Development of a Predictive Management Tool for Orange River Blackfly Outbreaks

Report to the

Water Research Commission

by

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Executive Summary

Background and Motivation

Blackfly outbreaks along the middle and lower Orange River have the potential to cause losses to livestock production estimated conservatively at R300 million per annum. Such outbreaks occur periodically, with the most recent outbreak in 2011, and before that in 2000-2001. Economic losses occur along some 1200 km along the middle and lower reaches of the Orange River between Hopetown and Sendelingsdrif. Typically, the blackfly species causing the problem is *Simulium chutteri*, although other species including *S. damnosum* and *S. adersi* cause outbreaks periodically. The outbreaks occur in spite of a scientific Control Programme, based on aerial (helicopter) applications of two different larvicides. The success of the control programme depends largely on correct timing of larvicide applications.

The Control Programme makes considerable economic sense, with benefits outweighing costs to a ratio of 10.7. The beneficiaries of the programme are not restricted to livestock farmers, but also to other sectors and the wider community, including irrigation farmers, tourists and residents in the area. However, despite considerable research and funding since the control programme was initiated in 1991, outbreaks continue to occur every five to ten years. This results in scepticism of the value of the Control Programme. Reasons for repeated and ongoing outbreaks are complex, and include: higher-than-normal winter flows; changes in turbidity; changes in the dominant blackfly species; larvicidal resistance; and management challenges.

There have been several attempts to reduce incidences of outbreaks including an integrated control programme and ongoing monitoring; probabilistic matrix-based model to predict annoyance periods of adult females; optimization of larvicide applications; and formation of an Advisory Committee, but these have not had the desired outcomes. Part of the reason for this is that stakeholder interest tends to fade during periods when the problem has 'gone away', but resurfaces rapidly when there is an outbreak. This problem is typical of most pest control programmes, and highlights the need for long-term oversight and supervision of the control programme.

Aims

1. Test and refine the current probabilistic blackfly outbreak model by including temperature and turbidity data.
2. Undertake climate change scenario analyses to assist future management planning.
3. Provide a framework to monitor blackfly larval densities.
4. Provide a Blackfly Control Programme auditing system using a mobile phone application whereby the general public can report on nuisance levels of adult blackfly.
5. Build capacity among staff of the Blackfly Control Programme (Northern Cape Agriculture).

Methods

Consolidating the lessons learned

This was achieved through a prioritised list of driver variables for the model, which informed data collection gaps not already identified. It included a literature review and targeted stakeholder discussions, which provided the basis for refining the predictive model previously developed by Rivers-Moore et al. (2014).

Data Collection

This phase began with the team collating and analysing all previous monitoring data, with the twofold aims of understanding when outbreaks have occurred, and providing a dataset for validating the Bayesian network (BN) outbreak probability model (see next section). This was followed by a field data gathering phase, involving collection of time series data for flows and turbidity at 14 monitoring sites over one-two years (weekly turbidity data, hourly water temperature data). Turbidity data measurements were based on clarity tube depths that were converted to $mg.\ell^{-1}$. Seasonal collection of larvae and pupae across a range of hydraulic biotopes and habitats was undertaken to understand seasonal changes in relative abundance of different blackfly species. These data complement the larval and pupal scores already collected with spot water temperatures and flows every two weeks by the DAFF.

Model testing and evaluation

Following on from the first year's data collection, the model was re-run based on inclusion of temperature and turbidity data, together with an analysis of longer-term flow data for a number of gauging weirs, as per the approach of Rivers-Moore et al. (2014). This included refining the conditional probabilities on which the model data are based, through building a case file based on previous data.

This was followed by a process of assessment and validation of the BN model, using different species (based on hydraulic preference thresholds) and identifying periods of previous outbreaks, which will in turn be correlated with the monitoring data. This was possible because the theoretical framework of the model was deliberately designed to be aligned within the context of a velocity-seston (turbidity) model that predicts blackfly responses to different hydrological and turbidity conditions. Numerous iterations of the BN model were run, incorporating various flow and water temperature climate change scenarios.

Management

The likelihood of such a tool succeeding has been enhanced through the development of a website and mobile phone application to increase monitoring coverage, whereby the general public can input data from their cell phones on nuisance levels of adult blackfly. Nuisance levels of adult blackfly can be recorded and correlated with larval density classes, to estimate the time lag between recorded high densities of larvae versus outbreaks of adult blackflies. The framework allows for evaluation of the predictive management model as a framework for capacity building, adaptive management and ongoing auditing of the programme.

Extent to which the contract objectives were reached

Test and refine the current probabilistic blackfly outbreak model by inclusion of temperature and turbidity data, and using previous flows and monitoring data.

This was successfully achieved.

Undertake climate change scenario analyses to assist future management planning.

This was achieved, using the simulated mean daily flow data from the UKZN's Hydrology Department. Simulations were based on downscaled climate-change data, and indicated that intermediate future flows are likely to increase by 60% from present-day flows.

Provide an evaluation framework for monitoring data of blackfly larval densities, based on the outbreak model.

This aspect of the study was successful.

Provide a Blackfly Control Programme auditing system using a mobile phone Application whereby the general public can report on nuisance levels of adult blackfly.

This was successfully achieved.

Capacity building of Blackfly Control Programme (Northern Cape Agriculture) staff.

This achieved limited success, partly due to staff turnover. However, staff engagement was enthusiastic and participatory, and we believe that the results of this study will be well-received.

Summary of major results and key findings

- Water quality was fairly consistent between sites, but showed seasonal variation.
- Conductivity and pH had little impact on blackfly species patterns, with the exception of very high (> 1000μS.cm^{-1}) conductivities in the irrigation return flow channels. Diatom data do, however, suggest that conductivities in the main Orange River have been increasing.
- Turbidity was a key driver in triggering ecosystem switching between dominance of pest blackfly species, and other blackfly species co-occurring with benthic algae.
- Flow volumes and water temperatures affect turbidity levels, efficacy of larvicides, and availability of habitat for various ecosystem components (benthic algae, blackfly species).
- Thresholds were successfully identified from the abiotic-biotic relationships, which were incorporated into a Bayesian network model to predict the probability of blackfly outbreaks.
- A predictive management framework was successfully constructed.

Discussion, recommendations for further research, knowledge dissemination and technology transfer

Larvae of *S. chutteri* exhibit a wide tolerance of water quality conditions (conductivities of 2-55 mS.m^{-1}). Water temperatures are favourable throughout the year for blackfly life history development, although the marked cooling during autumn and winter is likely to lead to reduced numbers of generations over this period, and favouring larger larvae that develop into more fecund adults. The negative correlation between *S. chutteri* and *S. damnosum* showed that only one of these species dominates at any one time at a site, with the other species largely competitively excluded. Changes in turbidity cause switches in blackfly species populations and a concomitant increase in benthic algae. A combination of reduced flows, increased water clarity and more alkaline water tends to favour the “standard complex” fan structure blackly species, which are also not regarded as major pest species, while the opposite of these variables favours conditions that increase the likelihood of pest blackfly outbreaks.

For the predictive management framework to be successful, the following will need to occur:

- Ongoing collection of blackfly density monitoring data, but to also include collection of turbidity data and presence/ absence of benthic algae;
- Uploading of these data, together with Fly Worry Index data, via the website;
- Updating of the BN with these data, and periodic audits of the various data components, with ongoing model refinement;
- A "champion" who would administer the framework, with supporting funding for monthly hosting of the App;
- A revision of the economic impacts of blackfly in the four economic zones.

Technology transfer will occur after completion of the study, by making stakeholders aware of the framework. This will also be achieved through a follow-up article in the Landbouweekblad, following on from the earlier article of October 2016.

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Glossary of Terms

Term	Definition
Abiotic controls	Habitat variables (e.g. turbidity, discharge) that affect blackfly numbers
Bionomic	The study of an organism, and its relation to its environment
Biotic controls	Biological drivers (benthic algae, abundance of reeds, predators) that affect blackfly numbers
Child node	A variable in a Bayesian network model with links feeding into it from other variables
Conditional Probability	The probability that a child node will be in a given state, conditional upon the interacting state probabilities of its parent nodes
Diapause	State of arrested development during any one developmental stage (egg, larva, pupa or adult)
Gonotrophic	Relating to the feeding and egg-laying components of a life cycle
Multivoltine	A species with multiple (and overlapping) generations per year
Node	Element of a Bayesian network representing a variable, and associated with variable states
Ontogeny	Origin and developmental process of an organism
Outbreak	Defined as when blackfly larval densities exceed a threshold score of 6, and/ or when adult blackfly annoyance levels reach a maximum score of 3
Parent node	A variable in a Bayesian network model with links going out of it to other variables (i.e. to child nodes)
Quiescence	State of dormancy
Univoltine	A species with one generation per year
Voltinism	Term used to denote the number of generations of an organism (usually insects) during a year

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1. Introduction

The Orange River has a unique place in South Africa's bio-geographical, hydrological and political histories. It is the oldest river system in South Africa with a unique fish parent diversity (Skelton, 1986), and is the longest and biggest (by volume) river in the country. Moreover, it has been a rich water resource in the driest part of South Africa, where the stone-age implements and place names reflect human use going back for millennia. Diamond mining in the 1870's, social upliftment for so-called "Poor Whites" in the 1930s, and nationalist policies in the 1960s, forms the background to the gradual impoundment of this river (van Vuuren 2012). The first of these was the Buchuberg Irrigation Scheme, opened in 1934: a 10.7 m high weir with 121 km of irrigation channels. Next came the Gariep Dam (previously Hendrik Verwoerd Dam), which began storing water in September 1970. This is the largest impoundment in South Africa, with a capacity of some 5, 340, 000 Mega litres. Not only does this dam provide irrigation water and power (some 889 GWh capacity from four 90 MW hydro-electric power generators), but it also forms the head of the Orange-Fish River inter-basin transfer scheme. Some 130 km downstream of Gariep Dam is the van der Kloof Dam (previously PK le Roux Dam), with half the storage capacity of the Gariep Dam, but still the second-largest dam in South Africa, and the impoundment with the highest dam wall at 108 m from foundation. This impoundment is the main control for water releases downstream into the Orange River, also generating 932 GWh annually from two 120 MW turbines.

1.1. The blackfly problem: History of Blackfly research projects on the Orange River

The relatively steep slope of the Orange River not only proved to constrain impoundment schemes for many years due to development costs (van Vuuren 2012), but also provided the habitat for species of naturally occurring blackfly with preferences for high flow velocities and turbidity. Blackfly outbreaks along the middle and lower Orange River have the potential to cause losses to livestock production estimated conservatively at R300 million per annum (Rivers-Moore et al. 2014). This figure excludes losses in the tourism and irrigated agricultural sectors, primarily attributed to loss of tourist and labour days through high annoyance levels (Mullins 2007). Economic losses occur along some 1200 km along the middle and lower reaches of the Orange River between Hopetown and Sendelingsdrif. The major pest species is *Simulium chutteri*, with more than 250 breeding sites (riffles) identified along the affected river sections, but *S. damnosum*, *S. nigritarse* and *S. adersi* are also culprits (De Moor 1994, and citing others). Adult females of *S. chutteri* and *S. damnosum* feed primarily on mammals (livestock), whereas *S. nigritarse* and *S. adersi* feed primarily on birds.

In response to the "blackfly problem" has been a research history of more than 25 years, strongly supported by the Water Research Commission. Projects included fundamental research of blackfly ecology on the Orange River, and the design of the Blackfly Control Programme by Palmer (1997), with a follow-up project ten-years later to explore alternative larvicides due to larval resistance of temephos (Palmer et al. 2007). This project further recommended stakeholder involvement, with a multi-stakeholder Control Programme management structure proposed, but the recommendations were never implemented. Studies were also undertaken on adult stages of blackfly (Myburgh 2003), although the final consensus was that the blackfly larval stage remained the most effective control option.

Despite a long history of research, monitoring and management, outcomes have been met with mixed success (Palmer et al. 2007; Rivers-Moore et al. 2014). Periodic outbreaks of blackfly continue to occur, with the most recent outbreak in 2011 (Rivers-Moore et al. 2014), and before that in 2000-2001 (Palmer et al. 2007). Conditions along the Orange River have also changed with the completion of Phase 1 of the Lesotho Highlands Water Programme, resulting in changes in water quality, flow patterns and blackfly species (Palmer pers. obs. in Rivers-Moore et al. 2014; Moonsamy 2015), and particularly with respect to increased conductivity values (Moonsamy 2015). Reasons for repeated and ongoing outbreaks are complex, and include: higher-than-normal flows (Palmer et al. 2007), changes in turbidity levels promoting real or perceived switching of dominant blackfly species (Fredeen 1977; Rivers-Moore et al. 2014); larvicidal resistance (Palmer and Rivers-Moore 2008), and management challenges (Rivers-Moore 2014). This is only likely to become worse due to anticipated increased populations of blackfly during the year in response to global warming (Rivers-Moore et al. 2013c).

Whereas blackflies can be considered pest species, they also serve as an important source of food for many predators within water bodies (Carlsson 1967; Palmer and Palmer 1995), so that a management goal should be control rather than eradication of pest blackflies. Ultimate solutions to this problem are constrained by the conflicting resource needs of the various stakeholder sectors along the middle and lower Orange River. Thus, while flow manipulation may be feasible in theory, its application is complicated by the income that would be lost to ESKOM through hydro-electric power generation in winter months, where power demand is highest. Agricultural activities are typically mixed, with the same land owners who suffer livestock losses also needing irrigation water for vineyards. At the same time, the DAFF is tasked with controlling the problem through larvicide applications, but where the logistically more convenient larvicide is no longer effective because of larval resistance. The lower and middle Orange River blackfly problem can truly be described as a “wicked” problem, defined as difficult or impossible to solve because of contradictory user requirements, and complex interdependencies among variables (Rittel and Webber 1973 – see Box 1 for characteristics). However, by using a probabilistic approach, various scenarios can be assessed, thereby facilitating management options which are better or worse. This approach was successful in demonstrating that the cause of recent outbreaks was more likely to be a management-related rather than a biological issue (Rivers-Moore et al. 2014). Not only has this model shown the need to collect improved turbidity and water temperature time series data, but also highlights the potential for developing a framework for evaluating ongoing monitoring data through correlations with predicted previous outbreak periods using the Bayesian network model; basis for climate change scenario analyses to assist future management planning; and significantly a public participation tool for greater transparency and buy-in from all stakeholders to promote joint problem-solving approaches.

Box 1: Rittel and Webber's 1973 formulation of wicked problems in social policy planning were specified as having ten characteristics:

1. There is no definitive formulation of a wicked problem.
2. Wicked problems have no “stopping rule i.e. since there is neither a definitive problem formulation, nor a clear solution; there is also not a clear end-point to the management intervention process.
3. Solutions to wicked problems are not true-or-false, but good or bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial and error, every attempt counts significantly.
6. Wicked problems neither have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is unique.
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
10. The social planner has no right to be wrong (i.e., planners are liable for the consequences of the actions they generate).

1.2. Blackfly Control Programme

Pest blackfly outbreaks occur in spite of a scientific control programme, based on helicopter application of two different larvicides. The control programme extends over some 850 km of the middle and lower Orange River, where 148 rapids have been identified as optimal breeding habitat for pest blackfly species (Palmer et al. 2007; Figure 1). While impetus may fade during periods when the problem has 'gone away', this does not reduce the need for a stakeholder-driven, holistic and longer-term solution to the problem. The success of the control programme depends largely on correct timing of larvicide applications. The Orange River Blackfly Control Programme was initiated in 1991, and has generally been successful in controlling outbreaks of pest blackflies for most of the time. It is based on monitoring using a ten-point scoring system for larval and pupal densities developed by Palmer (1994), which is scientifically robust and simple to use. Larval density data are scored by the DAFF (Upington and De Aar offices) on a 2-weekly basis, using the 10 point scale developed by Palmer (1994), reflecting seasonal changes of larval densities of the main blackfly pest complex comprising *Simulium chutteri* and *S. damnosum* (Figure 2).

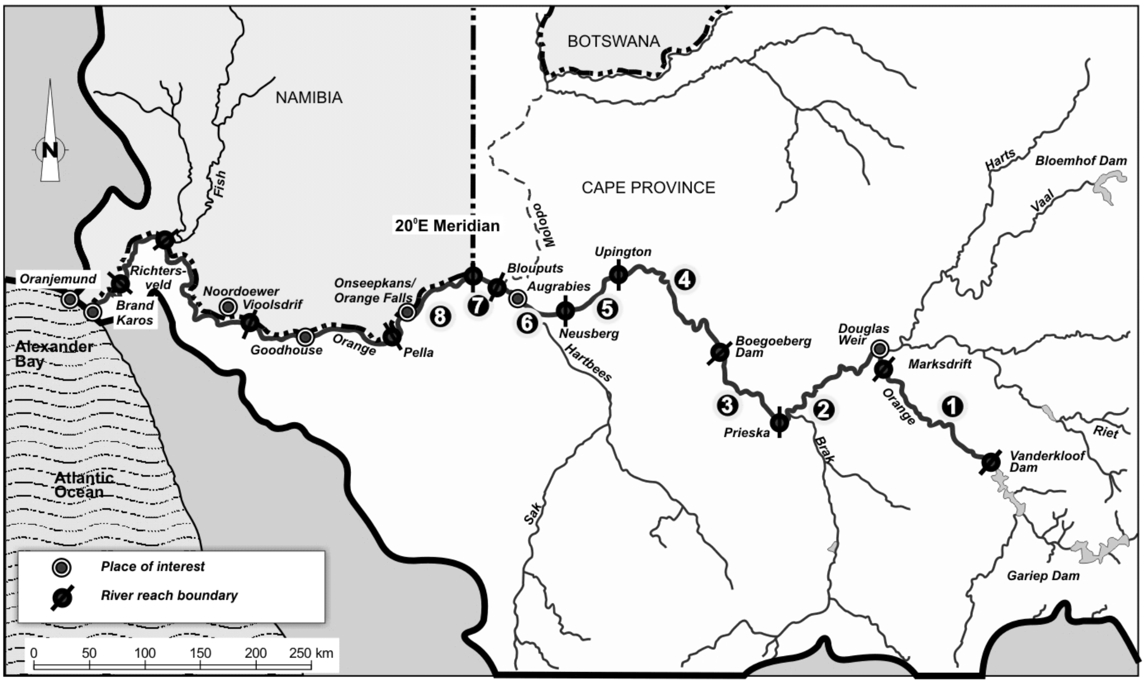

Figure 1 General locality map of the middle and lower Orange River, and reflecting extent of main pest blackly control programme. Numbers reflect river reach zones used by Palmer et al. (2007) for hydrological modelling.

There are a number of options for blackfly control, including flow manipulation, physical removal of aquatic weeds, aerial spraying of adult flies, protection of livestock using insecticides, biological control and larvicide application. The blackfly control programme along the middle and lower Orange River is based on aerial applications of larvicides to control the pest species *Simulium chutteri*. Larvicides are generally applied three times in autumn and six times in spring (Palmer and Palmer 1995). The two larvicides registered for blackfly control in South Africa are Vectobac® (produced from the naturally occurring bacteria *Bacillus thuringiensis* var. *israelensis* (B.*t*.i.), and Abate® (organophosphate temephos) (Palmer and Palmer 1995). Wide scale application of this larvicide, and blackfly larvae's continuous exposure to it, could lead to resistance being developed (Palmer and Palmer 1995).

Figure 2 Example of what a larval density score of 10 would look like using Palmer's (1994) scoring system

1.3. Blackfly lifecycle

While all four of the main problem blackfly species exhibit similar potential fecundities (based on numbers of ovarioles), with little difference in seasonality (Palmer 1997), subtle differences in life history strategies determine which species have greater pest potential. Brittain (1991) mentions a number of life history traits that enable aquatic invertebrates to thrive with regulated flows. The more primitive Simuliids (*Prosimulium*) are typically univoltine, while the more advanced species all display varying degrees of generalised, altricial life history patterns, making these species highly adaptive (De Moor 1989). These are typically bi- and multivoltine, and all have several gonotrophic cycles per annum. Multivoltine simuliid species are more common in the warmer temperature zones and the tropics, and these include *S. chutteri*, *S. nigritarse* and *S. damnosum*, with *S. adersi* being either bi- or multivoltine. Eggs for all species above are laid as patches on stones or trailing vegetation, except *S. chutteri,* which scatter eggs in pools upstream of riffles (Figure 3). This behaviour is regarded as more primitive than laying the eggs on substrates, but it gives *S. chutteri* a competitive advantage in rivers with regulated flows, as this trait reduces the risks of eggs drying when water levels drop.

De Moor (1994) identifies four idealised life-history styles of simuliids (Figure 4), with all Orange River species being categorised as "Type 3" life histories. Traits of this type include asynchronous development, flexible voltinism, and slower egg development, insensitivity to temperature change, rapid colonisation ability, and high mobility. Consequently, this means that larvae are present throughout the year, with habitat suitability attaining its highest value when abiotic influences are optimum and biotic influences minimum. These traits apply particularly to *S. chutteri*, which has two alternative life history strategies (Figure 5) depending on the thermal regime, and this gives a greater chance of survival in an unpredictable environment. The increase in size of individuals and population size in autumn and spring indicates that they are passing through an optimal thermal regime, maximising size and fecundity (Vannote and Sweeney 1980). In autumn smaller individuals are brought into this optimal thermal regime (15-18°C) and their offspring attain larger size and higher fecundity. The temperature in winter decreases below the optimum and growth rate and population growth slows down. There is an apparent synchronisation of adult emergence in spring to early summer, when the winter and spring populations emerge together (De Moor 1994).

Water temperature is a major factor in determining larval and pupal size and duration (De Moor 1982, 1994), and varies across species (Table 1). For example, *S. damnosum* has a highly synchronous hatch 9 days at 25°C after oviposition (Rivers-Moore et al. 2013b), and while this species is warm-water adapted, larvae are able to handle thermal variation. Three important thermal thresholds are recognised in determining life history success: a developmental threshold (DT), with larvae entering into quiescence below this; a maturation threshold (MT) that must be exceeded to allow ontogeny; and an optimal threshold (OT) that promotes maximum body size and fecundity (Vannote and Sweeney 1980: thermal equilibrium hypothesis). This has important bionomic implications in terms of control, since larger larvae result in more fecund adult females, which can lead to unexpected population outbreaks.

Figure 3 Typical ideal habitat for the aquatic stages of *Simulium chutteri*: an upstream pool where adult females scatter eggs that settle out into the finer sediment; these subsequently hatch and develop through seven larval instars into pupae, attached to rocks and reeds in the faster-flowing riffle zones (Photo: Rob Palmer)

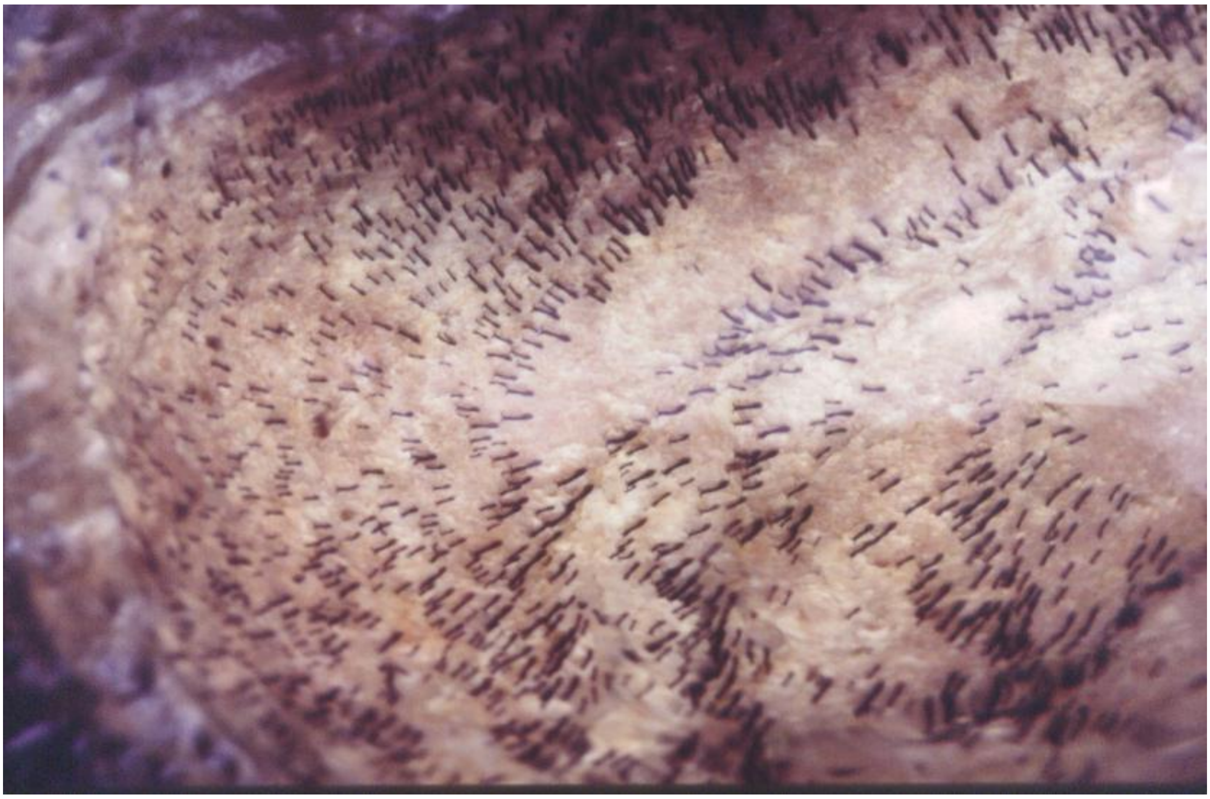

Figure 4 Example of blackfly larvae *in situ* on rocky substrate, with larval densities scoring a 7 using Palmer's (1994) scoring system.

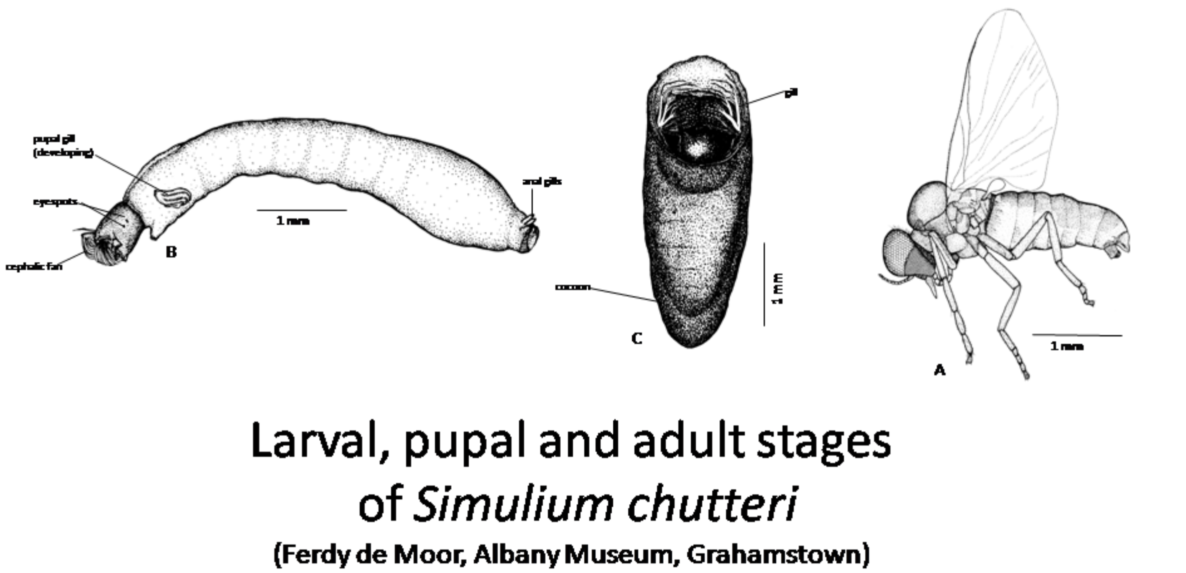

Figure 5 Main life history stages of *Simulium chutteri*

Table 1 Water temperature thresholds for key life history points of four species of blackfly on the Orange River

	S. chutteri	*S. damnosum*	*S. adersi*	*S. nigritarse*
Emergence period	All year; winter diapauses	All year	All year	All year
Days to hatch	7@25°C	7@25°C	13 @25°C[1]	13 @25°C[1]
Life cycle (days)	12-45	22-45	27-87	28-77
Optimum		25°C		
Lower thermal limit	10°C			6°C[1]
Upper thermal limit	26.1°C[4]	30°C		30°C

References: [1]Begemann 1980; [2]Begemann 1986; [3]De Moor 1982; [4]Rivers-Moore et al. 2014

1.4. Modelling approaches

Integrating the interacting effects of all of these variables can be challenging. Bonkewitzz and Palmer (1997) developed an interactive, flexible rule-based probabilistic model for river managers involved with the Orange River Blackfly Control Programme. The aim of the model was to minimise the number of applications and associated costs by assisting river managers in deciding when larvicides should be applied. The model predicts when the annoyance levels of adult *S. chutteri* females exceed a threshold value. The model was based on historical data linked to key driving variables, including flow volumes, water temperature, evaporation, larval abundances, and the abundance of blackfly predators and the presence of potentially toxic blue-green algae *Microcystis* sp. A matrix of all variables at a weekly timescale, with an associated table of probabilities of outbreaks correlated with each variable, formed the basis for calculations.

Complexity within ecological systems makes it difficult to predict disturbances and linkages amongst components within the system (McDonald et al. 2015). The preliminary Bayesian network model developed by Rivers-Moore et al. (2014) showed considerable promise, but could be greatly improved through the incorporation of turbidity and water temperature as additional model variables. A BN essentially consists of cause-and-effect relationships, and is an ideal tool for representing relationships among variables, even if the relationships involve uncertainty, unpredictability or imprecision, so that this approach is free from the arguments of too little data. BNs show good prediction accuracy, even using small sample sizes (Batchelor and Cain 1999; Uusitalo 2007; Kjaerulff and Madsen 2008). There are two steps to defining a BN (Kjaerulff and Madsen 2008; Jensen and Nielsen 2007):

- *Qualitative component*: Identification of variables, states (events) and relationships between them;
- *Quantitative component*: Knowledge on (usually) causal relations, conditional (joint) probabilities.

Each node has system states, and the state of the child node is conditional upon the states of its parent/s nodes, with that relationship defined by conditional probability tables that may be derived using either qualitative or quantitative data. Nodes have a number of possible outcomes associated with it, called states (McDonald et al. 2015). States can be discrete and their values are mutually exclusive which are representative of the nodes possible conditions (Castelletti and Soncini-Sessa 2007). Nodes can have a varying number of states, and the higher number of states associated with a node, the more complex the network is, and vice versa (Chen and Pollino 2012). When the probabilities of the states of the "parent" nodes are specified, the BN undergoes a process of belief updating, meaning that the probabilities of the "child" nodes are also updated (Stewart-Koster et al. 2010; Chen and Pollino 2012). This means that inference can be made, on the basis that BNs have causal relationships between "parent" and "child" nodes, that probabilities of the different states within the independent "parent" nodes will have an influence on the probabilities of different states of the dependent "child" nodes (McDonald et al. 2015).

Nodes, states of nodes and directed arcs between nodes are conditional structures that are required within Bayesian networks. The basis of the quantitative component of BNs is based on the strength of the relationships between variables (Aguilera et al. 2011). After the conditional structures of the network have been determined, the model needs to be configured or learned from Conditional Probability Tables (CPTs) (McDonald et al. 2015). Degrees of belief for which a node will be in a particular state are conditional on the states of the contributing "parent" nodes (Castelletti and Soncini-Sessa 2007; Chen and Pollino 2012)). CPTs require *a priori* data which populates the BN for it to be quantified (Stewart-Koster et al., 2010). *A priori* data can be quantitative or qualitative knowledge (or a combination of both) for variables within the network that is known prior to the development of the model (Uusitalo 2007; McDonald et al. 2015). Expert knowledge can be used to specify the CPTs, or depending on the complexity of the network, CPTs can be specified by various learning algorithms (Stewart-Koster et al. 2010). A requirement of a BN is that of the assumption of the Markov property, which means that populating each CPT should only be done by considering the direct "parent" nodes of the "child" node that is being quantified (Stewart-Koster et al. 2010).

An inclusive and robust stakeholder engagement process that feeds into an iteratively developed Bayesian network model, in turn informed by probabilities based on solid science, is likely to have buy-in (Chen and Pollino 2012). Knowledge and expertise from different sectors of society can be used and combined to ensure that a more complete understanding of the system at hand can be known, and also to ensure that a common purpose between stakeholders and modellers (Chen and Pollino 2012).

2. Methods

2.1 Study sites

Fourteen sites were identified for this study: 12 sites initially identified in the first survey of November 2015, with a further two sites added to extend the study river length in March 2016. The sites were distributed along some 600 km downstream of van der Kloof Dam, across the blackfly problem area on the middle and lower Orange River, with many of the current sites corresponding to existing Department of Agriculture, Forestry and Fisheries (DAFF) monitoring sites and/or sites from previous studies (Figure 6; Table 2). The study sites span three of the four economic zones defined by Mullins (2007; Figure 6), and identified to enable sampling across a range of hydraulic habitats (Plate 1). These sites extended over an altitudinal range of some 600 m (Figure 7). Sites were chosen to represent both single-channel and multiple-channelled (anastomosing) river reaches, as well as agricultural return flow streams and canals (Figure 8). With the exception of Site 1 (Douglas/ Marksdrift), the remainder of the sites were located downstream of the confluence of the Orange and Vaal Rivers. Sites 3-10 are located on an ecotonal profile zone of the Orange River, with Site 11 downstream of Augrabies Falls (Figure 7).

Channel type was previously identified by Rivers-Moore et al. (2014) as affecting flow rates and current velocities. Multiple channel sections were identified using GoogleEarth™, and plotted on the river profile for this segment. The spatial distribution of sections with multiple channels was characterised based on the association between points (degree of clustering versus regular spacing) as a measure of clumping or dispersion at a range of scales. The co-ordinates of all in-stream barriers, and downstream distances between point pairs were calculated for 2 x n and n x n matrices. These matrices were used in Second Order Analyses, a suitable technique for assessing clustering of points in one or more dimensions (Fortin and Dale 2005; Rosenberg and Anderson 2011). Outputs are modified Ripley's K values that are a function of how many points fall within a series of different radius values for each point.

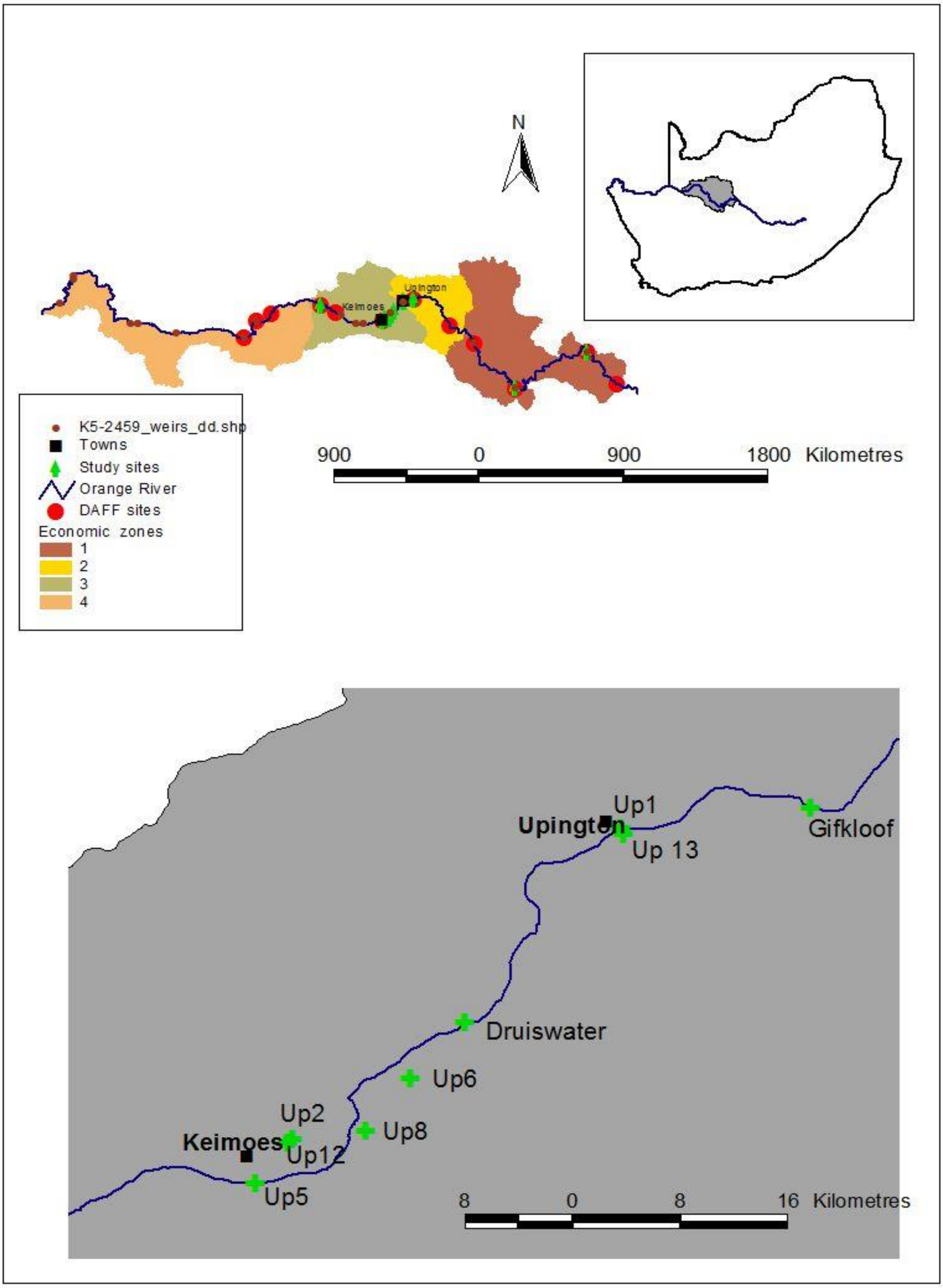

Figure 6 Map of study area within context of economic zones used by Mullins (2007) (top) and within context of South Africa (inset). Clustering of sites between Upington are shown in more detailed the lower figure

Plate 1 View of Orange River near Upington, showing typical hydraulic riffle habitat for *Simulium chutteri*, as well as reeds along the riparian zone which is also used as blackfly habitat

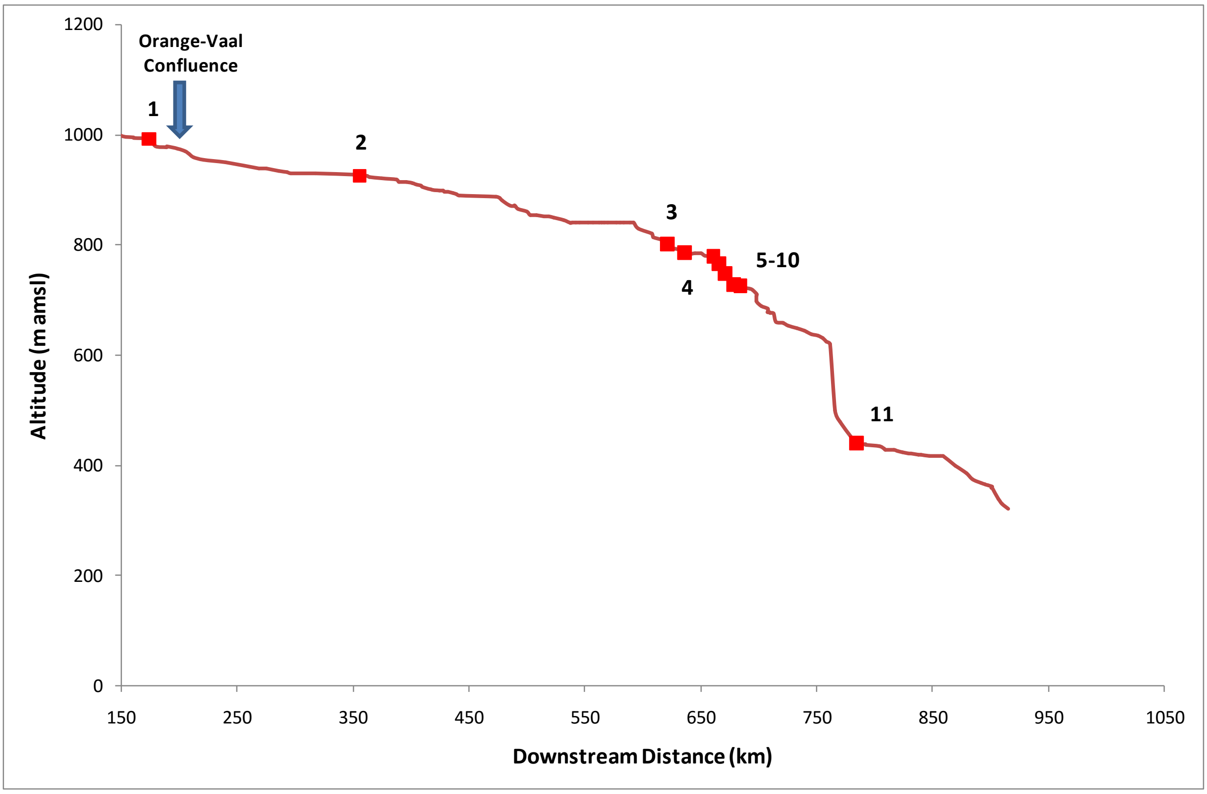

Figure 7 Orange River profile based on downstream distance from Van Der Kloof Dam, showing study sites relative to altitude (red squares)

Table 2 List of study sites, showing site numbers and names in this study, and relative to sites identified by previous studies (Palmer 1997; Rivers-Moore et al. 2013b). Sites as a function of downstream distance (DD) from van der Kloof Dam, and elevation are reflected

Site	Site name	Palmer (1997)	2013 study	Latitude	Longitude	DD (km)	Elev. (m amsl)	Channel type
1	Douglas	Marksdrift	-	-29.16194	23.69623	174.6	993	Single
2	Prieska	Prieska	-	-29.65553	22.74592	355.1	926	Single
3	Gifkloof	Gifkloof2	-	-28.43743	21.40092	621.6	800	Single
4	UP1	GifKloof5	UP1	-28.45798	21.26165	636.5	785	Single
5	UP13	-	-	-28.45262	21.25943	636.5	785	Single
6	Druiswater	Damkop Weir	-	-28.60385	21.14277	660.3	778	Single
7	Kanoneiland	Blaauwskop Weir 2	UP6	-28.46768	21.10197	666.5	765	Single
8	UP8	Koeieland	UP8	-28.68780	21.06878	671.8	746	Single
8a	UP8 (stream)	-	UP8	-28.68780	21.06878	671.8	746	Return flow
8b	UP8 (channel)	-	UP8	-28.68780	21.06878	671.8	746	Return flow
9	UP12	Skaapeiland	UP12	-28.69490	21.01452	679.3	726	Multiple
9a	UP2 (Soverby)	-	UP2	-28.69490	21.01438	679.3	726	Multiple
10	Ikaia Lodge	Keimos Bridge	UP5	-28.72913	20.98595	683.8	724	Single
11	Blouputs	Blouputs	-	-28.51377	20.18694	785.0	439	Single

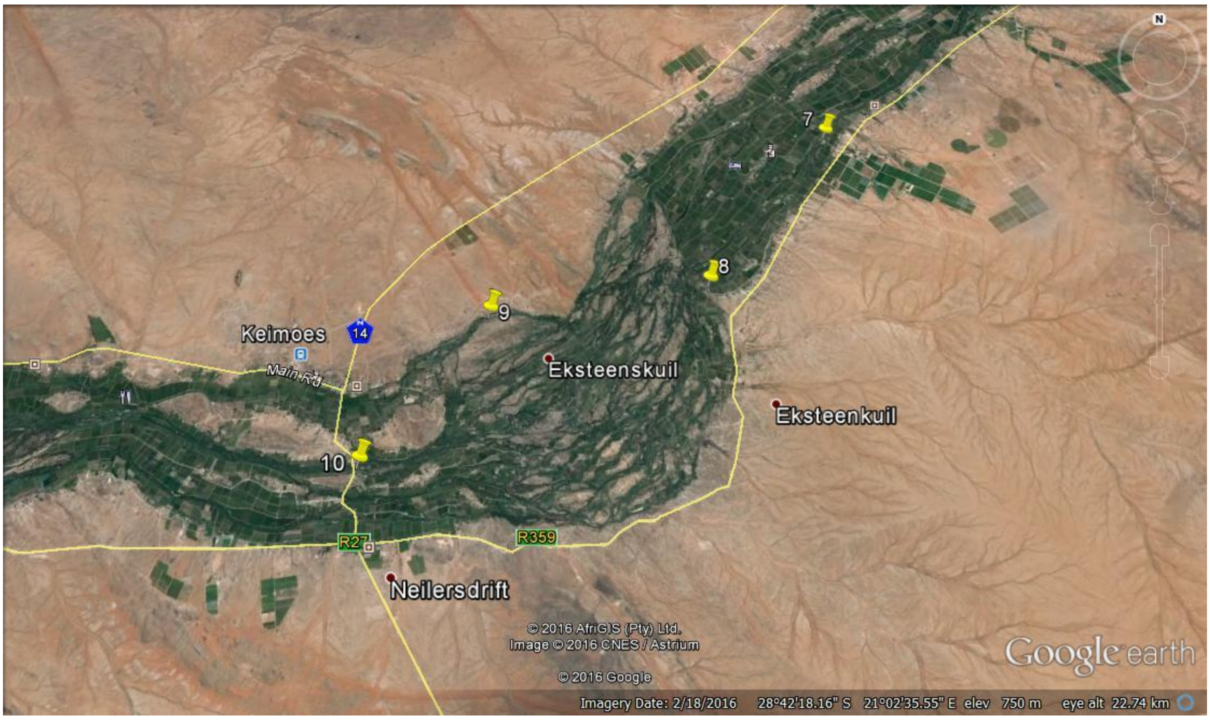

Figure 8 Selection of study sites between Kanoneiland (7) and Keimos Bridge (10) located in single channel sections of the Orange River, with site 9 within a multiple-channelled section.

2.2. Field surveys

Sampling was undertaken in late spring (November 2015), late summer (March 2016), winter (July 2016), and early summer (December 2016). The data collecting protocol (Appendix 1) for this study was based on the experience gained from previous studies (for example, Rivers-Moore et al. 2014), and the initial field trip for this study, which was undertaken from 1-9 November 2015.

2.3. Abiotic data collection

2.3.1. Hydraulic and hydrological data

For the hydraulic data, current velocity was measured at each sampling point, using a transparent velocity head rod. Differentials in depth between the current "head" and the lower depth were converted to velocities (Plate 2). Sampling point depths (cm) were recorded using a depth stick. For the hydrological data, observed mean daily flow data time series were obtained from the DWS Hydrological Information System (www.dwaf.gov.za/Hydrology) (Table 3). Subdaily 12-minute interval primary flow data were compared for two sites to compare patterns in flow patterns downstream of van der Kloof Dam linked to hydro-electric power generation. Observed daily flows were compared against simulated mean daily flows for historical (1950-1999), present (1971-1990) and intermediate future (2046-2065) flows for corresponding quinary catchments. Time series of simulated mean daily flow rates are available for all 5838 quinary catchments for South Africa as part of a database developed in previous WRC projects (K5/1562; K5/1843) that used the daily time step process-based ACRU agro-hydrological model. Simulated flows were based on median values derived from four different regionally downscaled climate change models (CCC = Canadian Centre for Climate modelling and analysis; CNRM = Centre National de Recherches Meteorologiques; ECH = Max-Planck-Institut for Meteorology; IPS = Institut Pierre Simon Laplace), i.e. a multi-model consensus approach or ensemble modelling approach. The projected change in mean daily flows per month was calculated as the percentage change between present and intermediate future flows. A critical discharge threshold of 100 $m^3.s^{-1}$ was derived from the velocity-discharge relationships in Palmer (1997), and using a critical velocity of 1 $m.s^{-1}$ for both *S. chutteri* and *S. damnosum*. Return intervals of flows exceeding 100 $m^3.s^{-1}$ were calculated for D7H005 (Upington) for pre- and post-impoundment periods (1942-1977; 1978-2016).

Plate 2 Researchers measuring current velocity using a transparent velocity head rod

Table 3 Flow data for gauging weirs in the middle and lower Orange River used in study analyses

Gauging weir	Name	Data period	Notes
D3H008	Marksdrift	2 Nov 1935-31 Dec 2016	Subdaily; quinary 1926
D7H002	Prieska		Reeds
D7H005	Upington	1 Oct 1942-31 Dec 2016	Subdaily; quinary 2025
D7H014	Neusberg		Reeds
D8H003	Vioolsdrift	1 Sept 1962-31 Dec 2016	Quinary 2277

2.3.2 Water quality

Turbidity (cm) was collected using a clarity tube (Plate 3). These data were collected in association with the presence/ absence of algae, which reduces blackfly habitat (Plate 4). Turbidity values were converted to seston concentrations (mg.ℓ^{-1}), according to Equation 1 (Palmer 1997; Rivers-Moore et al. 2007). Palmer (1997) identified an exponential relationship between flow rates and seston concentration (Equation 2). Based on this, seston concentrations were calculated from observed daily flows, with return intervals calculated for a threshold value of 60 mg.ℓ^{-1}. Three spot readings of pH and conductivity (μS.cm^{-1}) were recorded and averaged for each site, using a calibrated Hanna pH/conductivity meter, as these were expected to vary seasonally and spatially (Plate 5).

$$TSS = exp\left(\frac{log\frac{SD}{256}}{-0.616}\right) \qquad [1]$$

Where *TSS* is Total Suspended Solids (mg.ℓ^{-1}) and *SD* is clarity (cm)

$$Seston = 1.92 * Flow^{0.755} \qquad [2]$$

Plate 3 Field measurement of turbidity using a clarity tube

Plate 4 Algae on rocks in typical blackfly hydraulic habitat

Plate 5 Water conductivity is much higher in agricultural return flow channels than in the main river channel, favouring different blackfly species

2.3.3 Temperature data

Water temperatures are a controlling variable for a system variables, including larvicidal efficacy (Palmer 1997), algal mats (De Moor 1994), and blackfly larval development (De Moor 1982, 1994). Hourly water and air temperature data were collected at 13 and three sites respectively, using Hobo

TidBit v2 water temperature loggers and Dallas *i*-Button air temperature/relative humidity loggers (Plate 6). The air temperature data were interpolated to all sites using altitude and lapse rates (0.7°C).

Plate 6 *In situ* air temperature logger at Gifkloof

Hourly data for all water temperature sites were aligned for a common period from 4 November 2015 – 2 November 2016. In cases where data were missing (for example, because of staggered dates in logger installation, or loggers being above the water level for periods of time), gaps were patched using linear regression relationships between sites where data were complete (Table 4). Hourly data were summarized using box-and-whisker plots. Next, hourly data (air and water temperatures, RH) were summarized into daily minima, maxima and means. Water temperature data were processed into metrics describing magnitudes, frequencies, durations and timing of thermal events (Rivers-Moore et al. 2013a). These included calculations of frequency and duration of exceedance of thermal thresholds for *S. chutteri*, derived from Table 1: Minimum threshold and annual degree days at 10°C; 7-D moving average threshold for mean daily temperatures of 26.67°C, and 30°C as an LT_{50} threshold. Trends in water temperature data were described using plots of seven-day moving averages of daily means, minima and maxima, and cumulative degree days > 10°C. Definition of thermal seasons was determined using regime shift detection software (Rodionov 2006). Seasons were divided based on observed mean daily water temperatures ($p < 0.01$; cut-off length = 30; Huber's weight parameter = 1). Simple linear regression was used to describe relationships between mean daily air and water temperatures.

Table 4 Regression coefficients for study sites correlated with hourly water temperatures from Site 5 (Sun River Lodge)

Site	Constant	*β*	R^2
Douglas	-1.428	0.988	0.973
Prieska	-2.092	1.033	0.974
Gifkloof	0.015	1.001	0.992
UP1	0.224	0.993	0.999
Druiswater	0.356	0.984	0.997
UP6	0.536	0.982	0.997
UP8	-0.452	0.99	0.972
UP12	0.244	0.957	0.993
Ikaia	-0.026	0.982	0.99
Blouputs	1.781	0.946	0.99
UP8_stream	-2.015	0.915	0.727
UP2_Soverby	-3.767	1.117	0.924

2.4. Biotic data collection

2.4.1. Blackfly species data

Moving from downstream to upstream so as not to contaminate or trample downstream sites, we sampled across a range of hydraulic habitats and reeds where blackfly species were expected. Samples were either collected from reeds cut and preserved, or using a 250 μm-mesh net downstream of fist-sized rocks. Larval densities were rated according to the 10-point scale of Palmer (1994). Blackfly pupae and larvae were collected and preserved in 70% ethanol alcohol. Each sample was identified to species and relative abundances recorded, in the laboratory using the taxonomic keys in De Moor (2003). All data for each sample at each site and per seasonal sampling event was collated into spreadsheet data matrices, with associated hydraulic and water quality data, and manipulated using pivot tables. Raw abundance data per species and life history stage were used in analyses, as well as presence/ absence data, and transformed percentage data. Blackfly species data per site for each sampling season, and overall per season, were compared using radar diagrams. Blackfly species turnover between seasons and sites was compared using a Bray-Curtis analysis (McCune and Mefford 2011).

2.4.2. Additional ecological data

The presence or absence of benthic algae was recorded from site observations at each field survey, because benthic algae typically occurs in low-turbidity conditions and decreases rocky substrate habitat for blackfly larvae. Site groupings were assessed using a Principal Components Analysis (correlation matrix) (McCune and Mefford 2011), based on turbidity, pH and conductivity, and categorical site scores for benthic algal presence or absence.

Diatom samples were collected at six sites as part of the December 2016 field survey, using the methods in Taylor et al. (2006). Samples were sent to Dr Jonathan Taylor for analysis. Part of these data collected included collection of diatomaceous crust on rocks in July 2016, which were sent to an accredited laboratory for XRF analysis. Also during the December 2016 survey, the diversity and qualitative abundances of aquatic macrophytes was assessed. Species of molluscs were noted at each site, and identified using Griffiths et al. (2015).

Reed areas extending 100 m upstream and downstream at all sites were calculated using on-screen digitizing of satellite images from GoogleEarth™. Change in reed area over approximately one decade was determined at sites 2 and 11 using historical satellite imagery.

2.4.3. Abiotic-Biotic interactions

Raw abundances of blackfly species for all field surveys were combined and plotted against pH, conductivity and seston concentration values recorded. In the case of blackfly species responses to stream velocity, the maximum abundances for each sample (n=5) were plotted against velocity, and response curves fitted. The probability of occurrence of all six blackfly species was modelled using logistic regression in the statistical software R (R Development Core Team 2009), using water clarity as a predictor variable. Similarly, the probability of occurrence of benthic algae was modelled using water clarity and blackfly abundance (density scores and total abundance of *S. chutteri* and *S. damnosum* larvae).

Reed area over time for sites 2 and 11 was plotted against mean daily flows for the same period, and trend lines were fitted. Sites with high numbers of the density-independent blackfly predator *Cheumatopsyche* sp. (Trichoptera: Hydropsychidae) were noted during each field survey. Abundances were estimated based on habitat area measured on-site, and density calculated from scale photographs.

2.5. Blackfly Bayesian network model

The user needs of the stakeholders for the modelling framework will be assessed using responses received from the questionnaire in Appendix 2. Data from the fourteen study sites were used as the basis for developing the Bayesian network model. The conceptual model of Palmer and Craig (2000) which postulates that the presence of blackfly species can be characterised by a two-dimensional plot of seston preference (turbidity levels) and flow velocity was used as the conceptual framework for the data collection (Figure 9). Palmer and Craig (2000) proposed that seston availability was a major factor in the evolution of blackfly labral fan structure, and that particle concentration and water velocity were two of the most important determinants of blackfly larval distribution. Here, labral fan structure could be used to predict the habitat of blackfly species, with the model predicting four broad labral fan groups based on relative position along axes of water velocity and seston availability. *Simulium impukane* larval labral fan structure falls into the “weak complex” group, reflecting a preference for slow water velocities and low seston availability (clear water). By contrast, the labral fans of *S. chutteri* fall into the “strong porous” group (diametrically opposite *S. impukane*), where larvae are typically associated with high velocities and high seston availability. The “lesser” problem blackfly species are characterised as having a “standard” labral fan structure. Using this model has the advantage that should species not be available for laboratory experiments, predicted species in terms of velocity/food availability groups can be assumed. On the strength of this logic, and for the sake of model parsimony, the BN model objective node was restricted to two node states, viz. the “strong porous” species as the main problem species, and the “standard” species as non-problematic species. This choice was made in order to restrict the model to estimating outbreaks per problem type rather than per species.

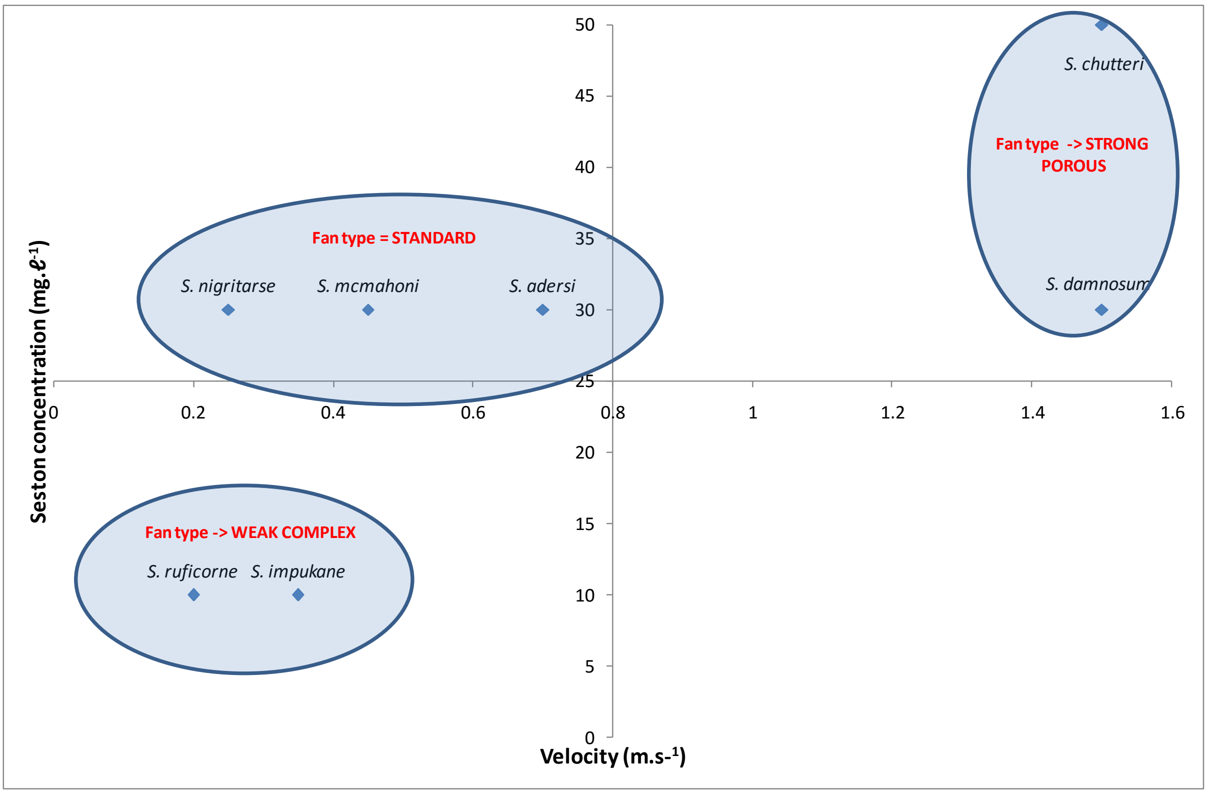

Figure 9 Conceptual grouping of Orange River blackfly species, based on seston concentration and velocity preferences (Palmer and Craig 2000)

2.5.1. Model resolution – spatial and temporal

BN models are not explicitly able to reflect temporal or spatial patterns. The approach to dealing with this was to build as many models as required to represent study area spatial units, and relevant time periods. Sites were grouped according to seasonal values of pH, turbidity (cm) and conductivity ($\mu S.cm^{-1}$). These data were analysed using a Principal Components Analysis (correlation matrix), and sites classified using a cluster analysis (Euclidean distance measure; Group Averaging linkage method). In the second approach, sites were grouped according to thermal metrics describing water temperature time series, based on the methods of Rivers-Moore et al. (2013a), and the thermal data collected in this study. These data were analysed using a Principal Components Analysis (Correlation matrix), and sites classified using a cluster analysis (Euclidean distance measure; Group Averaging linkage method).

2.5.2. Nodes, states and probabilities

The BN model was designed to take the following into account:

- Algae dominating the substrate habitat, and controlled by water temperature and seston concentration (De Moor 1994);
- Larvicidal efficacy as a function of water temperature and seston concentration (Palmer 1997);
- Outbreak probability as a function of dominance of the "strong porous" species, and affected by water temperature;
- Dominance of the pest blackfly species complex determined by the moderating nodes of "Abiotic" and "Biotic" conditions dominating (De Moor 1994).

Nodes were linked in cause-and-effect sequences using the Bayesian software Netica v 4.16 (Norsys 2010). Each variable was assigned two-three variable states. The probabilities of each state of the parent nodes were defined based on a number of approaches, for example, for flow conditions the return intervals for flows below or exceeding 100 m^3s^{-1} were calculated from flow data for the Upington weir (D7H005). This threshold corresponds with optimal velocity thresholds for both *S. chutteri* and *S. damnosum* (Palmer 1997; Palmer and Craig 2000). Return intervals were calculated for two periods, viz. 1942-1977 versus 1978-2016, and probabilities calculated for each state.

Using these data, conditional probabilities of the "strong porous" blackfly species (*S. chutteri* and *S. damnosum*) versus the "standard" species group (non-problem species) were generated based on combinations of parent node variable states. All variables used discrete states, arranged from most positive to most negative, with two states assigned to each variable, apart from one variable which had three. Nodes were linked in cause-and-effect sequences using the Bayesian software Netica v 4.16 (Norsys 2010). Cost-benefit curves for each economic zone were generated by standardising the Rand values from Mullins (2007) to values between 0 and 1. These were applied to three scenarios ("Base" – impact of pest blackflies with the Control Programme in effective operation; "Pessimistic" – the period prior to the implementation of the Blackfly Control Programme, but after the construction of dams; "Optimistic" – total control including the Blackfly Control Programme and flow manipulation). Each scenario was included as a management option in a management node, and cost: benefit values as utility nodes. Development of a BN was an iterative process of testing the logic of relationships and keeping the network as parsimonious as possible. In this study, no more than three parent nodes were linked to any child node, because the elements of a conditional probability table increase exponentially according to i^n based on number of states (i) and the number of parent nodes (n) (Cain 2001).

2.5.3. Model verification

Monthly outbreak probabilities were compared against historical data of adult blackfly annoyance levels. The Fly Worry Index was previously used in the 1990s (Palmer 1997), as a 4-point scoring system reflecting the annoyance levels of adult blackfly (Figure 10). It is assumed that there will be a 1-2 week time lag between the larval density data and the adult fly worry index data, on the basis of the temperature-dependent time lag between larval and adult life history stages.

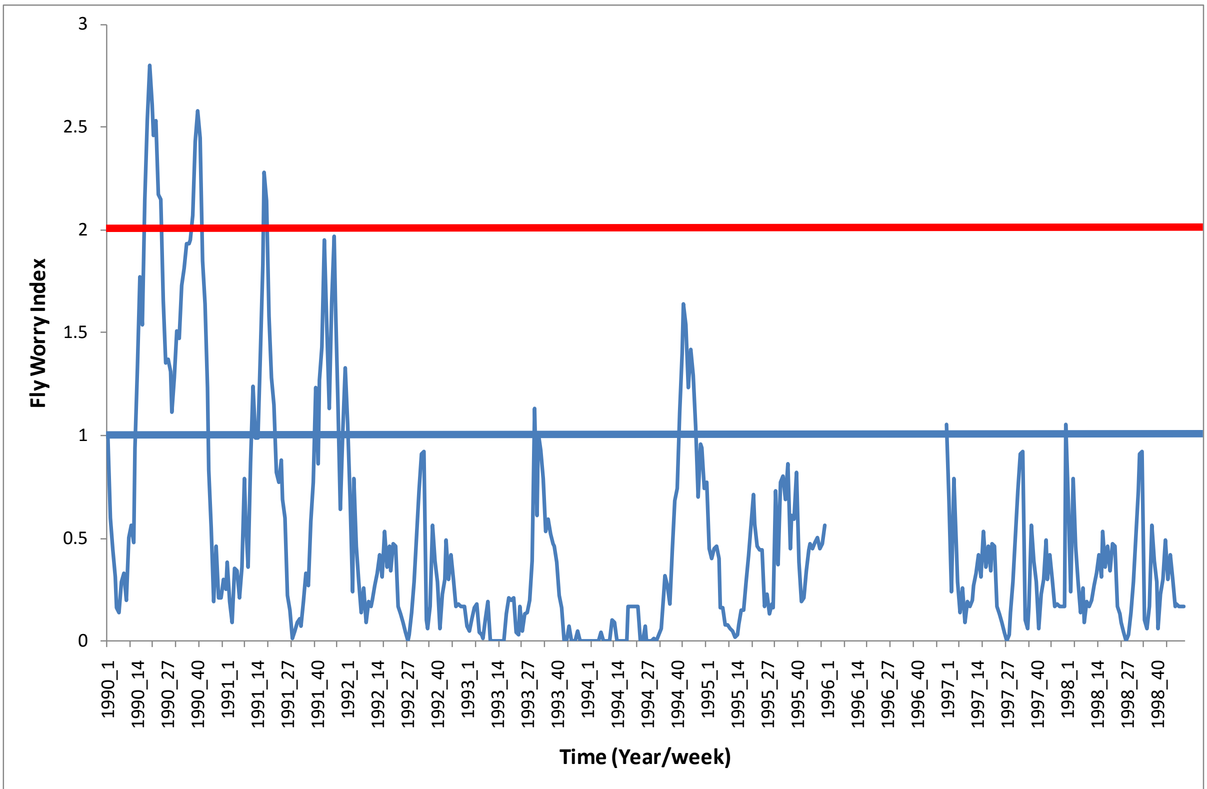

Figure 10 Fly Worry Index scores on a weekly basis from 1990-1998, where date suffixes represent weeks of the year. The scores from multiple users are averaged, and are based on discrete values, where 0 = no flies; 1 = some flies; 2 = moderate levels of annoyance, and 3 = extreme levels of annoyance (Palmer, 2017, unpub. data)

2.5.4. Scenario assessments

Monthly and default outbreak probabilities were generated using currently available data, based on the following scenarios:

- Pre-impoundment flows and simulated seston concentrations;
- Post-impoundment flows and simulated seston concentrations;
- An assumed 2°C increase in mean daily water temperatures, and a 60% increase in flow volumes as a global climate change scenario.

3. Results

3.1. Site characterisation

A total of 25 multiple-channelled sections were identified on the middle and lower Orange River (Figure 11). Multiple channel zones were strongly clustered within 60-80 km segments, but with clusters regularly spaced at larger scales (Figure 12).

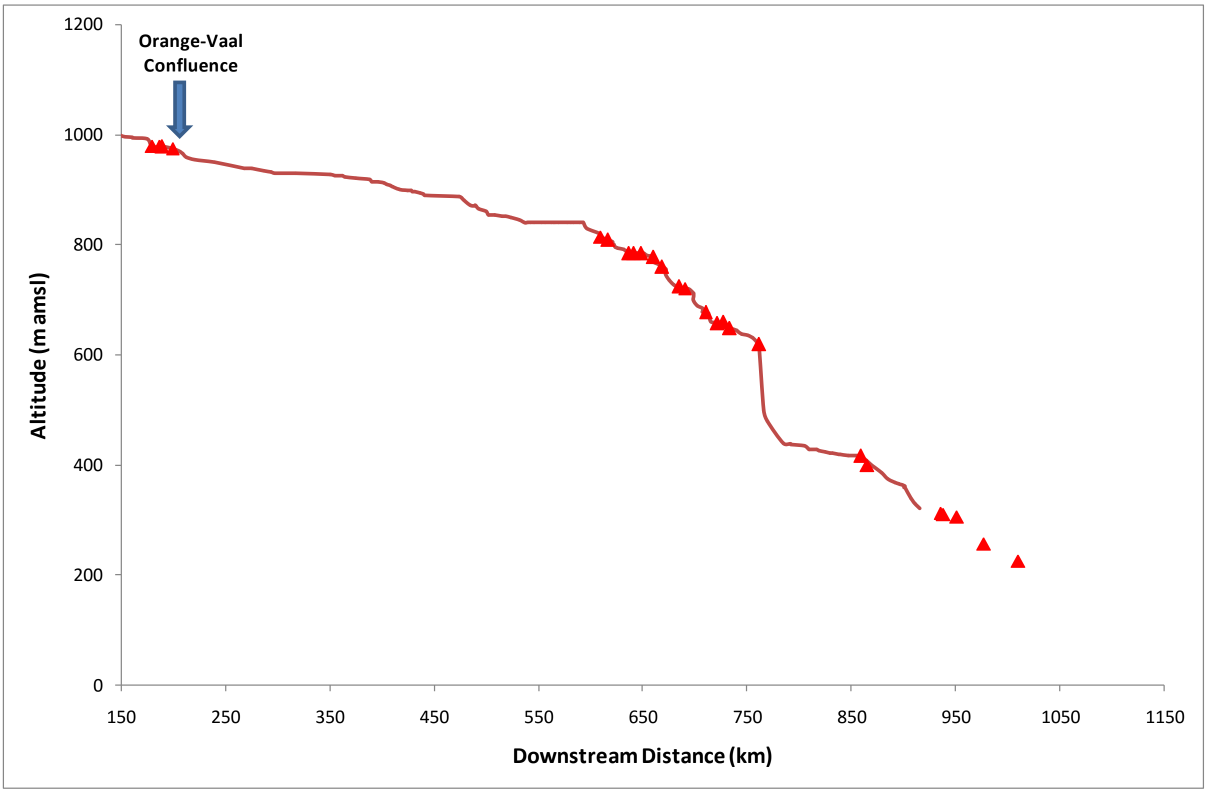

Figure 11 Distribution of multiple-channelled sites on the Orange River downstream of van der Kloof Dam

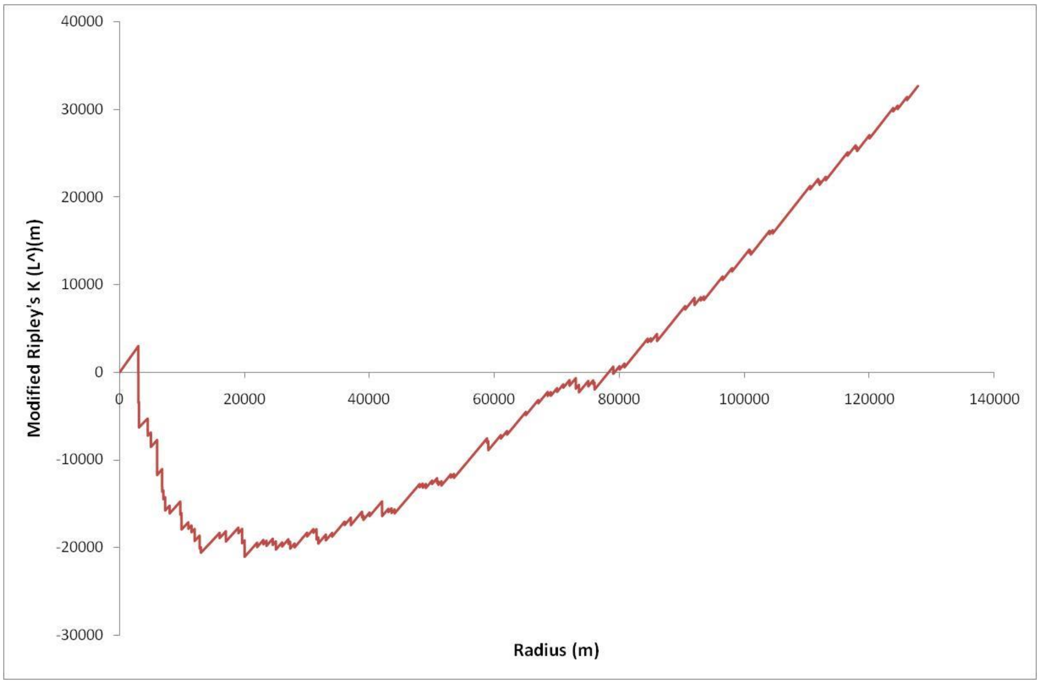

Figure 12 Results of Ripley's K analysis on one-dimensional data of barriers along the lower and middle Orange River. Values of zero reflect random distributions, while values < 0 indicate clumping and values > 0 indicate regular spacing.

3.2. Abiotic data

3.2.1. Hydrology

Return interval curves were different for pre- and post-impoundment flows (Figure 13), with probability of occurrences > 100 $m^3.s^{-1}$ being 48.98 and 54.55% respectively. Mean daily flow volumes did not reflect the differences in sub-daily range of variation, as expressed as a percentage of mean daily flows. These were significantly different between sites 1 (Douglas) and 4 (Upington) (Figure 14; $p < 0.05$, One-tailed Student's *t*-test). Flow volumes for all four global change scenarios were comparable (Figure 15). Simulated and observed median daily flows per month were not directly comparable, with simulated flows for all three scenarios being considerably more than the observed flows. However, intermediate future flows compared against current simulated flows showed an increase of approximately 60% for sites 1, 4 and 11 (Figure 16).

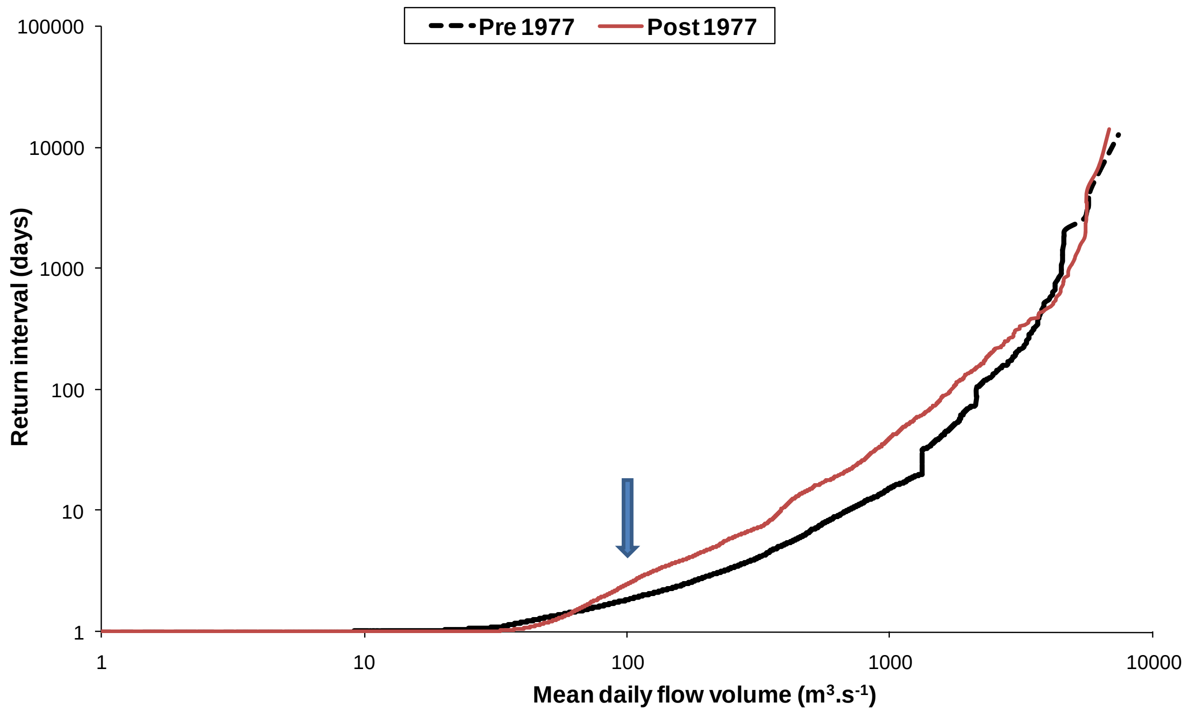

Figure 13 Return interval curves for gauging weir Up7H005 (Upington) for pre- and post-impoundment periods (1942-1977 and 1978-2016)

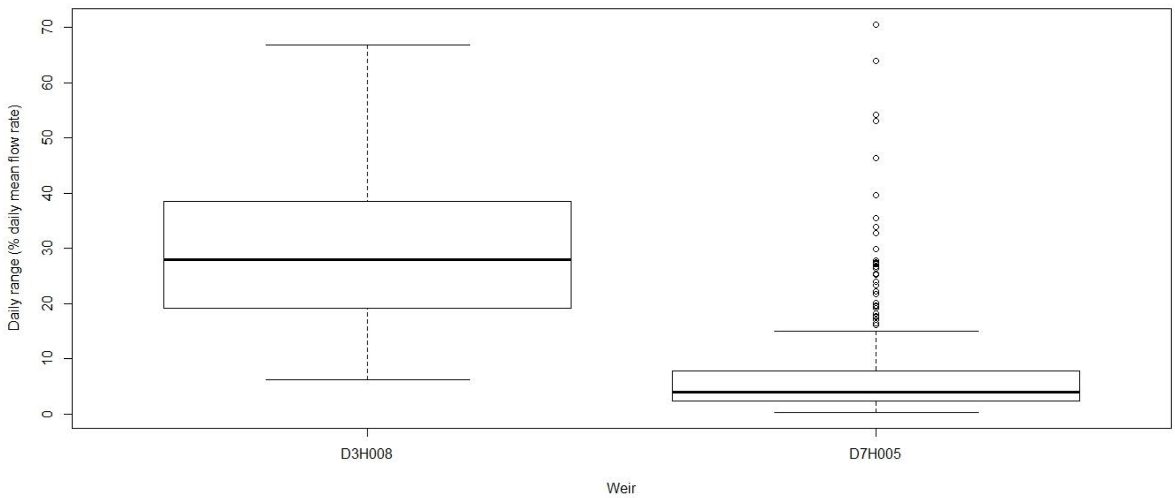

Figure 14 Box-and-Whisker plot of 12-minute interval subdaily flow range as a percentage of daily mean flow rate for site 1 (Douglas – D3H008) and site 4 (Upington – D7H0005) for 1 October 2015 – 30 September 2016

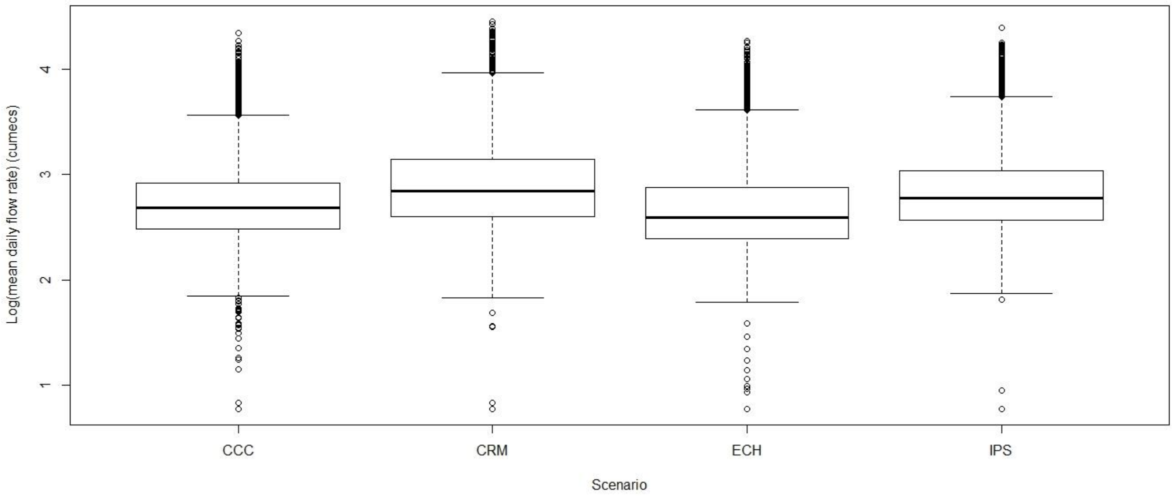

Figure 15 Box-and-Whisker plot of flows for four intermediate future climate change models for quinary 2025, corresponding with D7H005 at Upington

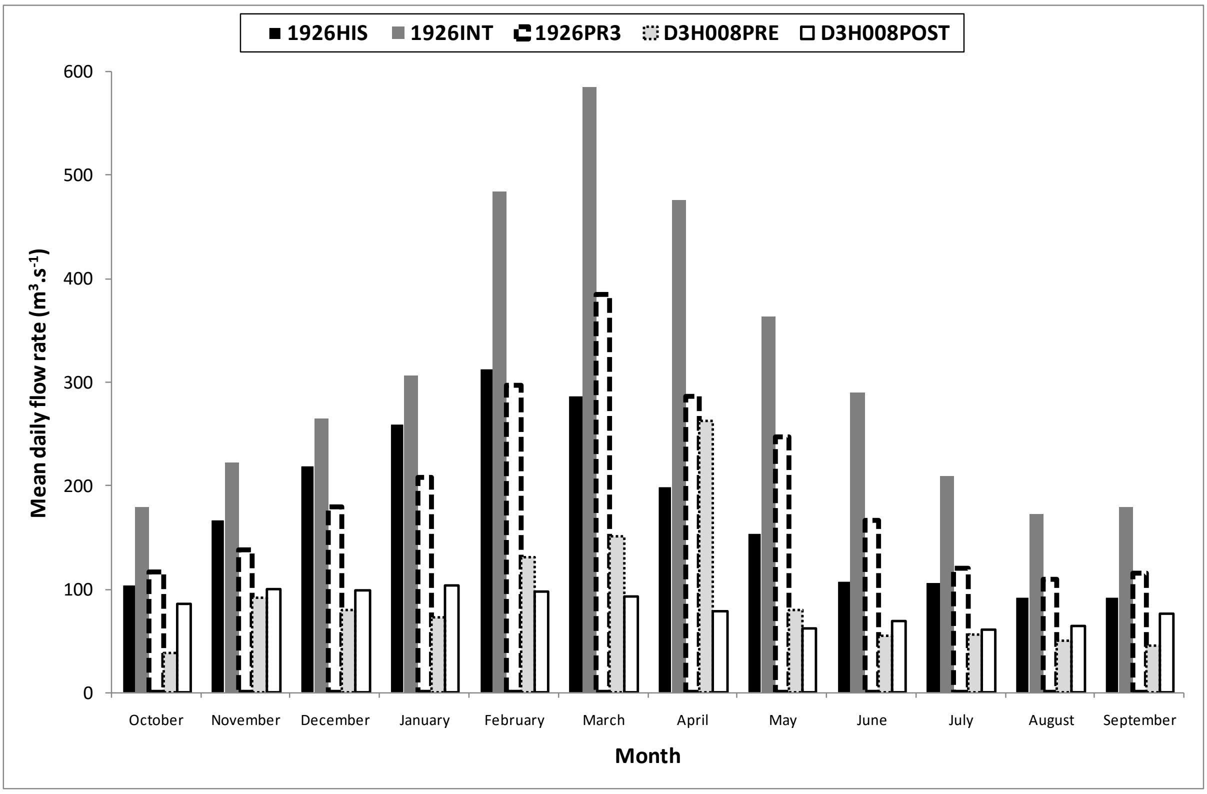

Figure 16 Median daily flow rates per month for five flow time series

3.2.2. Water Quality

All water quality data generally exhibited seasonal differences, but little difference with respect to downstream gradient, with the exception of Sites 8a-b (UP8_stream and UP8_channel; agricultural return flow stream and canal) and Site 9a (small channel stream; UP2_Soverby). Water clarity was generally low, with the exception of Sites 8a-b, 9a (Figure 17). Clarity was highest during the July 2016 survey, with correspondingly high levels of algae on the rocks. Based on the seston concentration versus flow volume curves, low seston concentrations occurred at low flows (Figure 18), but with distinct seasonal patterns (Figure 19). Values of pH generally reflected neutral to slightly alkaline conditions at all sites (7.0-8.5; Figure 20). Conductivity values generally ranged from 400-600 $\mu S.cm^{-1}$, with the exception of Site 8b, where values were between 600 and 1500 $\mu S.cm^{-1}$ (Figure 21). Conductivities were highest during the July 2016 survey, corresponding with relatively lower flow volumes.

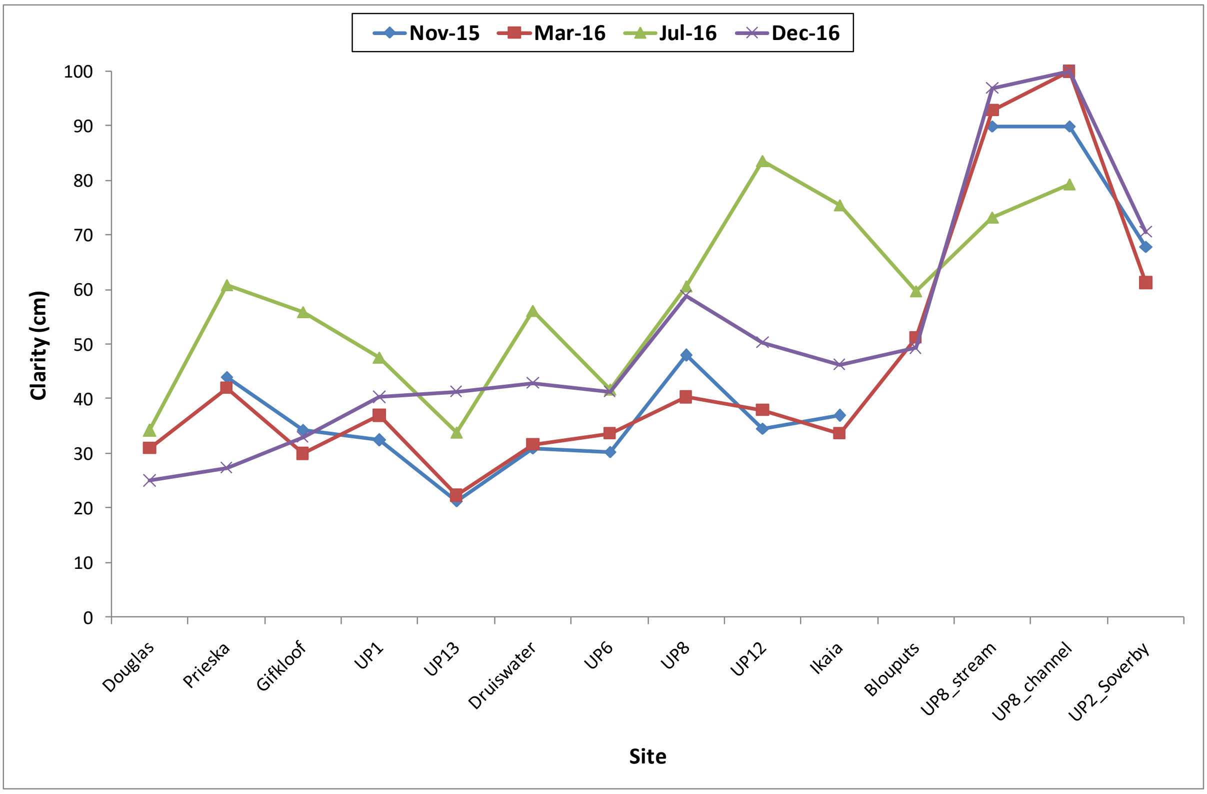

Figure 17 Turbidity for late spring (November 2015), late summer (March 2016), winter (July 2016) and early summer (December 2016) for study sites, going from upstream to downstream

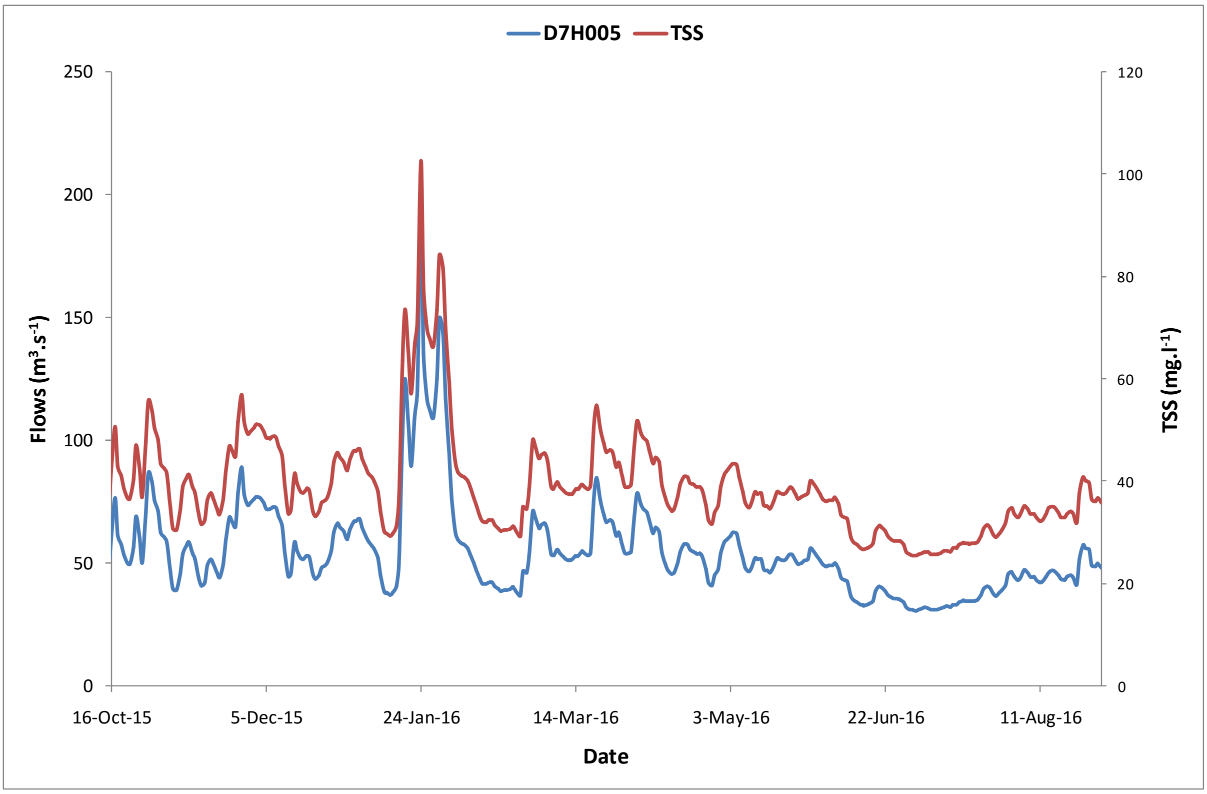

Figure 18 Plot of mean daily flow volumes and seston concentration

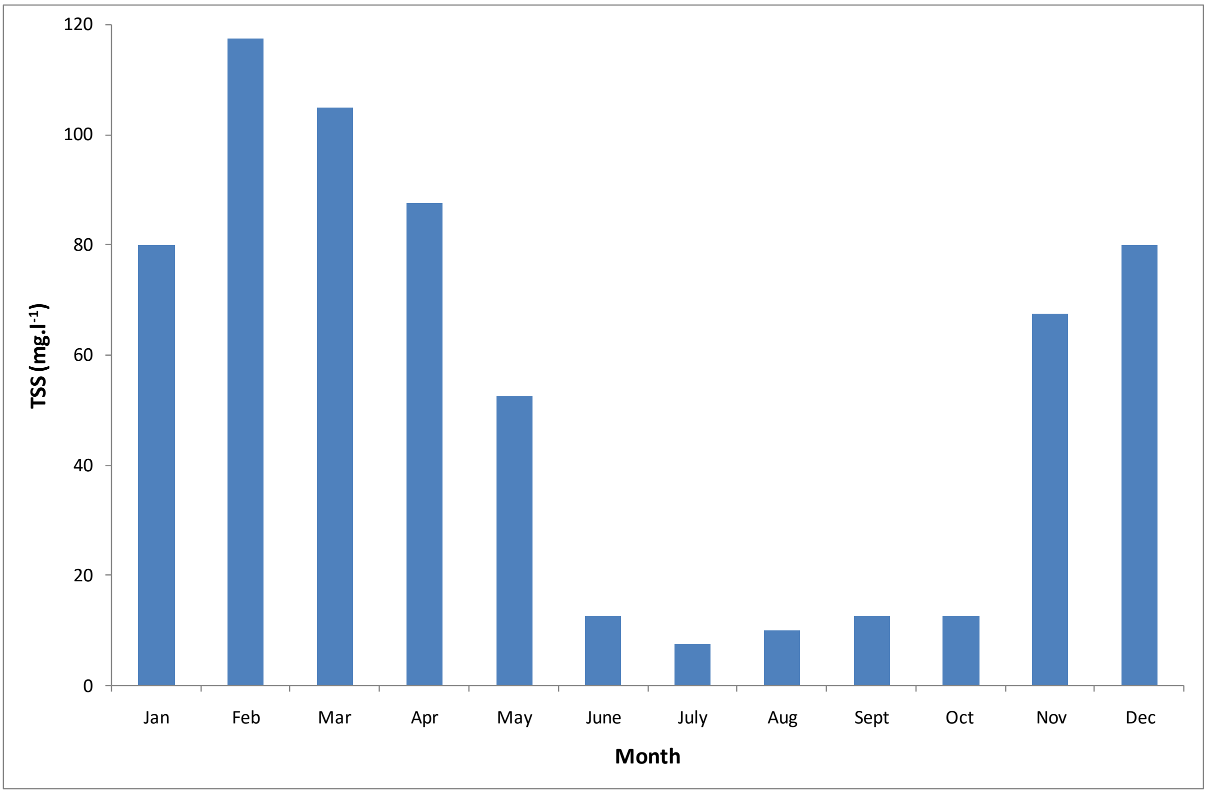

Figure 19 Seasonal variation in seston concentration (Palmer 1997)

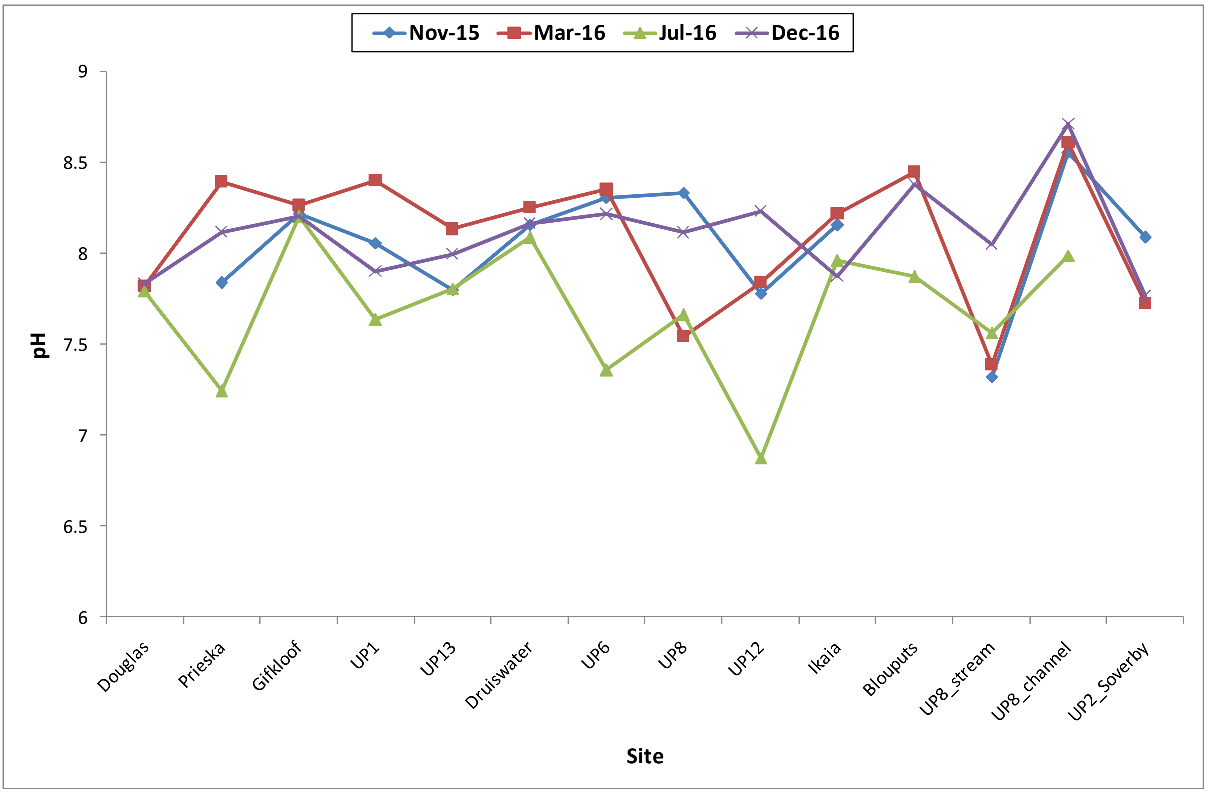

Figure 20 pH values for late spring (November 2015), early summer (March 2016), winter (July 2016) and early summer (December 2016) for study sites, going from upstream to downstream

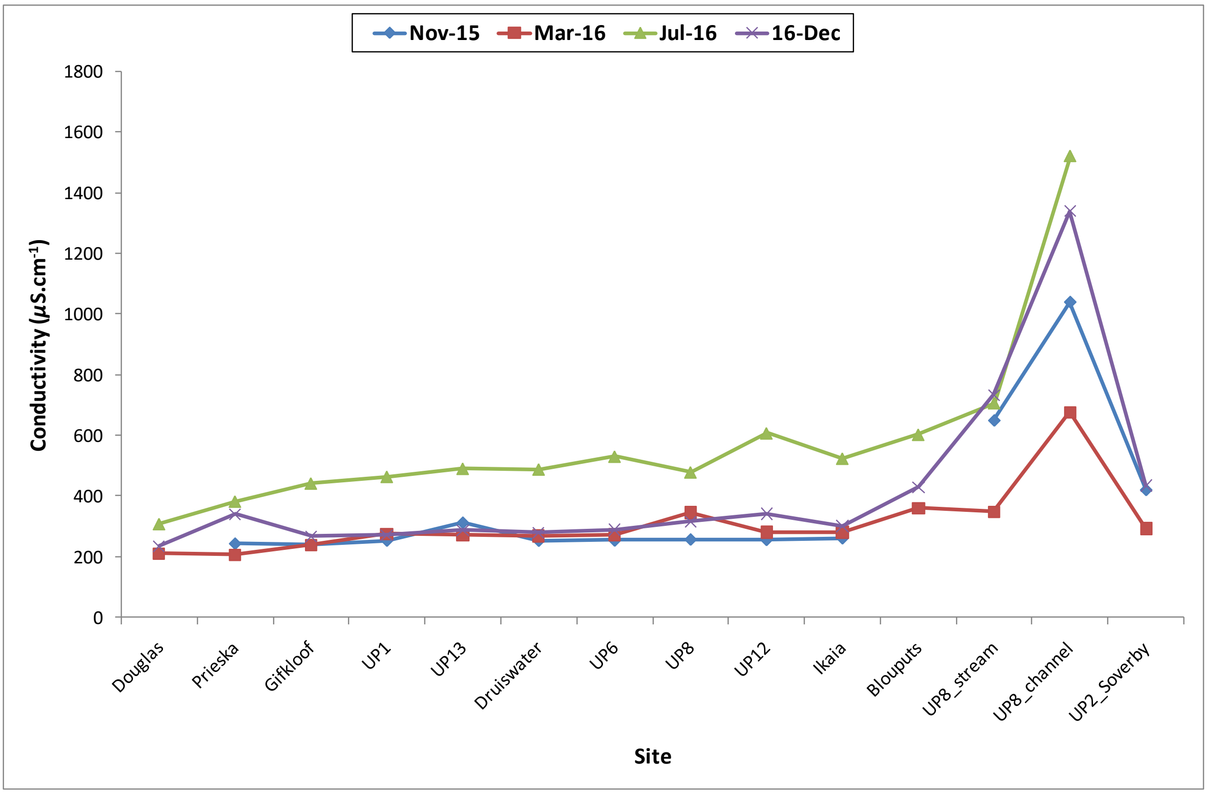

Figure 21 Conductivity values for late spring (November 2015), late summer (March 2016), winter (July 2016) and early summer (December 2016) for study sites, going from upstream to downstream

3.2.3. Water and Air temperature data

Relative humidity values were consistent across all three sites, with minima and maxima ranging from 5-100%, and median hourly values at 50%. The 25th and 75th percentile data ranged from 30-60% (Figure 22). Hourly air temperatures were considerably more variable than hourly water temperatures, although both data variables exhibited a marked cooling trend from late March 2016 (Figure 23). Hourly water temperatures exhibited considerable homogeneity between sites (Figure 24), although sites 1-2 were slightly cooler than the remaining downstream sites, which became most pronounced when expressed as cumulative degree days >10°C for mean daily water temperatures (Figure 25). This was largely a consequence of a marked reduction on daily water temperature ranges and a cooling trend from late March, as reflected using the seven-day moving averages of daily mean, minimum and maximum water temperatures (Figure 26). Mean daily air and water temperatures based on the observed data from November 2015 to July 2016 showed strong correlations based on a linear regression relationship (R^2=0.84; Figure 27). The annual thermograph showed ten significant changes in mean daily water temperatures (Figure 28).

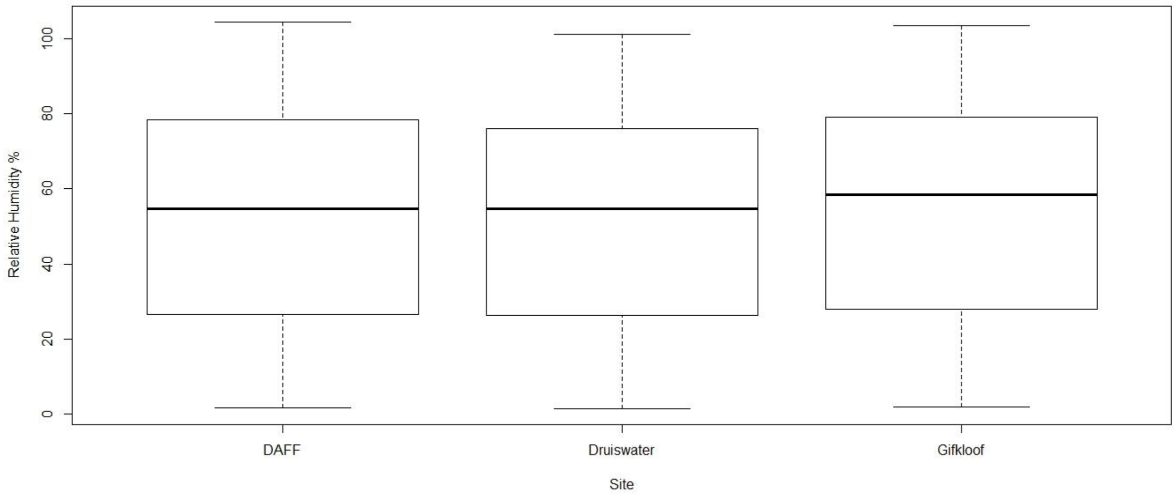

Figure 22 Box-and-Whisker plot of hourly relative humidity data (%) for three air temperature logging sites, showing median values and 25th/ 75th percentiles, and minimum and maximum values as "whiskers"

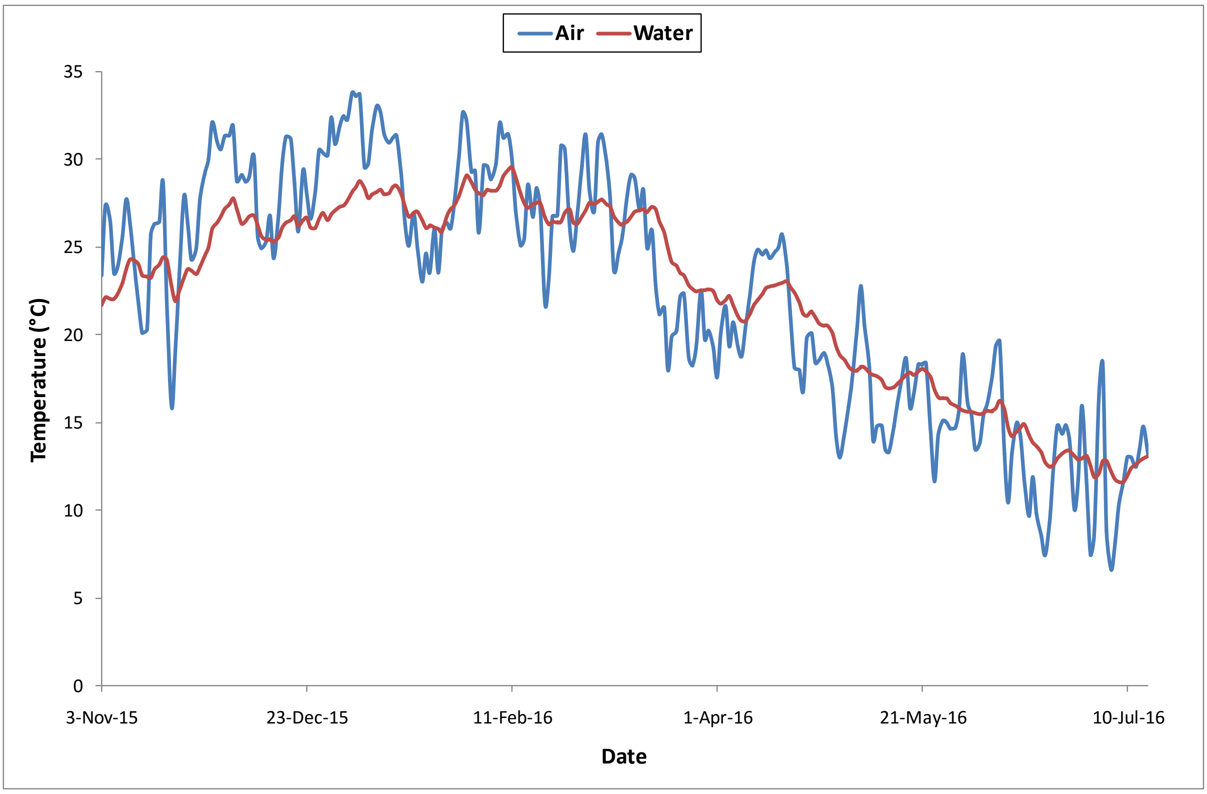

Figure 23 Hourly water and air temperature data for site 5 (Sun River Lodge, Upington) from 4 November 2015 – 10 July 2016

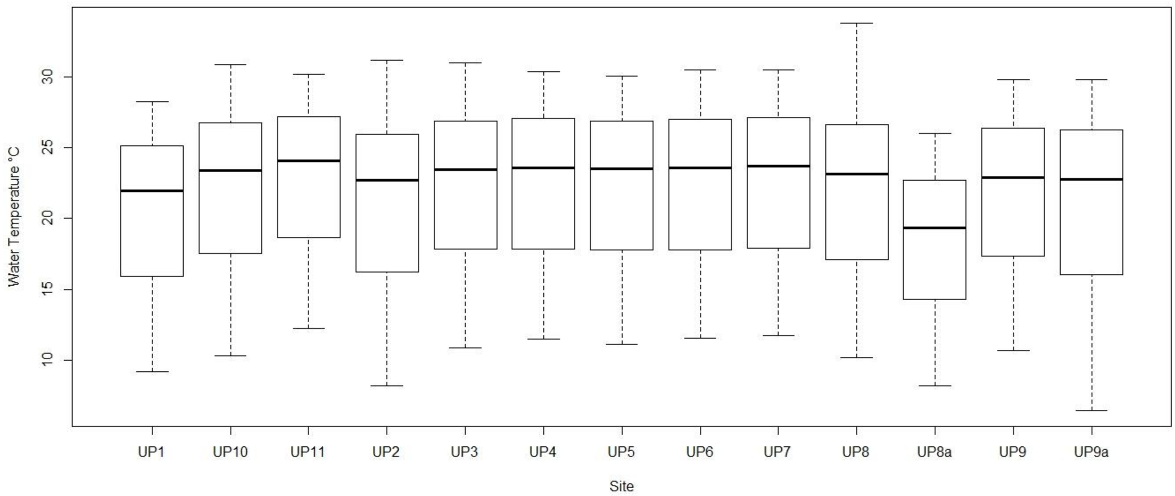

Figure 24 Box-and-whisker plots of water temperatures for 13 study sites, showing median values and 25th/ 75th percentiles, and minima and maxima per site reflected as "whiskers"

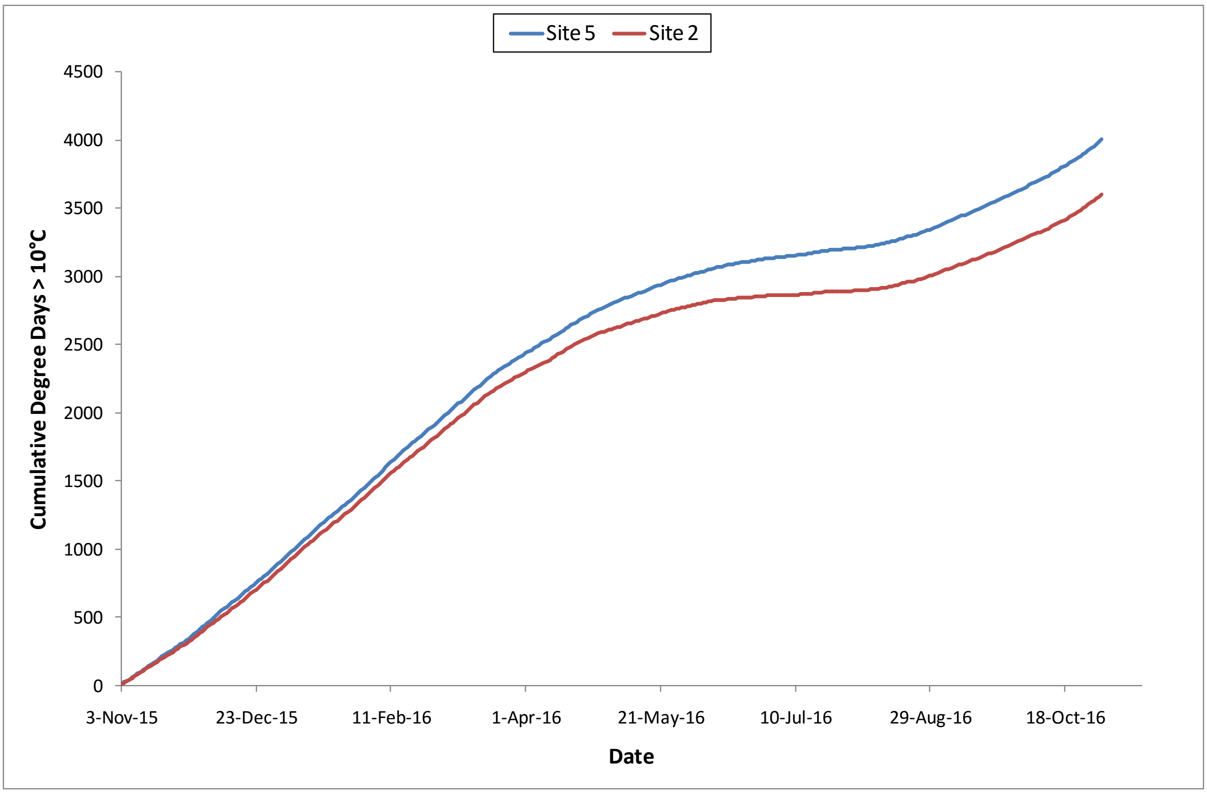

Figure 25 Cumulative degree days > 10°C for sites 2 (Prieska) and 5 (Sun River Lodge, Upington) based on mean daily water temperatures from 3 November 2015 – 2 November 2016

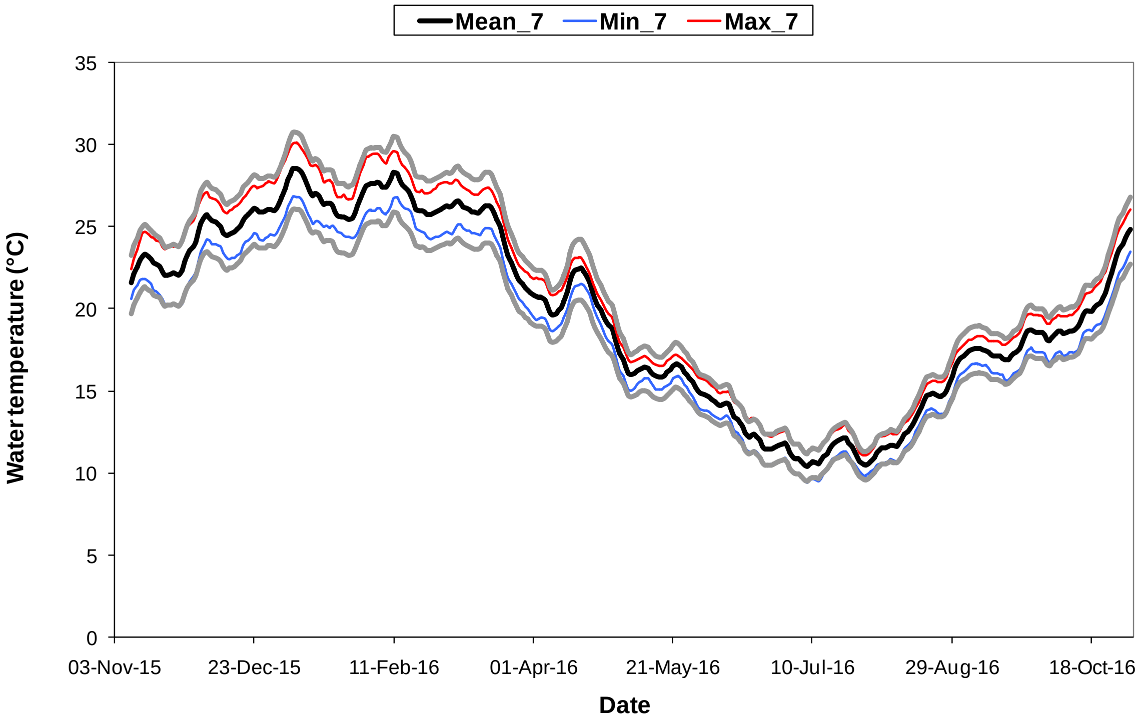

Figure 26 Seven-day moving average of mean, minimum and maximum daily water temperatures from 4 November 2015 – 2 November 2016 at site 2 (Prieska)

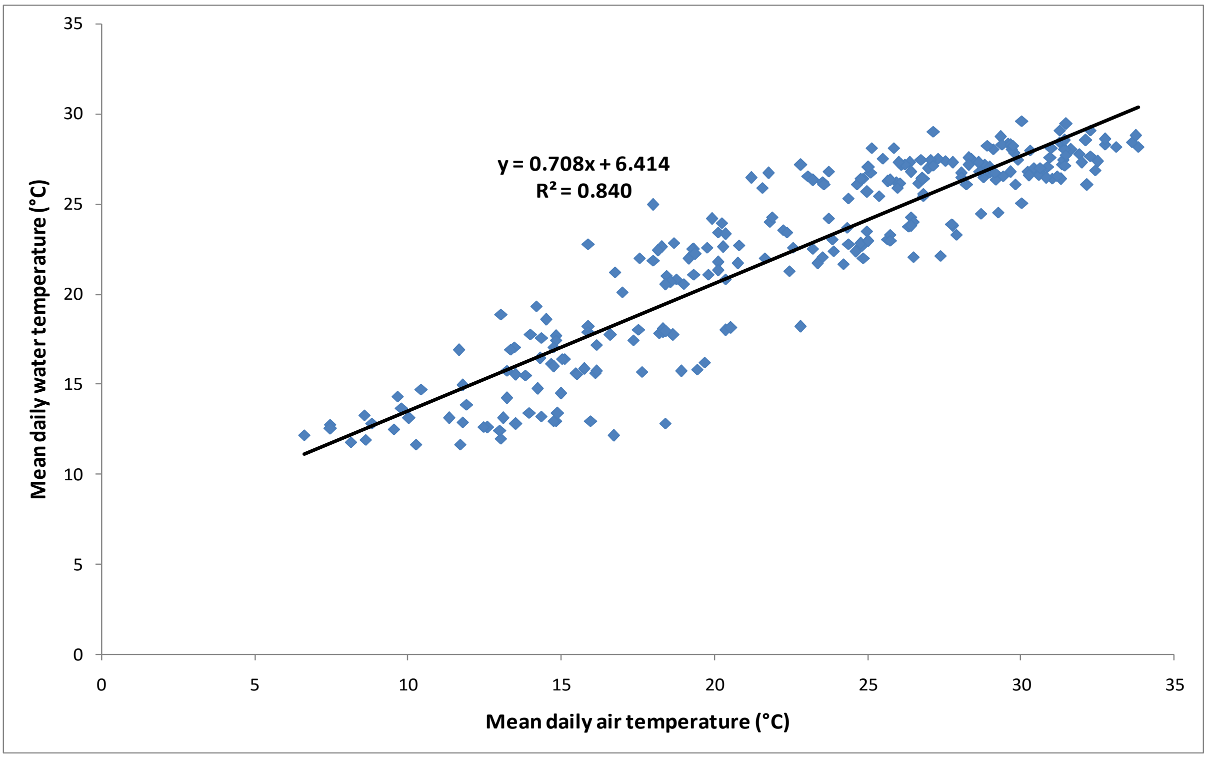

Figure 27 Linear regression between mean daily water temperatures for study site 5 and air temperature logger located at DAFF office, Upington

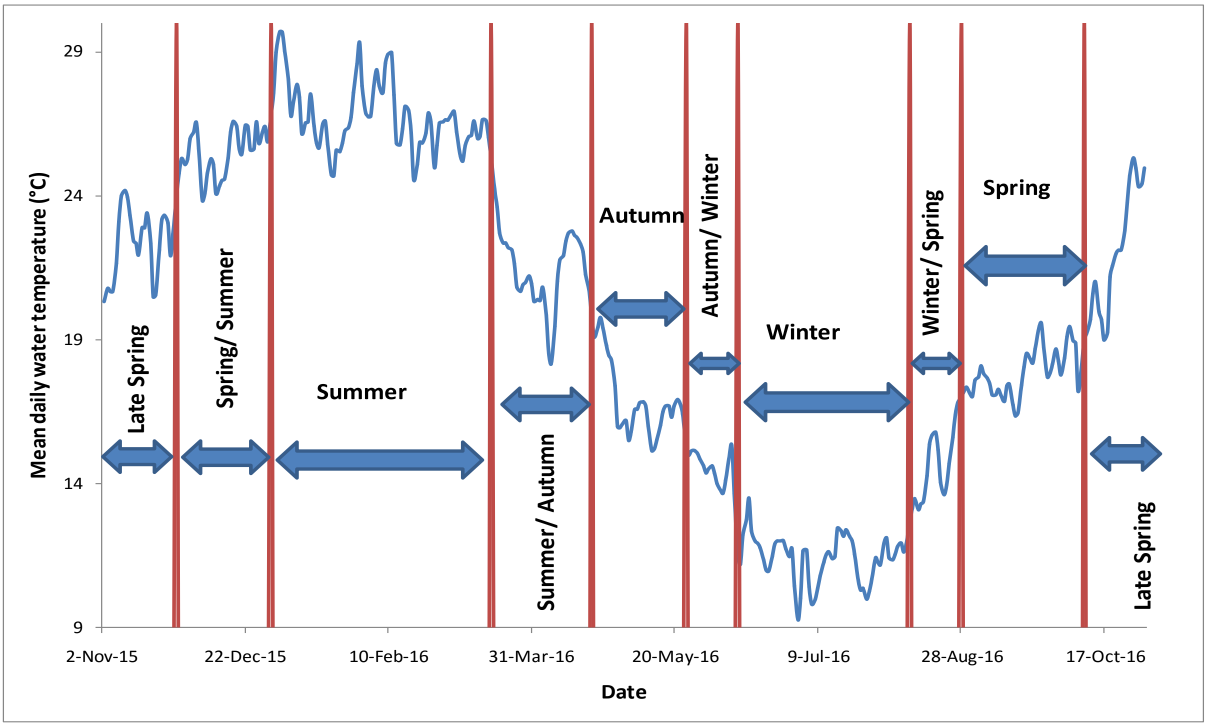

Figure 28 Significant thermal regime shifts for mean daily water temperatures at Prieska, whereby the annual thermograph has been divided into distinct thermal seasons

3.3. Biotic data

3.3.1. Blackfly species data

Blackfly species data were based on the processed samples for November 2015, and March, July and December 2016 (see Appendix 3 for raw abundance data). Almost 80% of the November 2016 sample consisted of *Simulium chutteri*, with the second-most dominant species being *S. damnosum*, but at four times lower abundance (Figure 29). This trend was similar for the March 2016 survey, but with the 10% reduction of *S. chutteri* abundance replaced with three lower-flow blackfly species (Figure 30). Seasonal plots of the relative proportions of contribution to overall sample numbers showed clear switching of dominant species between sites and seasons (Figure 30), but with specific site clusters based on species abundances (Figure 31). *S. chutteri* and *S. damnosum* showed a negative association (Figure 32), which, when compared with the radar diagrams showed limited co-occurrence of both species.

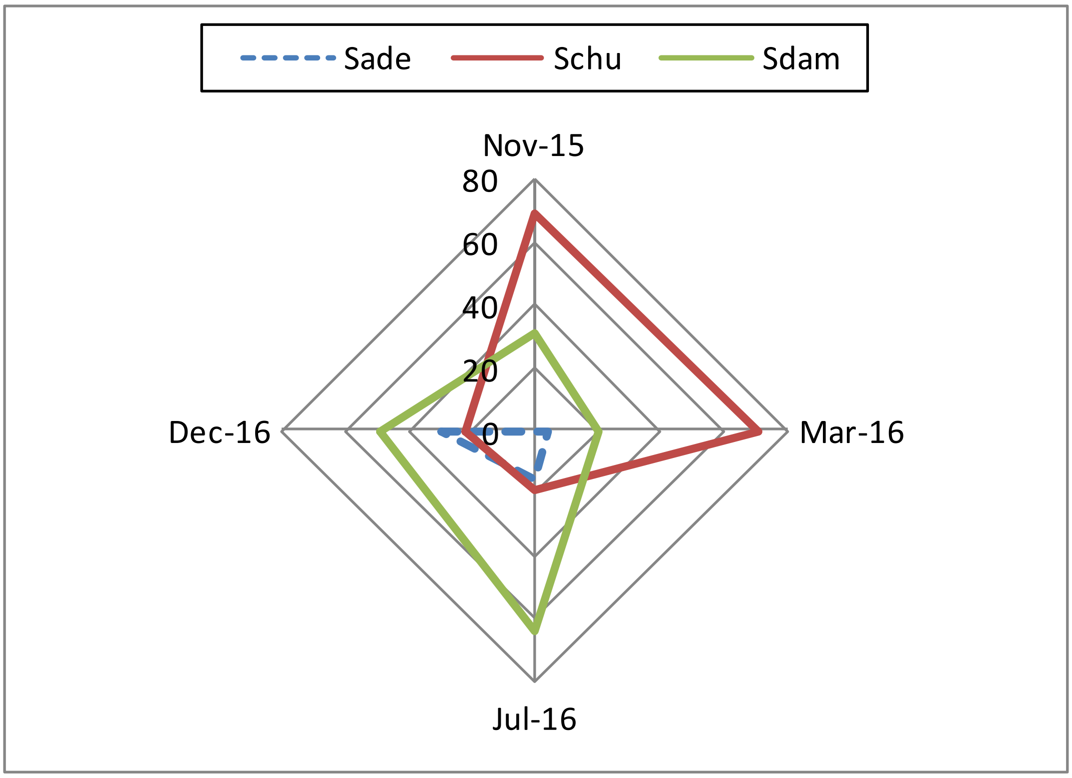

Figure 29 Radar diagram showing the percentage contribution of the three most dominant species of blackfly sampled across all sites and seasons

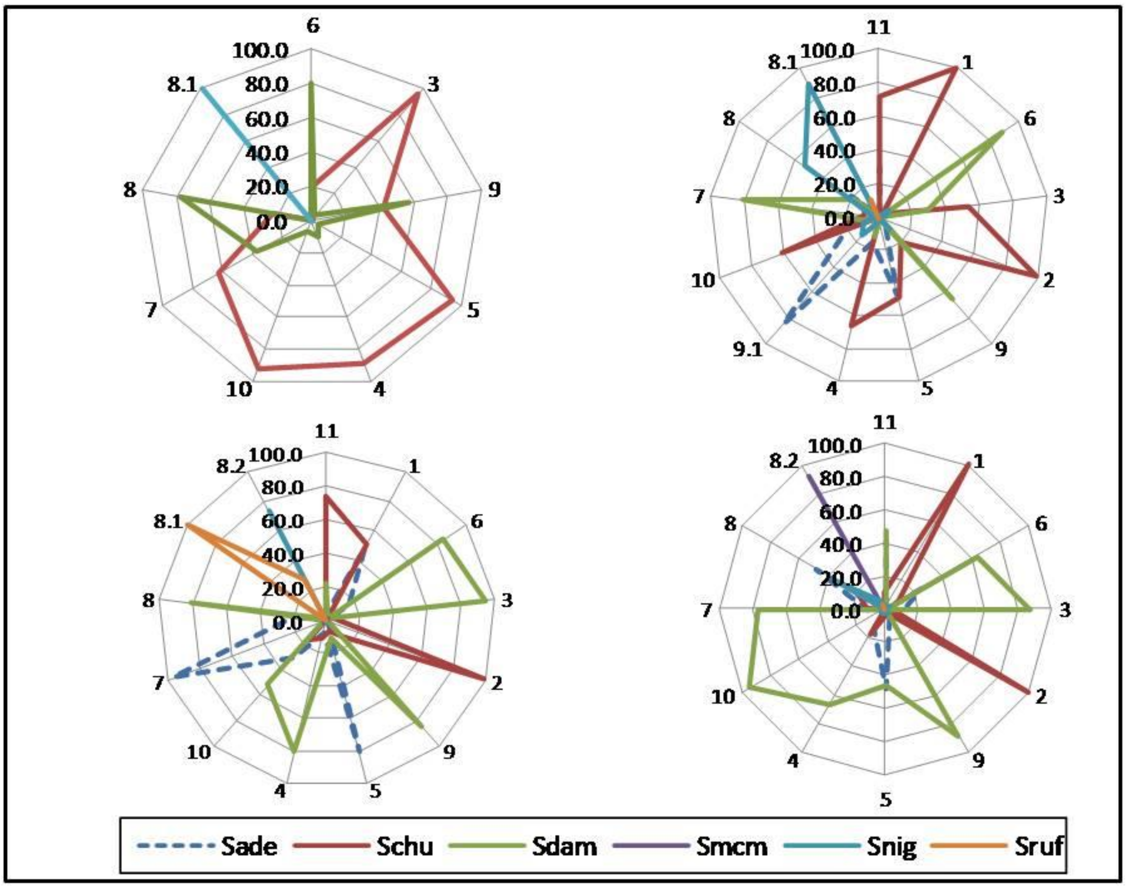

Figure 30 Radar diagrams showing percentage contributions of six blackfly species at each site over four sampling visits. Clockwise from top left: November 2015; March 2016; July 2016; December 2016

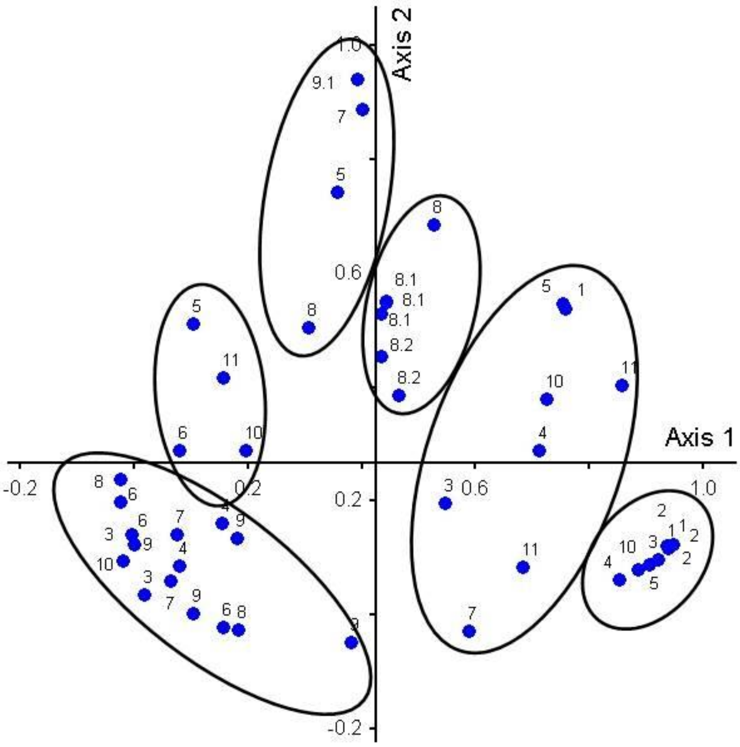

Figure 31 Bray-Curtis ordination of sites surveyed, based on simuliid species data (percent contribution of each species' relative abundance to total number per sample)

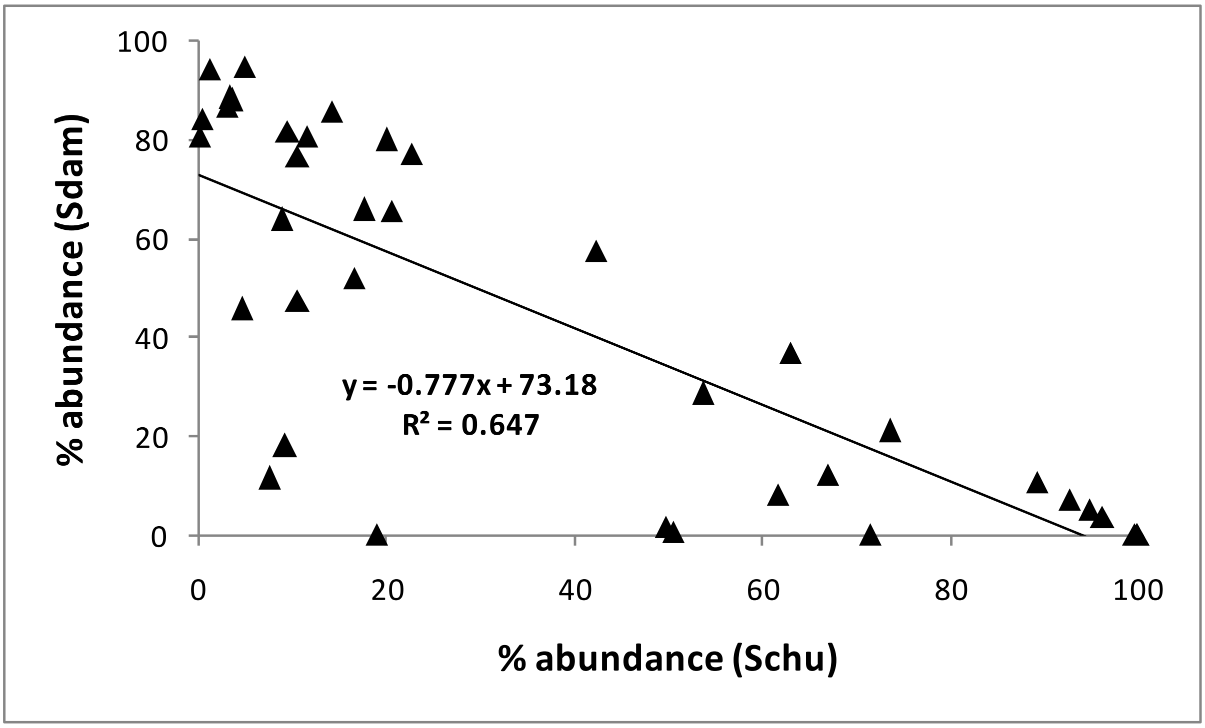

Figure 32 Negative correlation between abundances of *Simulium. chutteri* and *S. damnosum*

3.3.2. Additional ecological data

There was a clear distinction between sites where benthic algae dominated (Figure 33; Table 5), versus sites where it was absent. Separation of sites was largely attributed to Axis 2, which is largely explained by a pH gradient, and sites with benthic algae present being associated with more alkaline pH values.

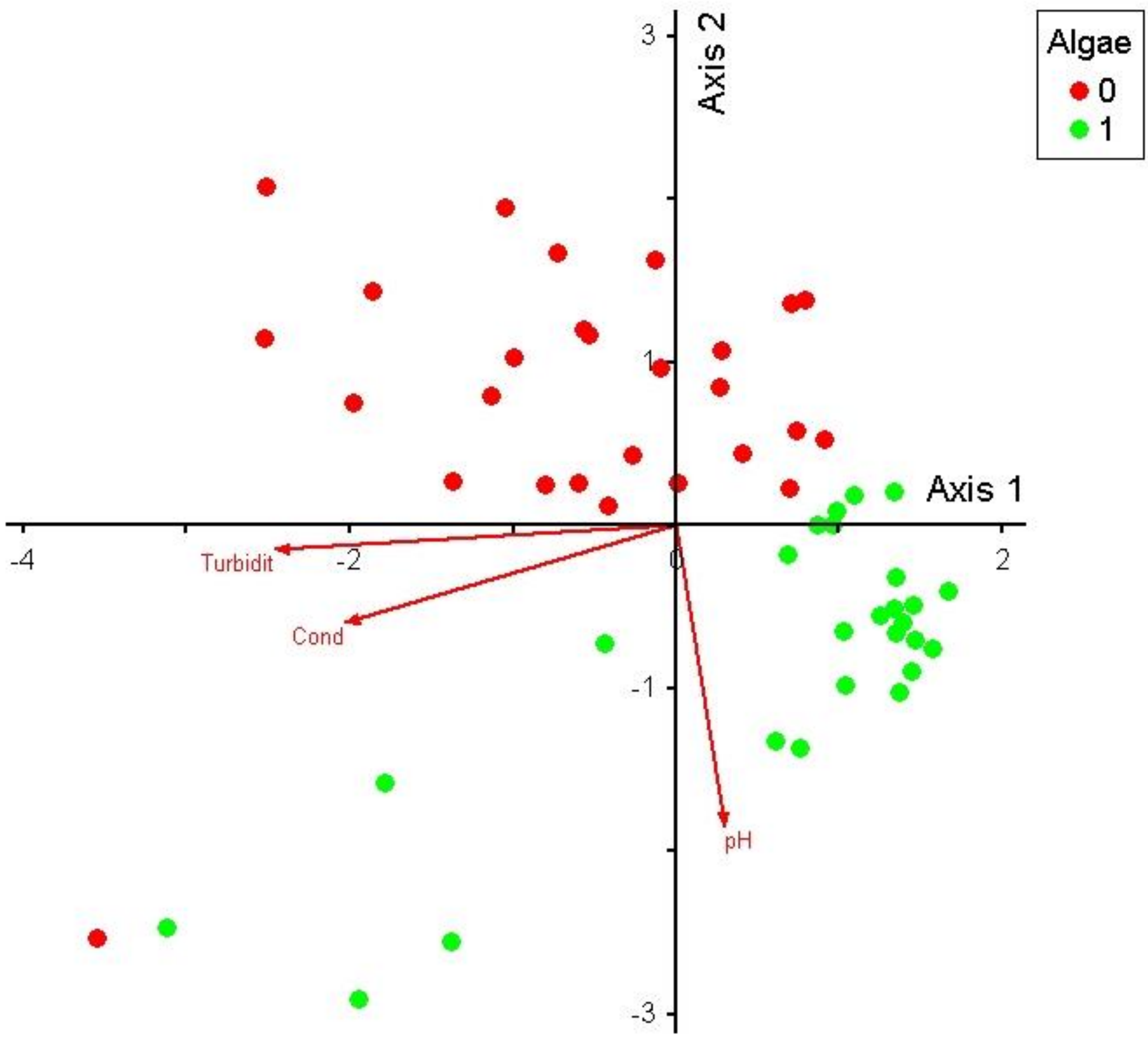

Figure 33 Principal components analysis plot showing distribution of sampling sites of four sampling seasons, based on water quality. Sites were defined in terms of algal presence or absence, with axes 1 and 2 accounting for 45 and 34% of variability respectively

Table 5 Eigenvalues for seasonal water quality variables associated with the 14 blackfly study sites on the middle and lower Orange River, with presence/ absence of benthic algae as a categorical value

	PC Axis 1	**PC Axis 2**
Cumulative % variance	45.23	79.04
Variables	**Eigenvalues**	
pH	0.236	-0.676
Turbidity	-0.673	-0.193
Conductivity	-0.611	-0.384
Benthic algae	0.344	-0.599

Diatom cells were present in 4 of the 6 samples collected, with a total of 63 diatom species recorded across the samples (Appendix 4). Diatom index scores indicate moderate to good water quality; the exception was site 9a, with poor water quality (Table 6). There were zero deformed cells, where > 2% may indicate presence of toxins. Site 3 (Gifkloof) was entirely dominated by sponge spicules of a variety of forms. One species – *Pseudostauropsis geocollegiarum* – was common across most samples. This species was originally found in the Baltic Sea but about a decade ago it started appearing in the Orange River and seems to be linked to increasing salinisation from irrigation returns (Taylor 2017, pers. comm.). Preliminary data shows that as land use shifts towards pivot irrigation this taxon becomes dominant, and has completely replaced the endemic species *Fragilaria sundayensi*s Archibald as a dominant species. Site 4 was dominated by the centric diatom *Pleurosira leavis*, usually found in subtropical waters with higher conductivities, and in heated power plant effluent. It is the first time this species has been observed in the west of South Africa (Taylor 2017, pers. comm.). Analyses of the diatomaceous crust on rocks indicated that the two main components of the crust are a large organic component (40.33%), Calcium (26.4%) and Silica (7.43%) (Appendix 7).

Table 6 Descriptive statistics for diatom samples from six sites on the middle Orange River

Site	Count	No. spec.	SPI	%incl. in SPI	BDI	%incl. in BDI	%PTV
2 (crust)	400	39	13.1	95	16	85	4.7
2	400	22	12.9	95	15.9	82	1.2
1	200	26	14.4	92	15.2	81	3.9
4	0			*No diatom cells in sample*			
9a	100	15	9.3	94	9.2	74	2
3	0			*Dominated by sponge spicules*			

Interpretation of index scores

Ecological Category (EC)	Class	Index Score (SPI Score)
A	High quality	18 - 20
A/B		17 - 18
B	Good quality	15 - 17
B/C		14 - 15
C	Moderate quality	12 - 14
C/D		10 - 12
D	Poor quality	8 - 10
D/E		6 - 8
E	Bad quality	5 - 6
E/F		4 - 5
F		<4

Eighteen aquatic macrophyte species were recorded across six sites (Appendix 5), including two alien species. Two macrophyte species occurring as "abundant" across all sites sampled that are likely to impact significantly on blackfly abundance and the efficacy of the Control Progamme, namely *Phragmites austraulis* and *Cladophora cf glomerata*, due to their effect of downstream carry of larvicides. Three species of molluscs were found during field surveys (Table 7), with the Melania snail being found only in the return flow irrigation canal (site 8b), with the African porcelain mussel occurred in large abundances at sites 9 and 11 (Plate 7).

Table 7 Common mollusc species sampled during the study

Common name	Family	Specific name	Sites
Cape River mussel	Unionidae	*Unio caffer*	*1*
African porcelain mussel	Corbiculidae	*Corbicula fluminatis*	*9, 11*
Red-rimmed Melania snail	Thiaridae	*Melanoides tuberculata*	*8b*

Plate 7 Large numbers of living *Corbicula fluminatsi* encountered at site 9 on each field survey

3.4. Abiotic-biotic interactions

Maximum abundances relative to velocity values showed clear species-specific responses, with *S. chutteri* and *S. damnosum* abundances peaking at 1.2 m.s^{-1}. In contrast, *S. adersi* and *S. nigritarse* showed preferences for velocities of 0.6 and 0.8 m.s^{-1} respectively (Figure 34; Table 8).

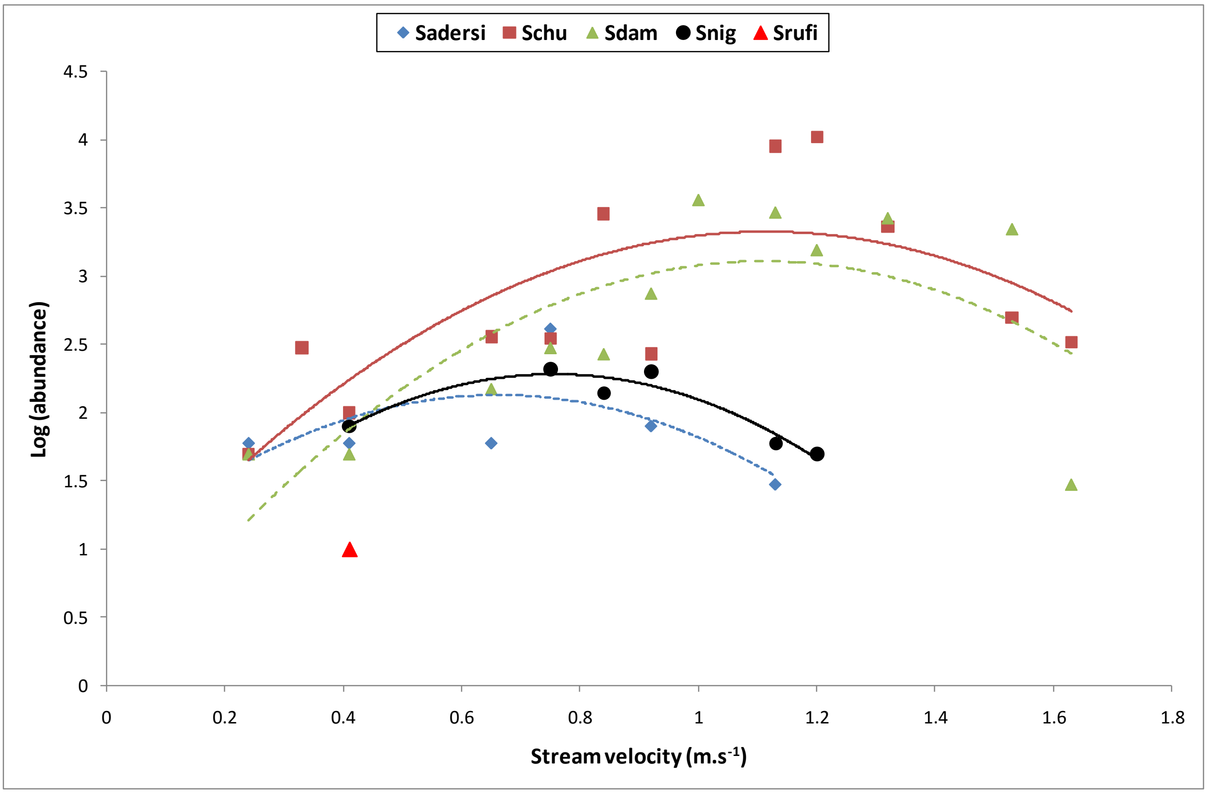

Figure 34 Log-transformed abundances of five species of blackfly based on combined sample data from November 2015 and March 2016. Velocity preference curves are based on maximum abundances for velocity values (see Table 8).

Table 8 Second-order polynomial equations describing relationship between stream velocity and relative abundance for four species of *Simulium* (see Figure 20)

Species	Equation	R^2
S. adersi	y=-2.712x^2+3.589x+0.942	0.41
S. chutteri	y=-2.192x^2+4.886x+0.602	0.59
S. damnosum	y=-2.522x^2+5.600x+0.008	0.58
S. nigritarse	y=-3.150x^2+4.766x+0.479	0.92

The relationship between relative abundance and seston concentration appeared to be less pronounced, but with trends of different blackfly species favouring different seston concentrations

(Figure 35). Water clarity was a strong predictor of probability of occurrence for five of the seven blackfly species sampled, as well as for benthic algae (Figure 36; Table 9). Models indicated that at high turbidity *S. chutteri* and *S. damnosum* are more likely to occur, although each species showed different responses. Conversely, as water clarity increases, the "strong porous" fan complex species are less likely to occur, while the probability of occurrence of the "standard" fan complex species increased. System switching from "strong porous" pest blackfly to "standard" fan complex blackfly and dominance of benthic algae occurred in the region of 60 cm water clarity (≈ 11 mg.ℓ$^{-1}$ seston concentration). There was little relationship between blackfly species abundances and pH or conductivity (Figures 37-38).

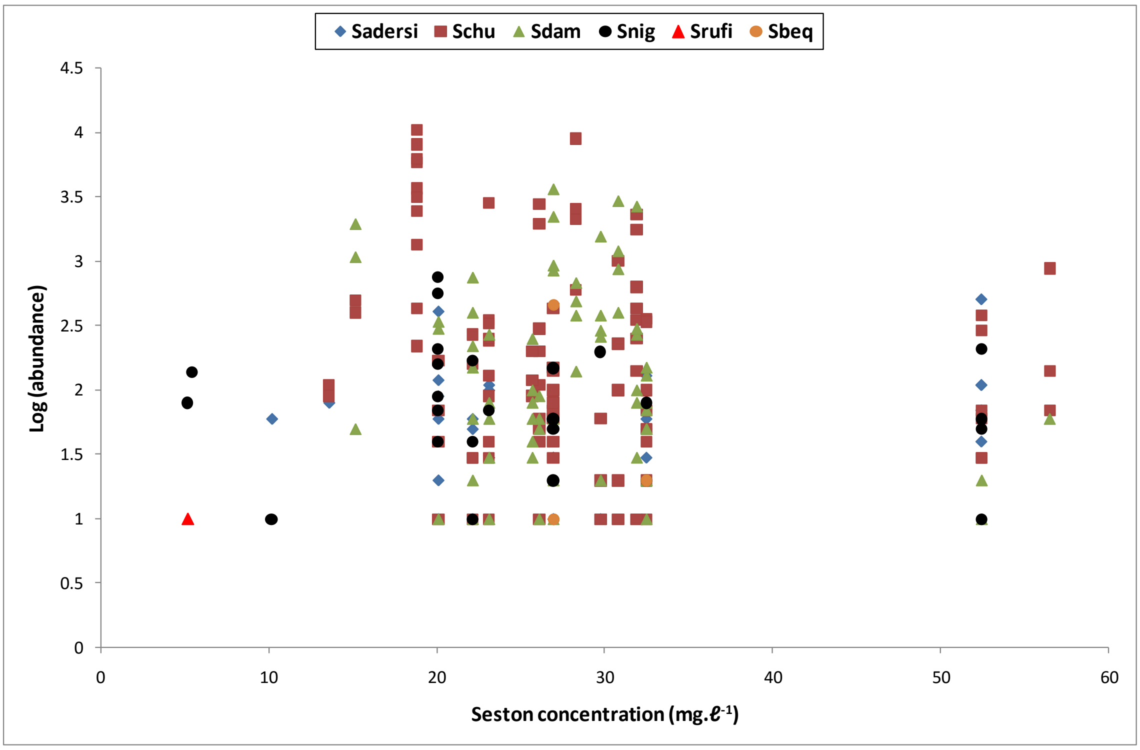

Figure 35 Log-transformed abundances of five species of blackfly based on combined sample data from November 2015 and March 2016 versus seston concentration

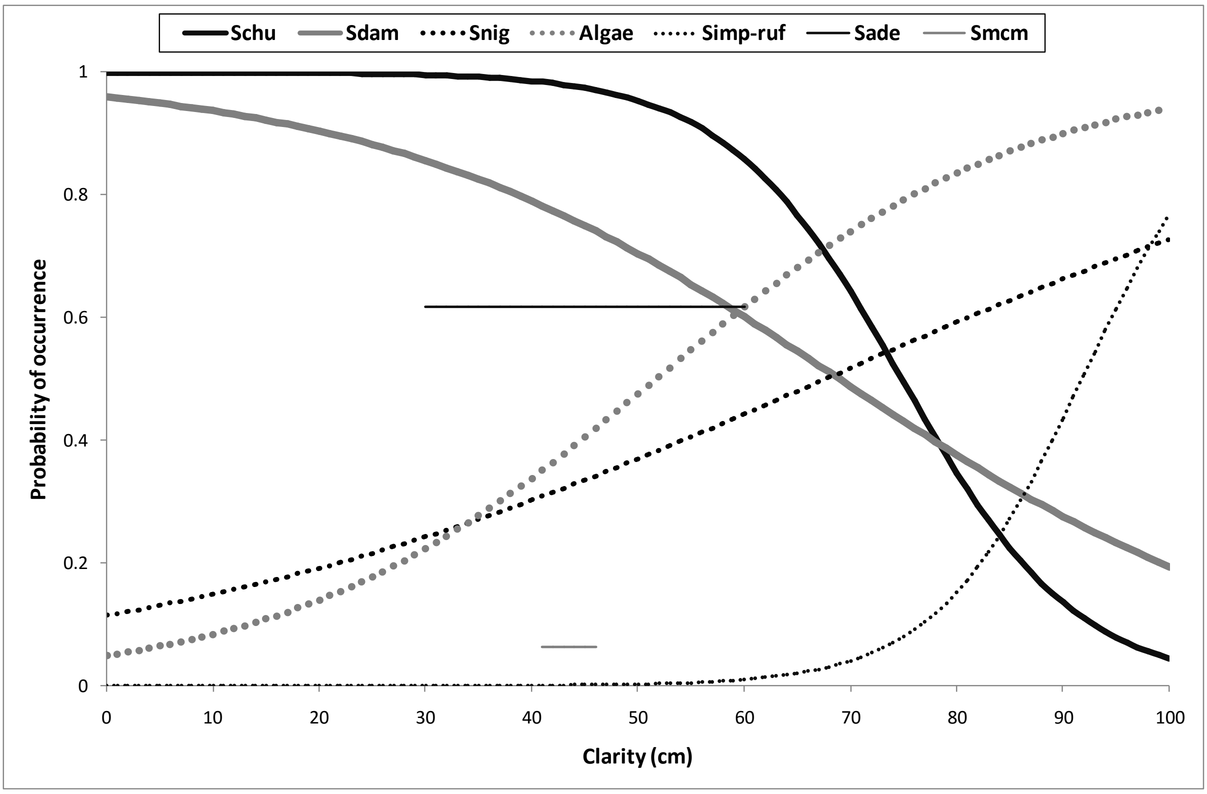

Figure 36 Probability of occurrence of seven blackfly species as a function of water clarity (cm), and benthic algae

Table 9 Logistic regression model coefficients describing interactions between blackfly and turbidity (Schu = *S. chutteri*; Sdam = *S. damnosum*; Snig = *S. nigritarse*; Simp-ruf = *S. impukane* and *S. ruficorne* labral fan complex), and benthic algae versus turbidity and blackfly density scores (*** p<0.001; ** p<0.01; * p<0.05; $^{\prime}$ p<0.1; 46 d.f.)

	Schu	Sdam	Snig	Simp-ruf	Algae
Constant	$9.116 \pm 2.679^{***}$	$3.160 \pm 0.976^{**}$	$-2.047 \pm 0.847^{*}$	$-13.353 \pm 5.511^{*}$	$4.061 \pm 1.631^{*}$
$\boldsymbol{\beta}_{clarity}$	$-0.122 \pm 0.039^{***}$	$-0.046 \pm 0.018^{**}$	0.030 ± 0.016`	$0.145 \pm 0.060^{*}$	$-0.057 \pm 0.031^{\prime}$
$\boldsymbol{\beta}_{density}$					$-0.273 \pm 0.140^{\prime}$

$$p = \frac{e^{\alpha+\beta_1 x_1+\beta_2 x_2}}{1+e^{\alpha+\beta_1 x_1+\beta_2 x_2}} \qquad [4]$$

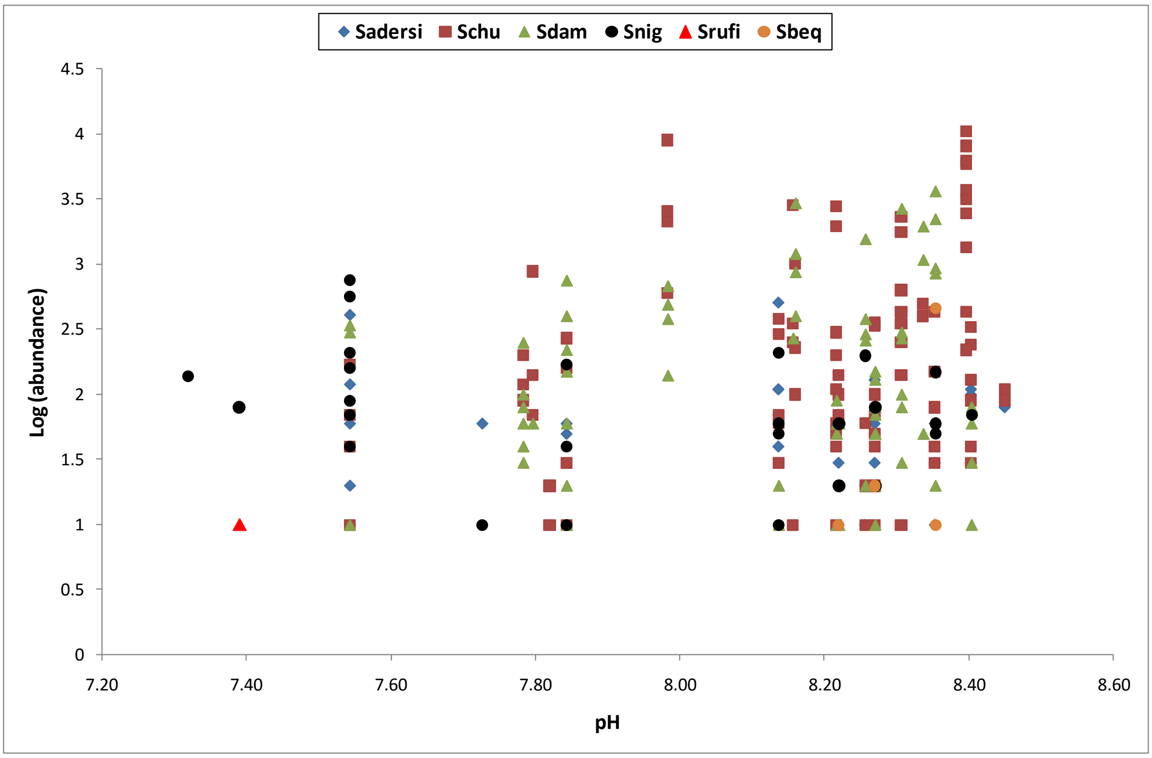

Figure 37 Scatterplot of log-transformed abundances of six species of blackfly based on combined sample data from November 2015 and March 2016 versus pH values.

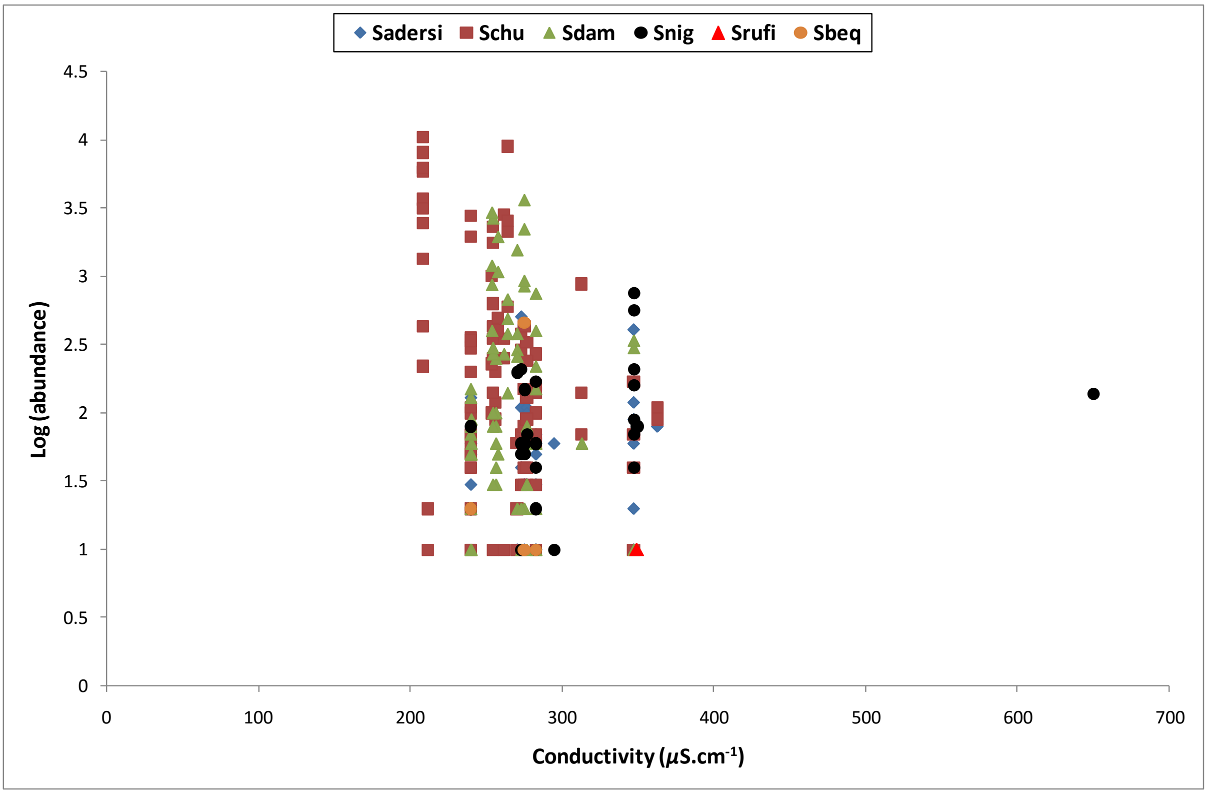

Figure 38 Scatterplot of log-transformed abundances of six blackfly species versus conductivity

Trichoptera occurred in abundance at sites 7 and 8 when water clarity exceeded 40 cm. Densities were approximately 20 webs per 10 cm^2, so that for the 9x1 m ridge at site 7 (Kanoneiland), there was maximum potential habitat of ≤ 180 000 trichopterans (total area of 90 000 cm^2 = 9000 habitat units of 10 cm^2). Hypothetical plots of potential abundances of trichopterans and pest blackfly using Palmer's (1994) scoring system, as well as predator: prey ratios indicate that above a density class of 6, predation effects of trichoptera on pest blackly become increasingly irrelevant (Figure 39). Reed areas at both Prieska and Blouputs increased exponentially during 2010-2012, corresponding with decreased flows at both sites (Figures 40-41).

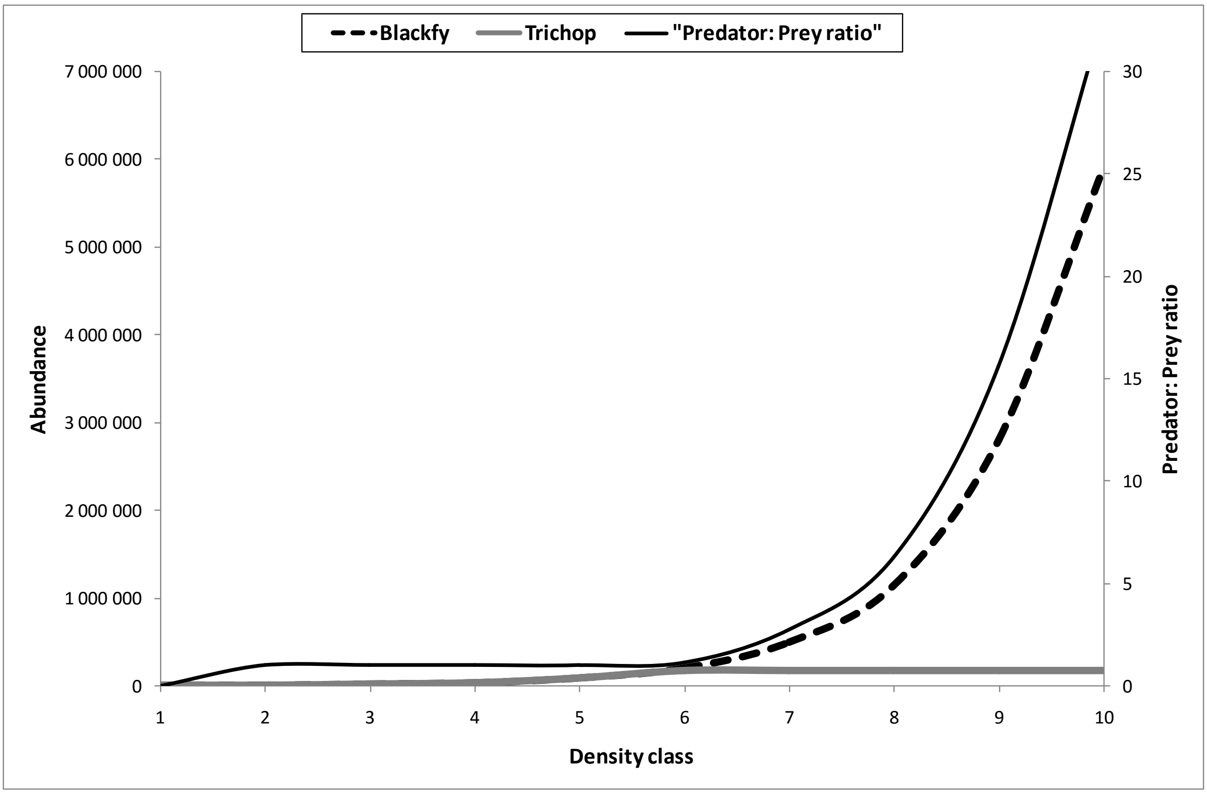

Figure 39 Potential numbers of blackfly and caseless caddisfly larvae as a function of density classes for a habitat area of 90 000 cm^2, and associated predator: prey ratios

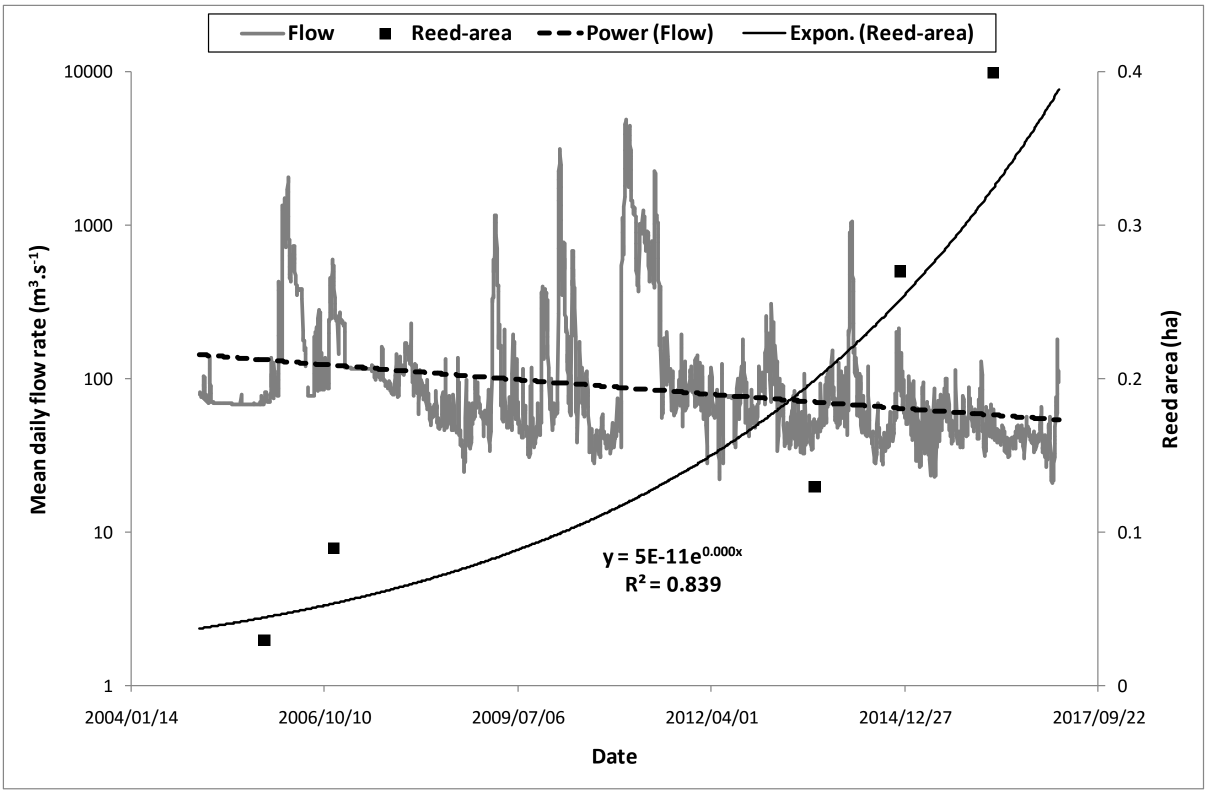

Figure 40 Change in reed area over a thirteen-year period at site 2, and corresponding mean daily flow rate time series for gauging weir D7H002 (Prieska)

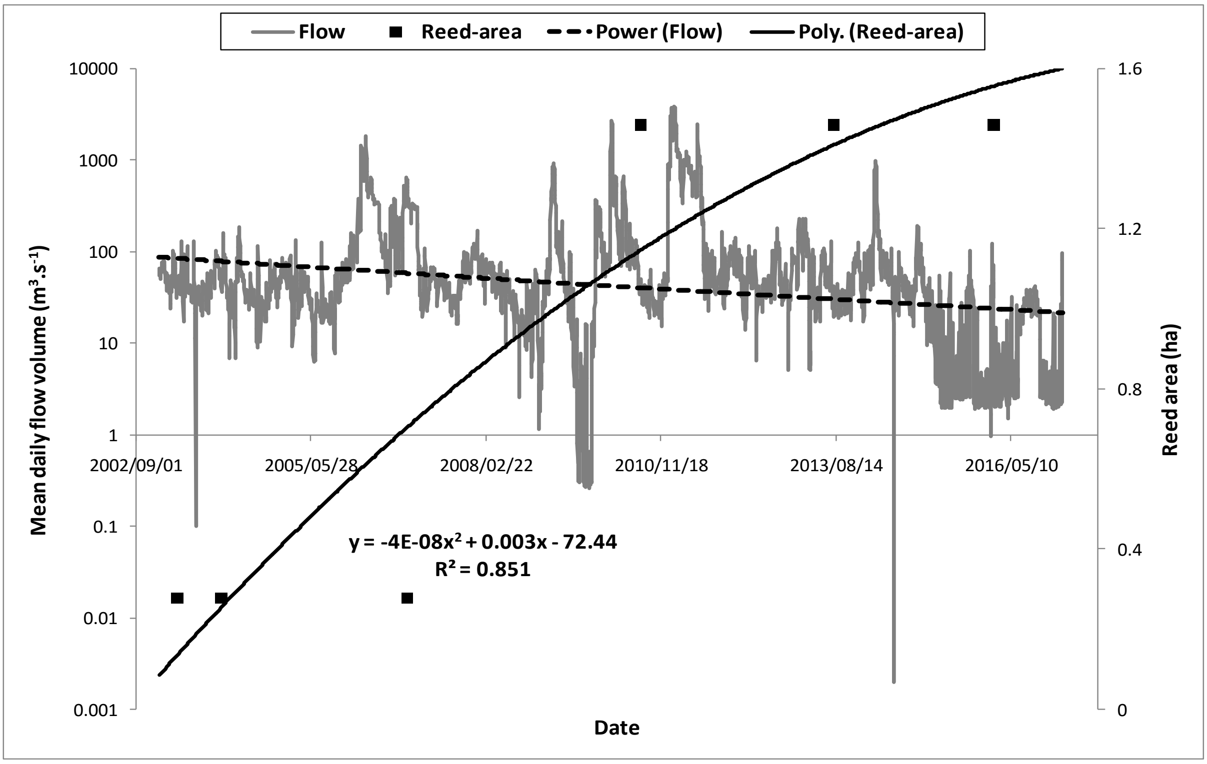

Figure 41 Change in reed area over a thirteen-year period at site 11, and corresponding mean daily flow rate time series for gauging weir D7H014 (Neusberg)

3.5. Blackfly Bayesian network model

3.5.1. Model Resolution

In terms of water quality, all sites exhibited similar characteristics, with little evidence to support grouping of sites based on water quality. What was apparent, however, was a seasonal shift in water quality, with winter water quality driven by relatively higher conductivity and clarity values. The exception to this trend was site 8b (Table 3; irrigation return flow channel), that exhibited the highest conductivities and greatest water clarity (Figures 42-43; Table 10). Here, site variability in terms of water quality was driven by conductivity and clarity (Axis 1), and alkalinity for Axis 2. Sites were generally clearer but with higher conductivity levels, and higher alkalinity during winter, and transitioning to more turbid, neutral pH conditions with greater dilution of salts. Conversely, sites could be divided into three distinct thermal groups, based on their thermal metrics (Figures 44-45). Here, the Douglas and Prieska sites (sites 1-2 plus site 9a) clustered together as relatively cooler sites than the remainder of the main channel Orange River sites, which could all be clustered together. Site 8a (agricultural return flow stream) was the coldest site observed.

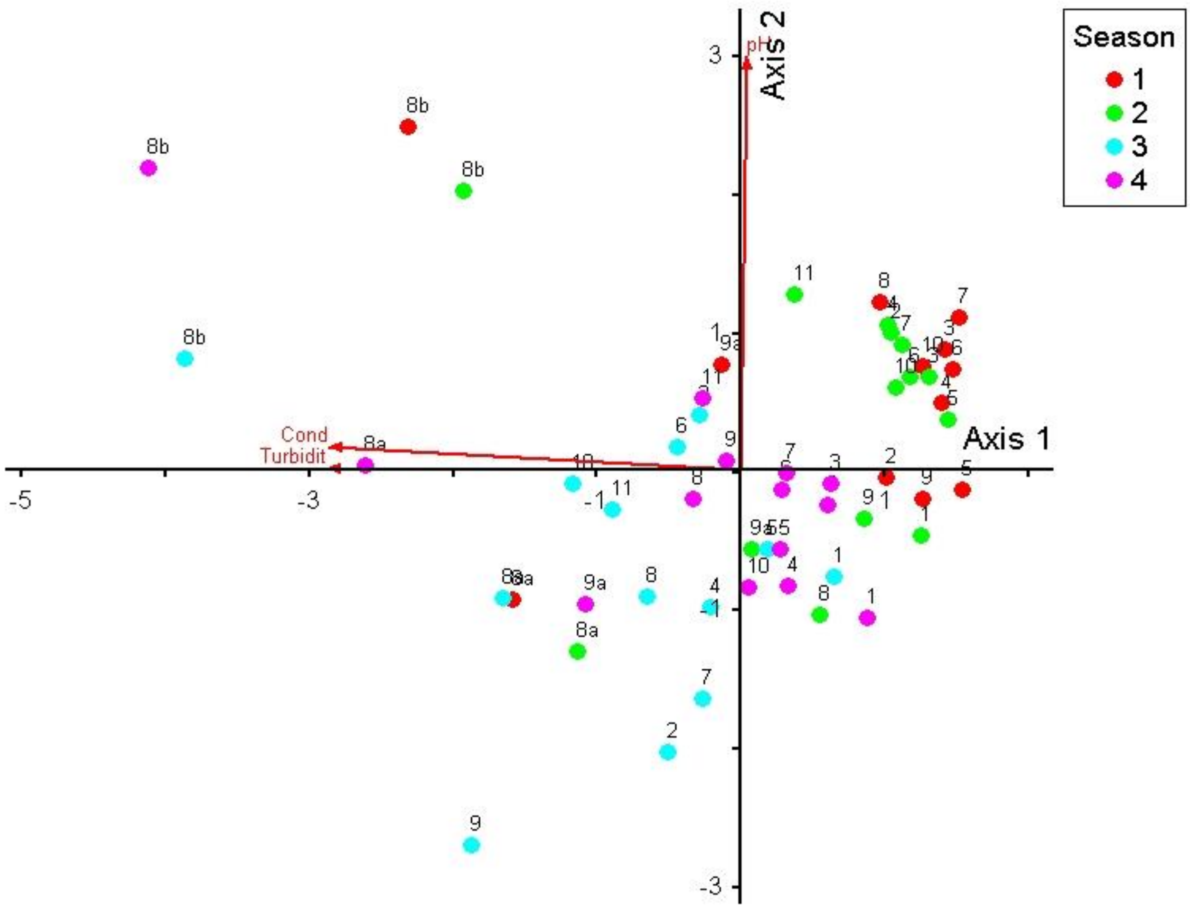

Figure 42 Principal Components Analysis of study sites based on water quality variables for November 2015, March, July and December 2016. Seasons 1-4 represent the data collected for the late spring (November 2015), late summer (March 2016), winter (July 2016) and early summer (December 2016) sampling periods respectively.

Table 10 Eigenvalues for seasonal water quality variables associated with the 14 blackfly study sites on the middle and lower Orange River

	PC Axis 1	PC Axis 2
Cumulative % variance	50.28	76.56
Variables	**Eigenvalues**	
pH	-0.365	-0.687
Turbidity	0.571	-0.373
Conductivity	0.574	-0.428
Season	0.460	0.453

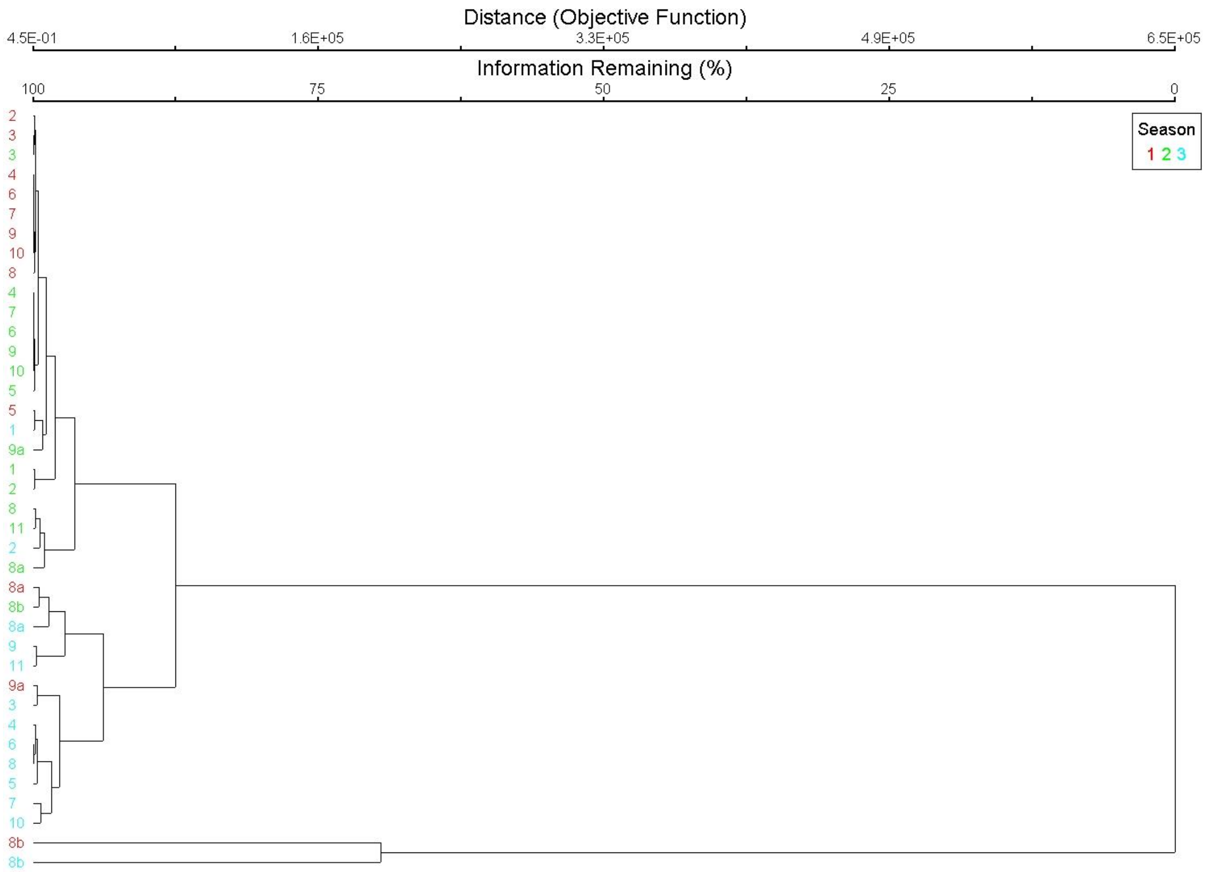

Figure 43 Cluster analysis of study sites based on water quality variables

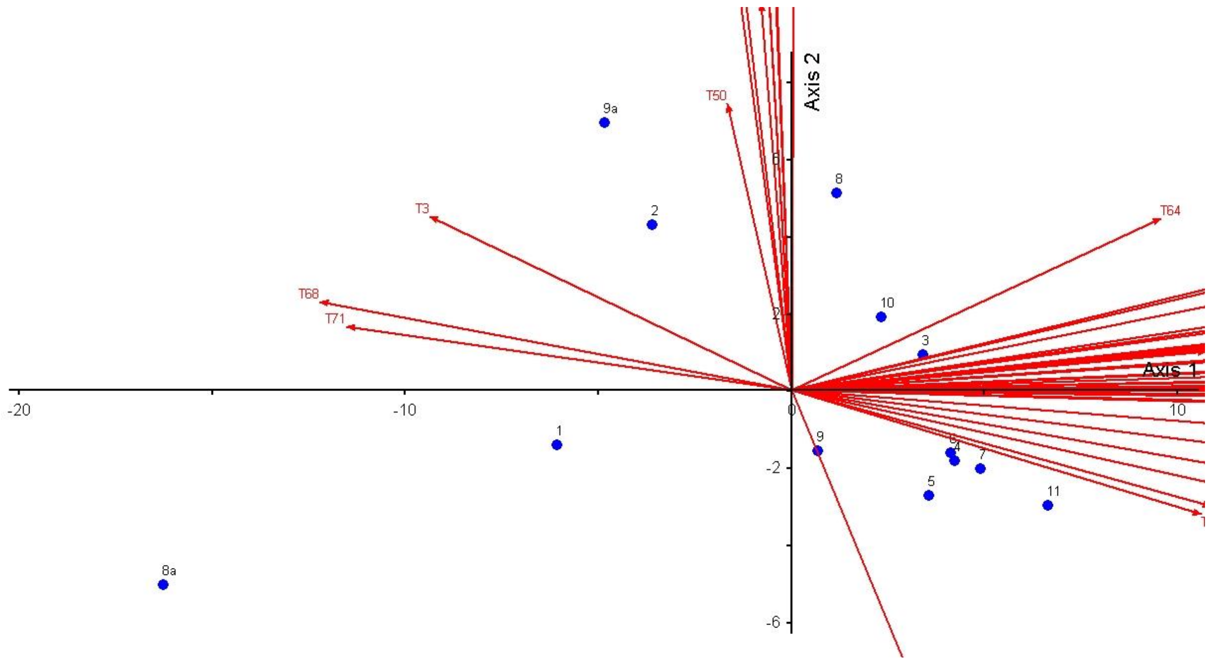

Figure 44 Principal Components Analysis of study sites based on water temperature metrics. PC axes 1-2 contributed to 65.6 and 86.9% of site variation.

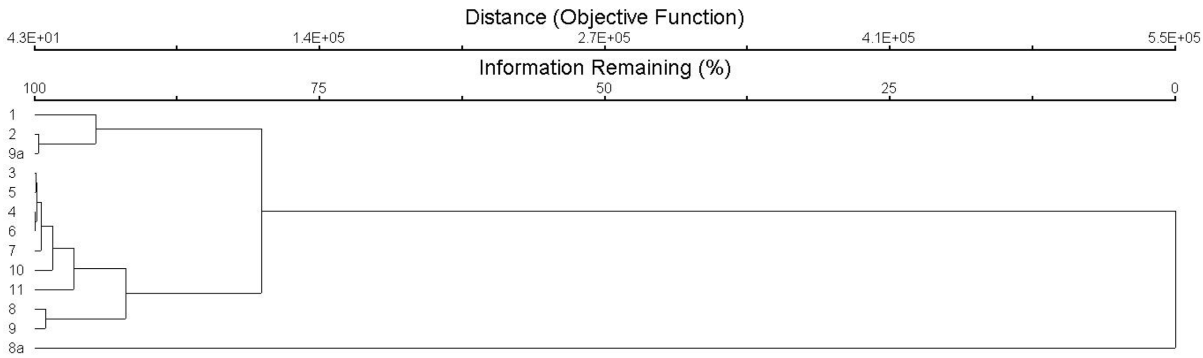

Figure 45 Cluster classification of study sites based on water temperature metrics

On the basis of the analyses from this study, two BN models would be required to capture spatial differences (Douglas + Prieska sites; remaining downstream sites), and 8-12 temporal models (thermal seasons versus months) to capture seasonal probabilities. In other words, a suitable BN modelling framework would require 16-24 free-standing BN models, with the relevant return intervals calculated for affected nodes.

3.5.2. Model nodes, states and probabilities

Fourteen nodes were identified for the BN model, with each node having two to three states (Table 11). This was made up of 11 nature nodes (i.e. variables), a decision node, and two utility nodes for incorporating costs and benefits. Threshold values for discharge, seston concentration and water temperature were based on the results described in sections 3.2-4. In the case of the water temperature threshold, that was linked to a number of child nodes each likely to have a particular temperature threshold, a trade-off was made in assigning a 20°C mean daily water temperature threshold as being a reasonable compromise threshold to serve all three variables. For the utility nodes, cost: benefit curves were defined for each of the four economic zones (Figure 46).

Table 11 Bayesian network model nature nodes, system states, and thresholds where relevant

Node	States	Thresholds
Channel type	Multiple/ Single	NA
Discharge	Low/ High	Low < 100 $m^3.s^{-1}$> High
Seston concentration	Low/ High	Low < 60 $mg.ℓ^{-1}$> High
Benthic algae	Present/ Absent	N/A
Reed abundance	Sparse/ Abundant	N/A
Water temperature	Cool/ Warm	Cool < 20°C > Warm
Larvicide efficacy	Optimal/ Suboptimal	N/A
Biotic controls	Strong/ Weak	N/A
Abiotic controls	Unfavourable/ Favourable	N/A
Simulium fan complex	Standard/ Strong Porous	N/A
Spraying	Successful/ Unsuccessful	N/A
Outbreak probability	Low/ High	N/A

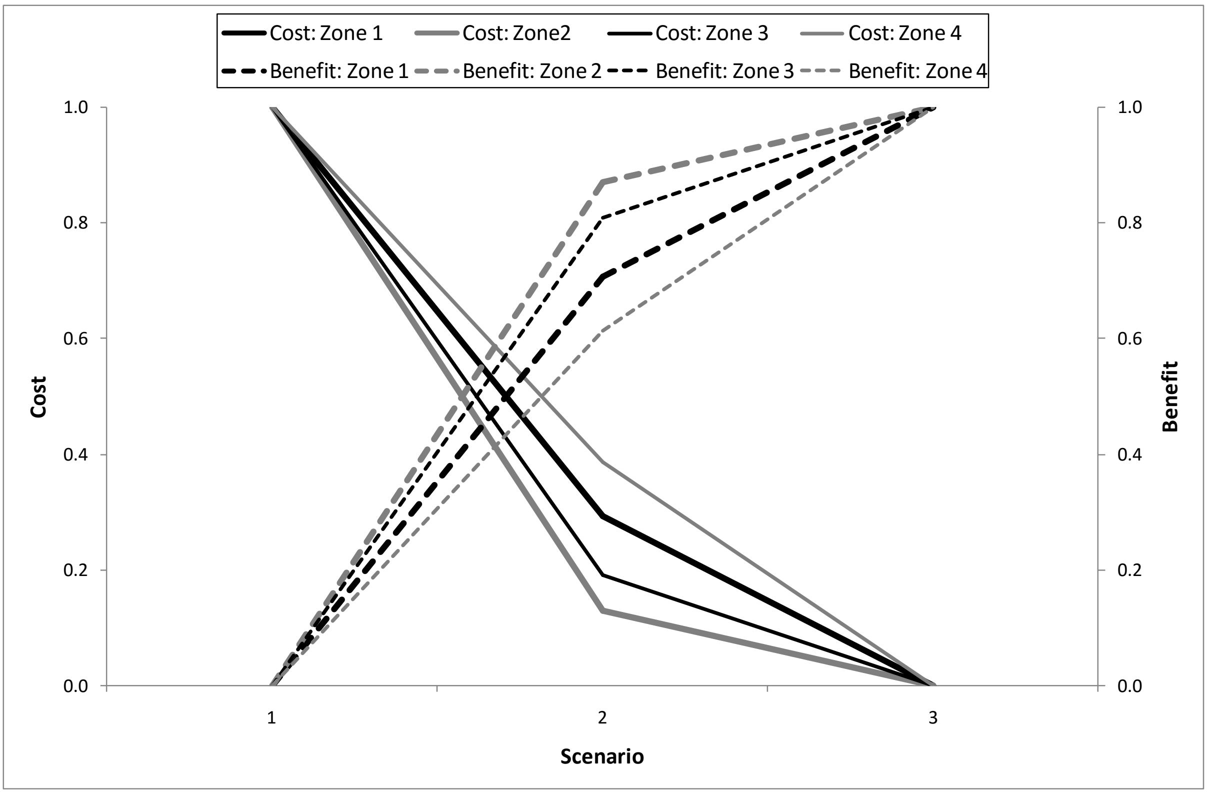

Figure 46 Cost-benefit curves standardised to scores between 0 and 1, for three management scenarios (1 = base; 2 = optimistic; 3 = pessimistic) and four economic zones

A number of broad-scale trends facilitated derivation of probabilities for the parent nodes (Table 12). Conditional probability data was estimated based on expert opinion, with probability values of each state for the parent and child nodes provided in Tables 13-14.

Table 12 Parent node state probabilities

Node	State Probabilities
Channel type	20% Multiple/ 80% Single
Discharge	37% < 100 $m^3.s^{-1}$/ 63% > 100 $m^3.s^{-1}$
Seston concentration	42% < 60 $mg.\ell^{-1}$/ 58% > 60 $mg.\ell^{-1}$
Water temperature	30% < 20°C/ 70% > 20°C
Reeds	80% absent/ 20% present

Table 13 Conditional probability values for five child nodes with two parent node inputs

Parent Nodes		Child Node states	
		Simulium Node	
Biotic	**Abiotic**	**Standard**	**Strong porous**
Strong	Unfavourable	100	0
Strong	Favourable	20	80
Weak	Unfavourable	80	20
Weak	Favourable	0	100
		Biotic Node	
Benthic Algae	**Reeds**	**Strong**	**Weak**
Present	Sparse	100	0
Present	Abundant	80	20
Absent	Sparse	40	60
Absent	Abundant	0	100
		Algae Node	
Seston concentration	**Water temperature**	**Present**	**Absent**
Low	Cool	60	40
Low	Warm	100	0
High	Cool	0	100
High	Warm	20	80
		Larvicide Efficacy Node	
Water temperature	**Seston concentration**	**Optimal**	**Suboptimal**
Cool	Low	60	40
Cool	High	0	100
Warm	Low	100	0
Warm	High	70	30

Table 14 Conditional probability values for the "Abiotic" node, based on three input nodes

Channel	Discharge	Seston	Abiotic=Unfavourab	Abiotic=Favourable
Multiple	Low	Low	100	0
Multiple	Low	High	60	40
Multiple	High	Low	55	45
Multiple	High	High	33	67
Single	Low	Low	80	20
Single	Low	High	48	52
Single	High	Low	44	56
Single	High	High	0	100

3.5.3. Scenario assessments

The final BN model represented relationships among all system variables, with good parsimony. Internal logic was correct, with probabilities of systems states changing in accordance to the understood system behaviour and relationships presented in this report (Figure 47). Data indicated an increase in the probability of pest blackfly outbreaks between pre- and post-impoundment flows, with a further increase in outbreak probability with an assumed 2°C warming in water temperatures in response to global climate change (Figure 48). The highest probabilities of outbreaks, according to the model, were for February to April (Figure 49). Verification data using maximum monthly values of the fly worry index showed a lag of one to two months, which is not surprising given that the BN model prediction probability of suitable habitat conditions for larvae, while the fly worry index reflects adult blackfly: depending on water temperatures, the time required for life cycle completion is 12-24 days.

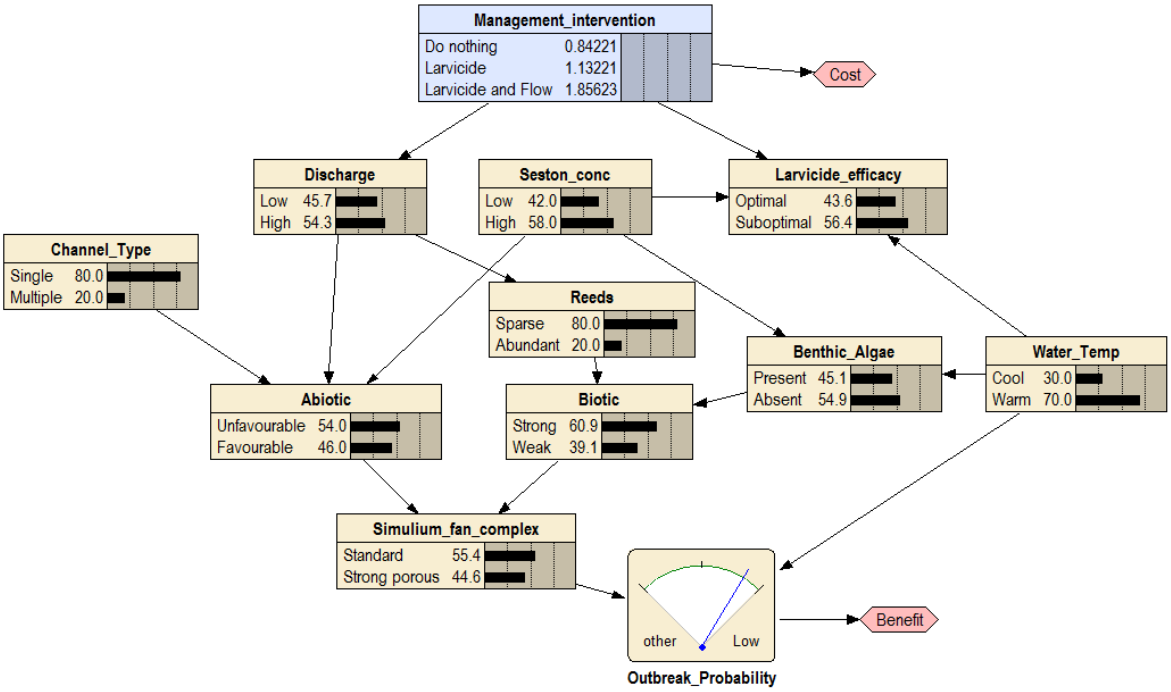

Figure 47 Bayesian network model, showing parent and child nodes together with management and utility nodes

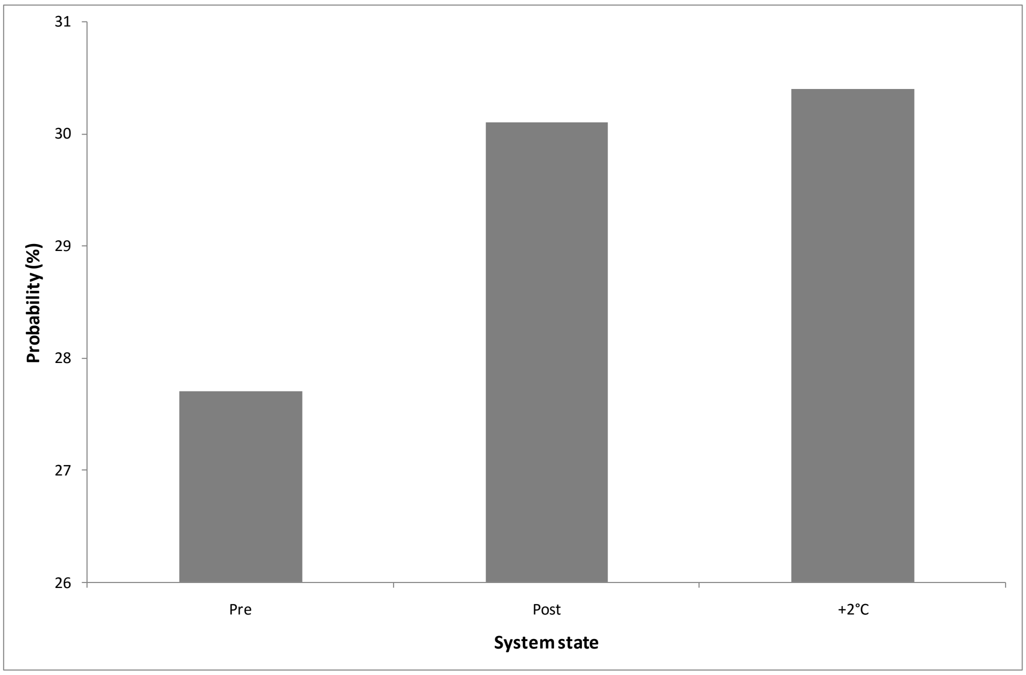

Figure 48 Probability of blackfly outbreaks under pre-impoundment, post-impoundment and future global climate change scenarios

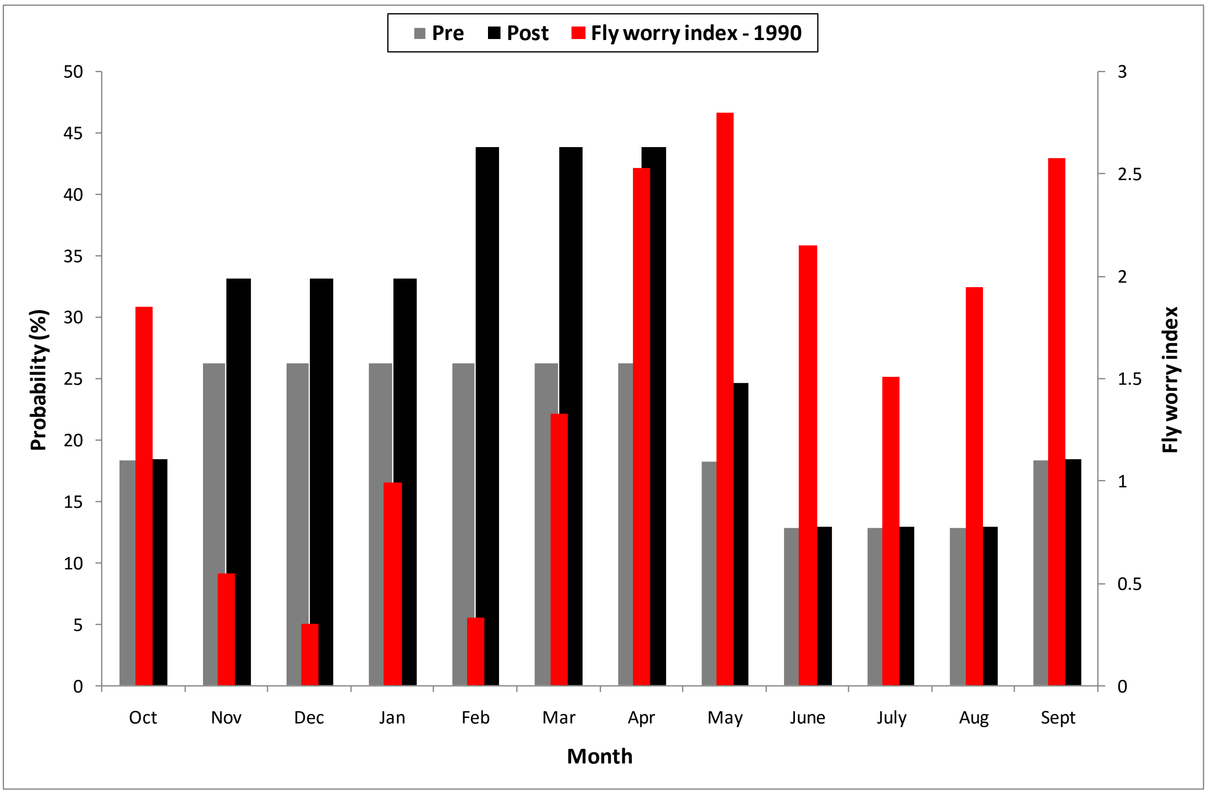

Figure 49 Seasonal variation in blackfly outbreak probabilities for pre- and post-impoundment flow conditions

4. Discussion

4.1. Abiotic-biotic relationships

Orange River blackfly species conform to the fan type complexes defined by Palmer and Craig (2000). Water quality conditions were relatively consistent across the 600 km study axis, with the exception of peripheral habitat that caters for different blackfly species with specific water quality preferences. Larvae of *S. chutteri* exhibit a wide tolerance of water quality conditions (conductivities of 2-55 $mS.m^{-1}$). Similarly, De Moor (1982) noted that fluctuations in pH in the Vaal River were minor (7.8-8.4) and not considered to account for larval size variation. Water temperatures are favourable throughout the year for blackfly life history development, although the marked cooling during autumn and winter is likely to lead to reduced numbers of generations over this period, and favouring larger larvae that develop into more fecund adults. This is particularly so for the Prieska and Douglas sites, which are slightly cooler than the other downstream sites. However, an important difference between the Douglas and Prieska sites was that the former site experiences significantly higher levels of sub-daily flow variability that sites further downstream, because of the water releases from van der Kloof Dam for hydro-electric power generation. While these constant high and low flow pulses over each 24-hour time period are mitigated with downstream distance, the ecological consequence is that pest blackfly are more abundant at elevated but stable flows, and less abundant at elevated by highly variable sub-daily flows.

A number of interesting blackfly ecology dynamics emerged from this study. The negative correlation between *S. chutteri* and *S. damnosum* showed that only one of these species dominates at any one time at a site, with the other species largely competitively excluded. Changes in turbidity cause switches in blackfly species populations and a concomitant increase in benthic algae, also noted in the Vaal River by De Moor (1994). A combination of reduced flows, increased water clarity and more alkaline water tends to favour the “standard complex” fan structure blackly species, which are also not regarded as major pest species. Associated with this species switch is a growth in benthic algae, and a crusting on rocks. The crusting appears to be a mix of diatoms and calcium carbonate. The chemistry of what causes the precipitation of calcium carbonate onto the rocks is not obvious, because while water temperatures, conductivity and pH all affect precipitation of calcium carbonate, the range of these variables is not large enough to explain the precipitation reaction (Appendix 6). Conceptually, however, the relationships between variables relative to a system switch are given in Figure 50.

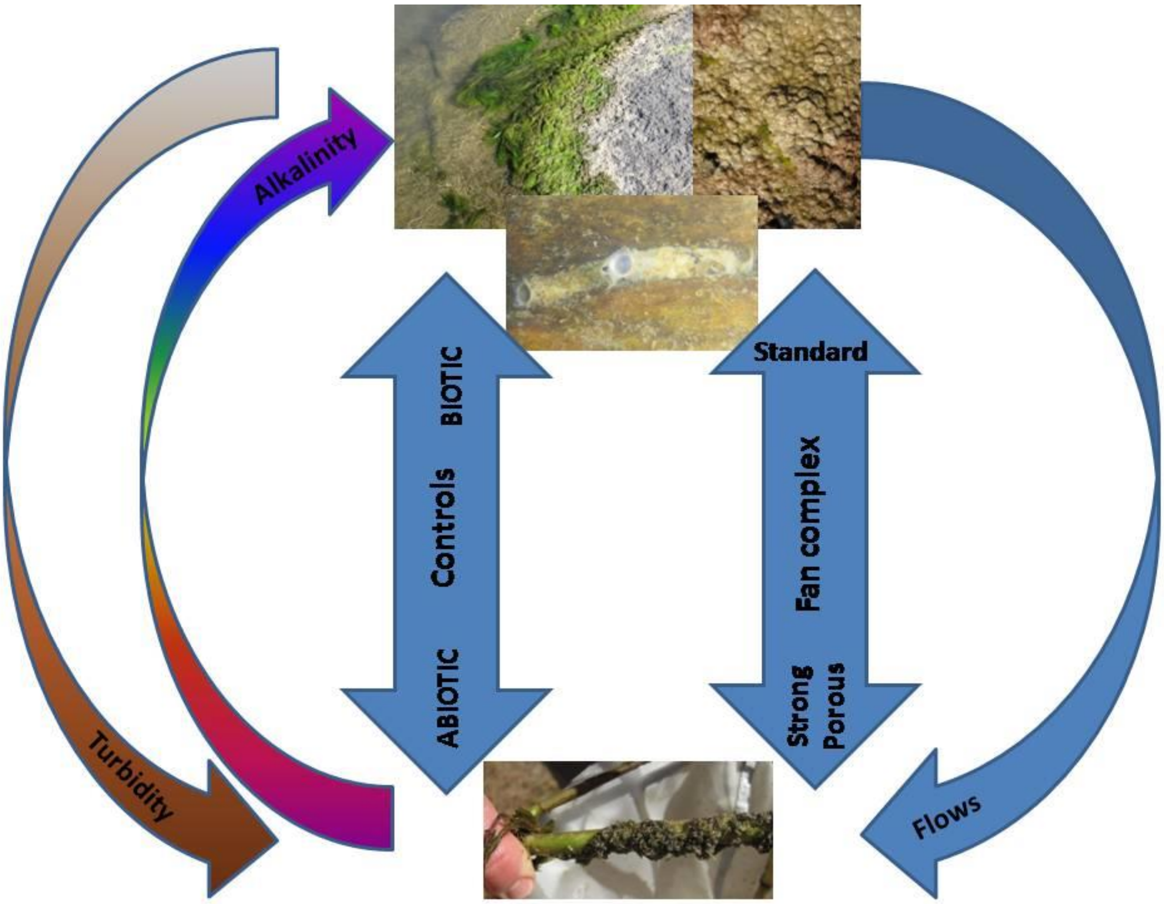

Figure 50 Conceptual model of abiotic-biotic interactions as they relate to switching of dominant species states

4.2. Predictive modelling framework

A predictive modelling framework has been established to link monitoring, outbreak and larvicide application data into a user interface. The purpose of this framework will be as a means of communication between the DAFF and farmers in seeing when larvicide applications are scheduled. This interface consists of a mobile phone application and a website (http://muggies.org) where data are input and collated, including the predictions from the BN model (Figure 51). The App will be freely available and provides a tool for reporting nuisance levels that can be used by the general public to increase monitoring coverage. The target audience and users for the App are farmers along the Orange River, SANParks, tourism-related organisation (for example, river rafting), Government Departments (DAFF staff involved in the Control Programme, DWS), ESKOM, researchers and scientists. Users will be registered on a simple stakeholder database, and be able to access basic information on the Blackfly Control Programme, and life history information on selected blackfly species. Information will comprise text, images, and links to further resources (for example, reports and scientific papers). The App will form the primary interface that links to a website. Components of the website include purpose of the App and how to use it; information on the Control Programme, and the ability to view monitoring, outbreak and spraying data. This will provide not only a resource of historical data, but also current data, and the basis for comparing correlations among monitoring data, control, and outbreaks. Users are able to upload data and access predictions.

Periodic auditing of the data, and updating of the BN model predictions would need to be undertaken by a suitable specialist. Each monitoring data record will be added to the existing BN as a case file. Since the accuracy of predictions improves as the number of case files increases through the software learning algorithms, this model will become increasingly useful if updated. Outputs from the BN model have the potential to be used as a planning tool for longer-term budgeting of larvicide applications, and as a post-application auditing tool to compare the accuracy of predictions against the larval density monitoring data, and any actual outbreaks experienced by stakeholders. Using available data, the BN model reaffirmed that the highest utility value for managing pest blackfly outbreaks is to continue with the current Blackfly Control Programme.

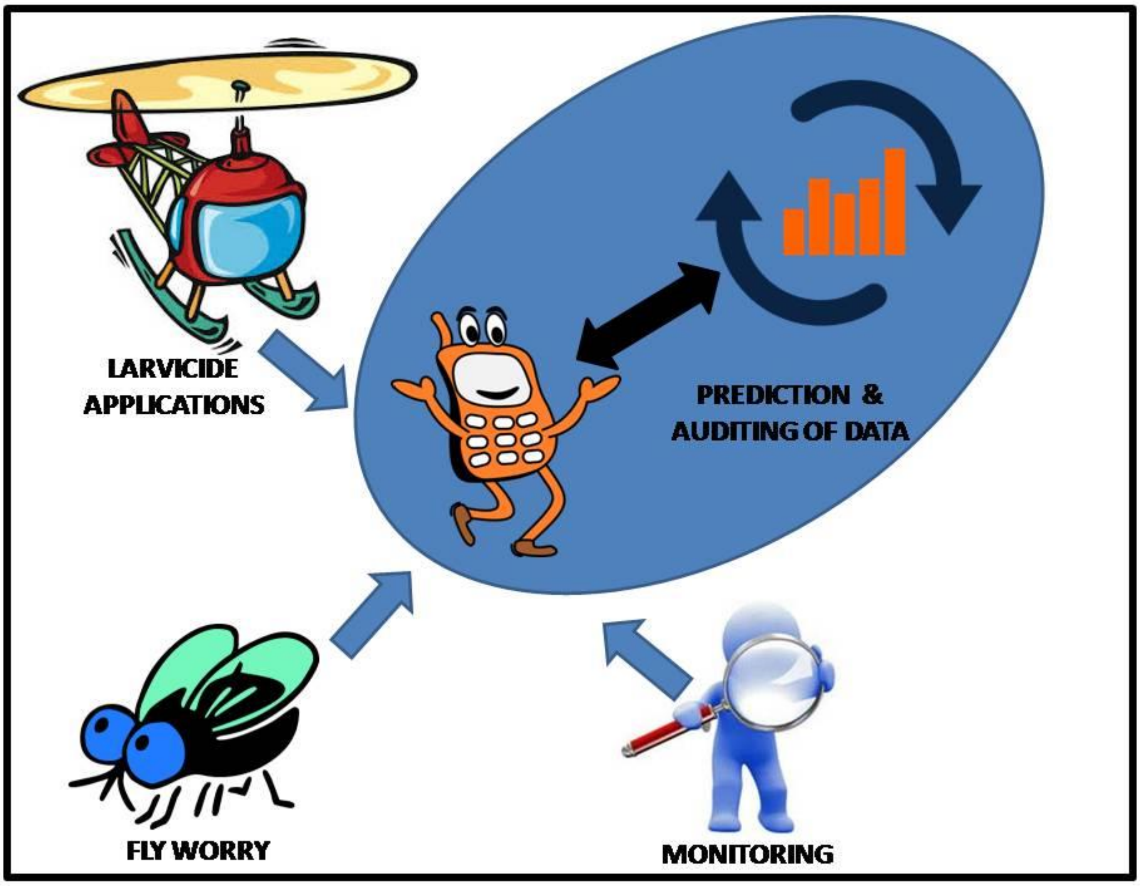

Figure 51 Roleplayers and components of the Blackfly App

4.3. Recommendations for future research

For the predictive management framework to be successful, the following will need to occur:

- Ongoing collection of blackfly density monitoring data, but to also include collection of turbidity data and presence/ absence of benthic algae;
- Uploading of these data, together with Fly Worry Index data, via the website;
- Updating of the BN with these data, and periodic audits of the various data components, with ongoing model refinement;
- A "champion" who would administer the framework, with supporting funding for monthly hosting of the App;
- A revision of the economic impacts of blackfly in the four economic zones.

Technology transfer will occur after completion of the study, by making stakeholders aware of the framework. This will also be achieved through a follow-up article in the Landbouweekblad, following on from the earlier article of October 2016.

5. Conclusions and Recommendations

This study has potential for consolidating much of the previous research related to the Blackfly Control Programme over the past 25 years into a useful predictive management framework. There are a number of outcomes of this project:

- firstly, a predictive management model for use by the DAFF for estimating the likelihood of blackfly outbreaks (and which species are most likely to be the cause) under different flow conditions;
- secondly, a mobile phone application as a tool for reporting nuisance levels that can be used by the general public to increase monitoring coverage;
- three postgraduate studies (one Honours and two Master of Science dissertations [Appendix 8]).

Together, the components of this framework are different from previous aspects of the Blackfly Control Programme, because they provide a structured means for auditing the successes and failures of the Blackfly Control Programme, and there is the basis for evaluating the most likely scenarios of future blackfly outbreaks in response to climate-change induced water temperature increases. This will facilitate more streamlined and proactive control management strategies of blackfly, and promote adaptive management (learning by doing, especially mistakes). Such models provide a powerful framework for assessing management uncertainty based on a number of competing and interacting variables, acting as a decision support tool that can also include cost and utility value variables to evaluate costs and benefits under different management scenarios (Stewart-Koster et al. 2010).

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7. Appendices

Appendix 1: Data collecting protocol

Biological data

Moving from downstream to upstream so as not to contaminate or trample downstream sites, sample across a range of hydraulic habitats and reeds where blackfly species are expected to occur. Collect samples of pupae and larvae, preserved in 70% ethanol alcohol, for identification to species and calculation of relative abundances, in the laboratory. Record current velocity at each sampling point – we used a transparent velocity head rod to do this, where differentials in depth between the current head and the lower depth are converted to velocities.

Next, score the density of blackfly larvae and pupae across a number of 16 cm^2 areas, using the ten-point scoring system developed by Palmer (1994) (Tables A1-2), and document by taking photographs. Scores are based on a log-scale of abundances (Figure A1).

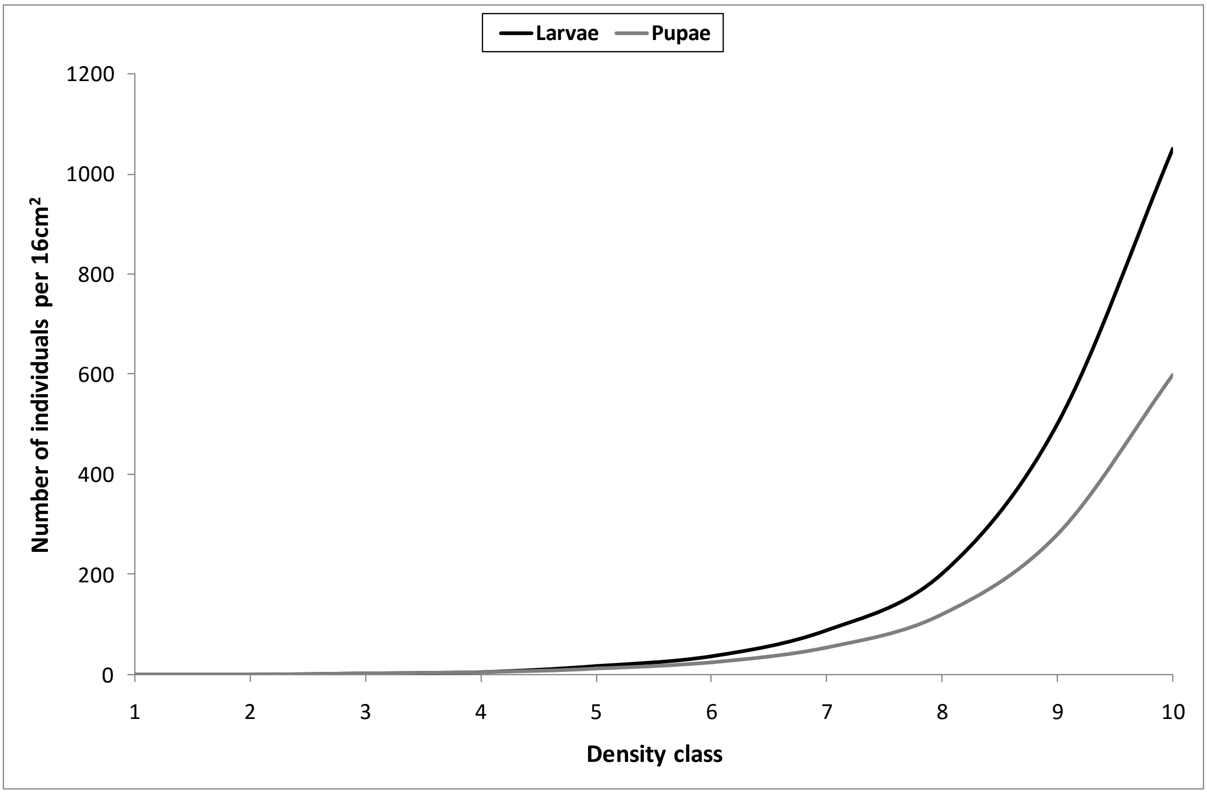


Figure A1 Logarithmic relationship between numbers of blackfly larvae and pupae versus the ten-point scores from Palmer (1994)

Abiotic data

The following data must be collected at each site:

- Turbidity (cm) using a clarity tube;
- Presence of algae, which reduces blackfly habitat;

Sampling point depths (cm) using a depth stick

- Channel type (single or multiple) and width (using GoogleEarth™)
- pH and conductivity ($\mu S.cm^{-1}$), which will vary seasonally and spatially

Table A1 Larval density classes (Palmer 1994)

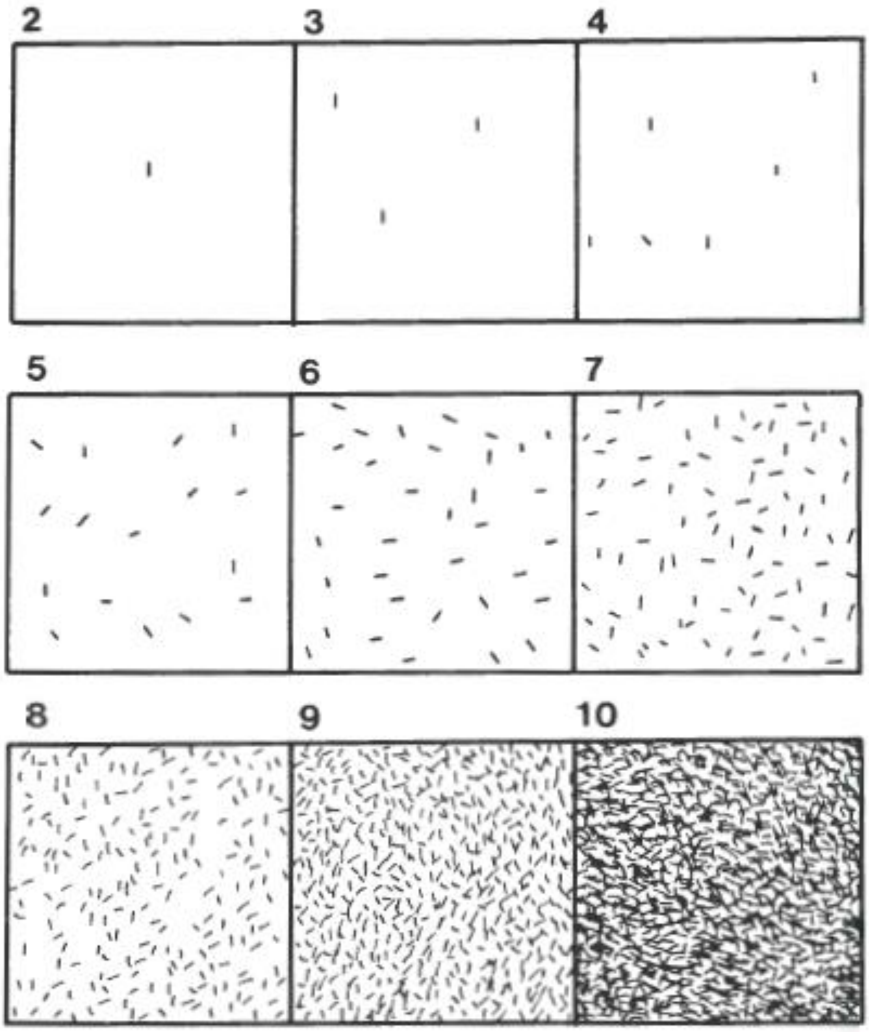
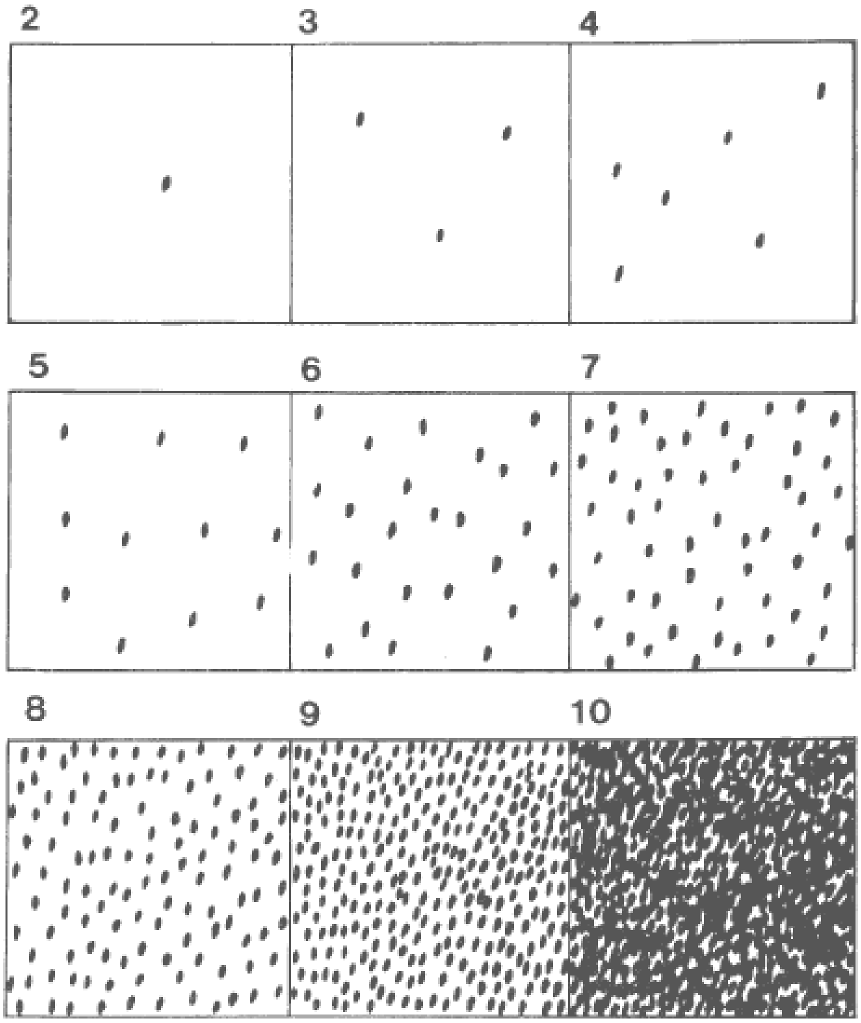


Table A2 Pupal density classes, using Palmer (1994)



Appendix 2: Questionnaire on the use of a cell phone App to assist in information sharing and feedback for the Orange River Blackfly Control Programme

19 December 2016

Background

The Blackfly Control Programme has been in place for some twenty years, and while impetus may fade during periods when the problem has 'gone away', this does not reduce the need for a stakeholder-driven, holistic and longer-term solution to the problem. The Control Programme makes considerable economic sense, with benefits far outweighing costs in the region, not only to sheep farmers but also to the wider regional human population. Despite considerable research and funding investments over the past twenty years, outbreaks continue to occur every five to ten years, with the most recent one during 2011 and a previous outbreak also reported in 2000-2001. Reasons for repeated and ongoing outbreaks are complex and include higher-than-normal flows, changes in turbidity levels promoting switching of dominant blackfly species; larvicidal resistance, and management challenges.

In situations where the Orange River Blackfly Control Programme is not operating efficiently, blackfly outbreaks cause agricultural losses in the region of at least R300 million per annum to the local economy. Economic losses occur along a length of some 850 km along the middle and lower Orange River between Upington and Augrabies. The outbreaks occur in spite of a scientifically robust integrated Control Programme framework, based on a rapid ten-point qualitative scoring system, to monitor blackfly river population levels.

There is a need to re-consider previous research within a new predictive framework, using a public participation tool for greater transparency and buy-in from all stakeholders to promote joint problem-solving approaches. To work towards this, the overall aims of this study are to develop a predictive management model for use by the DAFF for estimating the likelihood of blackfly outbreaks (and which species are most likely to be the cause) under different flow conditions. This will be used in conjunction with a mobile phone application as a tool for reporting nuisance levels that can be used by the general public to increase monitoring coverage. This mobile phone Application has the potential to increase monitoring coverage whereby the general public can input data on nuisance levels of adult blackflies. The App will be freely available, and form the basis for a community of practice amongst all stakeholder groups. More information on the study is available in an article published in the Kortliks section of the Landbouweekblad on 18th November 2016 (https://www.pressreader.com/south-africa/landbouweekblad/20161118/281998967033452).

Questions

1. Please provide details on where you are based (e.g. farm name and location)

2. Please indicate the region you fall into

Hopetown – Boegoeberg	Boegoeberg– Upington	Upington – Blouputs	Blouputs – Sendelingsdrif

3. Please indicate the main economic sector your activities fall into

Grapes	Livestock	Citrus	Tourism	Other

4. On a scale of 1-5 (1 = no impact; 5 = severe), please indicate the level of impact on your main activity due to blackfly problems

1	2	3	4	5

5. Please indicate the months of the years when problems are most severe

J	F	M	A	M	J	J	A	S	O	N	D

6. On a scale of 1-5 (1 = not aware; 5 = very aware), please indicate your level of awareness of the Blackfly Control Programme

1	2	3	4	5

7. On a scale of 1-5 (1 = not satisfied; 5 = extremely satisfied), please indicate your current level of satisfaction with Blackfly control programme

1	2	3	4	5

8. On a scale of 1-5 (1 = not useful; 5 = extremely useful), how useful do you think an interactive cell phone App would be in assisting management of the Orange River Blackfly Control Programme

1	2	3	4	5

9. Would you be willing to upload a simple blackfly worry index score via the App?

Y	N

10. Please indicate the frequency you would be willing to spend five minutes inputting a fly worry score into the app. A reminder would be sent to you based on this preference

Weekly	Two-weekly	Monthly

11. Please add comments on any further features you would like to see included in the App

Appendix 3 Raw abundance data of blackfly species per season and life stage

Date	Species	Stage	1	2	3	4	5	6	7	8	8b	8a	9	9a	10	11
Nov-15	Sade	Larvae	NS	NS												NS
		Pupae	NS	NS												NS
	Schu	Larvae	NS	NS	528	1104	95	124	485	50			29		320	NS
		Pupae	NS	NS	21	314	14	10	103	40			12		26	NS
	Sdam	Larvae	NS	NS	20	87	6	381	305	113			42		27	NS
		Pupae	NS	NS	1	82		160	40	195			14			NS
	Simp	Larvae	NS	NS												NS
		Pupae	NS	NS												NS
	Smcm	Larvae	NS	NS												NS
		Pupae	NS	NS												NS
	Snig	Larvae	NS	NS								14				NS
		Pupae	NS	NS												NS
	Sruf	Larvae	NS	NS												NS
		Pupae	NS	NS												NS
16-Mar	Sade	Larvae			14	24	77	2	3	68			11	6	14	8
		Pupae			13		7	1	7	3			1		3	
	Schu	Larvae	3	3420	68	73	86	6	62	16			46		47	11
		Pupae		756	50	26		3	26	17			4		6	9
	Sdam	Larvae			48	10	1	187	587	30			113		7	
		Pupae			15	8	2	64	178	35			48			
	Simp	Larvae														
		Pupae														
	Smcm	Larvae														
		Pupae			2				47						1	
	Snig	Larvae			8			20	21	20		8	21		6	
		Pupae			2	7			5	170			1	1	2	
	Sruf	Larvae										1				

		Pupae														
16-Jul	Sade	Larvae		5	390	225	680	132	122	82			86		7	43
		Pupae			60	32	249	26	4	23			16			300
	Schu	Larvae	94	1853	125	310	88	56	119	41			66		11	85
		Pupae		125	2	24			1							3
	Sdam	Larvae			3440	1128	883	266	678				1570		889	368
		Pupae			347	125	13	144	201				124		100	30
	Simp	Larvae									46					
		Pupae									9					
	Smcm	Larvae														
		Pupae														
	Snig	Larvae				55	46	13	18	72	3				40	10
		Pupae						4					60			
	Sruf	Larvae														
		Pupae									2					
16-Dec	Sade	Larvae	1077		3	205	695	98	1077	197					61	2
		Pupae														
	Schu	Larvae	1115	801	68	305	63	2	7				78		34	28
		Pupae														
	Sdam	Larvae	14		1348	2173	98	534	14	826			477		107	8
		Pupae														
	Simp	Larvae														
		Pupae														
	Smcm	Larvae	2						2						4	
		Pupae														
	Snig	Larvae										8				
		Pupae														
	Sruf	Larvae									2	3				
		Pupae														

Appendix 4: Diatom species from three sites and four samples

Taxon	Site			
	Prieska (crust)	**Prieska (diatoms)**	**Douglas (diatoms)**	**UP (soverby)**
Abnormal diatom valve or sum of deformities	3	4	3	
Achnanthidium eutrophilum (Lange-Bertalot)Lange-Bertalot	2			
Achnanthidium minutissimum (Kützing) Czarnecki	1			
Achnanthidium saprophilum (Kobayasi & Mayama) Round & Bukhtiyarova	7			
Adlafia bryophila (Petersen) Moser, Lange-Bertalot & Metzeltin	3			
Amphora copulata (Kützing) Schoeman & Archibald			2	
Amphora pediculus (Kützing) Grunow	2	3		3
Aulacoseira granulata (Ehrenberg) Simonsen		1	2	
Cocconeis neothumensis Krammer		2		
Cocconeis pediculus Ehrenberg	1	11		2
Cocconeis placentula Ehrenberg	3	2	4	
Cocconeis placentula var. *euglypta* (Ehrenberg) Grunow				7
Cyclostephanos dubius (Fricke) Round	1			
Cyclostephanos invisitatus (Hohn & Hellerman) Theriot, Stoermer & Hakans	18	1		
Cyclotella meneghiniana Kützing	1			
Cyclotella ocellata Pantocsek	10	3	5	
Cymbella hustedtii Krasske	1	2		
Cymbella kappii (Cholnoky) Cholnoky	3		24	
Cymbella kolbei Hustedt			2	
Cymbella subleptoceros Krammer	1		3	
Cymbella turgidula Grunow			15	3
Diatoma vulgaris Bory	1			
Encyonema minutum (Hilse) D.G. Mann				
Encyonema silesiacum (Bleisch) D.G. Mann				
Encyonopsis minuta Krammer & Reichardt	37	8	9	

Fragilaria capucina var. *vaucheriae*(Kützing) Lange-Bertalot			4	
Fragilaria ulna (Nitzsch) Lange-Bertalot			12	
Fragilaria ulna var. *acus* (Kützing) Lange-Bertalot	1			
Frustulia vulgaris (Thwaites) De Toni	1			
Gomphonema affine Kützing			1	
Gomphonema parvulum (Kützing) Kützing	1	1		
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot			2	
Gomphonema sp.	13	7	7	
Gyrosigma sp.				3
Navicula capitatoradiata Germain	1			
Navicula cryptotenella Lange-Bertalot	7	2	2	
Navicula kotschyi Grunow	1			
Navicula reichardtiana Lange-Bertalot	1			
Navicula rostellata Kützing	2			
Navicula sp.	1			
Navicula vandamii Schoeman & Archibald	4			
Navicula veneta Kützing		1		
Nitzschia inconspicua Grunow	3		1	
Nitzschia kurzii Rabenhorst				1
Nitzschia linearis (Agardh) W.M.Smith				1
Nitzschia recta Hantzsch				1
Nitzschia sinuata var. *tabellaria* Grunow	14	4	7	
Nitzschia sp.	7			1
Pinnularia subbrevistriata Krammer	41	77	66	9
Placoneis sp.	2	2		
Planothidium frequentissimum (Lange-Bertalot) Lange-Bertalot			1	
Planothidium rostratum (Oestrup) Round & Bukhtiyarova			1	
Pleurosira laevis (Ehrenberg) Compere				26
Pseudostaurosiropsis geocollegarum (Witkowski & Lange-Bertalot) Morale	101	158	1	25
Reimeria uniseriata Sala, Guerrero & Ferrario	1	2	3	1

Rhoicosphenia abbreviata (C.Agardh) Lange-Bertalot				11
Sellaphora pupula (Kützing) Mereschkowksy			1	
Staurosirella pinnata (Ehrenberg) Williams & Round	76	106	20	6
Stephanodiscus agassizensis Håkansson & Kling	27	3	5	
Surirella elegans Ehrenberg	2	4		
Tryblionella apiculata Gregory	1			

Appendix 5 Aquatic macrophytes (#Irrigation canal only; *Alien) Scoring categories: 0 = not present; 1 = rare (>0-5%); 2 = sparse (>5-25%); 3 = common (>25-50%); 4 = abundant (>50-75%); 5 = predominant (>75-95%); 6 = near-entire (>95-100%)

Groups	Family	Species	Common Name	Upington	Kanoneiland	Blousekop	Soverby	Keimoes	Blouputs
Chromalveolata	Vaucheriaceae	*Vaucheria sp.*	-	3	3			3	
Mosses	Fontinalaceae	*Fontinalis antipyretica*	Lesser water-moss		2				
Green Algae	Cladophoraceae	*Cladophora cf glomerata*	-	4	4	4	4	4	
Green Algae	Cladophoraceae	*? Rhizoclonium sp.*	-						3
Green Algae	Ulvaceae	*Ulva intestinalis*	Gutweed			3#			
Green Algae	Zygnemataceae	*Mougeotia sp.*	Green algae						3
Green Algae	Zygnemataceae	*Spirogyra sp.*	Water silk	3		3		3	
Ferns	Salviniaceae	*Azolla filiculoides *1b*	Red water fern	2				2	
Monocots	Ceratophyllaceae	*Ceratophyllum demersum*	Water hornwort	3	2	2			
Monocots	Lemnaceae	*Lemna minor*	Lesser duckweed			1			
Monocots	Poaceae	*Phragmites australis*	Common reed	4	4	4	4	4	4
Monocots	Potamogetonaceae	*Potamogeton crispus*	Curled pondweed					1	
Monocots	Potamogetonaceae	*Stuckenia pectinata*	Fennel-leaved pondweed					4	4
Monocots	Typhaceae	*Typha domingensis*	Tall bulrush				3		
Dicots	Apiaceae	*Berula erecta*	Cut-leaf water parsnip				2		
Dicots	Brassicaceae	*Rorippa nasturtium-aquaticum *2*	Watercress				2		
Dicots	Onagraceae	*Ludwigia adscendens*	African willow herb				4		
Dicots	Scrophulariaceae	*Veronica anagallis-aquatica*	Water speedwell	1			1		

Appendix 6 Information on preciptiation of calcium carbonate

Using the nomograms provided by Loewenthal & Marais (1976), precipitation of $CaCO_3$ in such a water as the worst from Paray would require the pH to rise to 11.25. Should the same type of water occur in the summer at a temperature of 20 °C, the pH required for $CaCO_3$ precipitation would be 11.12, which illustrates the minor role of temperature in the processes leading to $CaCO_3$ precipitation.

The nomograms can be read another way. Given the existing chemistry of the water at Paray, we may ask the question: At what concentrations of calcium and total alkalinity would calcium carbonate precipitation take place? The required concentrations (in mg $litre^{-1}$) are shown in Table 5.1:

TABLE 5.1: Concentrations of calcium and of total alkalinity required to initiate calcium carbonate precipitation. (Data taken from Loewenthal & Marais (1976)).

Calcium	Total alkalinity
300	160
220	200
180	240

We can forsee no reasonably probable circumstance in which either the pH of Katse Reservoir would rise to above 11 or the calcium and total alkalinity concentrations would rise to the levels given above. From the information available to us, we conclude that calcium carbonate from Katse Reservoir will not be deposited on the walls of the Katse/'Muela transfer tunnel.

Appendix 7 Chemical analysis of diatomaceous crust

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16th NOVEMBER 2016

ANALYTICAL REPORT

OUR REF:	W1699Y16.REP
COMPANY NAME:	NICK RIVERS-MOORE CONSULTING
COMPANY ADDRESS:	65 HILLARY ROAD, HILTON, 3245
CONTACT PERSON:	NICK RIVERS-MOORE
QUOTATION NUMBER:	QU104384
DATE SUBMITTED:	21/10/2016

One [1] sample was submitted to the laboratory for XRF analysis. The results are presented below.

MAJOR ANALYSIS BY XRF

DETERMINAND	ANALYTE	UNITS	RESULTS
			W1699/16
			ORANGE RIVER ROCK DEPOSIT
Silica	SiO_2	% g/g	7.43
Titanium	TiO_2	% g/g	0.27
Aluminium	Al_2O_3	% g/g	2.27
Iron	Fe_2O_3	% g/g	1.19
Manganese	MnO	% g/g	0.04
Magnesium	MgO	% g/g	2.28
Calcium	CaO	% g/g	26.40
Sodium	Na_2O	% g/g	0.10
Potassium	K_2O	% g/g	0.21
Phosphorous	P_2O_5	% g/g	0.09
Chromium	Cr_2O_3	% g/g	0.01
Sulphur	SO_3	% g/g	0.03
Loss on Ignition (1000 °C)	LOI	% g/g	40.33
Total	Total	% g/g	92.87
Loss of moisture (105 °C)	H_2O^-	% g/g	12.22

Comment: % g/g is equivalent to wt %
The sample has low totals possibly due to an organic phase not measurable on XRF. Complimentary techniques might be required to fully identify the unknown fraction.

Vanessa Talbot
TECHNICAL DIRECTOR

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Appendix 8: Digital resources on Data DVD

File Name	Description
Moonsamy.docx	Honours thesis on water quality changes pre- and post Lesotho Highlands inter-basin construction
Ndou.pdf	MSc thesis on abiotic-biotic relationships
Naidoo.pdf	MSc thesis on Bayesian network model
Talbot.pdf	Chemical analysis report on crusting on rocks
LBW.pdf	Landbouweekblad article
Macrophytes.xlsx	Aquatic macrophytes list and pictures
Temperatures.xlsx	Water temperature data