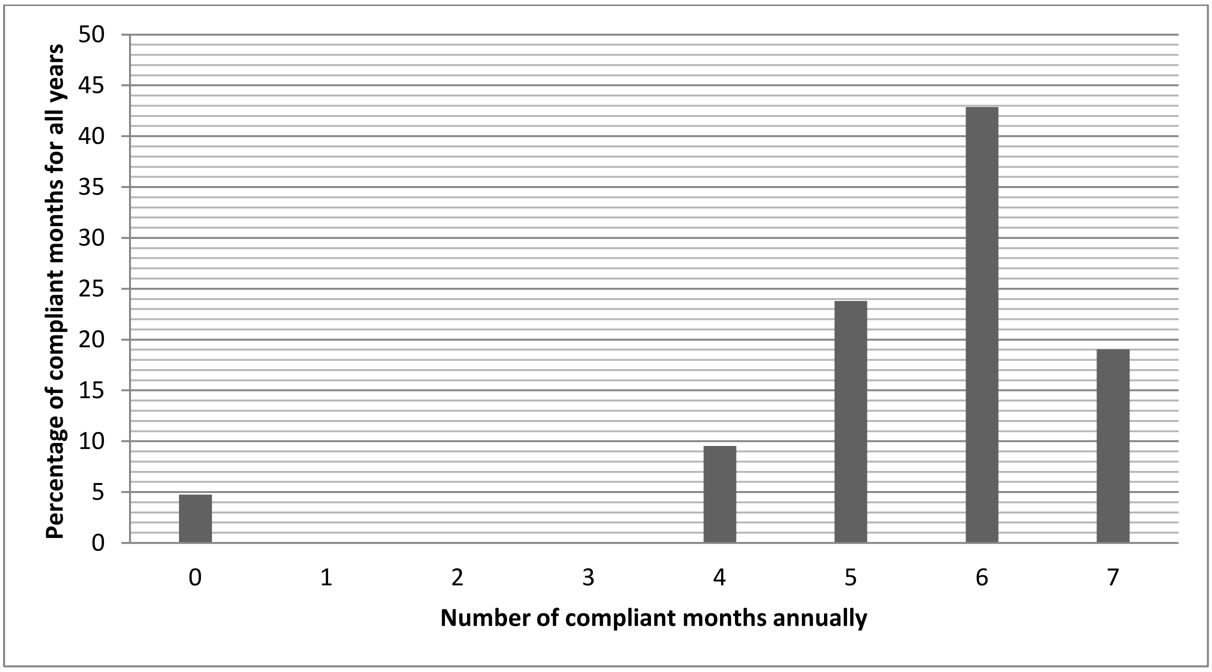

Figure 3.11. Bar graph illustrating the percentage breakdown of monthly compliance with maintenance higher IFR flow for full year periods at the MariteSabie IFR site (1979 – 1999).

3.3.2.1.2. Drought Higher Flow compliance at the MariteSabie IFR site:

Drought higher flows are specified for the January to April and then November and December months at the MariteSabie IFR site. Transgression of drought higher flow specifications (refer back to Table 1-1) for the MariteSabie IFR site did not occur for a single month over the entire study period. Non-compliant flows only occurred for a total of 11 days between 1st of December 1978 – 31st of December 1999. This took place in the December of the drought year of 1992 and in the last four days of April 1996. While the 1992 drought is documented as being one of the worst in the history of South Africa, the failure to meet drought higher flows for a few days at the end of the wet season of April 1996 is no cause for concern, particularly since all the other days in the month were compliant.

The universal compliance at the MariteSabie IFR site against the drought higher flow specifications leaves very little to report against the objectives of this chapter. However, the ecological effect of this state of affairs is of interest and will be explored in the following chapter.

3.3.2.2. InsideKNP IFR Site

Data for evaluating compliance of maintenance higher flow IFR's at the InsideKNP site are derived from three flow gauges; X3H004, X3H006 and X3H011. As documented in Section 3.3.2.1, the data record for flow gauges X3H006 and X3H011 is very good, and this is also the case for flow gauge X3H004. Flow gauge X3H004 was the first flow gauge constructed in the catchment and is still functional. For reasons outlined in Section 3.2.1.2.1 of this chapter, the good data record for flow gauge X3H004 cannot be put to use in its entirety since flow data from the gauge can only be used with data from periods when flow gauges X3H006 and X3H011 were functioning concurrently (1st of December 1978 – 31st of December 1999).

Maintenance and drought base flow compliance was not high at the InsideKNP site when compared with the other sites, with particularly low compliance against maintenance base flows. Despite this, compliance with maintenance higher flows at the InsideKNP site was relatively good when compared against the other IFR sites in the study.

3.3.2.2.1. Maintenance Higher Flow compliance at the InsideKNP IFR site:

The summary below shows all months for the period over which I applied the analysis of daily flow volumes at the InsideKNP IFR site. The period between May and September has no information associated with it since higher flow specifications are not prescribed for the dry season flows. The major graph in Figure 3.12 shows compliance against maintenance higher IFR for the entire data period using the specifications for the 1:1 year return interval. The small inset bar graph to the right illustrates the compliance rate with the maintenance higher flows at the 1:3 year return interval specified for February.

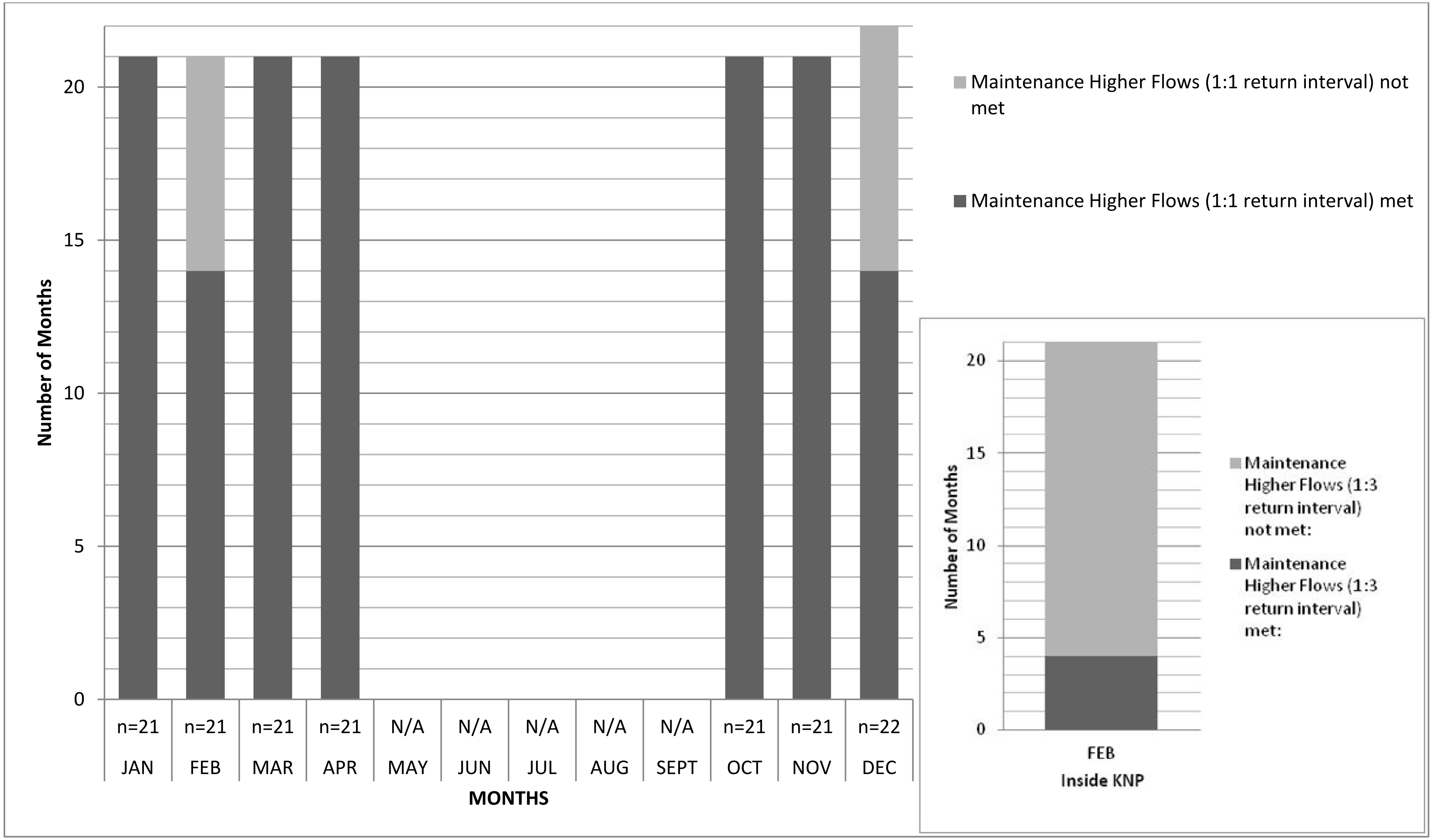

Figure 3.12. Summary of results of maintenance higher flow compliance at InsideKNP IFR site for all months at 1:1 year return interval. Inset illustrates the 1:3 year return interval for February.

Inspection of the bar graph above yields an interesting pattern of maintenance higher IFR compliance. For this IFR site, compliance occurs in all months but for February (both 1:1 and 1:3 year return intervals) and December. This site shows overall better compliance with IFR specifications as compared with the MariteSabie site, but a similar pattern of non-compliance is shared with MariteSabie. Like the specifications for the MariteSabie site (Table 1-1 in Chapter 1), we see that the IFR table for the InsideKNP site (Table 1-2 in Chapter 1) also has higher flow volume specifications for both February and December. Also like the MariteSabie IFR site, these flows are specified to occur over longer periods; 10 days for February (and 14 days for the 1:3 year return interval flow) and 7 days for December. It is worth noting that flow specifications with a longer duration appear to be problematic in terms of IFR maintenance at this site. Keeping in mind the fact that compliance with both maintenance and drought base flow specifications at the InsideKNP was very low, it appears that flow requirements that are specified for any duration longer than 5 days are difficult to meet at this site.

The importance of sequential monthly higher flow compliance was noted for the MariteSabie IFR site and also applies at the InsideKNP IFR site and others. Table 3-14 shows the pattern of maintenance higher compliance at the InsideKNP IFR site.

Table 3-14. Pattern of maintenance higher compliance at InsideKNP IFR site (1978 – 1999).

	MONTHS							
YEAR	JAN	FEB	MAR	APR		OCT	NOV	DEC
1978								
1979								
1980								
1981								
1982								
1983								
1984								
1985								
1986								
1987								
1988								
1989								
1990								
1991								
1992								
1993								
1994								
1995								
1996								
1997								
1998								
1999								

KEY:
Maintenance Higher IFR Compliance
Maintenance HigherIFR Transgression

The problem of consecutive months of non-compliance has been pointed out for the MariteSabie IFR site, but does not pose any problem for the InsideKNP IFR site since only February and December show non-compliance and these are not consecutive. Specific consecutive months of inter-annual non-compliance could periodically be responsible for the loss of specific functions in the catchment linked to that month's flows (eg: consecutive February's and December's from year to year, as we see in this example). For instance, with maintenance IFR compliance for February being very low at the InsideKNP IFR site between 1982 and 1984 (as well as other years), it could be expected that the functions associated with February higher flows did not take place. An example of this would be channel and habitat maintenance associated with higher flows over that period. Over the period of 1982 to 1984, channel encroachment and sedimentation would likely have occurred at the InsideKNP site.

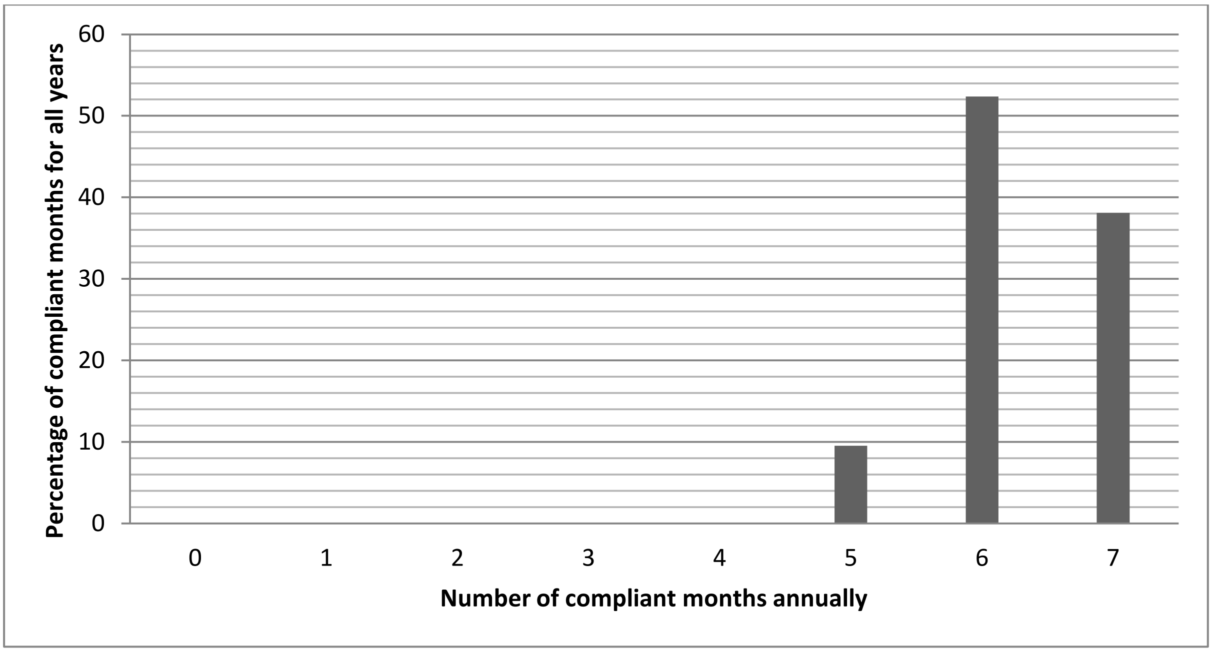

Figure 3.13. Bar graph illustrating the percentage breakdown of monthly compliance with maintenance higher IFR flow for full year periods at the InsideKNP IFR site (1979 – 1999).

Figure 3.13 shows an annual breakdown of the percentage of monthly maintenance higher IFR targets for the InsideKNP IFR site that are met for the duration of study period (ie: 1979 – 1999). As compared with the MariteSabie IFR site (Figure 3.11), Figure 3.13 shows a summary of much better overall flow compliance with maintenance higher flow specifications at the InsideKNP IFR site. Surprisingly, the severe drought of 1992 did not show the poorest performance in meeting IFR specifications, with 1982 and 1997 showing the weakest compliance at 5 out of seven monthly targets achieved. Otherwise, it is apparent that in just over 50% of the years sampled for the InsideKNP site we can expect compliance for 6 out of seven months, with December being the most likely to not comply. For the 21 years of complete data, we see that 8 years (or 38% of the sample) of full compliance with maintenance higher flows occurred. No years were observed in which none, one, two, three or four out of seven monthly IFR specifications were met.

3.3.2.2.2. Drought Higher Flow compliance at the InsideKNP IFR site:

Drought higher flows for the InsideKNP IFR site are only specified for February and November. Transgression of drought higher flow specifications (see Table 1-2) for the InsideKNP IFR site did not occur for a single month over the entire period. Non-compliant flows only occurred for a total of 17 days between 1^{st} of December 1978 – 31^{st} of December 1999. A single day of non-compliant flow occurred in February 1996, but two of the three flow gauges were not functional on that day and so no accurate record of flow volume for that day could be obtained. It is notable that the day preceding the non-compliant flow, and the one thereafter were both compliant; it is therefore likely that the flow on the one failed day was probably compliant but not measured. During the drought period of 1992, December had 9 days of non-compliant flows but the overall month did meet December drought higher flow IFR objectives and flows were compliant with even maintenance higher flows that month. Seven days of non-compliant flow occurred in November 1995 as well, but as in 1992, compliant flows did otherwise occur during that month. As for the MariteSabie IFR site, the InsideKNP does not show any interesting pattern since all drought higher flows during the study period were compliant. However, this pattern is of interest since it may yet prove to have ecological consequences that have not been accounted for explicitly in the IFR determination process.

3.3.2.3. Skukuza IFR Site

Data for evaluating compliance of maintenance higher flow IFR’s at the Skukuza IFR site is derived from only one flow gauge, namely X3H021. This flow gauge is the most recent addition to the network except for the two gauges added in 2002 on the main stem of the Sabie River. The data record for flow gauge X3H021 is not as comprehensive as the three flow gauges dealt with in the previous two sections. The data record for this flow gauge extends from the 1^{st} of December 1990 to the present day, although audited data were only available up until the 30^{th} of April 2013 at the time of analysis.

Maintenance higher flow compliance at the Skukuza IFR site was low, ranking as the second worst site when compared against all IFR sites. Despite this, like the MariteSabie and InsideKNP IFR sites, no single month of drought higher flow non-compliance occurred during the analysis period.

3.3.2.3.1. Maintenance Higher Flow compliance at the Skukuza IFR site:

The summary below shows all months for the period over which I applied the analysis of daily flow volumes at the Skukuza IFR site. The period between May and September has no information associated with it since higher flow specifications are not prescribed for the dry season flows. The major graph in Figure 3.14 shows compliance against maintenance higher IFR for the entire data period using the specifications for the 1:1 year return interval. The small inset bar graph to the right illustrates the compliance rate with the maintenance higher flows at the 1:3 year return interval specified for February. Periods for which no data were available are shown in black on the bar graph.

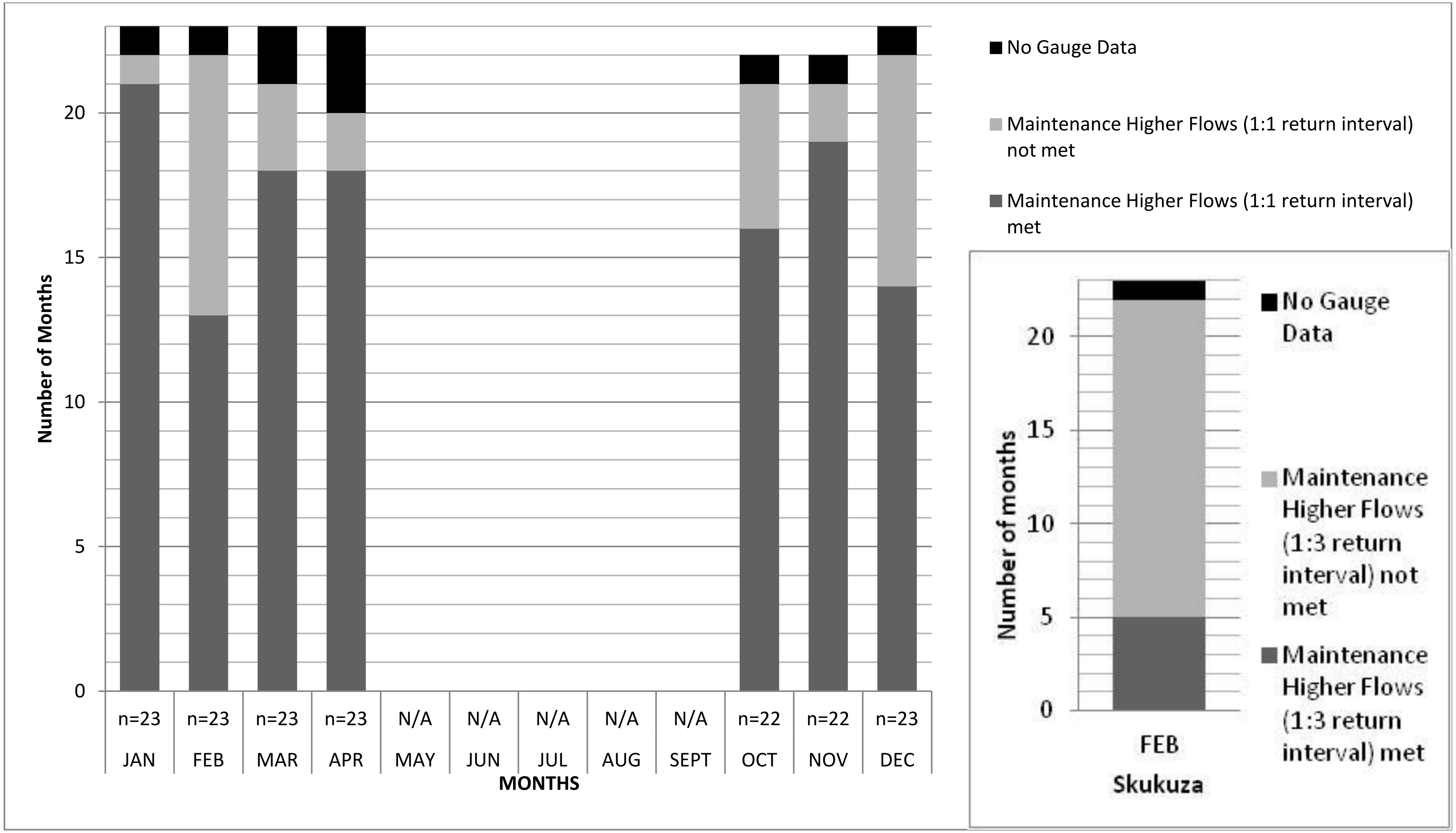

Figure 3.14. Summary of results of maintenance higher flow compliance at Skukuza IFR site for all months at 1:1 year return interval. Inset illustrates the 1:3 year return interval for February.

Figure 3.14 above shows a pattern of maintenance higher IFR compliance that is similar to that observed at both the MariteSabie and InsideKNP IFR sites. Compliance is again lowest in February and December over the analysis period, with relatively fewer non-compliant months during the remainder of the period for which maintenance higher flows are specified. However, a feature that is noticeable at the Skukuza IFR site but different to the other sites is the much lower October compliance figure. This state of affairs is partially responsible for the fact that the Skukuza IFR site shows poor compliance with maintenance higher flows in comparison with other sites.

The sequential facet of the flow profile over monthly and inter-annual time-scales has been noted as important. Table 3-15 shows the pattern of maintenance higher compliance at the Skukuza IFR site.

Table 3-15. Pattern of maintenance higher compliance at Skukuza IFR site (1990 – 2013).

	MONTHS							
YEAR	JAN	FEB	MAR	APR		OCT	NOV	DEC
1990								
1991								
1992								
1993								
1994								
1995								
1996								
1997								
1998								
1999								
2000								
2001								
2002								
2003								
2004								
2005								
2006								
2007								
2008								
2009								
2010								
2011								
2012								
2013								

KEY:
Maintenance Higher IFR Compliance
Maintenance HigherIFR Transgression

As with the two other IFR sites above, inter-annual compliance with maintenance higher IFR flow volumes is lowest for February and December. Also congruent with the above sites, it stands to reason that specific consecutive months of inter-annual non-compliance could periodically be responsible for the loss of specific functions in the catchment linked to that month's flows (eg: consecutive February's and December's from year to year). Again, it could be expected that the functions associated with February higher flows did not take place at the Skukuza IFR site as regularly as the IFR specification would have intended to ensure.

Many months of non-compliance occur between December 2002 and December 2005. After the large floods of February 2000 (which temporarily rendered flow gauge X3H021 out of service) reset the ecological template to one with greater bedrock influence, the lack of higher flows between December 2002 and December 2005 would have exacerbated sedimentation and channel encroachment at the Skukuza IFR site.

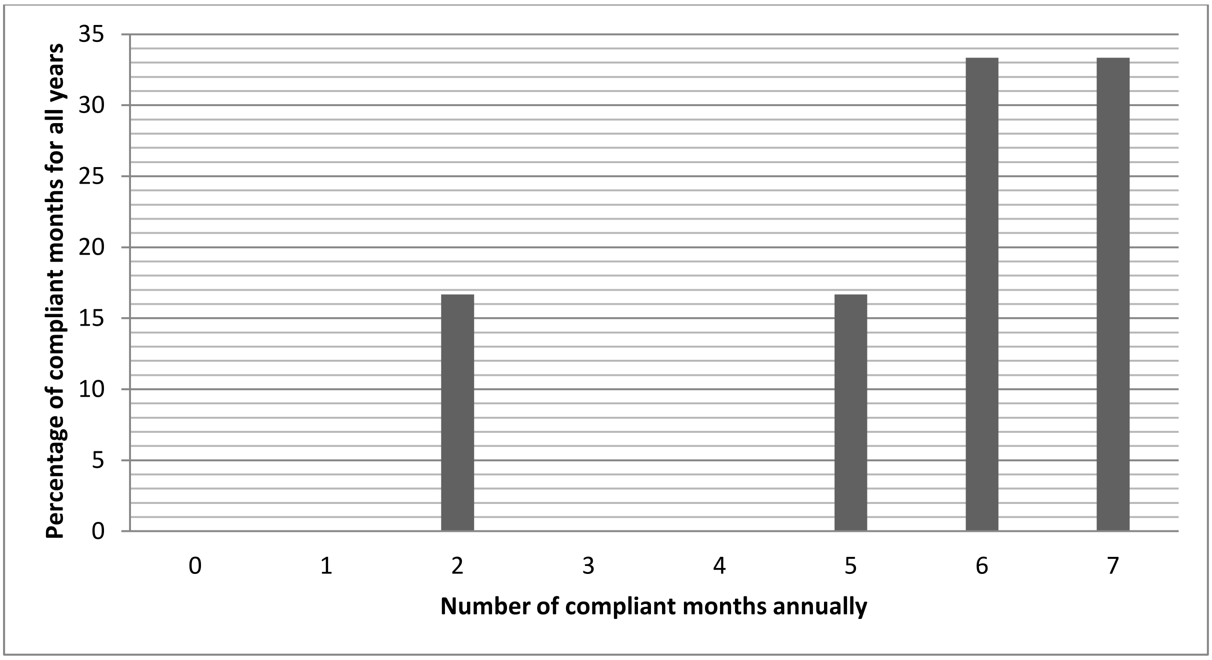

Figure 3.15. Bar graph illustrating the percentage breakdown of monthly compliance with maintenance higher IFR flow for full year periods at the Skukuza IFR site (1990 – 2013).

Figure 3.15 shows an annual breakdown of the percentage of monthly maintenance higher IFR targets for the Skukuza IFR site that are met annually for the duration of study period (ie: 1990 – 2013). Only years in which flow data were available for all months were used for the analysis, hence the mismatch with the number of years against Table 3-15. Figure 3.15 shows that full compliance in seven out of seven months occurred six times or 33% during the period of analysis. In another 6 years of the sample, 6 out of seven monthly IFR targets were met, also representing 33% of the sample years. In three separate years only 2 out of 7 months in that year were compliant. No instances of zero, one, three or four compliant months out of seven were recorded. Figure 3.15 suggests that small changes to flow regime, particularly during the months of February and December, could enhance the probability of achieving higher IFR compliance in those months and thereby ensure that sequential months of maintenance higher IFR flows are achieved.

3.3.2.3.2. Drought Higher Flow compliance at the Skukuza IFR site:

Drought higher flows for the Skukuza IFR site are specified for January to April, as well as November and December. Transgression of drought higher flow specifications (see Table 1-3) for the Skukuza IFR site did not occur for a single month over the entire study period. However, drought higher IFR non-compliant flows occurred for a total of 47 days during the analysis period, if we exclude the days on which the flow gauge did not record data. The majority of the non-compliant days (32) happened during the drought period of 1992, and occurred in February (9), March (8), November (5) and December (10). The December of 1994 was the second driest in the dataset, and had 6 non-compliant days. Eight days of non-compliant flows occurred in November 1995, and November 2005 had a single higher IFR non-compliant day.

3.3.2.4. SabieSand IFR Site

Data for evaluating compliance of maintenance higher flow IFR's at the SabieSand IFR site is derived also from only one flow gauge, namely X3H015. This flow gauge was planned and installed in the mid-1980's, and remains active. The data record from this gauge is adequate for this analysis but is fairly patchy with long gaps (see Section 3.2.1.2.4 of this chapter). The flow record began on the 1st of January 1987 and the flow gauge is still operational. As for flow gauge X3H021, audited data were only available up until the 30th of April 2013 at the time of analysis.

Maintenance higher flow compliance at the SabieSand IFR site was relatively good, ranking as the most compliant across all sites. However, the SabieSand IFR site was the only site to record an entire month of flows that did not comply with drought higher specifications, and on that basis was the worst performer in that regard.

3.3.2.4.1. Maintenance Higher Flow compliance at the SabieSand IFR site:

The summary below shows all months for the period over which I applied the analysis of daily flow volumes at the SabieSand IFR site. The period between May and September has no information associated with it since higher flow specifications are not prescribed for the dry season flows. The major graph in Figure 3.16 shows compliance against maintenance higher IFR for the entire data period using the specifications for the 1:1 year return interval. The small inset bar graph to the right illustrates the compliance rate with the maintenance higher flows at the 1:3 year return interval specified for February. Periods for which no data were available are shown in black on the bar graph.

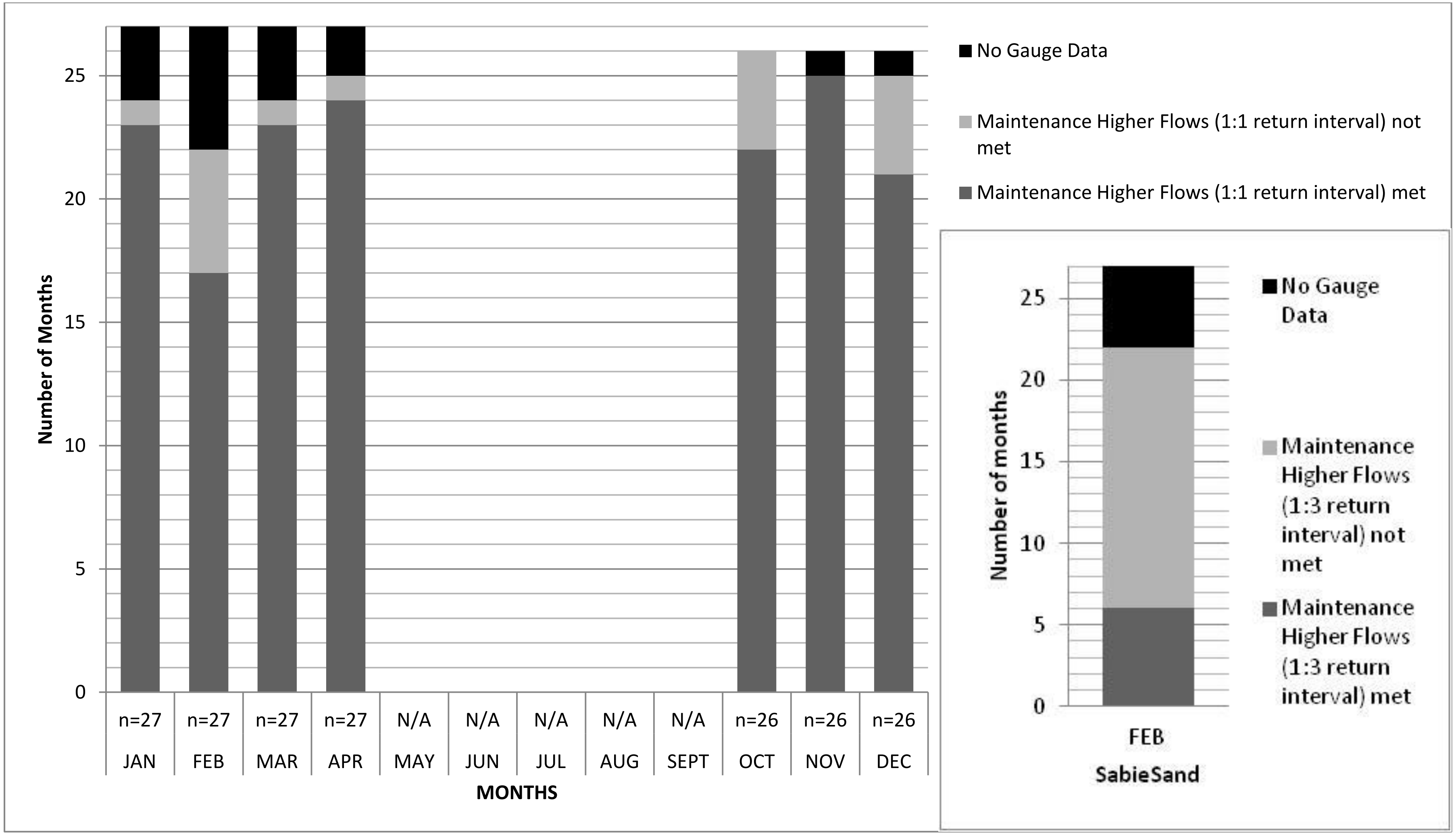

Figure 3.16. Summary of results of maintenance higher flow compliance at SabieSand IFR site for all months at 1:1 year return interval. Inset illustrates the 1:3 year return interval for February.

Figure 3.16 above shows a pattern of maintenance higher IFR compliance that is similar to that observed at the Skukuza IFR site, with February, October and December showing multiple cases of non-compliance. November flows do not show a single instance of non-compliance for the data set, with a single instance in January, March and April. February shows the highest proportion of months with no data (5). This is likely a result of outflanking of the flow gauge structure by flows of larger dimension. These flows are typical for the end of the wet season.

Table 3-16. Pattern of maintenance higher compliance at SabieSand IFR site (1987 – 2013).

	MONTHS							
YEAR	**JAN**	**FEB**	**MAR**	**APR**		**OCT**	**NOV**	**DEC**
1987								
1988								
1989								
1990								
1991								
1992								
1993								
1994								
1995								
1996								
1997								
1998								
1999								
2000								
2001								
2002								
2003								**DROUGHT FLOW NON COMPLIANCE**
2004								
2005								
2006								
2007								
2008								
2009								
2010								
2011								
2012								
2013								

KEY:
Maintenance Higher IFR Compliance
Maintenance HigherIFR Transgression

As for the pattern of sequential flows, Table 3-16 above shows us that except for the drought year of 1992, no month during the analysis period is followed by another non-compliant month of flow. Two instances of non-compliance of inter-annual consecutive months occur for February (1994-1995) and October (1992-1993) at the SabieSand IFR site. The relatively low levels of non-compliance at the SabieSand IFR site means that the physical signatures of ecological change we expect to happen at the other IFR sites may not be detectable at this site. Conversely if we notice significant ecological change in this IFR site, that would lead us to believe that the IFR specifications could be nonsense in ecological terms.

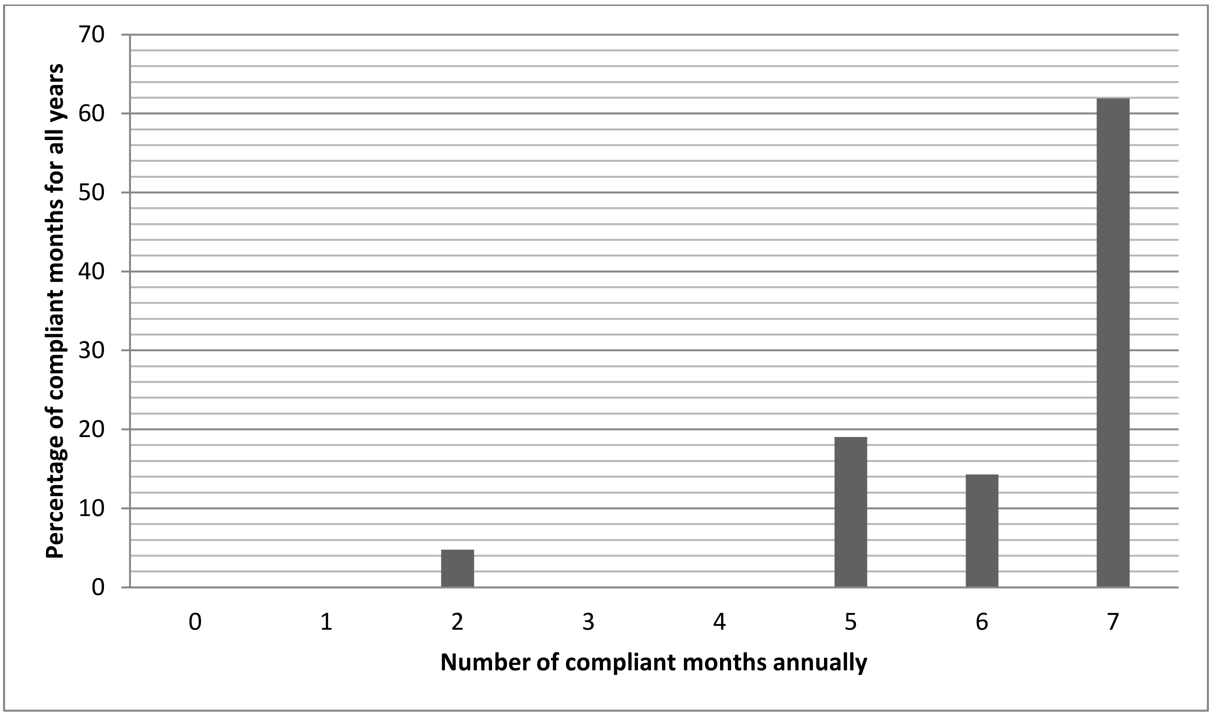

Figure 3.17. Bar graph illustrating the percentage breakdown of monthly compliance with maintenance higher IFR flow for full year periods at the SabieSand IFR site (1987 – 2013).

Figure 3.17 shows an annual breakdown of the percentage of monthly maintenance higher IFR targets for the SabieSand IFR site that are met annually for the duration of study period (ie: 1987 – 2013). Only years in which flow data were available for all months were used for the analysis, hence the mismatch with the number of years against Table 3-16. Figure 3.17 shows that full maintenance higher IFR compliance occurred in seven out of seven months 13 times from a potential 21 years. This is the highest compliance of maintenance higher IFR's of all sites. In 3 years higher maintenance flows were complied with 6 out of 7 months, and in four years there was 5 months out of 7 that were compliant. Bar 1992, in which only two months of 7 of compliance were observed to be compliant, all years showed between 5 and 7 out of 7 months of maintenance higher flow compliance.

3.3.2.4.2. Drought Higher Flow compliance at the SabieSand IFR site:

Drought higher flows for the SabieSand IFR site are only specified for February and December. Transgression of drought higher flow specifications (refer to Table 1-4) for the SabieSand IFR site occurred in a single month; December 2003. This was the sole instance for the non-compliance with drought higher flows for all months in all years at any site. Although a single month of drought flow non-compliance may not be cause for concern, an extended period of low flow during this time of year may have left some ecological signature occurring at short timescales. While it is unlikely that any significant channel encroachment would have occurred during the 31 days of December 2003, small changes to habitat for invertebrates may have occurred, leading to shifts in the community structure for a short period.

While few days of drought higher non-compliant flows occurred in February at the SabieSand IFR site (18 days during the drought of 1992), extensive non-compliance was noted for a total of nine Decembers in the dataset, totalling 100 days over the study period. These have been tabulated below in Table 3-17.

Table 3-17. Number of days of drought higher non-compliant flows per December at the SabieSand IFR site.

YEAR	DEC
1987	2
1988	1
1990	5
1991	11
1992	12
1993	13
1994	21
2003	31
2005	4
TOTAL	100

Even though only one month of drought flow non-compliance was observed for the dataset at the SabieSand IFR site, the number of days of non-compliant flows is cause for concern. If even small increases in up-catchment abstraction occur, many more months of non-compliance might prevail should the threshold of drought higher IFR be breeched. Major ecological changes may arise from such a situation.

3.3.3. Results of the Theil-Sen Trend Analysis:

The results of the trend analysis for all possible permutations for base flows showed that there is no statistically significant difference in compliance rates across any pairs in the regression analysis. This means that the pattern in compliance for all IFR sites is similar.

Using a Z-test the p-values for the base flow analysis ranged from between 0.3037 to 0.9329, showing that there is no distinguishable pattern occurring at any site when compared with other sites.

The same test statistic was used for the trend analysis of higher flow compliance, with similar results. No significant difference was noted for any higher IFR permutation except the comparison between compliance at the InsideKNP IFR site and the Skukuza IFR site. The p-value for the pair was 0.0067 showing that the trends in compliance between these two sites are statistically different.

3.4. Discussion

3.4.1. Overview:

The discussion for this chapter will take the form of a general, over-arching exploration and lead into the following chapter which will explore the changes to each IFR site in terms of the shift in flow regime, and the response to that shift of a range of organisms and physical processes.

Actual flow dimensions often do not fulfil the flows required to meet the IFR at all sites. Two possible outcomes may arise from such a situation. Firstly, since different flow volumes are specified with the intention of maintaining ecological functionality in the Sabie-Sand River, if the flows are not met then we may see the failure of ecological components and a shift from the current system state of the river and riparian zone. This will occur however, only if these flows as specified are strictly responsible for the functions that they have been attributed with safeguarding. Secondly, if these flows are not responsible (ie: flows of a different dimension are capable of fulfilling the functions that the IFR has been assumed to ensure) for particular aspects of ecological maintenance, then we are obliged to identify the flows responsible for particular functions and thereby incrementally enhance our knowledge of the Sabie-Sand River and the drivers of ecological change in the Sabie-Sand River system. It appears that this will enable us to harvest more water in most instances, but this depends on whether the lower flows we have seen with respect to IFR's are capable of maintaining all the ecological functions and ecosystem services we expect from the Sabie-Sand River.

It is also noticeable that the meteorological drought period occurring between 1991 and 1992 led to a hydrological drought in the Sabie-Sand River, thereby causing non-compliance with the IFR. Sustained periods of meteorological drought, or particularly severe meteorological drought has definite linkages to IFR non-compliance despite the fact that meteorological and hydrological drought are decoupled to some extent, particularly in a river with a strong baseflow signature such as the Sabie River. This is often exacerbated by amplified extractive (from the river) water use during droughts mostly by the agricultural sector because less water for crops in available as rain. The cause of IFR non-compliance during the 1992 drought was due to the particular severity of the drought.

3.4.2. Patterns of IFR compliance in the Sabie-Sand River:

There seems to be no obvious pattern to compliance (and by extension non-compliance) across the four IFR sites in this study. When we consider base flow compliance for both maintenance and drought scenarios, no unexpected geographic or spatial pattern emerges. Moving down the catchment in an easterly direction, base flow IFR compliant flows per month are highest at the MariteSabie IFR site (the most westerly) at 74.7%, and lowest at the InsideKNP IFR site (adjacent to the MariteSabie IFR site) at 31.6%. Base flow compliance at the Skukuza IFR site then rises again to 61.8% before falling to under half of months (49.2%) at the SabieSand IFR site, the most easterly of the IFR sites.

The region in the vicinity of the MariteSabie IFR site has been cultivated for many years, and also has a fairly long data record by the Sabie-Sand River standards. Irrigated agriculture is reliant on a good knowledge of water availability and as such the base flow characteristics of the river in the MariteSabie IFR site region appear to be quite well understood. Consequently, the fact that base flow IFR compliance is highest at the MariteSabie site may be related to the greater volume and availability of data and information on this stretch of the stream. A similar situation is true for the InsideKNP IFR site. However, a long history of cultivation in the area coupled with an extensive data record has apparently not translated into a strong knowledge of the flow regime of the river at the InsideKNP IFR site. As a result, we see poor base flow IFR compliance at the InsideKNP IFR site even though the MariteSabie and InsideKNP IFR sites are adjacent to one another.

Further demonstrating the lack of any geographical organisation to IFR compliance, we see a different pattern of higher flow IFR compliance compared with base flow compliance. Overall, compliance with higher flow IFR specifications is better than base flow compliance. This can be attributed to two main reasons. Primarily, higher flows are only specified during periods coincident with rainfall. Less irrigation water is used for agriculture during the wet season since rain falls on the crops, lowering the necessity of using relatively costly irrigation water and thereby reducing the volume of water taken from the Sabie-Sand River by irrigators. Secondly, higher flows are specified for shorter periods within a month, while base flows are specified for the entire month. The opportunity for interception by humans of short duration flows is low, while interception of water by the large dams and forestry (see Figure 1.2 and Figure 1.3 in Chapter 1) higher up in the catchment are likely responsible for reduction in base flows (Gordon et al. 2004). Short duration, peaky flows are derived from localised processes such as thunderstorms over a small area, which are difficult to intercept as explained in the Rationale of this study (Section 1.1 of Chapter 1). Base flows are more reliant than higher flows on geohydrological processes that occur over large spatial scales. The construction of a large-capacity dam, fed from large catchment areas would have obvious and detrimental consequences for base flows.

Forestry is currently classed as a Streamflow Reduction Activity (SFRA) under Section 36 of the National Water Act of 1998 (No. 36 of 1998) (DWAF 1998). Plantation forestry is ubiquitous in the upper catchment and as such impacts the base flow in the Sabie-Sand River, further attenuating base flows (le Maitre et al. 2002). Where base flow IFR compliance at the MariteSabie site was the highest, it is the lowest at the MariteSabie IFR site with respect to meeting higher flow compliance, with 77.7% of months in the study period showing compliance. The adjacent IFR site, InsideKNP, has the second highest number of months comprising flows that are compliant with higher IFR specifications; 89.9% of the sample is compliant. Flows at the Skukuza IFR site also show relatively poor compliance against the higher IFR's, with only 79.9% of flows in months in the sample meeting or exceeding specifications. The SabieSand IFR site was the best performer against the higher IFR specification, with 90.6% of months in the study period recording compliant flows. It was however the only IFR site for the entire analysis period to demonstrate drought higher IFR non-compliant flows (in December 2003). All other drought scenario higher IFR specifications were met for all sites for the duration of the study.

Another interesting aspect of the results is the actual return interval of the larger February floods specified to occur every third year. None of the IFR sites see flows of sufficient magnitude at the desired return period. The MariteSabie IFR site is the worst performer, with floods of sufficient volume and duration only occurring once in seven years on average (see inset graph in Figure 3.10). The InsideKNP IFR site is also a poor performer; floods that should occur every third year only occur every 5.25 years (see inset graph from Figure 3.12). The Skukuza (Figure 3.14) and SabieSand IFR sites are slightly better but not adequate, showing values of 4.4 year return period for the former and 3.7 for the latter. These larger infrequent flows are crucial in terms of removing or limiting the sedimentation of the Sabie-Sand River. This is explored in greater depth in a number of sections within Section 4.5 in the following chapter.

Even though the percentage of base IFR compliant months differs substantially across the four sites, the pattern over time in which this occurs is similar, and this is corroborated by the Theil-Sen analysis. The trend analysis shows that years in which base flow compliance is poor at one IFR site will also mean poor compliance is likely at all of the other IFR sites. Although this is a logical conclusion and likely the cause of the seasonal change in flow dimensions, the trend analysis is nevertheless useful because significantly different trends in compliance for a given IFR site as compared to the others would suggest that the flow profile for that IFR site may not be biologically cognisant or relevant. However, since all IFR sites show substantial and frequent non-compliance without the loss of ecological integrity (ie: the system is functional with no species loss), the fact that the trend analysis shows no statistical difference in compliance means that base flow specifications for all IFR sites should be reformulated. An ideal scenario would be one in which the percentage IFR compliance is similar for all sites, the trend analysis reflects no statistical difference in compliance as demonstrated here, and there is no loss of biodiversity or system function.

Although the trends are similar, the different rates of compliance (as demonstrated in Sections 3.3.1 and 3.3.2) at the IFR sites points towards a lack of understanding of specific stretches of the river and as a result, the overall ecological factors at play in the Sabie-Sand River. Adjacent IFR sites, for example the MariteSabie and the InsideKNP IFR sites have such a massive disparity in compliance (particularly for base flow IFR's) that the present lack of hydrological and ecological knowledge and/or information renders the current flow specifications ecologically irrelevant. For example, base flow compliance at the InsideKNP IFR site is so sporadic, and flows so much lower than the IFR, that measuring ecological performance against the IFR values would be ineffectual. It may prove more useful to measure the performance of a number of ecologically relevant factors under prevailing flow conditions, and measure changes in their response against historical satellite imagery and aerial photography of the Sabie-Sand River when flows were larger and closer to the virgin flow regime.

Despite this, adherence to SAM principles would allow us to salvage information from the IFR exercise if correctly applied by mainly managers and scientists, but also other role players where possible including farmers and citizens deriving livelihoods from the river. However, the lack of review and changes to the IFR specifications is evidence that managers and scientists have not embraced the adaptive management strategy illustrated in Figure 3.1 of this chapter. The first circuit of the "plan and do" phase of the SAM loop was adhered to adequately, but the second portion, namely the "evaluate, learn and adjust" section appears to be a weakness in the system. This study addresses the “evaluate and learn” portion of the “evaluate, learn and adjust” portion of SAM. The findings of Chapter 3 must be addressed and will comprise an exploration of the ecological consequences of this widespread non-compliance with IFR’s in greater detail. Chapter 4 deals with each IFR site, exploring particular aspects of the potential effects that may be realised due to IFR non-compliance.

3.4.3. Change in flow management of the Sabie-Sand River and comparative compliance between the IFR and real-time flow management system:

Towards the end of this study, information released by the IUCMA stated that the IFR system would be replaced by a new real-time decision support system that would more readily allow managers to assess the downstream requirements for ecological maintenance and human water uses on an ongoing basis (Sawunyama et al. 2012). This would mean that the IFR system would become obsolete, and the new decision-support system would become the means by which to manage flows in the Sabie-Sand River. A background information document stating the intent of the IUCMA to implement the decision-support sytem was released in May 2013 (ICMA 2013).

The real-time decision support system appears to be less rigid than the IFR system in terms of flow requirements since it does not have a set of prescribed flow volumes. This is due to the inclusion of a rainfall-runoff component within the model, which forecasts flows in the river based on catchment antecedent rainfall and what proportion of the rainfall would become streamflow (Sawunyama et al. 2012). Information on this system has proven to be even more difficult to obtain than that of the IFR system. The available information shows that flows are now only monitored at two points on the river; upstream of flow gauge X3H021 (close to the InsideKNP IFR site) and downstream of flow gauge X3H008 (on the Sand River upstream of the SabieSand IFR site). Data for compliance with the real-time model at flow gauge X3H008 were not available. The system no longer specifies flows for drought and maintenance conditions, or base and higher flows. Rather, weekly flows are forecast by the model and compared with observed flows. Levels of concern are specified (in percentages of the forecast values) for when the observed flows deviate from forecast flows (either too high or too low).

The real-time system shows much better compliance than the IFR system. This is due to a significant reduction in the volumes required for compliance. Upon discovering that the new system had been implemented, I intended to do a comparative analysis of compliance between the two systems but the decision to do this was reconsidered upon viewing the compliance figures under the new system. The new system shows very few instances of non-compliance. Data for the flows passing flow gauge X3H021 are available from the 2nd of August 2012 and end on the 8th of September 2014.

A gap in the data (no reason was specified by the supplier of this information) occurred between the 28th of January 2013 and the 15th of April 2013, giving a total of 88 weeks of data. Only five weeks showed non-compliant flows during this period. These flows are analogous to maintenance base flows, and Table 3-18 shows comparative compliance at the four IFR sites against the real-time model compliance at X3H021 for maintenance base flow.

Table 3-18. Comparison among IFR Maintenance Base Flow Compliance against real-time model compliance in the vicinity of InsideKNP site.

IFR Site Name:	**MariteSabie**	**InsideKNP**	**Skukuza IFR**	**SabieSand IFR**	**Real-Time Model @X3H021**
Compliance:	**74.7%**	**31.6%**	**61.8%**	**49.2%**	**94.3%**

The fact that the IFR model has been replaced by the real-time model corroborates the findings of this research with respect to the lowering of the flow requirements for the river. Continuous non-compliance is not useful for management, so I would recommend a review and a lowering of the IFR values. In addition, there is a point to be made about the process: the feedback loop to monitor the effects of non-compliance is either not functional, or not documented in the public domain. So even though my recommendations are corroborated by the switch to a new system, I cannot assess the effectiveness of the SAM feedback loop to drive this decision, in the absence of a transparent decisionmaking process. These findings are in line with what managers observed and possibly prompted the switch, but the same lack of public data that I experienced in exploring the determination of IFR dimensions is also apparent in the switch to the new system. This seemingly systemic problem is likely to manifest itself again, and overall, hamper efforts to improve river management. As stated above, the recommendations from this study are to review the flow volumes for ecological maintenance down but it is important that the IFR system is retained as the tool of choice. Taking this action would reduce instances of IFR non-compliance but without any negative ecological effects, since much can be inferred from the literature regarding the ecology of the Sabie-Sand River and its health (see Chapter 4). By retaining the IFR system, managers and scientists can build on the knowledge already garnered through the use of the system as it stands, since there is much to learn about the ecology of these rivers in periods of non-compliance with IFR. If the IFR system had been retained, a further recommendation would be that managers must be aware of sectoral water uses and accurately forecast their growth or decline and be aware of the location of these changes, at regular intervals. This information must inform the IFR of that part of the river. However, the new system has a built in awareness for this aspect of water use; dam releases occur with all sectoral uses planned for in anticipation that the water user will remove their water from a known point, leaving sufficient water for downstream users and the human use and ecological Reserve.

Chapter 4 is an exploration of the literature on changes to the ecology of the Sabie-Sand River in the face of consistent IFR non-compliance. It appears that the variability of the flow regime of this river system is more important than ensuring that particular and precise flow volumes occur, although much research must be conducted on the biota of the river before this statement can be made with confidence.

3.5. References

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4. Chapter 4 - The ecological implications of IFR non-compliance and reductions in flow

4.1. Overview of the major issues facing the flow regime of the Sabie-Sand River:

As the preceding chapters have shown there appears to be two major problems related to the flow of the Sabie-Sand River. Firstly, there is a long term gradual reduction in daily flow rate and volume for the river as measured using one of the major flow gauges (X3H006) on the Sabie River (see Figure 1.6 in Chapter 1). This gauge was positioned below the major commercial agricultural and forestry areas of the Sabie-Sand River catchment before it was washed away by floods in 2000, and as such was capable of detecting the influence that large-scale land cover change and climatic changes would have had on the flow regime of the Sabie River. Compared to the average daily flow rate (rate = 6.404 m/s, volume = 0.553 M m^3/day, n = 3 570) for the first ten years of daily flow data for flow gauge X3H006, the long term daily flow rate and consequently flow volume (rate = 6.088 m/s, volume = 0.526 M m^3/day, n = 14 692) has been reduced by approximately 5%. This amounts to almost 10 M m^3 per annum; almost enough water to fulfil the IFR requirements for maintenance flows at the MariteSabie IFR site for both September and October. Juxtaposed to this long-term decreasing trend, daily flows as measured at X3H015 (see Section 3.2.1.2.4) and X3H021 (see Section 3.2.1.2.5) have seen an increase over the long-term.

A similar investigation of the moving average of daily flow rate for flow gauge X3H001 (not part of the IFR investigation) also yielded evidence for a gradual increase in flow volume closer to the headwaters of the Sabie River. The flow gauge is situated downstream of the town of Sabie, and as a result receives runoff from the town and its quaternary catchment. The flow gauge began recording data in 1948, and in the period between 1948 and the present the town of Sabie has expanded, with more tarred roads and surfaces present. The catchment itself has also undergone much land cover change from virgin forest and veld to forestry and sealed surfaces (Coetzer et al. 2010). These factors lead to lower soil infiltration by precipitation, and thereby cause a greater proportion of the precipitation to move overland and enter streams (Poff et al. 1997). Despite this, investigations into the rate of compliance with Instream Flow Requirements (IFR) show that the Sabie-Sand River carries substantially less water than it did under virgin flow conditions, but more importantly, far less than what is necessary to maintain the IFR. These findings corroborate the work of Scott et al. (1998), Nel et al. (1999) and le Maitre et al. (2002).

The recognition that the flow regime is the primary driver of riverine and riparian ecosystems is well-established (Naiman et al. 1995; Bunn and Arthington 2002; le Maitre et al. 2014). Dams and reservoirs are also major drivers of change in flow regime, with the Da Gama and Inyaka Dams of particular interest in the Sabie-Sand River Catchment. Historically, large impoundments such as these were built on rivers to enhance their potential for human uses, with very little consideration for downstream ecological impacts caused by the impoundment (Richter et al. 2003). Changes to land use in catchments have impacted flow regimes of rivers around the world, also leading to changing flow regimes (Kalantari et al. 2014). Changes to flow regime almost always cause the loss of other ecosystem services (Arthington et al. 2010). Scientists recognise this, and there is growing awareness that the trade-off caused by construction of large impoundments against ecosystem services is no longer acceptable if sustainability is to form the cornerstone of resource management in the present and future (Richter et al. 2003). Flow is a major determinant of physical habitat in streams, which in turn plays a major role in biotic composition of both the aquatic and riparian aspects of the river (Bunn and Arthington 2002). The life history strategies of this biota have evolved in response to the natural flow regime of the river and so the maintenance of a flow regime that is as close to natural as possible should ensure that the suite of biota is maintained (Bunn and Arthington 2002). The previous paragraph has mainly focused on the effect on flow regime of changing flow rates and volumes, but the timing of flows is another component of the flow regime that is affected by the factors mentioned above (ie: land cover change and the effect of impoundment). These factors can often have substantial effect on the ecological functions of a river (Bunn and Arthington 2002). However, the natural high variability in timing of changes in flow of the Sabie-Sand River means that the biota of the stream are likely to have evolved under variable conditions, and are thus capable of dealing with some degree of change in flow regime (Poff et al. 2010).

The simultaneous reduction and increase in flow rate and volume in different reaches of the river presents a particular set of problems, but the fact that the flow regime has been irrevocably modified, has and will continue to cause ecological changes that may prove detrimental to river health and ecosystem services. This is cause for concern since the Sabie-Sand River remains the healthiest of the lowveld rivers (Goetsch and Palmer 1997) and remains a flagship for conservation and rivers research. The simultaneous increase and decrease of rate and volume of water in different reaches of the river also highlights the difficulty facing catchment managers in terms of localised solutions to meet IFR's and water requirements from other use sectors.

The second major issue and the theme of this research is the inadequacy of actual flows versus the Instream Flow Requirements (IFR's) that are deemed necessary for the maintenance of a beneficial and healthy system state for the Sabie-Sand River. The Threshold for Potential Concern (TPC) for River Flow and Quality as published by the Scientific Services of the KNP states that "continuously having rivers just on or below the IFR levels is only just acceptable" (du Toit et al. 2003). The results of the research show that base flow IFR's are not met often enough at all IFR sites (for both maintenance and drought scenarios). The same outcome prevails for higher flow IFR's, albeit with a higher frequency of compliance (see Table 4-1 of this chapter) at all IFR sites when compared with base IFR compliance levels. The outcomes and potential ecological ramifications from non-compliance of the two types of IFR's, namely base and higher flows is different since these two flow types are specified to perform or aid different ecological functions in the river.

4.2. Summary and revision of IFR compliance findings:

Table 4-1. Summary of IFR compliance (measured as percentage of all months in the data set) for each IFR site.

IFR Site Name:	Span of data record (y)	Base flow compliance (%)	Higher flow compliance (%)	1:3 year flood compliance (%)
MariteSabie site	1978 – 1999	74.7	77.7	14.3
InsideKNP site	1978 – 1999	31.6	89.9	19.0
Skukuza site	1990 – 2013	61.8	79.9	22.7
SabieSand site	1987 - 2013	49.2	90.6	27.3

Section 3.4 in Chapter 3 is a short overview of the potential causes for the patterns of compliance that we see at the IFR sites in the Sabie-Sand River. The disparity across sites of base and higher compliant flows versus the IFR varies. This should result in the different IFR sites demonstrating different levels of ecological health if the values specified in the IFR tables found in Chapter 3 are indeed ecologically relevant (Table 1-1 to Table 1-4 in Chapter 3). For example, all ecological factors for which base flows are responsible should be performing best at the MariteSabie IFR site since it shows the best compliance against the base IFR specifications, and very poorly at the InsideKNP site because of the very low base IFR compliance at this site. With respect to higher flows, the functions linked to higher flow IFR compliance are likely to be performing poorly at the MariteSabie IFR site and functioning relatively well at the SabieSand IFR site. Here I must reiterate the caveat that this will only be the case if the values in the IFR tables are actually responsible for those functions, and if the higher flow functions are not dependent on base flows too. Such a complex ecological system is unlikely to be so simply summarised in IFR tables, and this will be explored in greater detail below.

An examination of the IFR tables shows a distinct difference between the specifications for the drought and maintenance scenarios. It is therefore assumed that in months and years when flows do not exceed drought IFR specifications, ecological processes reliant on flows greater than drought level specifications will not occur if they are threshold-dependent, or occur partially if they are threshold-independent of the drought IFR values. An *a priori* assumption that drought years and maintenance years would be neatly partitioned into hydrological years proved to be unrealistic and rarely occurred; not even the severe meteorological and hydrological drought of 1992 showed such a pattern for base flows at any sites. At all sites for 1992, compliant, maintenance non-compliant and drought non-compliant flows occurred. This situation made it very difficult to detect the attrition of processes that could fail when flows drop below IFR threshold values because of the erratic movement across compliance, maintenance non-compliance and drought non-compliance within such short timescales. Nevertheless, the fact that compliance with both base and higher IFR's differs across sites should mean that the processes and functions that rely on flows of particular dimensions outlined in Section 1.3.4 of Chapter 1 are taking place at some sites and not others, and to differing degrees.

4.3. The importance of base flow specifications in the IFR of the Sabie-Sand River:

Base flows in the IFR of the Sabie-Sand River are important because they define the timing of wet and dry seasons and ensure that the flow is perennial (King et al. 2008). The Sabie River is perennial and the Sand River is an ephemeral tributary. The suite of instream and riparian biota have evolved under these flow regimes, and so it is imperative to ensure firstly that flows never cease in the Sabie River and stop infrequently in the Sand River. Base flow volumes, especially those in the dry season months (ie: the lowest flows in the hydrological year) have also been linked to suppression of dispersal and recruitment of alien biota, particularly plants (Richter et al. 2006). Furthermore, the maintenance base IFR specifications were set as minimum flows which would prevent "unacceptable biodiversity loss" and were specified with the intention of very few instances of non-compliance (du Toit et al. 2003). Drought base flow IFR specifications were designed for infrequent instances in which low rainfall seasons would lead to reduced river flow, and the specifications would ensure the survival of only the critical species in the river (Louw et al. 2000).

4.4. The importance of higher flow specifications in the IFR of the Sabie-Sand River:

Higher flows in the IFR of the Sabie-Sand River are important because they are responsible for the mobilisation of moribund sediment, nutrient dispersal, dispersal of riparian and riverine plant seeds as well as some mammal species, the replenishment of bank-water, and inundation of the macro-channel which provides the conditions for many species of amphibians, fish and invertebrates to breed. These processes are the most important in an extensive list. Higher flow specifications also comprise part of the greater variability (intra-and inter-annual per hydrological year) of the Sabie-Sand River and this is an integral attribute of the flow regime of the Sabie-Sand River. While maintenance base flow specifications are meant to prevent unacceptable biodiversity loss, the maintenance higher IFR is specified to ensure that the biota of the river is able to breed, for the reasons mentioned at the start of Section 4.4 of this chapter. If drought base IFR specifications should ensure the survival of critical riparian and riverine species, by extension the drought higher IFR must provide conditions in which these critical species can breed.

Because all IFR sites have shown some degree of non-compliance albeit at varying levels, the ecological health of the river should be in decline. This decline would include reduced flow volumes and velocities, siltation of the river, changing composition of riparian and instream communities (both plants and animals) and even species loss.

4.5. Scenarios of change to factors influencing the ecological health of the Sabie-Sand River:

The potential changes to factors that influence the ecological health of the Sabie-Sand River were explored in Section 1.3.4 of Chapter 1. Here, we will provide scenarios of likely change that are possible in the Sabie-Sand River in response to non-compliant flows. Where possible we will corroborate these changes against literature and information derived from images of the various sites.

4.5.1. The effect of non-compliance with IFR specifications on riparian resources and products for human use:

Riparian and riverine goods and services are many and varied, and their importance is dependent on the requirements of the surrounding users. All of these goods and services were considered in the planning phase of the IFR process, with flows designed to conserve and perpetuate them (du Toit et al. 2003). Non-compliance with the Sabie-Sand IFR specifications may jeopardise the preservation of these goods and services. The comprehensive review in Section 1.3.4.1 of Chapter 1 of all the factors affecting the ecological health and by implication the structure and functional characteristics of the Sabie-Sand River equips us with the knowledge to postulate a scenario of the status of goods and services for human use in the Sabie-Sand River under IFR non-compliant flows.

In the context of this study, the four IFR sites divide into two groups on the basis of the goods and services required from the surrounding riparian and instream environments and the IFR sites themselves. Those outside the Kruger National Park (KNP) are mainly required to provide natural products that are physically harvested and utilised, and those inside are used as an indicator for aesthetic evaluations of the health of the river and riparian zone. The two IFR sites outside the KNP (MariteSabie and the northern bank of the InsideKNP site) must be able to provide a larger suite of goods and services compared with those inside the KNP. Both the MariteSabie and InsideKNP sites, and the stretch of the SabieSand River between the two are in close proximity to a number of villages with populations that may be reliant on resources and services derived directly from the river and riparian zone. These services include water for drinking, washing and cooking purposes, plants and animals for food and medicinal products, macro-channel soils for agricultural production, and grasses for thatching and grazing. Non-consumptive cultural, religious and aesthetic uses are also implicit in the IFR at these sites. The Skukuza and SabieSand IFR sites are situated on parts of the river that are entirely within the KNP and activities such as resource harvesting and cultivation of crops are forbidden within the borders of the KNP reserve. As such, most of the goods and services provided by the Sabie-Sand River in the proximity of the Skukuza and SabieSand IFR sites are non-consumptive and centre on aesthetic and cultural aspects (for consideration under this section).

With respect to the use of water directly from the Sabie-Sand River for drinking purposes, the South African government has reported progressive improvement regarding access to piped water for all South Africans (SAIRR 2012). As a result, the number of people in the Sabie-Sand River catchment utilising water directly from the river for drinking and cooking purposes is very low (SAIRR 2012). However, many people still make use of the river to wash clothing (Mokgope and Butterworth 2001). The fact that IFR flows are not compliant is not important with respect to drinking, cooking, hygiene and washing of clothing, since most of the adjacent population utilises piped water. Even in periods of sustained low flow conditions, people are capable of finding pools or modified techniques (such as digging into sandy stretches of riverbed) in which to wash clothing, even if water quality is slightly compromised. Drinking, cooking and hygiene continue even when there is non-compliance with IFR, with clothes washing less easily undertaken but of no great concern under IFR non-compliant conditions.

The cultivation of soils in the river macro-channel is less important in the Sabie-Sand River than other rivers in South Africa such as the Mfolozi River floodplain (Grenfell et al. 2009), but is nevertheless undertaken, and more extensively so in the Sand River sub-catchment than the Sabie River. However, in the macro-channel of the Sabie River between the MariteSabie IFR and InsideKNP IFR sites there is extensive commercial and subsistence cultivation. The use of both water and soil is affected by IFR compliance. If flows are IFR non-compliant then less water is available for use in agricultural production. IFR non-compliant flows are also less capable of carrying sediments and so large-scale deposition will enhance channel encroachment and incision of the streambed, making periodic inundation more infrequent (Acreman and Dunbar 2004). This inundation is necessary for the periodic renewal of macro-channel soils and to prevent desiccation of the *in situ* soil (Petts 2009). Progressive drying of soils will require greater volumes of irrigation water from the river to obtain productive yields. This process is reliant on meeting both the base and higher IFR specifications. If base flows continue to be non-compliant and channel incision occurs in the dry season, a situation may arise in which even flows of equal to or exceeding higher IFR dimensions may not be capable of reaching the macro-channel banks. As a result, even though higher flow compliance is superior to base flow compliance across all IFR sites, consecutive months (and years) of poor base IFR compliance may render flows compliant with higher IFR specifications functionally ineffective. An example of an ecosystem service which may be lost or be significantly impaired if higher flows do not reach the macro-channel bank is fish spawning and the survival of juvenile fish (Gordon et al. 2004; King et al. 2010). As freshet flows cause the surface level of the water to rise and enter the macro-channel, key habitat components for immature fish are unlocked, providing them with warmer water, feeding opportunities and refuge against predators (Kingsford 2000).

The commercial portion of irrigation water use is less reliant on direct use from the river since commercial ventures are capable of sourcing water from alternative providers, but they are nevertheless users of water from the river because it is the most cost-effective means of irrigating crops. Provision is not made in the current iteration of the IFR for commercial users but their requirements have been noted and will be added to future flow determinations (du Toit et al. 2003). Commercial ventures requiring water for irrigation purposes will require water use licences in the future and will pay for water (DWAF 1998). If the water use licensing process is successful, there should be a reduction in illegal water use and that would likely increase flows in the river. Subsistence agriculturalists use water from flows incorporated in the IFR and as such they are vulnerable to IFR non-compliance, but also partially responsible for it. Water use by small subsistence farmers, by way of Chapter 4 and Schedule 1 of the National Water Act of 1998 (No. 36 of 1998) is exempt from the water use license process and all water use costs except for registration fees as a general authorisation user (DWAF 1998). If increases in this water use occur in the future it may jeopardise IFR base flow compliance, particularly in the late dry season when flows are low in the river and demand for irrigation water is greatest.

Should non-compliance with IFR lead to less frequent inundation of the macro-channel banks, we can also expect a change in the composition of the plant community of the riparian zone and macro-channel (Kingsford 2000). Progressive desiccation of the macro-channel will have a detrimental effect on plant species that require moist soils. Since plants that inhabit riparian zones are hydrophilic, many of these riparian species may diminish in numbers, or cease to occur in significant numbers if IFR compliance is not improved. Food and medicinal plant resources formerly harvested in riparian areas will be negatively affected under these conditions and will become more difficult to find or even absent altogether (Schlüter and Pahl-Wostl 2007). Grasses preferring moist soil environments (eg: *Panicum maximum,* Buffalo grass and *Urochloa mosambicensis*, Bushveld signal grass) and favoured by cattle will also decrease in proportion in favour of grasses capable of withstanding a more xeric environment (Scholes and Walker 1993). These grasses are less palatable to cattle and would support smaller herds, or animals of poorer health (van Oudtshoorn 2012; Fynn and o' Connor 2000). Riparian grasses such as *Hypharrenia hirta* (Common thatching grass) are also utilised for thatching of homesteads and weaving of mats (van Wyk and Gericke 2000). Progressive drying of the macro-channel favours grasses that are not useful for this purpose and so IFR non-compliance will attenuate the availability of useful grasses such as *Hypharrenia hirta*.

Non-consumptive uses of the river include cultural, religious and aesthetic uses. Relating these elements to the IFR is extremely difficult; some are dependent on pools within the river and as such are more reliant on topographical features within the river than actual flow volumes. However, it is well-established that reduction in flow volumes generally leads to siltation and alluviation of streams (Ferrier and Jenkins 2010). The situation of non-compliance with the IFR has seen the Sabie-Sand River experiencing higher rates of alluviation and this has been documented throughout the period in which this study took place and is backed up in the literature (Heritage and van Niekerk 1995; van Coller et al. 1997, McLoughlin et al. 2011). Although sedimentation in the Sabie-Sand River has been a long-term, multi-year process and some degree of siltation is acceptable within the IFR management regime, flows intended to scour the build-up of sediments have not been occurring as frequently as they should. The 1:3 year return interval floods as specified for February at all IFR sites should occur in approximately 33% of February's. Compliance at the MariteSabie IFR site is the lowest at 14.3%, and second lowest at the InsideKNP IFR site at 19.0%. This means that the return interval of flows meeting or exceeding the required threshold for February flood flows (100 MCM in a 14 day period every third year for both MariteSabie and InsideKNP IFR sites), are in the region of a 1:7 year return interval at the MariteSabie IFR site, and the InsideKNP IFR site experiences floods of the requisite magnitude and duration less often than a 1:5 year return interval (1:5.25 year return interval). This means that greater periods of time will pass before scouring of sediments in the stream. The resultant siltation of the Sabie-Sand River means that fewer pools will be present for religious and cultural purposes.

Of the non-consumptive uses of the Sabie-Sand River mentioned above, the most nebulous is the aesthetic value and how it relates to IFR's. Different people have diverse perceptions of what constitutes a healthy stream; there is consequently no single flow regime that could be designed to ensure "good" aesthetics for the Sabie-Sand River. Aesthetics is however, from a human use perspective the most important element for both the Skukuza and SabieSand IFR sites because of the recreational and cultural importance of the KNP. It is unlikely that there is any flow magnitude, duration or volume that can be attached to the IFR for aesthetics, save for ensuring that the Sabie portion of the Sabie-Sand River does not stop flowing. le Lay et al. (2008) use photo-questionnaires to garner an understanding of cross-cultural perception of riverscapes. Their work focuses on the role of large woody debris in eliciting emotional responses from people in different countries. Photo-questionnaires (showing pictures of known flow dimensions) could be used to find peoples preferences for river conditions should managers desire to integrate aesthetics into the IFR, although other more pressing matters may postpone the more frivolous aspects of IFR determination. It is thus apparent that whether flows comply or not with IFR's, the aesthetics of the river are unlikely to be jeopardised.

Table 4-2. Table showing the likely trajectory of change in ecosystem goods and services due to IFR non-compliance.

Domestic water	**Food resources**	**Grazing resources**	**Soil resources**	**Irrigation resources**	**Weaving resources**	**Religious uses**	**Non-consumptive resources**
↔	↓	↓	↓	↓	↓	↓	↔

Table 4-2 shows a summary of the expected trajectory of change with respect to goods and services for human use if compliance with the IFR is not improved. Each good or service is listed in Table 4-2, and the trajectory of each is indicated by the direction of the arrow (eg: domestic water and non-consumptive uses are expected to undergo no significant changes, while the remainder are expected to worsen).

It must be pointed out at this juncture that the link to water use for sanitation as explored in Chapter 2 is distinct from the water use within the ecosystem goods and services explored above. If a scenario arose in which a substantial volume of water was diverted from the river for the purposes of domestic sanitation, a considerable drop in flow for the Sabie-Sand River would occur and thereby further endangering the ecosystem goods and services as summarised in Table 4-2.

4.5.2. The effect of non-compliance with IFR specifications on instream and riparian habitat:

To understand the effect of non-compliance on instream and riparian habitat we must consider the habitat units present in the Sabie-Sand River. As outlined in Section 1.3.4.2 in Chapter 1, the major types present in the Sabie-Sand River include riffles, rapids, runs, pools, lotic wetlands (sparsely in the upper reaches of the Sand River) and the river macro-channel. Although heterogeneous in nature, for the purposes of this portion of the study the riparian zone is considered as a single unit and will be discussed in greater detail in the section on vegetation below. All of these habitat units named here are well-established in the literature and are also present in the Sabie-Sand River (Moon et al. 1997; Heritage et al. 2001a; Dollar et al. 2007).

The different habitat units will respond differently to IFR non-compliance and the degree to which IFR specifications are not met. Non-compliance with IFR specifications is linked to knock-on ecological effects that are likely to impair ecological functionality in these habitat units. These effects include increasing water temperature, decreased oxygenation, and most importantly, the *status quo* has and will continue to cause gradual siltation and alluviation of the Sabie-Sand River as a result of flows that are of insufficient magnitude, duration and volume (Gordon et al. 2004). Where non-compliance is highest, we expect the largest changes to occur (ie: InsideKNP IFR site for base flow IFR's, MariteSabie IFR site for higher and 1:3 year return interval IFR's).

Some of the habitat units mentioned above are less resilient to reduced flows than others and the associated effects as mentioned above and may cease to occur in the state they were in (o'Keeffe 2009). Since all habitat types are present in the vicinity of one or more of the IFR sites and all sites are experiencing flow reductions, here we will discuss the expected trajectory of change to each habitat type using the guidelines set out in Section 1.3.4.2 of Chapter 1. Due to the universal base and higher IFR non-compliance for all four IFR sites, we expect similar conditions to prevail in each habitat type, namely; increased water temperatures, reduced oxygenation of water, increased salinity derived from increased inflow from macro-channel banks, and lastly increased siltation (Hughes and Louw 2010).

Riffles are dominated by coarser sediments such as cobbles and boulders (Raven et al. 1998). They are uniquely productive habitat units in rivers due to the highly aerated waters, and many species of invertebrates, amphibians and fish utilise riffles for some portion of their life-cycle (Rivers-Moore and Jewitt 2007). The shallow depth of riffles means that they are particularly vulnerable to flow reductions and consequently IFR non-compliance. Flows of smaller volume will likely cause the area of riffle habitat in the Sabie-Sand River to diminish over the short-term by leaving cobbles and boulders in the stream high and dry. And in the longer-term, riffles will be lost mostly as a result of alluviation over the cobbles and boulders crucial to riffles. Should the 1:3 year return flow obligations (flushing flows) not be met (as is currently the case at all IFR sites) then the periodic flushing flows that clear finer sediments from the riffles may not be of a large enough capacity to clear these sediments, and unless larger more infrequent flood flows manage to perform this function riffles may cease to exist in the Sabie-Sand River in the long-term, especially since they are already an uncommon feature in the river (Heritage and van Niekerk 1995). Results obtained from higher flow analyses in this study show that while all IFR sites have flushing flood flow specifications requiring a 1:3 year return interval for the large February flood, in reality flows of the requisite duration and volume occur every 1:7 years at the MariteSabie IFR site, every 1:5.25 years at the InsideKNP site, every 1:4.4 years at the Skukuza IFR site, and every 1:3.7 years at the SabieSand IFR site. Under these conditions, it appears that riffles in the Sabie-Sand River are in a poor condition with temperature, oxygen and salinity profiles that are unsuitable to the biota in the stream (Gordon et al. 2004). Besides this, it is also likely that riffles in the river are shrinking where they are still present. Examination of Google Earth imagery shows that no riffles are present in close proximity to the IFR site with the poorest base flow IFR compliance (InsideKNP site – 31.6% base flow IFR compliance). Whether this is because riffles are simply not present in the locale, or have already been inundated with alluvium is a point of speculation but worth investigating in future studies, perhaps post future-flood. Between the Skukuza and SabieSand IFR sites a few patches of riffle are present and should be closely monitored so that action may be taken if they seem to be performing poorly under the current (inadequate and non-compliant) flow regime. Overall, the outlook for riffles under IFR non-compliant flow conditions is poor.

Rapids are often similar to riffles, but are more often the result of exposed bedrock as opposed to sediment accumulation as is the case with riffles (Heritage et al. 2001a). Rapids are always steeper than riffles, and waterfalls are large rapids. Rapids play an important role in the oxygenation of water in the stream (Gordon et al. 2004). While rapids are more resilient to attenuated flow conditions (ie: IFR non-compliant conditions) when compared with riffles, it follows that flows of reduced volumes and velocity will not take on as much oxygen upon entering the downstream plunge pool as a larger flow might. Therefore, IFR non-compliant flows will exhibit higher temperatures and lower oxygen content than compliant flows, with detrimental effects to the biota that usually inhabit these habitat types. Rapids are unlikely to take on macro-channel derived saline waters as is the case with riffles. The majority of waterfalls and rapids in the Sabie-Sand River are bedrock examples, and so the hydrological connectivity between the channel and stream is low here, as in most bedrock controlled streams (Stanford and Ward 1993). Cases of extremely low flow for extended periods (such as the drought of 1992) may cause siltation of the plunge pools below rapids, thereby completely submerging the rapids in alluvium, although this is highly unlikely. However, even if sustained periods of low flow prevail large floods should allow for the scouring of unwanted sediments in the plunge pool and rapid. Once again, we see that these flows appear to be absent from the Sabie-Sand River at regular enough intervals, enhancing the potential for the loss of the smaller rapids from the Sabie-Sand River. Species preferring highly oxygenated waters favour stretches of the river immediately downstream of rapids and in cases of severe drought are likely to diminish in numbers or undergo local extinctions. Overall, rapids are quite resilient to IFR non-compliance but are highly vulnerable in situations in which serious and sustained drought conditions may cause alluvium to overwhelm the rapid, thereby changing the state of the rapid to another channel type. Smaller rapids are more susceptible to inundation by alluvium while larger ones are less vulnerable.

Runs are sections of the river characterised by laminar flow over any substrate present in the Sabie-Sand River including bedrock, alluvial or mixed streambed types (King et al. 2008). Runs carry moderate aerobic loads and vary in their hydrological connectivity depending on the streambed over which they run (King et al 2008). Bedrock sections have low connectivity while water moves freely between the macro-channel and the stream in alluvial sections of the river. Runs are the most resilient habitat type in the Sabie-Sand River to changes in flow, and changes in flow do very little to modify temperature, oxygen levels, dissolved salts and siltation regimes. With this in mind, the gradual reduction in flows in the Sabie-Sand River and concomitant non-compliance with IFR would slightly increase temperature, salinity levels and deposition of sediments in runs, while simultaneously we would notice a decrease the oxygen content of the water. It must be stressed that this effect would be negligible and of very little concern even under conditions of non-compliance. Runs make up the largest habitat type by area in the Sabie-Sand River. This is logical because ecological systems are known to move towards stable states until large perturbations reset the template to the same or a different stable state (Gunderson 2000). The outlook for run sections of the Sabie-Sand River is fair to good under IFR non-compliant flow conditions.

Stretches or portions of the river dominated by deeper water of reduced flow velocity with finer underlying sediment units (rarely is it rocky) are known as pools (Gordon et al. 2004). These conditions are conducive to increased temperature, salinity levels and sediment deposition, and hypoxic water conditions when compared with runs (Gordon et al. 2004). Much like runs, pools are fairly stable habitat units and are unlikely to undergo state change under IFR non-compliant flow conditions. The stability of individual pools is dependent on size, with larger pools showing less effects to low flow conditions than smaller pools. In short-term low flow periods, conditions in pools may become hypoxic, warmer and more saline, with a concomitant drop in pH (Benson and Krause 1980). Longer periods of low flow conditions (such as those that occurred during the drought of 1992) may lead to siltation of pools. The simultaneous alluviation and evaporation of water from pools will eliminate some pools, and decrease the depth of others. In pools where water remains, conditions may become lethal to the biota dwelling in them due to highly hypoxic (in extreme cases anoxic) and saline conditions, with extremely high water temperature. Most pools in the Sabie-Sand

River occur on sandy substrates, and as such have strong hydrological connectivity. However, large dams and extensive forestry have altered and diminished subterranean water movement as witnessed by the poor levels of compliance with the base flow IFR (le Maitre et al. 2002). Although this may have a detrimental effect on pools within the Sabie-Sand River, it is not likely to be of much consequence in those parts of the river that are far from the forestry regions and any large dams. Overall, pools in the Sabie-Sand River, particularly those farther west in the catchment remain stable under IFR non-compliance and reductions in flow.

Although present, wetlands are fairly scarce in the Sabie-Sand River. Headwater wetlands are present in the upper reaches of the Sand River, although these are not at all common. Due to the location of these wetlands far from any flow gauges used for my study, I am reluctant to comment on whether flow reductions and poor IFR compliance may be detrimental to the wetlands. However, since these wetlands are situated in the headwaters of streams and drain small surface areas (Riddell et al. 2012), it is unlikely that water can be intercepted for human use before it reaches the wetlands. Land cover change, particularly the use of these wetlands for cultivation is more likely to be the cause of demise of these wetland features (Riddell et al. 2012), and that is beyond the scope of this section. While these wetlands are likely to be stable under IFR non-compliant conditions, the distance to IFR sites precludes them from this analysis, and other factors mean they are under severe threat. They may also not be resilient to longer spells of drought, but there are no nearby flow gauges to measure the wetlands response against flow conditions.

Since the macro-channel and the riparian zone are inextricably linked to each other as the riparian zone is situated in the macro-channel, they will be discussed together here. The macro-channel is defined as that part of the river that shows the extent of higher magnitude, lower frequency flow events, as depicted in Figure 1.12 of Chapter 1 (Moon et al. 1997; van Coller et al. 1997). Floodplains (the macro-channel in this case) have also been described as the portion of the ecosystem that experiences alternate flooding and drying cycles (Bayley 1995). The portions of the macro-channel closest to active river channel will experience more quick alternation of flooding and drying, while the outer and uppermost parts of the macro-channel will experience inundation only during very infrequent but substantial flooding events (Pettit et al. 2005). Most active channels within the Sabie-Sand River change over short time-scales, with alluvium controlled sections responding quickly to changes in flows and bedrock dominated sections responding more slowly. The macro-channel of the river changes over much longer time-scales (Pettit et al. 2005). Flood flows large enough to alter the macro-channel of the Sabie-Sand River occur infrequently (Parsons et al. 2006). IFR flows are not specified to have any considerable effect on the greater macro-channel, and no further reference will be made to this portion of the macro-channel. The lower portion of the macro-channel (the macro-channel floor) will be discussed since flows of IFR-scale are capable of altering the macro-channel floor (Hood and Naiman 2000). It is well established in this discussion that IFR non-compliant flows have previously led to, and will continue to cause the gradual sedimentation of the Sabie-Sand River as a result of the reduced flows. This process affects mainly the macro-channel floor rather than the macro-channel banks. Investigations of the IFR sites show non-compliance against the IFR for all sites and so we can expect that alluviation of the river channel is occurring throughout the river, only differing by rate depending on the degree of non-compliance at specific sites. Riparian zones in arid ecosystems such as the lowveld are known to be vulnerable to flow reductions, especially the base flow component derived from subterranean water (Stromberg et al. 1996). It is likely that this situation is occurring in the Sabie-Sand River because of the severe effect that forestry and large dams have on the movement of subterranean water in the catchment. The effect of this is base flow reduction coupled with the enhanced alluviation of the channel contributes to the terrestrialization of the riparian zone (Naiman et al. 2005; Pettit and Naiman 2007). The periodic inundation of the entire macro-channel floor is also not occurring as frequently as it should, as would be the case if the IFR specifications for higher flows were met consistently. The situation is however better than that of base flow IFR compliance. Frequent failure to meet higher flow IFR's will allow species favouring xeric conditions to colonise the upper edges of the macro-channel and riparian zone. These factors contribute to the conclusion that the health of the river macro-channel and associated riparian zone habitat types have declined due to IFR non-compliant flows in the Sabie-Sand River. The macro-channel floor is particularly vulnerable to reduced flow conditions, and the riparian area is expected to shrink if the prevailing IFR non-compliant flows continue to occur.

Table 4-3. Table showing the likely trajectory of change in instream and riparian habitat units due to IFR non-compliance.

Riffles	Rapids	Runs	Pools	Headwater wetlands	Macro-channel	Riparian areas
↓	↓	↔	↔	↔	↓	↓

Table 4-3 shows a summary of the expected trajectory of change in habitat units present in the Sabie-Sand River if compliance with the IFR is not improved. Each habitat type is listed in the table above, and the trajectory of the health and outlook for each is indicated by the direction of the arrow.

4.5.3. The effect of non-compliance with IFR specifications on the hydrological regime and river structure and function:

The hydrological regime describes the long-term natural flow profile of a river. The premise underpinning the IFR system is that there are portions of the flow profile that are ecologically unimportant, or at least less important than others, and this portion of the flow regime can be excised and deployed for human use (King et al. 2008). By virtue of this fact, the very existence of the IFR has a negative effect on the hydrologic regime since it seeks to remove certain flows from the virgin flow profile. However, if we assume that the IFR serves as the new “virgin” hydrological regime, then the non-compliance with these specifications is detrimental to the ecological health of the Sabie-Sand River since ecologically significant flows will not be met. To correctly identify the ecologically unimportant flows, scientists need to have a good grasp of which flows are essential for biological maintenance (King and Louw 1998). If this assertion that there indeed exists portions of the flow regime that are ecologically unnecessary, and the least important flows are removed for other purposes, there should be no loss of species or biodiversity of any kind. Extensive literature searches have yielded no evidence of recent species loss in the Sabie-Sand River even though there is frequent non-compliance with IFR. It is unlikely that this is as a result of the precise and accurate identification of biologically relevant flows by scientists. Rather, I believe that the remarkable natural variability in the virgin flow regime of the Sabie-Sand River has exerted an intense evolutionary effect on the biota in the riparian and riverine zones. This evolutionary effect has resulted in a suite of species that are highly resilient to inter- and intra-seasonal variability in flow, and may even require this variability for survival (Townsend and Hildrew 1994). The species that currently occupy the Sabie-Sand River have evolved life history strategies and mechanisms to cope with this extreme variability and so the burden that extraction of water for human uses has placed on these species has not caused any large-scale attrition of individuals or species. We can therefore assume that the diversity of flows captured in the range of IFR specifications for both maintenance and drought scenarios has lead to environmental conditions that sit between the lower and upper lethal ranges for these organisms.

The expectation that non-compliance with IFR specifications would lead to changes in the structure and function of the Sabie-Sand River was reasonable when IFR’s were first introduced, and the measurement of this change was something that should have been part of the monitoring component of the management plan for the Sabie-Sand River. Monitoring of ecological objectives against IFR’s was planned and outlined in a document entitled “Sabie Monitoring Report” and hosted on the Department of Water and Sanitation Institute for Water Quality Studies (IWQS) website, under an initiative called the Water Resources Monitoring and Assessment Information

System (WRMAIS). The document can be obtained at http://www.dwaf.gov.za/iwqs/wrmais/other/Sabie_Monitoring_Report.pdf. The website is defunct and so information on the results and any updates of the monitoring programme cannot be found; whether they are now hosted elsewhere is unknown but exhaustive searches and numerous requests from DWA employees yielded no such information.

Changes to structure and function in the Sabie-Sand River have certainly occurred. Major floods in the river during the analysis period have considerably reworked the mosaic of structural units in the river and riparian zone (Parsons and Thoms 2007). With this change in structure has come the attendant change to the functions of the river (Parsons et al. 2006). The study by Parsons et al. (2006) found that the mosaic of channel types and physical and vegetation patches within the macro-channel of the Sabie-Sand River are more heterogeneous and variable after the large floods of 2000 than before. The principles of SAM allow for this kind of variability, and this is not perceived as a negative outcome; for a period some functions may be negatively affected while others will be improved (Holling et al. 1978). The KNP has integrated this concept in their mission statement by stating that they aim to manage the KNP to “maintain biodiversity in all its natural facets and fluxes” (du Toit et al. 2003). It must be pointed out that major floods of this magnitude are not addressed explicitly in the IFR since they are larger than any IFR specifications. As such, they have no place in the management design for the Sabie-Sand River, so evaluating the consequences of such floods against the IFR are null. They are nevertheless very important drivers of change in structure and function of the Sabie-Sand River and could not be ignored here.

In the absence of monitoring data and reports, and a paucity of literature on observed changes to river structure and function as a result of IFR non-compliance, no absolute conclusion can be drawn on whether IFR non-compliance has had a negative or positive effect on the structure and function of the Sabie-Sand River. Nonetheless, if we consider that heterogeneity is one of the goals of management of the Sabie-Sand River, we must acknowledge that even heterogeneity itself will be heterogeneous. Sometimes the mosaic of heterogeneous patches within the river and riparian zone will be highly heterogeneous in size, shape and composition and at other times less so. At this point, non-compliance with IFR specifications has led to a situation of steady siltation of the Sabie-Sand River over a number of years (Rivers-Moore and Jewitt 2007). These conditions are conducive to recruitment of particular plant species at the expense of others. As siltation progresses in the absence of flushing floods, these species will come to dominate the river, making the river and riparian zone less heterogeous. But the influence of a large disturbance such as a flood will reset conditions in the river and riparian zone to a more patchy and heterogeneous state (Parson et al.

2006). But on the basis of the results of the analysis undertaken here, the consistently low flows that cause non-compliance with IFR between 1976 and 2013 has led to flows that regularly do not match the mandatory flow regime, and have thereby simultaneously reduced the functional aspects of the river (due mainly to siltation), as well as lowered its structural heterogeneity.

Table 4-4. Table showing the likely trajectory of change in the hydrological regime, and river structure and function due to IFR non-compliance.

Hydrological Regime	River Structure	River Function
⬇	⬇	⬇

Table 4-4 shows a summary of the expected trajectory of change in flow regime, structural and functional components of Sabie-Sand River if non-compliance with the IFR continues. The trajectory of each is indicated by the direction of the arrow, highlighting the negative effect of reduced flows on the hydrological regime of the river. Note also the decline in structural and functional aspects of the river and riparian areas of the Sabie-Sand River because of recent historical as well as contemporary flow conditions.

4.5.4. The effect of non-compliance with IFR specifications on the hydraulics of the Sabie-Sand River:

We have established and discussed the fact that flows in the Sabie-Sand River are regularly too small to meet the IFR specifications, and this is the case for all the IFR sites in the river for both base and higher flows. Implicit in the IFR specifications are a number of flow characteristics that are linked to flow volume and flow rate, and these perform functions that are necessary if the river is to be maintained in the desired state. The major hydraulic factors that change when flow volumes and rates change include water velocity, discharge and shear stress (Gordon et al. 2004). Flows that are lower than those required to maintain IFR will exhibit lower water velocity, smaller discharge and diminished shear stress in comparison with IFR compliant flows (Bunn and Arthington 2002). The combined effect of this ultimately results in a lower capacity to transport sediments. This is in keeping with the patterns established above and also in the literature and imagery of the Sabie-Sand River and so will not be discussed further.

Another effect of this reduction in flow velocity, shear stress and discharge is concerned with respiration and feeding rates of instream organisms. The hydraulic aspects of streamflow play an important role in the diversity and distribution of aquatic organisms (Statzner and Higler 1986). Flows of reduced velocity carry less oxygen and food since less units of water pass a particular point in the river than a flow of higher velocity. As a result, conditions during non-compliant flows may aid species with lower oxygen requirements in colonising new environments (Erős et al. 2014). Mérigoux and Dolédec (2004) found that along a gradient of shear stress in a Mediterranean river, that environments with higher shear stress are host to fewer invertebrate taxa. Although this state of affairs may not be applicable to the Sabie-Sand River, if such a pattern does occur then the non-compliance with IFR values may favour greater species richness in the river. This is unlikely in the Sabie-Sand River, and the combined effect of reduced oxygen and less opportunity for filter feeding will in all likelihood reduce taxonomic diversity in the river because the Sabie-Sand River has a higher proportion of filter-feeders than Mediterranean streams and these taxa are the most sensitive to flow reductions (Picker et al. 2004). Literature on the effect of altered hydraulics in lotic systems is not common, and the majority of work on the subject comes from the 1980's and early 1990's. Work conducted by Wallace and Merritt in 1980 found that reductions in flow velocity (a consequent process if IFR specifications are not met, due to the reduced flow volume) had negative effects on the net-spinning activity of the Hydropsychidae larvae of the Trichoptera. Wallace and Merritt (1980) also point out that Simuliid Dipteran feeding efficiency is highly dependent on current velocity, and slower currents cause Simuliid feeding apparatus to operate less efficiently. In South Africa, this phenomenon has been successfully used to control black fly populations in the Orange River and elsewhere by modifying the flow regimes of rivers to limit the feeding efficiency of black flies, and consequently their populations (Palmer 1993). Further corroborating this work is a study by Power and Dietrich (2002) that found that there is notable shift in the structure and dynamics of of aquatic invertebrate communities in response to reductions in stream velocity and volumes. Their study was undertaken in coastal California, where flows are far more predictable than those in the lowveld. Lowveld rivers, including the Sabie-Sand River have a far more erratic flow profile than those of California, so the biota inhabiting these streams are likely to have evolved greater resilience to rapid changes in flow. The biotic community might not undergo any significant changes because of this resilience, but this should nevertheless form part of the monitoring protocol. The original protocol design did include an invertebrate monitoring program, as outlined in the Sabie Monitoring Report. This protocol was based on the performance of ten taxa that disappeared from the Sabie River during the drought of 1992. Unfortunately, no follow up results are available on the now defunct website or any associated websites at DWA. The unpredictable nature of the Sabie-Sand River's flow makes for an ideal situation in which to study intra- and inter-annual changes to community structure of aquatic invertebrates in response to flow. In addition, it may be useful to make comparisons to invertebrate response to changes in flow from other parts of the world. This would give us information on the stability and resilience of the Sabie-Sand Rivers aquatic biota to reduced flows, and will definitely aid in formulating a more accurate IFR regime.

The riparian zone rarely experiences any hydraulic features of the river, unless the river floods to a level beyond the specifications of the IFR. As a result, we will not explore the effect of the hydraulic aspect of flow in relation to the riparian zone, save for noting that in periods of extremely high flow the immense water velocity and shear stress associated with the higher discharge is very destructive to riparian plants. The higher the plants are situated up the banks of the macro-channel, the larger the flow has to be to reach them. Flows of this magnitude usually result in anaerobic soil conditions, and thus are responsible for the die-off of the riparian plants that are not swept away in the flood.

The above discussion gives us an idea of what happens to the important components of river hydraulics (water velocity, discharge and shear stress) under conditions of IFR non-compliance. These characteristics are easily summarised since they are primary physical processes related to fluvial geometry of the stream (Gordon et al. 2004). In summary, under conditions of IFR non-compliance, water velocity is reduced as is discharge and shear stress, and all these factors play an important role in sediment transport and community composition of instream biota.

Table 4-5. Table showing the trajectory of change in the hydraulic features of the Sabie-Sand River due to IFR non-compliance.

Water velocity	Flow discharge	Shear stress
⬇	⬇	⬇

Table 4-5 shows a summary of the trajectory of change in key hydraulic components of the Sabie-Sand River. The trajectory of each is indicated by the direction of the arrow, highlighting the negative effect of reduced flows on the hydraulic qualities of the river.

4.5.5. The effect of non-compliance with IFR specifications on the geomorphology of the Sabie-Sand River:

Current levels of IFR non-compliance have exacerbated the pre-existing patterns of sediment accumulation in the river, which were documented by Heritage et al. (1997). This has the effect of changing the Sabie-Sand River from a historically bedrock dominated river into one dominated by geomorphological features comprised of sediments, such as single and braided alluvial channels (Broadhurst and Heritage 1998; Heritage et al. 2001a). If the pattern of regularly not meeting IFR’s is perpetuated, an increasingly less heterogeneous mosaic of geomorphological units will prevail. It is likely that this decline in heterogeneity will diminish available habitat types in the Sabie-Sand River, thus negatively affecting biodiversity (van Coller et al. 1997). Consistent compliance with the IFR would arrest this process but it is obvious that this is not happening and sedimentation continues at greater rates than managers of the Sabie-Sand River require for the river to be managed in the desired state.

As outlined in Section 1.3.4.5 of Chapter 1, five common geomorphological templates occur in the Sabie-Sand River (Heritage et al. 1997). Each of these templates reacts differently to changes in flow. Here we will examine how IFR non-compliance affects each of these templates. These templates exist along a continuum based on the influence of alluvium in each. On one side of the continuum is bare bedrock and on the other is the braided alluvial channel-type (Moon et al. 1997). When large floods occur in the catchment, the river is reset to a state in which the bedrock template dominates (Parsons et al. 2006). As time passes, the river becomes dominated by channel types comprised of ever-greater proportions of sediment.

Continued non-compliance with IFR's will lead to diminishing influence of bedrock channel types in the Sabie-Sand River catchment. Geomorphological characteristics are shaped in part by base flow IFR specifications, but it is the higher flows that are responsible for the mobilisation of sediments and therefore the preservation of bedrock elements in the river. While we have seen that compliance with higher IFR specifications has been substantially better than that of base flow compliance (this pattern holds for all IFR sites), this does not mean that the sediment flushing flows are performing what they have been specified for. This is because persistent non-compliance with base flows has led to greater rates of sedimentation than expected throughout the entire year, and so the higher flows are unable to move all of the sediment that has accumulated over this period. To maintain the bedrock patches in the river, higher flows than specified in the IFR are needed to perform the function of sediment removal, and these occur at very infrequent intervals. The results of the analysis in Chapter 3 showed that floods of a volume expected to occur every third year in reality only occur between every 5.25 to 7 years depending on which IFR site one inspects. This means that floods that are capable of moving the additional sediment load will occur even less frequently.

The pool-rapid sequence is the closest geomorphological unit to the bedrock channel type on the continuum (Heritage et al. 2001a). As described in Section 1.3.4.5 of Chapter 1, the flow dynamics of the stream are very complex in the pool-rapid channel type. Rapidly changing flow characteristics typify these channel types, making generalised patterns of the interaction of water and the underlying template quite difficult for this channel type. Due to this complex interplay among water movement, sediments, and upstream streambed morphology in pool-rapids, our extrapolative capacity with regard to how these factors interact in different parts of the same river is low (Thompson and Wohl 2009). This study has revealed the fact that IFR non-compliance is universal at all IFR sites, but we cannot use this information to infer a common pattern of sediment transport in pool-rapids for the Sabie-Sand River at the scale of the pool-rapid. The lower flows linked to IFR non-compliance may be simultaneously responsible for the erosion and sedimentation of pool-rapid complexes in different parts of the river. However, at the broader scale we know that the Sabie-Sand River as a whole is undergoing large-scale sedimentation and has done so for a number of decades (Heritage et al. 1997). This knowledge, coupled with the understanding that pool-rapid channels were once bedrock channels on a path towards a channel type with greater alluvial influence means that at this juncture, it is likely that the pool-rapid channel type is showing waning influence in the river. As the system state matures (with little disturbance such as floods), the channel types with bedrock components will become engulfed in alluvium. A large flood would reset this template, giving bedrock elements greater influence once more. Work conducted by Parsons et al. (2006) showed that of the major channel types, pool-rapids in the Sabie River underwent the greatest degree of change in response to the large flood of February 2000. This befits pool-rapids as they occupy a transitional state on the bedrock-alluvium continuum.

Another transitional channel type is the mixed anastomosing channel. This channel type is underlain by bedrock with varying proportions of sediment present. The proportion of sediment is strongly predicted by the time since the last large flood (Rountree et al. 2000). The longer the period since the last flood, the greater the sediment to bedrock ratio. Parsons et al. (2006) found it to be the most dominant channel type before the large floods of February 2000. Appropriately for a transitional channel type, the mixed anastomosing channel type underwent the second largest change in response to the floods of February 2000, second only to the pool-rapid channel type (Parsons et al. 2006). The mixed anastomosing channel type was less prevalent immediately post-flood, but IFR non-compliant flows have reversed this trend and there is once again a greater proportion of mixed anastomosing channel in the Sabie-Sand River (Rountree et al. 2000; Rivers-Moore and Jewitt 2007).

Fully alluvial channel types represent the climax geomorphological system state since they occupy the opposite end of the spectrum to bedrock channels, and usually come to dominate in periods where large floods have not occurred for a long period. Sections of the stream that are fully covered by alluvium include both single and braided channels. Two opposing schools of thought exist regarding alluvial sections of rivers, and how they respond to changes in flow, particularly large flood events. Rountree et al. (2000) postulated an episodic disequilibrium model in which long periods of sediment accumulation occur and are broken by powerful, short duration events (floods) that strips sediments from the river. Parsons et al. (2006) found a different pattern. Their study concluded that between the years 1999 and 2000, the proportion of braided alluvial channel types more than doubled after the massive February 2000 flood. However, the work by Rountree et al. (2000) relates to the effects of the floods of 1996 in the Sabie-Sand River, which was substantial with a return interval of approximately 1:50 years (2 200 m³/s at its peak). The floods during February 2000 were enormous, calculated in the absence of flow gauging structures (the flood destroyed many) to be roughly 7 000 m³/s (Heritage et al. 2001b), possessing a return interval of more than 1:200 years (Smithers et al. 2001). The flood of 1996, while large and capable of significant sediment transport did not overtop the macro-channel banks, while the floods of February 2000 broke the banks of the macro-channel (Parsons et al. 2006). The flatter topography of the upland section beyond the macro-channel bank served to moderate and attenuate the power of the river flowing beyond the macro-channel banks, causing deposition of alluvial material derived from within the macro-channel in upstream sections of the river that did not break the macro-channel bank (Parsons et al. 2006). This had the effect of depositing sediments rather than denuding the river of alluvium as would be expected, illustrating that the ability of a stream to erode sediments is non-linear depending on the spatial extent and topography of the area under investigation. If we use this framework to understand the geomorphological components of the Sabie-Sand River, we see that the findings of Rountree et al. (2000) and Parsons et al. (2006) are congruent rather than disparate. It also allows us to view two different outcomes from large flood events as different ways of resetting the system template. It is upon this template that the current scenario of unmet IFR's occurs. The persistent non-compliance with IFR's will push the mosaic of channel types in the Sabie-Sand River towards a state in which alluvial channel types will represent a greater proportion of channels in the river, with progressively less influence from bedrock channels, which under the virgin flow regime and catchment land cover would likely have dominated the river.

Table 4-6. Table showing the trajectory of change in the geomorphological units of the Sabie-Sand River due to IFR non-compliance.

Bedrock anastomosing	**Mixed pool-rapid**	**Mixed anastomosing**	**Alluvial single thread**	**Alluvial braided**
⬇	⬇	⬆	⬆	⬆

Table 4-6 shows a summary of the trajectory of change in all five channel types of the Sabie-Sand River. The trajectory of each is indicated by the direction of the arrow, highlighting the fact that non-compliance with the IFR is linked to a mosaic of channel types that are inclined to have greater proportions of sediment present.

4.5.6. The effect of non-compliance with IFR specifications on the vegetation of the Sabie-Sand River:

The patterns of vegetation change and community composition that we see in the Sabie-Sand River is highly dependent on the geomorphological changes that occur. As explored in the previous sections, non-compliance with IFR's is linked to greater alluviation of the Sabie-Sand River, and this system state will favour plants that prefer sandy substrates at the expense of those that dwell in mixed anastomosing and bedrock channel types. Knowledge of this effect has been utilised to create a *Breonadia* model for the Sabie-Sand River for the KNP section of the river (McLoughlin et al. 2011). The riparian tree *Breonadia salicina* is known to favour rocky channel types. While the seedlings germinate readily on any substrate, they only establish on rocky substrates. Thus, monitoring of the population structure of *B. salicina* can be used as an indicator for diminishing influence of rocky substrates. The first monitoring assessment of the Sabie-Sand River using the model (a good example of SAM in action) shows that *Breonadia salicina* habitat (bedrock channels) is at critically low levels (McLoughlin et al. 2011). The progressive sedimentation of the river has led to a turnover in the vegetation community in the Sabie-Sand River over several decades. The nature of this turnover will be discussed here, as well as how this turnover affects the river's structure and function.

With the diminishing influence of bedrock and mixed anastomosing channel types in the Sabie-Sand River in response to the effects on flow linked to IFR non-compliance, plant species that favour these channel types are becoming less abundant. Van Coller et al. (1997) showed that the populations of two important species that have a preference for bedrock and mixed anastomosing channel types, namely *B. salicina* and S*yzygium guineense*, were already declining in 1997. With the closure of the Kruger National Park Rivers Research Programme (KNPRRP) and the Kruger River Post-Flood Research Programme, research on the Sabie-Sand and other KNP rivers has not been conducted at the same intensity over recent years (Breen et al. 2000; Parsons 2004). Consequently, literature on the current status of *B. salicina* and *S. guineense* populations is not readily available, save for the information documented by McLoughlin et al. (2011) outlined above, showing critical levels of favourable habitat loss for these species. The focus of the work reported by McLoughlin et al. (2011) is *B. salicina*, and so not much attention is given to *S. guineense* or the species that are now dominant on the Sabie-Sand River. However a report concluded in 1999 by McKenzie et al. found that the population of *Combretum erythrophyllum* (a species that thrives in alluvial sediments) appears to be flourishing in the Sabie-Sand River.

The reed *Phragmites mauritianus* is also adept at colonising newly laid alluvial deposits, and like *C. erythrophyllum* has been proliferating in the Sabie-Sand River over a number of decades. Even though *P. mauritianus* is regarded as a pioneer species (like most reeds), the extent of its expansion over a number of years before the floods of 2000, and then after the floods points towards a system state in which sedimentation is occurring very rapidly and extensively (Clements 1916; Heritage et al. 1997). *Phragmites mauritianus* is not a traditional pioneer species in that it is not rapidly succeeded by other species over time; it dominates the lower portion of the macro-channel especially the more mobile morphological units (eg: alluvium in mixed anastomosing channel types, and later the braid bars in the braided alluvial channel types) and to a lesser extent the outside edges of the macro-channel floor. The established reed beds support the consolidation of alluvial sediments, and after a number of years this process leads to a successional shift towards woody species, starting on the outer margins of the macro-channel (Kotschy et al. 2000). The sustained directional shift towards a system in which the reed *P. mauritianus* becomes more widespread on the macro-channel floor of the Sabie-Sand River is evidence for the recent alluviation of the Sabie-Sand River, since *P. mauritianus* recruits strongly on alluvial soils that are newly established (van Coller et al. 1997; Rogers and Biggs 1999). This effect coupled with the proliferation of *C. erythrophyllum*, which prefers well developed and stable alluvial deposits, shows both the long-term occurrence and increasing dominance of alluvial controlled channel types (van Coller et al. 1997).

While the changes in the plant communities along the length of the river are in themselves of interest to managers of the river, the ongoing directional species turnover has ramifications for the river that go beyond changing vegetation dynamics (Allan and Castillo 2007). Importantly, these changes affect many aspects of the structure and function of the river and these facets of the river have linkages to river health. Non-compliance with IFR specifications may not be the original cause of increased sedimentation in the Sabie-Sand River, but it is partially responsible for the present-day exacerbation of sedimentation rates. It is important to remember that riparian vegetation can be both a product and an agent of change in the river (Dollar et al. 2007). A case in point would be the role that plantation forestry has had on streamflow in the Sabie-Sand River. These plantations are responsible (as the agent of change) for substantial flow reductions in the river and are therefore partially responsible for the alluvation of the river. This has led to the enhanced recruitment of *P. mauritianus* (as the product of change) downstream.

Fluvial geomorphologists were consulted in the original design specifications of the IFR, and the role of the higher flow portion of the IFR was to maintain flows that would fully or at least partially arrest sedimentation, and flush excess sediment build-up with periodic large flows (King et al. 2008). Across all IFR sites it is apparent that these flows are not occurring with the requisite frequency, particularly the periodic large flood flows. This has led to a shift in the vegetation community in which the mosaic of vegetation patches is becoming less heterogeneous (Pettit et al. 2006). Riparian areas are a key element of river ecosystems (Merritt et al. 2010). They perform numerous functions of ecological and economic value (Merritt et al. 2010). The perpetuation of the suite of these functions is reliant on a heterogeneous mix of vegetation types (Power and Dietrich 2002). It therefore follows that the uni-directional shift described above will have the effect of reducing functionality and structural heterogeneity in the Sabie-Sand River. Rivers that have a heterogeneous mosaic of vegetation offer higher quality habitat for other plants and animals since a range of microclimates are available to biota (Lovett et al. 2006). The maintenance of a structurally diverse riparian zone has also been found to play a role in the reduction of anthropogenically-derived pollutants entering fluvial ecosystems (Jacobs et al. 2007). This is a risk factor for the Sabie-Sand River, mostly due to activities that cause land-cover change in the riparian zone, such as agriculture (Coetzer et al. 2010). The process of terrestrialisation of the riparian zone is mostly due to land cover changes, but IFR non-compliance cannot be underestimated as a contributor to this process. This occurs through reduced bank storage as a direct result of lower flow volume in the stream, as well as enhanced sedimentation rates that consolidate alluvial sediments and thereby do not undergo the alternate wet and dry cycle that characterises the riparian zone (Naiman et al. 2005). The non-compliance with IFR specifications at all IFR sites diminishes the heterogeneity of vegetation patches in the Sabie-Sand River. This has a negative effect on the ecological health of the stream.

The aquatic macrophyta of the Sabie-Sand River appear to be understudied and so no literature could be sourced regarding their actual response to IFR non-compliance.

Table 4-7. Table showing the trajectory of change in the vegetation heterogeneity and associated characteristics of the Sabie-Sand River due to IFR non-compliance.

Vegetation heterogeneity	Habitat availability	Terrestrialisation of riparian zone
↓	↓	↑

Table 4-7 shows a summary of the trajectory of changes in characteristics of the vegetation in the Sabie-Sand River's riparian zone. The trajectory of each is indicated by the direction of the arrow, highlighting the fact that non-compliance with the IFR is linked to diminishing ecosystem health.

Non-compliance of flows against the IFR specifications is indirectly linked to reductions in the heterogeneity of vegetation patches in the riparian zone, and this in turn reduces habitat availability for animals and other plants. Increased sedimentation has also been implicated as one of the drivers of terrestrialisation of the riparian zone.

4.5.7. The effect of non-compliance with IFR specifications on the aquatic invertebrate communities of the Sabie-Sand River:

Studies on the invertebrate communities of rivers have established that they are sensitive to flow changes as well as changes in habitat; this was explored to some degree in Section 4.5.4 (Bunn and Arthington 2002). The flow regime of a stream is linked to changes in habitat; in fact this is one of the fundamental tenets of the IFR system (King et al. 2008). Consequently, flow changes often lead to habitat changes and the relatively short life cycles of invertebrates result in quick responses of invertebrate communities to changes in flow (Poff et al. 2010). Similar to the vegetation and other components of the Sabie-Sand River, aquatic invertebrates are simultaneously products and agents of change in the river. First we will explore them as products of change in relation to the non-compliance of IFR, and then as agents of change.

As outlined in Section 1.3.4.7 of Chapter 1, it is not necessary to explore the aquatic invertebrates of the Sabie-Sand River at a finer level of detail than feeding guild for the purposes of this dissertation. The guilds to be discussed include the shredders, collectors, grazers and predators, after the River Continuum Concept set out by Vannote et al. (1980). It is at this level of organisation that a study of this nature would observe shifts in the composition of aquatic invertebrate communities. The reason for this is that the guild splits different aquatic invertebrates into groups on the basis of their means by which they obtain nutrition (Vanni 2002). These different invertebrate guilds utilise different habitats on the basis of their feeding strategy (Vannote et al. 1980), and we have explored the changes to habitat units in Section 4.5.5 above in this Chapter. Just as these habitat units (ie: channel types) have changed in response to the reductions in flow, so have the aquatic invertebrate communities.

The proportions of the various guilds vary in the different reaches of the river depending on a number of factors, the two most important are the food source they exploit and the channel type that they inhabit (Malmqvist 2002). The relationship between food source and channel type is complex; different channel types have varying levels of allochthony and autochthony and this has an effect on the composition of organisms depending on whether they are capable of exploiting allochthonous or autochthonous food sources (Gordon et al. 2004). It has been observed that the general pattern is for greater reliance by aquatic invertebrates on allochthonous material in bedrock dominated channel types and greater prevalence of organisms exploiting autochthonous production in alluvial influenced channel types (Doi 2009). We have observed that there is a strong and ongoing directional shift in the Sabie-Sand River towards channel types dominated by alluvial deposits. This state of affairs is unfavourable to the shredder guild, since members of this guild are mostly confined to either bedrock and mixed anastomosing sections of rivers and these sections are showing diminishing influence in the Sabie-Sand River. If this is a reality, we should observe a decline in the population of members of the following Orders over most of the Sabie-Sand River: Ephemeroptera, Plecoptera, Trichoptera, Megaloptera, many of the Odonata, some of the Diptera (Chironomidae and Simuliidae) and Coleoptera, as well as fewer freshwater crabs (Phylum Crustacea) (Picker et al. 2004). Unfortunately, little contemporary literature exists to either refute or corroborate this claim, but this situation does highlight the need for research into the status of the invertebrate communities of the Sabie-Sand River and possibly other rivers in the KNP. In support of the hypothesized attrition of the invertebrate populations from the Orders above, information gleaned from the document entitled "Sabie Monitoring Report" stated that under drought conditions in the past, 10 taxa disappeared from the Sabie River, including members from the Ephemeroptera, Trichoptera and Diptera. Other taxa (Order: Hemiptera and Phylum: Mollusca) prevalent in other channel types also disappeared, showing that lower flow conditions are not necessarily favourable for taxa that prefer alluvial channels, even if low flows enhance the development of favourable habitat for these taxa.

Collectors are a more diverse guild than the shredders, comprising taxa ranging from those that aggregate fine particulate organic matter for nutritive purposes, across the range to those that utilise filter feeding techniques (Cummins 1974). Defining the preference of this guild for any channel type is not as simple as that of the shredders. The more diverse feeding strategies in this guild lead to a wider channel type preference, although the mixed anastomosing channel type offers a suitable spectrum of habitats, some of which are more strongly influenced by bedrock and others by alluvium (Kingsford 2000). Those taxa within the guild that prefer habitat types with a stronger bedrock influence will inhabit reaches of the stream that offer such habitat while others with a preference for a mixed anastomosing habitat with greater alluvial influence will dominate in those portions of the stream (Parsons and Thoms 2007). Under current conditions of IFR non-compliance, this guild of aquatic invertebrates is likely the most stable of all the guilds, showing declines in those collectors that prefer bedrock influenced mixed anastomosing channels but also expansion of those taxa that have a preference for the more alluvially dominated mixed anastomosing channels (Walters and Post 2011). Some of the members of this guild that might see expansion of range would include some members of the Orders Trichoptera, Diptera and Ephemeroptera. Other invertebrates that would likely respond well under present conditions include the molluscs and nematodes (Vannote et al. 1980).

Grazers dominate in channel types where in-channel photosynthesis is greatest, because they rely on aquatic plants as a food source (Vannote et al. 1980). In the Sabie-Sand River, mixed anastomosing channels with a stronger alluvial influence show the highest production of instream plant material (Bunn and Arthington 2002). Thus, mixed anastomosing channels with a significant fraction of sediment are the most favoured channel type for grazers, provided sediment transport is low. Common taxa in this feeding guild include freshwater gastropods, a number of Baetid species (Order Ephemeroptera), adults forms of the Corixidae (Order Hemiptera) and the larval stages of some caddisflies (Order Trichoptera) (Picker et al. 2004). These taxa dwell in a channel type that oscillates between the mixed bedrock and alluvial type, and are therefore fairly tolerant of a range of habitats. However the directional shift towards a stream with a stronger alluvial signature has probably had a detrimental effect on the grazer population, and this condition is linked to IFR non-compliance.

The final feeding guild that we will discuss here is different to the others in that they subsist by feeding on the other guilds. Consequently, these organisms inhabit all sections of the stream in which a suitable food source is available (Vannote et al. 1980). Predators of aquatic invertebrates include a range on invertebrate and vertebrate organisms, but here we will pay attention to only the invertebrate taxa. Some of these invertebrates include both larvae and adults of members of the following Orders: Plecopotera, Hemiptera, Odonata, Megaloptera and the vast Coleoptera, from which the major predators include member of the families Dytiscidae, Gyrinidae and the Hydrophilidae (Picker et al. 2004). The composition of this guild varies in different channel types depending on prey preference and abundance. Food webs in aquatic environments have a greater number of trophic levels than terrestrial environments (Arim et al. 2010). Aquatic systems host predators that regularly prey on other predators, and the addition of the potential effects that changes in flow may add to the interaction of predators with other invertebrate guilds complicates these interactions further (Power et al. 1996). The fact that populations of aquatic invertebrate predators are regulated by the complex interplay of changes in prey populations and how prey reacts to changes in flow and habitat, and also the effect that changes in flow affect the predators themselves means that speculating on what happens to aquatic invertebrate predators in the absence of literature is futile. Furthermore, the presence of multiple predator trophic levels in aquatic ecosystems means that the detection of the loss of some of these predators can be quite difficult, since in many cases the niche of any particular predator may be filled by another if the first should disappear (Power et al. 1996). We can however speculate on how the composition of the predator guild might change under the current conditions of IFR non-compliant flows. As shown in Table 4-8 below, the current compliance levels (super-imposed on the pre-existing template of greater levels of sedimentation due to land cover change in the catchment) have had a negative effect on both shredders and grazers. Therefore, any predators that feed exclusively on taxa from these two guilds are likely to show declines in their population. Populations of predators that feed on collectors should remain stable, as should those predators that feed on other predators. It is unlikely that predators are incapable of switching to different prey items should their favoured food source diminish, since predators as a general rule have a wider range of nutritional options than their prey (Finlay 2001).

As agents of change in the Sabie-Sand River, aquatic invertebrates perform many functions crucial to the ecological health of the river. While the role of aquatic invertebrates in maintaining river health cannot be under-estimated, the fact that invertebrate organisms are so numerous means that many are not well described or understood (Clark and Samways 1996). Scientists therefore do not have a comprehensive understanding of the entire suite of functions performed by aquatic invertebrates. Here we will discuss some of the major ecosystem functions that would fail in the absence of aquatic invertebrates.

The ubiquity of these organisms and their proportional biomass versus instream vertebrate organisms means that aquatic invertebrates play an extremely important role in the nutrient cycling within rivers (Sanders 2000; Wallace and Webster 1996). Due to the lack of a full understanding of these organisms and the roles they play in nutrient cycling and other processes, we often do not realise their importance until they are lost from the system, and on occasion this is not even possible if the functional niche of the taxon of interest is filled by members from other taxa (Power et al. 1996). Aquatic invertebrates are also important for the movement of nutrients within the stream and beyond into the riparian zone (Fisher et al. 1998). The processes of nutrient cycling and movement within the stream is interlinked, and highly mediated through aquatic invertebrates, and they also have an influence on both primary production and decomposition processes depending on which feeding guild they are in (Wallace and Webster 1996). The complexity and interlinkages of these processes means that understanding them in the context of IFR non-compliance is extremely difficult. What is known is that many species within the various feeding guilds are sensitive to habitat change and reductions in flow and these processes are linked to IFR non-compliance (Dewson et al. 2007). While many taxa may be stable or resilient to the reductions in flow over shorter time-scales, the consequent effects (eg: changes in water quality, habitat changes) of persistent IFR non-compliance could negatively influence nutrient cycling and movement as well as production and composition (Gordon et al. 2004), and thereby cause state-change in the longer term. The detail and scope of this influence needs further research and should form part of any future invertebrate monitoring and feedback programme. Recent developments in stable isotope analysis holds much promise for the study of complex aquatic (and other) foodwebs, and may provide us with the ability to determine changes in composition of the various feeding guilds, as a measure of the health of their populations, and hence, stream health (Abrantes et al. 2014).

Table 4-8. Table showing the trajectory of change in the feeding guilds of aquatic invertebrates of the Sabie-Sand River due to IFR non-compliance.

Shredders	Collectors	Grazers	Predators
↓	↔	↓	↔

Table 4-8 shows a summary of the trajectory of changes in the aquatic invertebrate feeding guilds of the Sabie-Sand River. The trajectory of each is indicated by the direction of the arrow, highlighting the fact that non-compliance with the IFR is linked to diminishing health of the shredder and grazer feeding guilds. The collectors and predators appear to be stable in the face of sustained IFR non-compliant flows. The functional roles performed by the respective guilds will show a parallel trajectory of change.

4.5.8. The effect of non-compliance with IFR specifications on the fish community structure of the Sabie-Sand River:

The Sabie-Sand River is known to be the most fish species rich system in South Africa (Rivers-Moore and Jewitt 2007). This is noteworthy since most of the instream fauna were exterminated in the early 1900’s as a result of gold mining effluent entering the river, yet the river now hosts only 4 alien species out of a total of 49 (Pienaar 1985, Rivers-Moore and Jewitt 2007). Fish are important to the ecological function of the river since they occupy all feeding niches during their lifecycles (Sloman et al. 2005). Early ad hoc surveys of the ichthyofauna of the fish of the Sabie-Sand River led to the slow accumulation of the species list, and formalised surveys followed in the 1960’s (McLoughlin et al. 2011).

Currently, monitoring of fish is undertaken using a rapid assessment method that is capable of detecting changes in fish populations, but is not sensitive enough to identify whether habitat, river flow or water quality is responsible for the observed changes in population (McLoughlin et al. 2011). This is unfortunate in light of the fact that earlier work by Rivers-Moore et al. (2004) found that two members of the genus *Chiloglanis* have a preference for particular thermal regimes and could be used as indicator species for water quality on that basis. *Chiloglanis anoterus* and *Chiloglanis paratus* dwell in similar habitat types with regard to water depth, flow velocity and cover requirements but have different temperature preferences (Rivers-Moore et al. 2004). Because the two species are also ubiquitous and common in the Sabie-Sand River, their relative abundance can tell us much about aspects of streamflow quality (Rivers-Moore et al. 2004). Additionally, they both show a strong degree of habitat specificity to riffles (Rivers-Moore et al. 2005), which as discussed in Section 4.5.2 of this chapter are declining in both quality and area in the face of IFR non-compliance. They could thereby serve as indicators of habitat availability in addition to their viability as water quality indicators. The thermal features of the river can be linked to other aspects of a changing flow regime (Castellarin et al. 2004). An example of this is flow velocity and volume; reductions in flow velocity and volume are usually associated with an increase in water temperature (Vogel and Fennessy 1995). This example is pertinent here, because flows that do not meet IFR specifications are of a smaller volume and lower velocity than the flows needed to comply with IFR, and consequently will be warmer than they would be under conditions of IFR compliance. We also know that flows that are lower than the IFR cause changes to habitat through sedimentation. *C. anoterus* and *C. paratus* can therefore serve the dual purpose of indicating changes to water quality through their relative abundance, and also changes to habitat through their presence or absence in any chosen section of the Sabie-Sand River.

The effect of insufficient flow relative to the Sabie-Sand River IFR has other consequences for fish populations in general. Section 1.3.4.8 of Chapter 1 provided a comprehensive and detailed account of a number of aspects of the ontogenic and other aspects of the life cycle of fish that are dependent on cues from either streamflow or sunlight, or the combination of the two (Penman and Pifferrer 2008). Fish gonadogenesis is known to be reliant on cues from streamflow, and sex ratios in fish are determined by water temperature (Baroiller et al. 1995; Penman and Piferrer 2008). This investigation has shown that actual streamflow is insufficient to meet the IFR specifications. Consequently we know that the flow regime of the river has been modified, leading to changes in the timing of flows and altering aspects of water quality. This has the potential to disrupt ontological development, and the maintenance of the sex ratio of fish in the Sabie-Sand River, highlighting the potential for shifting flows to negatively affect fish populations at the individual, population and community level (Burt et al. 2011). Changes to the thermal regime of rivers has also been linked to the changing size of fish larvae, the efficiency of yolk utilisation, and even muscle physiology (Burt et al. 2011). These changes are not necessarily linked with an increase in water temperature, rather that the range of favourable temperature has been transgressed.

Changes to streamflow will occur under current IFR non-compliant flows; whether the changes will be sufficiently large to disrupt fish life cycles is at this point unknown but since fish play an important role in the Sabie-Sand River it is advisable that research into changing thermal regimes in the Sabie-Sand River should be initiated as soon as possible to avoid any disruption to functional components of the river.

Table 4-9. Table showing the trajectory of change to major aspects of fish health and populations of the Sabie-Sand River, linked to IFR non-compliance.

Individual fish health	**Fish community health**	**Sex ratios**	**Gonadogenesis (and other ontogenic features)**
⬇	⬇	⬇	⬇

Table 4-9 shows a summary of the trajectory of changes to the fish of the Sabie-Sand River. The trajectory of each is indicated by the direction of the arrow, highlighting the fact that non-compliance with the IFR is linked to diminishing health of individual fish, as well as populations of fish. Aspects of the development of larval fish appear to be under pressure due to the changing thermal regime of the river. The warmer water in the stream is also likely to have had an effect on the sex ratios of fish in the Sabie-Sand River.

4.5.9. The effect of non-compliance with IFR specifications on the groundwater of the Sabie-Sand River:

The link between groundwater and the baseflow of the Sabie-Sand River has been explained in a number of sections in this dissertation, most notably in Sections 1.3.4.3 and 1.3.4.9 in Chapter 1. Groundwater is extremely important to the Sabie-Sand River, especially the Sabie River because it is a perennial river. As such, the river is highly reliant on groundwater to maintain perenniality, particularly in years when precipitation is very low (Hughes 2000). Since the relationship between groundwater and baseflow is straightforward and dealt with elsewhere, I will not dwell on the subject here but rather concentrate on the functional aspects of groundwater, and how IFR no-compliance affects these important functions.

Infiltration of rainfall and the subsequent subterranean flow results in the baseflow component of the stream, and is the reason that the Sabie-Sand River flows in the dry season months. In the wet season, the river often carries so much water (in comparison with the adjacent groundwater) from overland flow that the river shows a net loss from the stream into the banks of the river (Gordon et al. 2004). This process is important because it aids in the retention of water in the catchment, and also mobilises ions that are important for the growth of riparian plants (Salama et al. 1994). Baseflow derived from groundwater is also important in the maintenance of certain channel types (mainly pools and riffles) during the dry season (King et al. 2008).

We have noticed that IFR compliance, particularly for the baseflow portion of the specifications whether examining the drought or maintenance scenarios, is very low with frequent consecutive months of non-compliance. This is especially evident at the InsideKNP IFR site as demonstrated in Chapter 3. Compliance with higher flow IFR's is stronger with less frequent infractions. From this, we can deduce that the process of water transfer from the stream to the riverbanks is likely to have become amplified over time. The reverse movement of water (from banks to stream) is likely to have been significantly attenuated. Low base flow compliance can be seen as a lower proportion of groundwater entering the stream as base flow, and so better high flow compliance (the "peak" overland flows) will see a greater volume of water entering the banks of the river due to the steeper gradient of saturation between stream and banks. The reverse process will not occur as strongly as occurred under the virgin flow regime since the banks now have much more potential to absorb water than years in which the base flow was greater. If the movement of water from stream to banks is sufficiently large to mobilise ions for use by riparian plants, then we should not observe any adverse effects on the health of the riparian plants. It appears that this is the status quo even though IFR's are not met regularly, as riparian plants are in good health in the Sabie-Sand River. However, this process may be sensitive to very severe reductions in baseflow, and if the level of groundwater drops below a critical threshold so that the combined height of groundwater plus the addition of water from the stream is insufficient to reach a level accessible by plants then we may see unfavourable conditions in the riparian zone. Such a scenario could be manifest if significant increases occur through the construction of large dams in the upper reaches of the dam, or if irrigation abstraction grew. It is likely that if this occurs, we would first see deterioration in the quality or even death of the shrubs and small trees in the riparian zone, as these plants possess shallower rooting systems that are unable to access a lower water table. The large trees may still be able to access deeper subterranean water sources and so would continue to live, although long-term suppression of the water table would limit recruitment of all riparian plants.

Table 4-10. Table showing the trajectory of change to functional aspects of groundwater of the Sabie-Sand River, linked to IFR non-compliance.

Stream to bank water transfer	Bank to stream water transfer	Ion mobilisation in streambanks
⬆	⬇	⬌

Table 4-10 shows a summary of the trajectory of changes to functional aspects of groundwater in the Sabie-Sand River. The trajectory of each is indicated by the direction of the arrow, highlighting the fact that non-compliance with the IFR does not have a major effect (at the moment) on ion mobilisation in the riparian zone. IFR non-compliance however does affect the transfer of water between the river and riverbanks, with greater movement from the stream to the banks and less in the opposite direction.

4.6. Conclusions on the relationship between ecological health and IFR compliance in the Sabie-Sand River:

A thread connecting all of the impacts to aspects of the Sabie-Sand River's structure and function is sedimentation. From all of the above summaries, we see that IFR non-compliance leads to sedimentation, and this is the most substantial driver of change in the Sabie-Sand River, having ramifications for a wide variety of structural and functional facets of the Sabie-Sand River. We can therefore conclude that management of sedimentation rates in the river at multiple spatio-temporal scales holds the key to managing the ecological health of the Sabie-Sand River, and management plans should take heed of this.

A fundamental premise underpinning the IFR system is that any flows extraneous to the ecological functions desired for the Sabie-Sand River are not included in the IFR flow regime (King et al. 2008). All flows in the IFR are designed to fulfil an ecological function of some description, so when IFR's are not met it is assumed that these functions remain unfulfilled. The regularity with which IFR's were not met over the analysis period did result in attrition of some functions within the Sabie-Sand River, but none of these appear to be significant enough to eliminate those functions from the ecosystem of the Sabie-Sand River. The IFR's are designed to be adjusted in response to better data and information on the Sabie-Sand River. Good data and information on flow are available for the Sabie-Sand River, yet the IFR values have not been adjusted since the inception of the system. If we consider this situation in conjunction with the fact that numerous IFR infractions have occurred, two problems arise. Firstly, management has failed in their duty to ensure flows meet IFR's. Secondly, neither the IFR specifications nor the IFR system has been appraised in a bid to identify where it has not performed adequately as a management tool.

Organisational failure in the management of the Sabie-Sand River is evident, in that the management unit tasked with maintaining IFR's has not ensured the consistent realisation of IFR's. From a theoretical standpoint and assuming that the IFR values are indeed representative of real ecological requirements, this is tantamount to wilful participation in the destruction of the ecosystem of the Sabie-Sand River. However, evidence as presented in Section 4.5 of this chapter shows that this is not the case and that the river, while undergoing gradual sedimentation, is in a functional state. Reasons for why the Sabie-Sand River and its ecology appears to be in better health than expected will be postulated in the section below.

4.6.1. Abiotic factors playing a role in stability and resilience of biota to IFR non-compliance:

As mentioned above in Section 4.3 of this chapter, IFR's were designed to be minimum design flows that "should avoid unacceptable biodiversity loss" as long as they are always fulfilled (du Toit et al. 2003). Results from Chapter 3 show that regular transgressions occurred for all IFR sites, sometimes showing large disparities between maintenance scenario levels and actual flows, and frequently falling below the requirements for even the drought scenarios. Yet no biodiversity loss has been reported for the Sabie-Sand River. This demonstrates that the biotic components of the Sabie-Sand River system appear to be highly stable under, and/or resilient to low flows. As an aside from IFR relevant issues, a number of large floods have occurred since records have been kept for the Sabie-Sand River with the riparian and instream biotic communities surviving these too with little or no species loss (Pettit et al. 2005). This points toward a stability and resilience under high flows, low flows and high flow variability rather than only low flows. The perpetuation of a range of species to such a wide array of flow characteristics means that it is likely that species that inhabit the river and riparian zone are likely to use a stability mode of colonisation post-disturbance rather than resilience modes, since it is unlikely that evolution has equipped all species with a wide array of effective but costly ways in which to combat different types of disturbance.

Abiotic factors play an obvious role in the resistance to disturbance that we witness in the biotic components of the Sabie-Sand River, by driving evolutionary change in organisms that inhabit the river and riparian zone. Other factors in the abiotic class that have been considered as role players in relation to resistance and resilience are pollution (although this factor may be biotic in some cases) and climate change (Folke et al. 2004). Neither of these factors was explored explicitly in this investigation over the time-scale for which the study took place and so will not be discussed in much depth.

After much consideration of potential reasons for why species appear to persist even during low flows in the Sabie-Sand River, a number of important factors come to the fore. These would include the fact that the Sabie-Sand River is relatively clean versus the other lowveld rivers such as the Incomati and Olifants Rivers (Breen et al. 2000; Mirumachi and van Wyk 2010). In periods of low flow or IFR non-compliance, effluents from various sources comprise a greater proportion of the flow in any river (Harwood 2014) so it fortunate that there is not a high effluent load in the Sabie-Sand River. Although this factor does not necessarily impart greater resilience to the Sabie-Sand

River's biota, it does mean that some portion of water quality has remained largely unaffected by human interference and in so doing does not place additional pressure on the biota that, in conjunction with other factors could negatively affect populations.

Another abiotic factor that may affect the resistance and resilience of the biota in the Sabie-Sand River is land use change in the catchment. Significant changes have occurred over a number of decades in the catchment, the most potentially destructive being the advent of forestry, and also mining. The effect of forestry on the flow regime has been adequately described in Chapter 1, and explored in Chapter 3. Currently no mining operations occur in the catchment, but were historically responsible for extensive degradation of the Sabie-Sand River from the 1910's until the Department of Mines took action against pollution in the river in the late 1940's, which at that stage was virtually sterile (Pienaar 1985; Rivers-Moore and Jewitt 2007). The biota of the river made a complete recovery, and the Sabie-Sand River in currently one of the most species rich in South Africa, further demonstrating unique resistance features since recolonisation of the river occurred successfully (Pienaar 1985; Rivers-Moore and Jewitt 2007). Change in land use due to anthropogenic activities was and continues to be a major contributor to the changes to the flow regime and water quality of the Sabie-Sand River (Pollard 2002). Up to the present it appears that the flow regime has not been altered drastically enough to adversely affect the biota in the stream; even though the IFR has not been met the biota appear to persist in the face of the preceding and present degree of change in flow regime. The fact that IFR non-compliance has not caused harm to the biota of the Sabie-Sand River, yet has never been adjusted will be revisited in the following section since it represents the most obvious disjunct in the SAM process.

Historical events in the catchment have presented the biota with different but more extreme conditions in the past (extensive land cover change during and after the expansion of forestry operations in the upper catchment, and the mercury and other pollution from mining operations) than IFR non-compliance. Yet, the biota have maintained a functional community from what was termed a sterile stream (as a result of mining effluent) in the 1930's (Pienaar 1985), and have survived the streamflow reductions associated with forestry in the upper catchment (Moon et al. 1997; le Maitre et al. 2002). The different pressures against which these biota are resistant are diverse. It is therefore unlikely that the entire community of species that comprise the biota of the Sabie-Sand River possess the ability to overcome such a range of pressures without the loss of species. From this we can deduce that it is unlikely that all species exhibit resilience traits because the possession of such dissimilar modes of resilience to the varied pressures in the Sabie-Sand Catchment would be evolutionarily costly (Brock et al. 2003). Rather, the river's biota are likely to be of the resistant variety, and are capable of colonising the river quickly post-disturbance (Labbe and Fausch 2000; McCluney et al 2014). But how is this possible, and what is the crucial difference in the Sabie-Sand River that sets it apart from the other lowveld rivers that are in poorer health?

Besides the above-mentioned features of the river, resistance of the biota of the Sabie-Sand River can be attributed to a number of other factors, and it is these which I believe to be the most important. They include the following:

- The unique mix of land uses in the catchment;
- The spatial arrangement of these land uses;
- The presence of relatively large seasonal and ephemeral tributaries (presence of tributaries from other catchments in close proximity);
- The location of the important tributaries;
- The size of the catchment.

The present mix of land uses in the Sabie-Sand River, while having transformed the catchment substantially from the pre-industrial land cover, has been less harmful to the riverine and riparian biota than it was in the past and also less harmful in terms of what it currently comprises. With the termination of gold mining in the upper catchment, water quality improved substantially leading to re-colonisation of the river by biota. To the north of the Sabie-Sand catchment lies the Olifants River. The highlands of this river lie in the Mpumalanga coal fields, much of which is currently mined. As a result of mining effluent, water quality in the Olifants River is poor in relation to the Sabie-Sand River (Hobbs et al. 2008; de Villiers and Mkwelo 2009). Forestry has also had a substantial impact on the Sabie-Sand River catchment, but besides the impacts on the flow regime which are far-reaching, the detrimental effects on biodiversity and ecosystems is mostly confined to the plantations, leaving the lowveld portion of the Sabie-Sand River relatively unharmed by forestry (le Maitre et al. 2002).

The importance of conservation areas is often under-rated when considering the role they play in the resilience of the adjacent non-conserved areas, but this is changing with the advent of the ecosystem conservation paradigm as opposed to biodiversity hotspot conservation (Poiani et al. 2000). A major consideration for why the Sabie-Sand River remains in good ecological condition over most of its length including some reaches outside of the KNP is because of the protection afforded by the KNP to the lower portions of the river and its tributaries. Of these tributaries, the Nwaswitshaka is likely to play a lead role in the resistance of riverine and riparian biota in the catchment, as both a refuge for organisms during disturbance episodes (Rivers-Moore and Jewitt 2007), but also as the source area in a source-sink dynamic system (Cabeza and Moilanen 2001).

While sophisticated methods for designing protected areas have come to the fore in recent years, it is by fortuitous chance that the geography and spatial arrangement of land use in the Sabie-Sand River and its tributaries allows for the persistence and recolonisation of the river and riparian zone by species from source areas such as the Nwaswitshaka (Cabeza and Moilanen 2001).

Although the Sabie-Sand River is part of a larger river system (the Incomati river system), if we consider only the catchment of the Sabie-Sand River, at 7 096 km^2 is a relatively small catchment compared with the rivers rising on the escarpment of southern Africa. In light of this, the role and importance of undisturbed tributaries in the KNP as refugia and source areas for colonisation are further highlighted (Rivers-Moore and Jewitt 2007). The small size of the Sabie-Sand Catchment means that dispersion of organisms from the tributaries situated in the KNP of the Sabie-Sand River can occur quite easily over short time scales since the distance that the colonising species needs to cover is never very large (Cumming 2014; McCluney et al. 2014). The Nwaswitshaka makes confluence with the Sabie River roughly halfway down the length of the South African portion of the Sabie River. This means that the Nwaswitshaka is ideally positioned since it is close to the western border of the KNP, over which the majority of the disturbance to the Sabie-Sand River is sourced. Post disturbance colonisation of impacted reaches of the Sabie-Sand River can occur quickly from biota in the Nwaswitshaka because of the proximity of the stream to the edge of the KNP. Moreover, the entire length of the Nwaswitshaka is protected; anthropogenically derived disturbance of the tributary is thus very limited and unlikely. Furthermore, the size of the Nwaswitshaka means that it is unlikely that the Nwaswitshaka could be devastated by flooding since its catchment area is relatively small (795 km^2). However, the riparian area of the tributary is prone to burning since fire management is not an active process in that portion of KNP, and this may negatively affect the species composition of the riparian zone and consequently the role of the Nwaswitshaka as a refuge for riparian plant species. However, KNP management does attempt to manage for the promotion of biodiversity using fire and so it is assumed that fire is unlikely to negatively impact species in the riparian zone of the Nwaswitshaka (du Toit et al. 2003). It has been established that ephemeral tributaries of perennial streams are capable of harbouring species in refugia even though the flow regimes may be very different (Stromberg et al. 2009; Chester and Robson 2011), so this is not a limiting factor in the role that tributaries play in the Sabie-Sand River.

The above description of the complex interplay between the land use types and the arrangement thereof, as well as the spatial organisation of tributaries in the catchment is currently the most important feature maintaining resilience to disturbance in the Sabie-Sand River Catchment. This includes the low flows associated with IFR non-compliance. In light of these findings, I will propose below some recommendations for the management of the Sabie-Sand River that I believe will be more favourable for all stakeholders in the catchment while maintaining the IFR albeit in a transformed condition.

4.7. Recommendations for better implementation of the IFR system in the Sabie-Sand River:

As mentioned in previous chapters, the primary and major flaw of the IFR system has been the lack of monitoring and feedback, ie: the breakdown of strategic adaptive management of the Sabie-Sand River. Recent literature has acknowledged this (McLoughlin et al. 2011), and early proponents of the approach did warn of its limitations should this aspect of the system not be adequately implemented (Rogers and Biggs 1999). Although this state of affairs is not acceptable, and in light of recurrent IFR non-compliance but no concomitant species loss, it appears that the IFR values may have been initially over-estimated and thus (fortunately) the consequences of IFR non-compliance have not been as ecologically detrimental as was hypothesized at the advent of the IFR management regime. The findings of this study have been justified since the IFR management model for the Sabie-Sand River has been superseded by a different approach (Sawunyama et al. 2012), which by virtue of its existence is an admission that the IFR system was fatally flawed. Additionally, the "new IFR" specifications are lower than the first iteration across all months and for both the maintenance and drought scenarios, further supporting the conclusions of this study (Sawunyama et al. 2012). The new system for managing the flows for ecological maintenance in the Sabie-Sand River operates as a real-time decision support system (Sawunyama et al. 2012). This system allows for managers to undertake assessment of conditions in the river on an ongoing basis and adjust flows accordingly ensuring maintenance of ecological and other flows (Sawunyama et al. 2012). The system integrates a rainfall-runoff model, a hydraulic model (for river flow management) and a water resource model (that is comprised of the Reserve, water use rationing and allocations components), showing a technological improvement on the original IFR system (Sawunyama et al. 2012). Successful implementation of the system is heavily reliant on releases from the Inyaka Dam, and good communication between dam operators and the catchment management agency (Sawunyama et al. 2012), but the addition of a rainfall-runoff model allows managers to make or curtail dam releases quickly with knowledge of what volume of the precipitation in the catchment will be converted to streamflow. Crucially, the system is sensitive to scheduled abstractions for irrigation from the river, and as such has the capacity to pinpoint where illegal abstractions have taken place (Sawunyama et al. 2012). Data on whether the rainfall-runoff model for the Sabie-Sand River is sensitive to soil moisture levels is not available, but this is likely to be the case. It is however important to consider that the proportion of rainfall converted to runoff is reliant on soil saturation antecedent of the rainfall event as this can affect the amount of rainfall converted to runoff (Arnold et al. 1998). This is particularly important in highly seasonal regions where rainfall and soil saturation differs substantially across seasons, and the Sabie-Sand River is highly seasonal (Viglione et al. 2009). Another important aspect of the change to a new management protocol relates to the fact that even though monitoring failed under the old IFR system and has been addressed with the new real-time system, clear standard operating procedures need to be implemented for monitoring flows and the biotic and abiotic response to changes in flow. If this is not undertaken with real intent, the new system is likely to fail for the same reasons as the first.

It is also very important that sedimentation be explicitly addressed in the new monitoring framework, and measurement of both sedimentation rates and ecosystem response to sedimentation be appropriately measured. More importantly, the measurement of sedimentation and ecological responses to sedimentation needs to have clear counter-actions associated with any breach of a defined threshold of sedimentation; otherwise the same mistakes regarding the closing of the SAM loop will be made as in the first iteration of the IFR. I have shown that increased sedimentation is a likely outcome of IFR non-compliance under the previous system. Without monitoring sedimentation explicitly together with one or two key biotic responders, it will also not be possible with the new system to show that flow thresholds do fulfill the required ecological functions they are meant to maintain.

In light of these recent developments regarding the new IFR, the recommendations of this study are slightly altered. Evidence presented in this chapter points towards the potential for decreasing the IFR values. The decision to lower the IFR specification was taken and IFR's are now approximately 75% of the volume of the original IFR across all months for maintenance and drought IFR scenarios. While this action will certainly result in increasing rates of alluviation, the biota in the Sabie-Sand River appear to be resistant to a certain degree of gradual sedimentation as long as periodic flushing flows occur. While flows considered of large enough volume and duration to be flushing flows were too infrequent to meet the requirements of the old IFR system, there was no serious (detrimental) effect on the biota besides a flux in the ratio of species that are resistant to alluviation and those that are not, or less resistant. This ratio is dynamic depending on the degree of alluviation and time since the last large flood and the dimension of the last flood, but in keeping with the KNP mandate of maintaining biodiversity in all its natural facets and fluxes. The "natural" aspect of the mandate may be regarded as contentious but in view of the highly variable nature of flows in the Sabie-Sand River, I believe that the current ecological state of the system and its biota is within the range of potential acceptable states of ecological health. The new real-time system is also stronger with respect to the KNP mandate since it incorporates the “fluxes” component more explicitly than the old IFR system. Table 1-1 - Table 1-4 in Chapter 3 give the IFR dimensions for only two potential scenarios (maintenance and drought); such a set of tabulated values is too rigid to recognise the flux component of the KNP biodiversity mandate.

Some other recommendations that I believe would benefit the IFR system are:

- IFR’s must be cognizant of ecological requirements beyond South Africa’s border with Mozambique.
- The primary iteration IFR’s need to be sensitive to extended meteorological drought and wet periods associated with El Niño and La Niña.

The maintenance of ecological systems beyond the borders of South Africa would overburden management in the Sabie-Sand River, and it is unlikely that funding for such an endeavour would be mobilised. While maintenance of ecological systems in neighbouring countries might be beneficial for the environment, it is also beyond the scope and mandate of the managers of the Sabie-Sand River. It is however important to remember that just beyond the border of the KNP and South Africa is the Corumana Dam. While it has been established that the biota of the Sabie-Sand River are capable with dealing with alluviation, lower flows in the Sabie-Sand River may contribute to the sedimentation of the dam (Palmieri et al. 2001). This could have knock-on effects upstream of the dam, since dams reduce upstream-downstream connectivity (McCluney et al. 2014). The successful management of the Sabie-Sand River is therefore reliant on good management of the river over the border in Mozambique. This is not adequately addressed in the real-time model now in use for the Sabie-Sand River.

As discussed above, the first version of the IFR is sensitive to the facets of biodiversity aspect of the KNP biodiversity mandate, but not to the fluxes having only a drought and maintenance specification for the IFR. Longer-term fluctuations (caused by El Niño and La Niña, or the Southern Oscillation hereafter referred to as SO) that affect the prevailing climate in the catchment are not adequately planned for in the IFR. While the maintenance and drought specification could theoretically cover the alternate extended (3 – 7 years) periods of wet and dry associated with the SO, I believe it is necessary to plan for maintenance and drought IFR specifications tailored for dry (El Niño) and wet (La Niña) periods (Crétat et al. 2012). Lower IFRs could be used during El Niño, and higher ones for La Niña. This will give managers more freedom since periods of sustained low rainfall will not have unreasonably large IFR’s to meet. The linkage among SO, rainfall and streamflow has already been explored in Australia (Chiew et al. 1998), but no evidence of research explicitly linking river flow to

SO events for South Africa appears in the literature. This is likely due to much of the focus and funding for climatological work in South Africa going to climate change (Pouris 2012). With the switch to the new real-time model, this issue is somewhat mitigated since the model deals with the flux component of river flow more comprehensively (Sawunyama et al. 2012). This also means that the new model is likely to be sensitive to climate change related effects on river flow although this is not mentioned by Sawunyama et al. (2012).

It appears that the new real-time model IFR system has seen higher rates of compliance with IFR mainly due to a reduction in the IFR flow volumes (rather than an increase in flow volume). The recommendations of this study were that the IFR be reduced, thereby freeing up water for use in poverty alleviation programmes and sectors that are capable of generating much needed jobs and money in the South African economy (Gleick 2000; DWA 2013). Water management in South Africa is fraught with difficulty; scarcity alone provides challenging conditions in which to manage the resource effectively. Matters are further complicated because all role-players in water resource management must be aware of the complex dynamics of the socio-political, economic and agricultural requirements of the country. Although progress is slow and flawed, if principles of SAM (ie: learning from errors and successes) are adhered to we will become progressively better at managing water resources for the benefit of all South Africans.

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