ASSESSMENT OF THE INTERACTION BETWEEN CAGE AQUACULTURE AND WATER QUALITY IN IRRIGATION STORAGE DAMS AND CANAL SYSTEMS

Report to the

Water Research Commission

by

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WRC Report No 1461/1/08
ISBN 978-1-77005-783-8
Set No 978-1-77005-782-1

DECEMBER 2008

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EXECUTIVE SUMMARY

Motivation and background

The aim of this study was to evaluate the potential use of open water systems, storage dams and canal systems, in particular, for cage aquaculture development. The addition of aquaculture into existing water structures can increase the production output per litre dam water, but only if aquaculture does not jeopardise the primary uses (irrigation and drinking water supply) of these water bodies. Of primary concern is the potential impact on irrigation structures and irrigation water quality as well as crop quality or aquacultural use itself.

Methodology

In order to answer the question whether aquacultural introduction into different dam systems is sustainable, two dam setups were chosen for the study: very small pump-house dams (0.25 ha) in the Makhathini flats canal system supplied by the Pongolapoort Dam with a high flow-through of water, and storage dams within the Cape Winelands area (<20 ha) near Drakenstein and Stellenbosch with three production sites (with fish) and two control sites (without fish production).

The general water quality and suitability for certain species was assessed for the Makhathini and Winelands setup and the water quality situation was evaluated. To monitor short-term and medium-term effects of aquaculture on the water quality of the dams, fortnightly water quality recording executed over two years and possible effects of aquaculture that were manifested through comparing the production sites with the control sites were analysed.

The requirements for optimal growth of the chosen species were compared to the given water quality conditions, and the production performance figures were examined.

In the Winelands setup, additional evaluations took place. A model developed by Phillips and Beveridge was chosen to estimate the carrying capacity of dams of different sizes and nutrient status for upper limits of stocking rates and minimum effect rates.

A major concern of dam owners with regard to aquacultural introduction relates to the implications for primary uses of the dams, irrigation water quality and crop quality. The possible impact of certain water constituents on irrigation structures as well as on crop quality was therefore discussed.

Canal systems

As an outcome for the canal system, it was discovered that the water quality conditions at Makhathini varied little between the production and the control sites. Only the ammonia content seemed slightly, but not significantly, higher at the control site (balancing dam), which is a more stable water body with less water exchange. Source water (canal), balancing dam and production dam showed relatively high pH levels that oscillated around 8.7. The pH at the sites was similar to the pH in the large Pongolapoort Dam that supplies the canal system. High pH is usually a sign of elevated organic matter content and elevated eutrophication levels (as they already occur in the Pongolapoort Dam). The phosphorus level at the sites usually revolved around 25 µg/L, the highest ammonia levels around 160 µg/L, with nitrate stabilising at 1,000 µg/L (= 1 mg/L). The nitrogen content can be categorised as high with regard to the potential impact on the overall Pongolapoort Dam ecology (phytoplankton biomass and species, speed and extent of oxygen consumption at the bottom level).

Despite the long-term tendency of the Pongolapoort Dam to become nutrient rich, the water quality of the canal system was highly suitable for fish production throughout the time of the study, specifically because of the high water exchange rate provided in the canal system triggered and regulated by water extraction for irrigation. The maximum growth rates and fish quality achieved in the pump-house dam approached optimal levels in summer (2.8% body weight per day, starting from 100 g). During the

study, it was shown that seasonal changes influence fish growth and production performance tremendously. The chosen catfish and tilapia species were tropical fish species that prefer warmer temperatures than the winter temperatures at Makhathini, which reflected strongly in lower winter growth rates. The catfish achieved only 2.9% increase of body weight per day starting from 20 g with an optimum of 9 to 11% during that stage, the tilapia achieved a body weight increase of 1.55% per day in winter, with an optimum of 2 to 2.5% during that stage.

Management and fingerling supply at Makhathini lead to cultivation of fish during winter instead of summer. In addition, the perception of the people in charge was that even suboptimal growth of fish was still sufficient for the purpose of food and income generation. However, the introduction of fish feed increased (higher food conversion ratios) with lower growth rates, which, according to the results of the study, would result in five times more nutrients added to the water system than would be added under optimal conditions.

As an example of the impact and influence of feed introduction, the tilapia production during the summer of 2004 amounted to about 2 tons, achieving a food conversion ratio (FCR) of 1.9. The production of tilapia under those conditions can safely maintain the conditions in the pump-house dam without jeopardising irrigation or crop water quality, similarly with catfish. Should FCR ratios around 1.2 be achieved, however, and only then, the production could be increased to 10 tons per pump-house dam with the same input of nutrients into the water. Summer production and good feeding practice can lead the way to those production levels.

Compared to the pump-house dams, the balancing dams and dams without an equivalent water exchange in KwaZulu-Natal should be stocked with caution and not without further investigations.

In conclusion, concerning the canal system sites, aquaculture proved to be a valuable option for additional usage of the pump-house dam water. Small-scale operations of below 2 tons will not have a negative effect on the water quality even if the production efficiency is not optimal. With optimised conditions (low FCR and optimum growth rate), the production can increase, but only if production takes place during phases of intensive water through-flow.

The quality of the Pongolapoort Dam water is currently monitored in proximity of the dam and the monitoring should be extended to the direct testing of the water that is released into the canal system.

Western Cape irrigation dams

Smaller storage dams (<20 ha) in the Western Cape were investigated for their suitability for trout production and the impact of aquaculture on the water quality of the dams for irrigation. The fish species chosen for production were rainbow trout and tilapia, a cold water and warm water species respectively produced during the winter and summer season only. In the Western Cape conditions, both species experience borderline and therefore suboptimal conditions for their growth, with hardly ever being exposed to optimal temperature conditions. Other water parameters such as pH, oxygen, salinity and unionised ammonia mostly allowed optimal growth of trout in the dams and always for tilapia. In the smaller dams of Stellenbosch, pH levels could become elevated, oxygen levels at the surface could drop below 4 mg/L and therefore affect the comfort zone for trout, and unionised ammonia levels could rise up to 0.19 (eight times higher than the critical effect value) for short periods during spring.

The pH levels of the dams were alkaline at most sample sites, with disconcertingly high pH levels of between 9 and 10, mostly in the smaller dams during spring. Total suspended solid levels and water clarity were mostly influenced by inflowing structures and rainfall patterns and no distinct influence of aquaculture was therefore measurable. The total suspended solids (TSS) values mostly remained below 20 and rose highest (up to 50) in dams exposed to high water runoff carrying sediments (Cape Olive and Glenbawn) after extended and strong rainfall.

Total phosphorus levels of the surface water did not show significant differences between the control and production sites. Similarly, there was no distinguishable pattern for ammonia, nitrate and nitrite content in the surface water. What differed in production and control sites was the total nitrogen to total phosphorus ratio, which, except for Nietvoorbij, which is rich in nitrogen, was mostly lower at the production sites. The low nitrogen to phosphorus ratio in the production sites favours the presence of blue-green algae which can assimilate atmospheric nitrogen.

While the water chemistry did not show effects of aquaculture or differences between production and control sites, the phytoplankton composition and biomass did. The overall biomass of phytoplankton was higher in the production sites than in the control sites, especially in winter during dam turnover; more cyanophytes were present at two of the three production sites (except at Nietvoorbij). At Nietvoorbij, *Ceratium hirundinella*, a large dinophyte prone to causing filter blockage, dominated the phytoplankton structure.

The zooplankton at the production sites was taken over by rotifers and protozoans, in contrast to cladoceran and copepod dominance or low abundance at the control sites, which is a sign of higher organic content in the water at the production sites.

The Beveridge and Phillips model to estimate the carrying capacity of a water body for fish production was used in this report as the best available tool at present. The model is greatly influenced by the inflowing water volume, as well as the water exchange rate. In that sense, it is a valuable model specifically to estimate suitability of dams for trout production with trout being a species that depends on high oxygen levels and cool and clean water resources. The results suggest that Rondawel Dam is not suitable for trout production on the applied scale, as reflected in oxygen depletion problems in the dam as well as high pH levels signifying organic pollution. The dam was also smaller than 2 ha in size, with a low water exchange rate. The second largest production site was Nietvoorbij Dam, which, according to what was predicted by the model, was overstocked with trout, but has after 10 years not experienced severe production problems. This phenomenon could be explained by the relatively great depth (more than 10 metres) and favourable total nitrogen to total phosphorus ratio in the dam (suggesting that dams with high nitrogen loading in relation to phosphorus, and great depth can sustain aquaculture even under suboptimal water exchange). The largest dam, Cape Olive, according to the model proved to be feasible for five tons of trout production, mainly due to the good water exchange rate of the dam and its overall volume. In order to achieve sustainable production even in larger dams, the FCR has to be maintained at 1.5 or less.

The effect of aquaculture on the quality of irrigation water and equipment was estimated for the Western Cape scenario. Due to low metal and cation content, the irrigation water tests ascribed a slightly corrosive character to the water from its ability to dissolve metal and concrete structures. The most likely impact of aquaculture on irrigation structures would be the additional clogging of filters as a result of changes in phytoplankton biomass and structure. However, these impacts could not be verified due to a lack of written records on filter backwashing activity and changing of equipment parts at the sites.

In relation to the requirements of the most prominent crops, the Drakenstein site dam water could supply up to 2.4% of the phosphorus needs of olives, as well as up to 18.0% of the nitrogen and 32% of the potassium needed. Dam water in Stellenbosch is mostly used to irrigate vines. In relation to the crop requirements, up to 7.6% of the nitrogen, 23.7% of phosphorus and 128.0% of potassium could be supplied by the surface dam water, while up to 47.2% of the nitrogen and 94% of the phosphorus requirement could be supplied by the bottom water fraction of these smaller dams,.

Bottom water quality was not investigated during the study, but experience with aquacultural production sites during the course of the study makes it possible to assume that changes in oxygen levels are taking place with deposits of aquacultural production. Higher hydrogen sulphide levels and other off-odours were experienced with bottom water extraction, which advises caution with such extraction for irrigation.

Overall conclusions

In conclusion, the study found the water exchange rate to be the deciding factor for the canal system in KwaZulu-Natal in allowing relatively high aquacultural production (up to 10 tons) in a 0.25 ha surface area dam. The water exchange in the canal system indeed is so high that hardly any build-up of aquacultural waste and faeces would be expected in the pump-house dams. The importance of water exchange also holds true for the Western Cape storage dams, where total full supply volume (larger volume usually means relatively greater maximum depth) and the exchange rate of the water are the main deciding factors concerning whether the water bodies are suitable for fish production. Inflowing water quality is very important in both systems and should be monitored for short-term and long-term changes.

At the Winelands sites, specifically at Stellenbosch, effects of aquaculture on phytoplankton biomass and composition were observed. In smaller dams, this could result in high pH levels and surface oxygen depletion, which affects trout health.

These changes in pH and phytoplankton biomass were also the parameters that would most likely affect irrigation structures and block filters. The irrigation water of dams with aquacultural production does not affect crops and can supplement and reduce the amount of fertiliser added to the irrigation water. Caution is advised (hydrogen sulphide and algal by-products) with bottom water extraction and irrigation of sensitive crops only.

In the long term, the usually low water exchange rate of the storage dams will make sediment build-up below the cages unavoidable and nutrient removal or mechanisms to collect the farming waste below the cages would be the best option for environmentally safe water provision. The nutrient build-up below the cages propagates oxygen depletion and anoxic hypolimnia, which sometimes results in the mass development of certain cyanobacteria. Hydrogen sulphide, which develops with the lack of oxygen, and algal by-products, as well as fish farming waste, can taint the bottom water.

Future research

Before extension and intensification of aquaculture projects within the Pongola Flats irrigation scheme, the irrigation water quality with aquacultural production should be monitored and the seasonal changes in through-flow of water through the pump-house dam should be understood.

The level of water release from the Pongolapoort Dam into the canal system and its influence on overall water quality within the canal system would be of great interest for the long-term supply of water of good quality.

In the Western Cape, the prevention and minimisation of pollution deriving from aquaculture is important. This can be achieved by developing polycultural techniques to remove nutrients from the system (no further addition of nutrients); the development of more environmentally-friendly aquafeeds; as well as the mechanical removal of aquacultural waste.

Monitoring of the long-term effects of aquaculture on the water body should be extended to the bottom level of the dams and continued at the surface level. Before and after studies should be attempted were dams are monitored a year or more in advance of aquacultural introduction.

Ways to include water quality levels in the dam water in fertilisation design should be developed.

ACKNOWLEDGEMENTS

The research presented in this report emanated from a project funded by the Water Research Commission entitled: "Assessment of the interaction between aquaculture and water quality in on-farm irrigation dams".

The Reference Group responsible for this project consisted of the following persons:

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Mr DJJ van Rensburg	Murray, Biesenbach & Badenhorst

The financing of the project by the Water Research Commission and the contribution of the members is gratefully acknowledged.

We also wish to mention the members of the Hands-On Fish Farmers Co-operative Limited, especially the Rustenburg, Nietvoorbij and Unlimited Olive People's Trust (Cape Olive) Fish Farming Projects, whose dams were used as research sites, and the farm management of Calais Farm, whose irrigation dam was made available as a reference site.

We would like to acknowledge the personnel of the Makhathini Research Station, for providing assistance and infrastructure and the staff of the Division of Aquaculture, for general assistance and availability of infrastructure and equipment.

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2D	Two-dimensional
AI	Aggressiveness Index
BEMLAB	Private analysis Laboratory, situated in Somerset West
BMP	Best Management Practices
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
DST	Department of Science and Technology
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of the United Nations
FCR	Food Conversion Ratio
GIS	Geographical Information Systems
HACH	Company that manufactures and distributes analytical instruments and reagents used to test the quality of water and other aqueous solutions
Hands-On	Hands-On Fish Farmers Co-operative Limited
LSI	Langelier Saturation Index
RF	Rural Foundation (non-governmental organisation)
RSI	Ryznar Stability Index
SAWS	South African Weather Service
TDS	Total Dissolved Solids
TN:TP	Total Nitrogen to Total Phosphorus ratio
TP	Total Phosphorus
TSS	Total Suspended Solids
US	University of Stellenbosch
USEPA	United States Environmental Protection Agency
WRC	Water Research Commission

GLOSSARY

Alkalinity

Alkalinity is a measure of the ability of water to neutralise acids to the equivalence point of carbonate and bicarbonate. The alkalinity is equal to the stoichiometric sum of the bases in solution. In the natural environment carbonate alkalinity tends to make up most of the total alkalinity due to the common occurrence and dissolution of carbonate rocks and presence of carbon dioxide in the atmosphere.

Ammonia

Ammonia is a compound with the formula NH_3. In water, free ammonia (NH_3-N) and ionised-ammonia (NH_4^+-N) represent two forms of reduced inorganic ammonia-nitrogen which exist in equilibrium depending upon the pH and temperature of the waters in which they are found. Of the two, the free ammonia form is considerably more toxic to organisms such as fish. Free ammonia is a gaseous chemical, whereas the NH_4^+ form of reduced nitrogen is an ionized form which remains soluble in water.

Anoxia

Literally, anoxic means the absence of oxygen. Within the report, the term is mostly used in context with anoxic hypolimnia (depletion due to decomposition rates and lack of mixing). The threshold for an anoxic hypolimnion was set at an oxygen content of less than 1 mg/L.

Catchment area

An area from which surface runoff is carried away by a single drainage system (river, basin or reservoir).

Corrosiveness

The equilibrium saturation point of water for calcium carbonate, as well as for other salts, is described by various indices which provide an indication of the scale-forming or corrosive potential of water. If the water is under saturated, it will be corrosive, dissolving anything it comes in contact with (e.g. plastic and concrete structures). Low alkalinity can increase the corrosiveness of the water as it will allow some metals from pipes and fittings to dissolve in the water.

Dam (Reservoir)

A dam is either a barrier constructed across a waterway to control the flow or raise the level of water or the body of water that is contained by such a barrier. Another term for dam would be reservoir. In South Africa, small farm dams mostly serve the purpose to store water for irrigation or drinking supply. In canal systems, balancing dams are needed to avoid uncontrolled overflow, the water for irrigation, however, is directly pumped from a small pump-house reservoir supplied by the canal.

Epilimnion

The epilimnion is the topmost layer in a thermally stratified water body, occurring above the deeper hypolimnion. It is warmer and typically has a higher pH and dissolved oxygen concentration than the hypolimnion. Being exposed at the surface, it typically becomes turbulently mixed as a result of surface wind-mixing. It is also free to exchange dissolved gases (O_2 and CO_2) with the atmosphere.

Eutrophication

This is the process of accumulating chemicals, especially the nutrients nitrogen and phosphorus. Eutrophication occurs as a natural phenomenon that is accelerated by human activities in the environment (sewage effluent, fertiliser runoff, etc.). Most commonly, the total phosphorus content defines the trophic level of the water body by phosphorus often being the limiting nutrient for algal growth. In South Africa, eutrophication levels are defined by the total inorganic phosphorus content (usually 50 to 80% of the total phosphorus content).

< 5 µg/L	oligotrophic
5 to 25 µg/L	mesotrophic
25 to 250 µg/L	eutrophic
> 250 µg/L	hypereutrophic

Food conversion ratio (FCR)

The true feed conversion ratio is the ratio of the gain in wet body weight of the fish to the amount of feed fed. Wasted feed and mortalities are included in that ratio. With commercial dry pellets, a feed conversion ratio of 0.8 is theoretically possible for trout. However, most performances range between 1:1 and 1:1.5 (e.g. 1 to 1.5 kg of dry feed has to be applied to achieve 1 kg of wet weight gain in the fish). Often, only the multiple factor for the feed is given as FCR value.

Holomictic

The term holomictic refers to the mixing regime of the water body. A holomictic lake or dam is completely mixed during a turnover event, whereas in some very deep lakes the deepest layer might not be involved in the mixing (meromictic). Most water bodies are holomictic.

Hypolimnion

The hypolimnion is the bottom layer of water in a thermally stratified lake, situated below the thermocline., In deeper water bodies, the hypolimnion temperatures often are similar to the average air temperatures in winter (in a Mediterranean or subtropical climate). Being at depth, the hypolimnion is isolated from surface wind-mixing, and usually receives insufficient irradiance (light) to enable photosynthesis. Oxygen exchange with the surface layer or air is also inhibited.

Macrophytes

Large aquatic plants in a body of water visible to the human eye, usually multicellular. They comprise macroalgae, non-vascular plants (e.g. mosses) and vascular plants (with flowering stage) and can be ecologically classified as emergent (rooted and most of the vegetative mass above water, e.g. water lilies), submerged (rooted and most of the vegetative mass below water; e.g. Characeae) or free-floating (e.g. lesser duckweed, filamentous green algae).

Monomictic

This term refers to the number of mixing events per year in a water body. In Mediterranean and subtropical regions, the temperatures of epilimnion and hypolimnion are isothermal (of the same temperature) in winter, so that there is only one mixing phase per year, lasting from two to several months. In temperate regions, most water bodies have two stagnation and two turnover phases and are referred to as dimictic (they mix twice in the course of one year). The periods of mixing here occur in spring and autumn and usually last some weeks only.

Phosphorus species

By convention, the phosphorus content of a water body is determined mostly by determining total phosphorus (to describe the trophic state) and dissolved inorganic phosphorus (also referred to as soluble reactive phosphorus), the latter as the most readily biologically available form of phosphorus (e.g. to phytoplankton).

The total phosphorus content of a water body can be divided into its dissolved or particulate (sometimes also referred to as soluble and insoluble) and inorganic or organic components (the latter often also referred to as reactive and unreactive P, inorganic P). Theoretically, there are eight subspecies of total phosphorus: Total inorganic P divided into dissolved inorganic P and particulate inorganic P, total organic P divided into dissolved organic P and particulate organic P, as well as the sums of total particulate and total dissolved P. There are no analytical methods that would allow the exact measurement of the content of each of these fractions.

Analytically and by scientific convention, the division into particulate and dissolved P is therefore made by filtration through a 0.45μm membrane. Filtered material is defined as dissolved and the residual P as particulate (this can only be determined by subtracting the dissolved component from the total P content). Inorganic (reactive) and organic (unreactive) P are separated analytically by the building of a vanado-molybdo-phosphate complex (of blue colour) of only the inorganic partition. The organic (unreactive) component can only be determined by subtracting the inorganic content from the total phosphorus content.

Phytoplankton

Phytoplankton consists of microscopic free-floating, mostly autotrophic (photosynthetic) organisms in aquatic systems. Mainly unicellular algae, sometimes organised in colonies. Own movement is sometimes possible, but phytoplankters, in contrast to larger hydrological forces, are drifters (plankton).

Stagnation phase/Stratification

In Mediterranean and subtropical climates, a thermocline develops during the summer months and divides the upper water layer (epilimnion) from the lower water layer (hypolimnion). Due to reduced water exchange by prevented mixture of water, this phase is called the stagnation phase.

TSS (Total suspended solids)

Total suspended solids (TSS) include both suspended sediment and organic material collected with the water sample. Suspended solids in water reduce light penetration in the water column, can clog the gills of fish and invertebrates, and are often associated with toxic contaminants because organics and metals tend to bind to particles (e.g. phosphorus, bacteria). They also cause the build-up of sediments in water bodies.

Turnover phase / Destratification phase

During the winter months, the temperature in Mediterranean and subtropical water bodies tends to be similar throughout the whole water body. During these months, the whole water body (depending on overall depth) can undergo mixture.

Zooplankton

Zooplankton consists of microscopic, free-floating, heterotrophic organisms in aquatic systems which can not produce their own food, but rely on debris and phytoplankton as food source.

1 GENERAL INTRODUCTION

1.1 Background

"Aquaculture is the farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants" (Food and Agriculture Organization of the United Nations (FAO) 2007a). Global aquaculture has been growing at a rate of 9% per annum since 1970 (FAO, 2007a) and has grown 5.2% per year between 2000 and 2004 for freshwater species (FAO, 2007a). It is furthermore estimated that aquaculture will become important to total world fish production because of increasing acceptance of fish as a feasible source of protein. Worldwide, aquaculture was already contributing approximately 32.4% (45 million metric tons) of total human fish consumption in 2004 (FAO, 2007a). Apart from the contribution to global food availability and food security, aquaculture also contributes to economic growth, socio-economic development and job creation in third world countries (FAO, 2007a). The increasing growth in rural populations and subsequent increasing unemployment numbers, underline the need for job creation and affordable protein sources. Africa is producing less than 1% of the world's aquaculture production (Hoffman et al., 2000) with wild stocks declining or catches being stable.

The global decline of wild marine and inland catches is providing the main impetus for aquaculture development. The African continent, however, is contributing less than 1% of world aquaculture production, with South Africa providing less than 1% of Africa's aquaculture production. The low contribution from Africa must be seen in stark contrast to its vast marine and inland water resources. The lack of aquaculture development on the African continent is mainly due to problems associated with socio-economic stability, technological isolation, access to markets and developmental capital (Hecht, 2000).

Inland (freshwater) aquaculture development is dependent on the sustainable utilisation of available resources. Aquaculture provides a unique opportunity to contribute to socio-economic development, food security and human resource development, through multiple and sustainable utilisation of water resources. The opportunity lies in the integration of aquaculture into existing agricultural development without an increased consumptive demand on water resources.

Existing freshwater reserves set the limitations for aquaculture operations. In practical terms these renewable water resources comprise streams, rivers, rainfall and replenished ground water. Globally, about 110,000 km^3 of precipitation falls on land per year and of this, about 70,000 km^3 of water is evaporated (30–50%) or transpired (50–70%) by plants from the land surface. The moisture left, roughly 40,000 km^3, runs to the sea. According to Davies & Day (1998), South Africa's mean annual runoff is between 50 to 60 km^3, of which only 8% flows back to the oceans. Sixty-six per cent of the mean annual runoff of about 49.000 m^3/year is caught and stored in dams (DEAT, 2006).

Demands for domestic water supplies and sewage disposal will increase considerably as the world population grows. The increase in agricultural productivity required to support food security needs and the resultant increase in demand for reliable supplies of water will similarly have to be satisfied. Irrigation and water management were identified by the Brandt Report (Independent Commission on International Development Issues 1980) as the biggest single category of investment required in developing countries. In terms of agricultural improvement, about 50–60% of the increase in agricultural output in developing countries has come from new or rehabilitated irrigated land over the last two decades.

Aquaculture in open water systems, such as pump-house and storage dams (irrigation and drinking water dams), is a relatively new development in southern African countries. The potential lies with areas where irrigation water is stored in dams, since in most of these cases there are opportunities to use these systems for fish production. For example, an assessment of aquaculture production potential of irrigation dams in the Western Cape Province, South Africa, has indicated a potential annual output of 8,000 tons of fish (Brink, 2002) equivalent to the per capita consumption of 3.2 million South Africans. It could further provide urgently needed livelihood opportunities to impoverished rural as well as peri-urban communities.

A substantial amount of information and technology exist for aquaculture in production systems based in open sea, estuary and lake locations. Modifications and adaptations to existing information and technology are required, however, with regard to the use of storage dams in particular. The effect of aquaculture on the quality of water and the fitness-for-use for other interest groups, such as irrigation, agriculture, aquaculture, human consumption, communal use and the environment, must therefore be determined in order to ensure sustainable development thereof.

At present, with the global emphasis on sustainable development, particularly in the agricultural sector, more and more effort is put into optimising resource use rather than exploiting new ones. The value of stored irrigation water can be increased by additional water-bound production techniques to increase the agricultural yield derived per unit of water. The agricultural sector utilises about 60% of the available water in South Africa for the irrigation of 10% of the cultivated land mass (Van der Merwe, 2001; DWAF, 2004), supplying 35% of agricultural export products (Davies & Day, 1998).

Freshwater resources are under threat in South Africa (DEAT, 1999). The population is growing and individual water demand is rising. The available surface water resources are almost utilised to full capacity and climate change scenarios predict declining freshwater supply (Arnell, 2004).

Already numerous small dams, both private and public, have been constructed to store water from catchment areas for irrigation, thus aquaculture can make non-consuming use of these water bodies. There have been a number of studies around the world which have successfully demonstrated the potential of integrating fish production within irrigation systems (Ingram et al., 2000; Gooley & Gavine, 2003; Tundisi & Matsumura-Tundisi, 2003). While the majority of these studies have indicated that there is great potential for the integration of these two systems, little attention has been paid to the effects of aquaculture on the irrigation systems. Countries such as Israel and Australia are on the leading edge of developing multiple water-use systems (Gooley & Gavine, 2003) and provide a number of examples by which aquaculture in South Africa can advance.

Water resources are a precondition for the existence of human populations, and one of the most important raw materials for our economic activity. Water is increasingly being seen as a limited resource and greater attention is focused on its allocation and management. The regular droughts affecting southern Africa, the problems of flood control and water quality in west and south-east Asia, and the impacts of development on coastal and inland waters in Latin America, all point to the particular and vital importance of water resource management in developing countries.

The growth of the South African population intensifies the problem of finding sufficient water for rural, urban and industrial demands, as well as agricultural needs for ever increasing food production requirements. The remaining water is increasingly threatened by pollution and other sources of quality reduction, affecting its efficient usage.

This document reports on consideration given to the integration of water used for irrigation with aquaculture and brings it into a wider context of planning, development and management of water bodies to present multi-use strategies of South Africa’s natural resources.

As water becomes an increasingly scarce commodity, it will become important that the feasibility of integrating aquaculture into irrigation systems in relation to climate, catchment area, water availability and flow regime, as well as irrigated demand area, becomes known. Combining irrigation water storage with aquaculture may not be feasible if the water quality requirements for irrigation are high due to sensitive irrigation water filtering systems or sensitive crops.

On the basis of productivity in relation to minimum surface area of the water body needed, fish yields from cage production in lakes and dams stocked to environmental capacity are approximately six to ten times lower than the production capacity of managed culture ponds of the same surface area (Masser, 1997; Lazur, 2000). Unmanaged pond production requires about the same surface area as cage production (Masser, 1997). If we are to increase the amount of utility gained from South Africa's existing water resources, it is important that all options are thoroughly investigated before they can become commercially viable. Not only will this prevent conflict between potential water users but it will also allow us insight into where these water-related industries may be able to expand in the future.

Floating cage aquaculture facilities are open systems that are situated in a natural standing water body. The nature of the system allows the discharge of waste such as uneaten food, faeces, fish scales, mucus and organic soluble wastes directly into the surrounding water environment (Stirling & Dey, 1990). During cage aquaculture, the cultured species are confined, but organic and soluble wastes fall from the cages and mix with the water column and sediment (Cornel & Whoriskey, 1993). This report focuses on the effects that floating-cage aquaculture may have on dam ecology, irrigation systems attached to the water resource and their associated crops. The critical concepts that had to be understood or verified for the Western Cape dams were those of timing and implications of turnover phases, water retention times and the self-cleaning ability of the dams. Major adaptations probably will have to be made to secure long-term sustainability of trout production in the country to stabilise small-scale economic enterprises in the making, political stability and supply to the ready market. The main impact of aquacultural production is the nutrient input and therefore the eutrophication process. Too many nutrients can change the phytoplankton pattern and increase the likeliness of oxygen depletion by crashing populations. Decomposition of uneaten feed and faeces below the cages can change the composition of irrigation water that is often extracted from the near-bottom basin.

Net-cage production can be perceived as relatively simple and therefore most profitable. One reason for the simplicity and cutting of costs, though, is that the self-cleaning ability of the water body as ecosystem service is presupposed. Therefore, this ability has to be guaranteed and the risk of water quality impact minimised, as water quality, once degraded, can only with difficulty be controlled in a natural system and only with high costs be restored.

1.2 Motivation for the study

The rationale of the WRC for soliciting this project was to assess the potential use of open water systems, storage dams and canal systems used primarily for irrigation for dual use with aquaculture in South Africa. Only responsible aquacultural development in terms of low impacts on overall water quality can live up to the expectation to contribute towards socio-economic development of rural communities and economic growth from a long-term perspective.

Inland (freshwater) aquaculture development is dependent on the sustainable utilisation of available resources. Aquaculture provides a unique opportunity to contribute towards socio-economic development, food security (in rural areas) or market satisfaction (with upmarket species such as trout) and human resource development, through integrated and sustainable utilisation of water resources. The opportunity lies in the integration of aquaculture into the existing irrigation water practices without consuming more water, and this can only function successfully if aquaculture does not affect the quality of water for irrigation.

The main aim in conducting this project was to assess the impacts of aquaculture on irrigation water quality and use. The primary use of the storage water, namely irrigation, is not to be jeopardised by cage fish farming operations in terms of the possible damage of mechanical irrigation structures, disturbance of irrigation management and effect of changed water quality on crops. It became evident that environmental aspects of dam water quality play a crucial role in overall dam, irrigation water and crop health. Adequate water quality also is the prerequisite for healthy fish growth; maintenance of water quality levels is therefore important for sustainable economic growth as well as for the viability of the aquaculture systems themselves. Not irrigation regulations only, but also environmental regulations have to be served to preserve the self-supporting ecological structures of the dam entities.

1.3 Objectives of the study

The objectives of the project, in their adapted order from the original project proposal (complete listing, but following the flow of the chapters in the report) were:

1) To assess the fitness-of-use and quality of the irrigation water on aquaculture activities
2) To conduct two case studies: (a) Makhathini Research Station (Jozini, KwaZulu-Natal) and (b) Nietvoorbij Dam (Stellenbosch, Western Cape); Rustenberg dam (Stellenbosch, Western Cape) and Cape Olive Dam (Drakenstein, Western Cape)
3) To quantify the impact of fish production and associated activities on water quality of irrigation dams, through on-farm trials and associated monitoring.
4) To determine the impact of changes in water quality on fitness-for-use for both irrigation and aquaculture
5) To model the storage dam systems in terms of sustainable production capacities
6) To establish the interaction between aquaculture and irrigation activities (contribution of essential nutrients, fertiliser savings, etc.) and detrimental effects (nitrification, filtration, preventive maintenance, clogging, etc.)
7) To assess the suitability of the outflow water quality and quantity for various irrigation crops (vineyards, deciduous fruits, cereals, vegetable, sugar cane, etc.)
8) To produce guidelines (Better Management Practices, e.g. production systems, stocking densities, feed types and feeding methods, monitoring procedures) to ensure fitness-for-use of water and sustainable fish farming on storage dams.

1.4 Approach followed to address objectives

The sites for the two study areas (Makhathini Flats in KwaZulu-Natal and Cape Winelands in the Western Cape) were chosen and sampled fortnightly. The methodologies are described in Chapter 2. Water quality data for a period of more than two years were collected for a total of five dams in the Cape Winelands (three production sites with fish production and two control sites without fish production) and three sites in Makhathini located in the Makhathini Flats (canal, balancing dam and pump-house dam, only the latter with fish production).

The results of these water quality assessments were compared to the requirements (according to literature) for the respective fish species to grow optimally. The findings satisfy Objective 1 and are described in Chapter 3. The data give insight into the suitability of given water conditions for growth of warm-water species in KwaZulu-Natal and cold-water species in the Western Cape.

The water quality data over two years provided insight concerning immediate impacts as well as possible long-term impacts of aquaculture on the ambient water quality of the selected sites (Objectives 2, 3 and 4) by observing medium-term trends. Long-term effects on the water quality change the dam environment and therefore feed back on aquacultural production as well. The results are discussed in Chapter 4.

The production capacity study was only determined for the Cape Winelands production sites. The site in KwaZulu-Natal was not suitable for the chosen Beveridge and Phillips model. Results are presented in Chapter 5 (Objective 5).

The additional data necessary for the analyses of the irrigation systems was only collected for the Cape Winelands sites. Effects of aquaculture in dams on irrigation water quality and equipment (Objectives 4 and 6) will be discussed in Chapter 6.

The effect of aquaculture on irrigation water (water quality at dam outlet) and the possible beneficial or disadvantageous effects on crops (Objective 7) for the Cape Winelands sites are discussed in Chapter 7, by comparing the nutrient composition in the water with the existing fertilisation regimes.

To fulfil Objective 8, the guidelines for Better Management Practices (BMPs) will be printed in a fish farmer friendly publication independently of the present WRC report. These guidelines will contain information from the recommendation section of this report. The results of this report, however, rather, are of value for the site selection process and permit generation for aquaculture operations in dams in South Africa. The most important influence of already existing aquaculture operations on dams is by the introduction of fish feed and therefore necessary information to hand out to fish farmers will have to consist of feeding strategies and methods to avoid feed waste. This particular information was generated by the Feed Technology Group of the University of Stellenbosch and will be added to the BMP booklet. An outline of the booklet is given in Appendix B.

A "Generic Environmental Best Management Practice Guideline for Aquaculture Development and Operation in the Western Cape" has been published by Hinrichsen (2007).

2 MATERIALS AND METHODS

2.1 Sites

The two main areas chosen as study sites are characterised by two different climates: a subtropical climate with annual to summer rainfall, humid summers and mild winters at the KwaZulu-Natal sites, and a Mediterranean climate with mild winters and hot, dry summers and winter rainfall at the Western Cape sites. The Makhathini Research station is located in the north-eastern corner of South Africa, bordering Swaziland and Mozambique. The Western Cape sites are situated at the south-western edge of the country in the Boland region (Cape Winelands district) (see Figure 2.1).

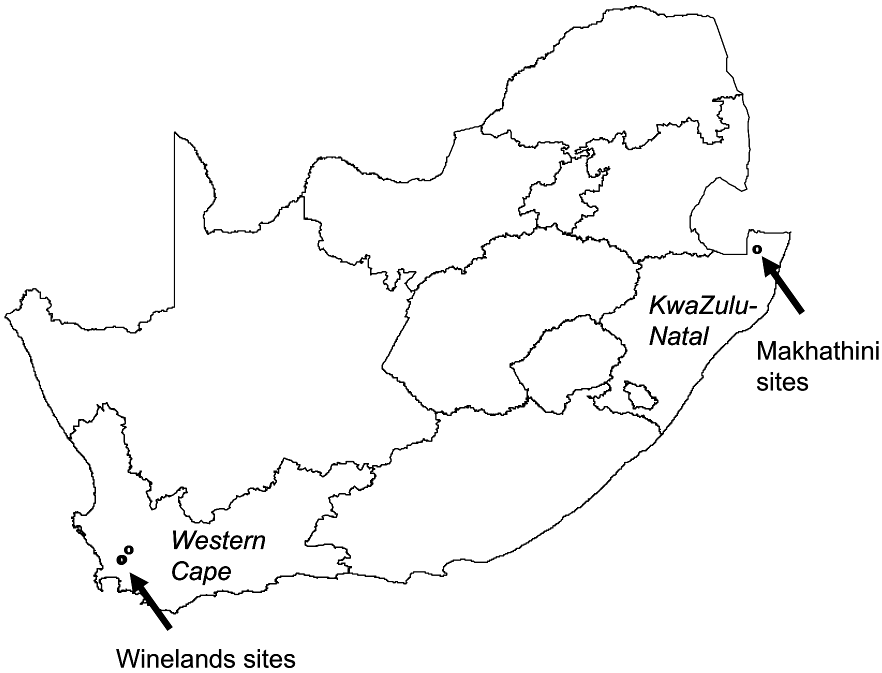

Figure 2.1: Map of South Africa with provincial boundaries. Arrows point to the small circles that represent the location of the study sites within the respective provinces, namely Western Cape and KwaZulu-Natal.

2.1.1 KwaZulu-Natal sites

The research sites in KwaZulu-Natal are situated at the Makhathini Research Facility and form part of the Makhathini Flats irrigation scheme. The irrigation scheme consists of a network of storage dams and canals, all supplied by water from the Pongolapoort Dam. The main canal originates at the Pongolapoort Dam and approximately 7 km downstream the main canal feeds a side canal with a width of 2.5 meter. At the dead end of the secondary canal, close to the Makhathini Research facility and about 7 km from the main canal, the secondary canal feeds a pump-house dam, as well as a balancing dam (see Figures 2.2 and 2.3). From the pump-house dam, water is distributed to various agricultural fields surrounding the facility. Crops under irrigation include cotton and vegetables. The research sites include three sampling stations, with the first point of sampling from the canal situated before it splits into the pump-house dam and the balancing dam. The second sampling station is located at the small pump-house dam that hosts net cage production of tilapia (*Tilapia rendalii*) and catfish (*Clarias gariepinus*), as well as some ornamental fish during the production season. The final sampling station is located in the nearby much larger balancing dam which served as control site. Table 2.1 presents the hydrological and geographical characteristics of the study sites.

The climate at the research site can be described as humid subtropical, with annual to summer rainfall, and warm.

Fish production of the different species took place year-round. The production system was not optimised or standardised as in the case of trout production in the Western Cape, and the production level was much lower. Continuous waste production took place throughout the year (by fish faeces and wasted feed). Initial problems with theft were overcome by choosing a pump-house dam that was protected by a fence.

Table 2.1: Hydrological characteristics and human utilisation of the research sites at the Makhathini Research facility

	Balancing dam	**Pump-house dam**	**Supplying canal**
Coordinates	S 27° 25' 13.2''; E 32° 10' 21.78''	S 27° 25' 20.64''; E 32° 10' 9.42''	S 27° 25' 21.54''; E 32° 10' 11.52''
Constructed	***1972***	1972	1972
Surface area	***1.5 ha***	0.25 ha	80 km length, 2.5 metres width
Volume / Throughflow	***60 000 m³***	6 250 m³	2 – 4 m³/s
Mean depth	***4 m***	4.1 m	1.5 m
Elevation	***Approx. 120 m***	Approx. 120 m	Approx. 120 m
Flow velocity	***Standing water, some backflow into canal***	Standing water, low retention time	1 m/s
Water supply	***Canal***	Canal	Primary canal of Pongolapoort Dam
Underlying geology	***Sand, mudstone***	Sand, mudstone	Sand, mudstone
Surrounding land use	***Cotton production,*** Vegetable crops, informal settlement	Cotton production, Vegetable crops	Informal settlements, crops
Resource utilisation	***Irrigation, recreation***	Aquaculture, Irrigation	Direct water to network of storage dams

Figure 2.2: Google Earth™ satellite photograph of the research setup at the Makhathini Research Facility

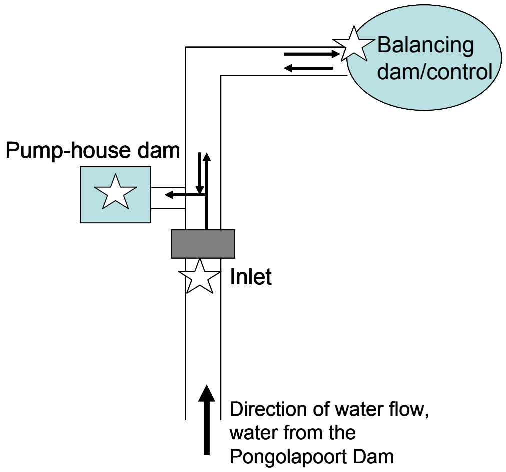

Figure 2.3: Sketch of the sites near the Makhathini Research Facility. Lower left corner represents North. The actual sampling positions are indicated by the stars, the arrows symbolise the water flow. The three sites comprise the canal itself (sampled at the bridge), the balancing dam and the pump-house dam.

2.1.2 Western Cape sites

Within the Western Cape, the research sites were located in the Cape Winelands District (formerly Boland district), within the subdivisions Stellenbosch and Drakenstein. Key sites and control sites were chosen, of which the key sites hosted net cage production of rainbow trout (*Oncorhynchus mykiss*) during the production season (the winter months).

In the Drakenstein area, the experimental site was the Cape Olive farm dam with the neighbouring Calais Dam as control site. The water of the Cape Olive Dam has been used for the irrigation of olive trees and vineyards and fish production since 2001. The main water source of both dams is a perennial river that is split into a channel 500 meter upwards from Cape Olive and into an underground pipe. Calais, the reference site, is fed by the piped water supply whereas Cape Olive farm dam experiences some further influence of organically polluted water released into the river by a nearby Buchu factory. Additional water quality influence derives from runoff water influenced by pine plantations and olive trees, in the case of Cape Olive, as well as vineyards, in the case of Calais.

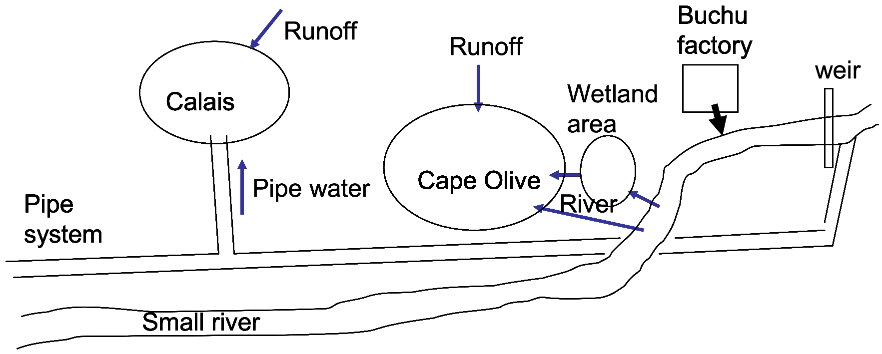

Figure 2.4: Sketch of the water supply situation at Cape Olive Dam (production site) and Calais Dam (control site). Calais is supplied by means of a pipe originating at the weir; Cape Olive is mainly supplied by river water that is slightly modified between the weir and the dam.

In the Stellenbosch region experimental sites comprised the Nietvoorbij Experimental farm dam and the Rondawel Dam as production sites, with Glenbawn Dam as control site. The latter two form part of the Rustenburg Wine Estate dam system. Nietvoorbij water is used for irrigation of vineyards and the dam is mainly fed by run-off water (passing through vineyards) as well as water recirculation through the wine cellar system (dam water mixed with tap water) and 30% water pumped from the Plankenbrug River. Fish production in Nietvoorbij started in 1997 and the dam has been used since. The dam was visited by large populations of Egyptian geese (300 to 400 birds from about December to April) throughout the study period.

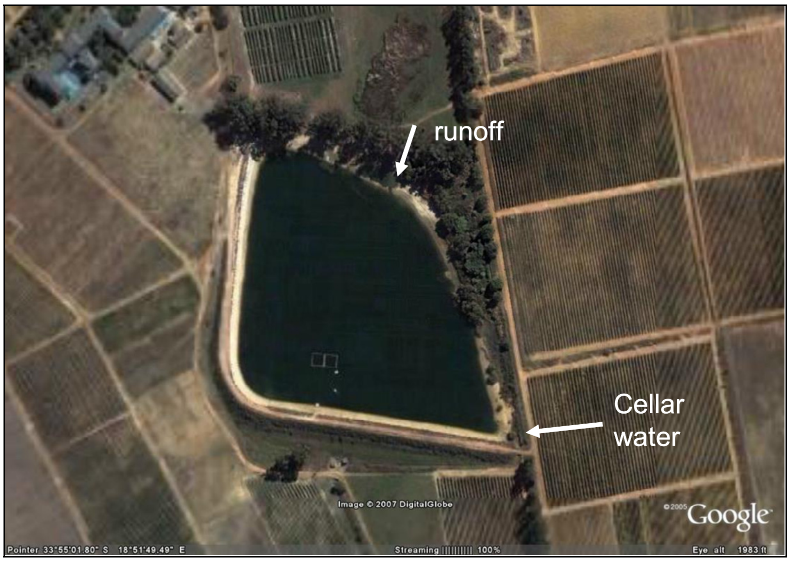

Figure 2.5: Google Earth™ satellite photograph of the study site on the Nietvoorbij Experimental Farm at Stellenbosch

Glenbawn Dam is mainly fed by a pipe system on the farm supplied by Theewaterskloof water or other farm dams, whereas Rondawel is mainly supplied by bottom water from Glenbawn Dam, which is situated on an elevated level next to Rondawel Dam. Supply by run-off water (passing through vineyards) will also support water levels in the Rustenberg dams, as well as influence their water quality. Rondawel has been used for fish production since 2003, except for 2005, but was only used for half a season in 2006 due to water quality problems (oxygen depletion in surface water) at the alternative site. The water from Rondawel is used mainly for the irrigation of grazing pastures and gardens, whereas the water of Glenbawn is used for irrigation of vineyards and fruit orchards.

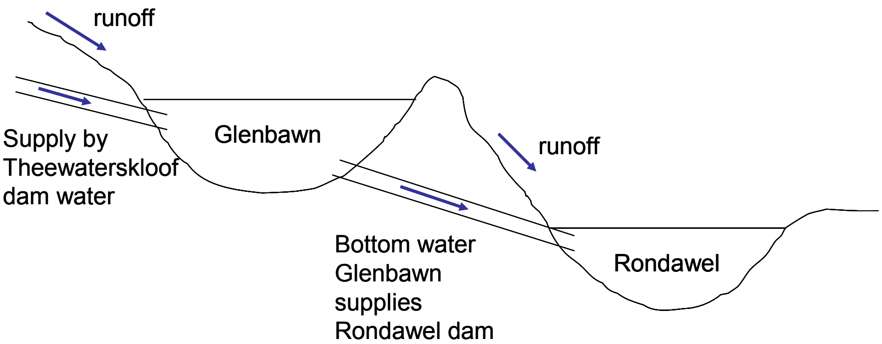

Figure 2.6: Sketch of the water supply situation on Rustenberg farm with the two dams Rondawel (production site) and Glenbawn (control site)

The climate at the Cape Winelands research sites can be described as Mediterranean, with hot, dry summers and cold winters with rainfall. Hydrological and geographical information for the sites can be drawn from Table 2.2.

Table 2.2: Hydrological characteristics and human utilisation of research sites in the Western Cape

	Cape Olive	Calais	Rondawel	Glenbawn	Nietvoorbij
Coordinates	S 33° 42' 22.8''; E 19° 1' 59.34''	S 33° 42' 20.34''; E 19° 1' 33.24''	S 33° 54' 27.0''; E 18° 53' 8.64''	S 33° 54' 24.54''; E 18° 53' 2.58''	S 33° 55' 4.02''; E 18° 51' 47.46''
Constructed	1972	1973	1968	1968	1978 (1985)
Surface area	7.5 ha	6 ha	1.8 ha	2.1 ha	4.2 ha
Volume	555 000 m3	250 000 m3	80 000 m3	140 000 m3	209 000 m3
Mean depth	7.4	4.2	4.4	6.9	5.0
Elevation	189 m	153 m	198 m	207 m	148 m
Water supply	River, runoff	River, runoff	Glenbawn, river, runoff	River, runoff	Plankenbrug River, runoff
Underlying geology	granite, alluvial, shale	granite, alluvial, shale	granite, shale	granite, shale	granite, shale
Surrounding Land use	Vineyards, olive orchards	Vineyards, olive orchards	Vineyards, fruit orchards	Vineyards, fruit orchards	Vineyards
Resource utilisation	Aquaculture, Irrigation	Irrigation	Aquaculture, Irrigation	Irrigation	Aquaculture, Irrigation

An overview of the occurrence of trout production in the dams in the respective winter seasons during the study period is elaborated in Table 2.3. There was no fish production (also not in previous years) at the two control sites. Nietvoorbij produced 5 tons yearly from 2004 to 2006, whereas Cape Olive and Rondawel had a gap year in 2005 (Cape Olive due to a low visibility of less than 5 cm due to sediment introduction, Rondawel due to surface oxygen problems in the 2004 season). In the second half of the 2006 season, Rondawel was again stocked with fish because of the equally difficult oxygen situation at the alternative site on the same farm.

Table 2.3: Trout production in the five study sites during the study period 2004 to 2006.

Dams	2004	2005	2006
Cape Olive	x		x
Calais (control)			
Nietvoorbij	x	X	x
Rondawel	x		x (½)
Glenbawn (control)			

2.1.3 Historical background of small-scale fish farming in the Western Cape

The Western Cape section of the given WRC study was embedded in the "small-scale farming programme" launched by the University of Stellenbosch. The aim of this programme is to develop and propagate trout cage farming in irrigation dams of the Western Cape by concurrently empowering and educating previously disadvantaged groups of the population.

2.1.3.1 Why was the programme initiated?

Between 1992 and 1993, the University of Stellenbosch (US), in collaboration with the Department of Agriculture, Western Cape, located at Elsenburg, and Kromme Rhee Agricultural College, Stellenbosch, ran trials with cage culture in farm dams. There were two experimental sites: one in the Elsenburg dam and the other in the Kromme Rhee dam. Trials were conducted with species of common carp (*Cyprinus carpio*) and rainbow trout (*Oncorhynchus mykiss*).

Aspects that were investigated included:

- Cage sizes (mechanical strength and economy of scale)
- Candidate species and performance

- Feeding methods and growth on different rations
- Stocking densities in correlation with water quality
- Husbandry and fish welfare

The most important aspect that was investigated was the feasibility of the husbandry of rainbow trout in farm dams (irrigation dams) with stagnant water and warmer conditions, given the nature of the species and its origin in the cooler North American climate.

In 1993, the Rural Foundation with its Rural Enterprise programme started to investigate the feasibility of freshwater aquaculture (fish farming) of rainbow trout as a possible rural enterprise. The project team comprised the Department of Agriculture, the University of Stellenbosch and the Rural Foundation. It was decided that the area of De Doorns in the Hex River Valley would be the ideal place to launch the pilot project. The project team undertook informal market research whereby freshwater fish (carp, tilapia) were distributed amongst members of the community who had to complete questionnaires relating to the product with reference to size preference, taste, cooking preparations, and the likelihood of the respondents purchasing freshwater farmed fish, if supplied fresh and affordable. Negotiations with farmers in the Hex River Valley were undertaken and the farm of Ganskraal showed the required commitment and interest. All profits realised were split between the owner, the farm manager and one farm worker, the latter two managing the project.

The project team searched for sponsors for the infrastructure for the pilot project and managed to gain one for the nets from Alnet, a local net manufacturing company. The floating structure was constructed on the farm with locally available material and seed capital from the project team. In October of 1993, the pilot project received their first fish. Since it was close to summer, the water temperature was higher and the team decided on trials with an indigenous tilapia species (*Oreochromis mossambicus*). Wild harvested tilapias of different sizes from Zeekoeivlei were stocked. These were sold from February to April through farm gate sales. The results indicated that freshwater fish was marketable. In April 1994, the pilot project was stocked with the first trout juveniles. From the onset it was perceived that the fish farming project would be managed as rotational production cycles with tilapia during summer months and rainbow trout during winter months. Tilapia harvests were envisaged for sales amongst the local communities and trout for the processing markets. It was tilapia for improving nutritional status and trout for generating additional income. The trout market contract was entered into with Three Streams Smokehouse, a private company in Franschhoek.

2.1.3.2 Development since 1996

Nine trout cage operations have been initiated since 1996 (listed in Table 2.4). Five of them had to be abandoned for various reasons. At Mount Joy and Suurbraak, the reason for abandoning the projects involved concern for environmental impact.

Suurbraak was not suitable due to dam water management and extremely variable water levels, as well as seasonal high levels of suspended solids in the water caused by sediment runoff during strong rainfall events. Mount Joy's farm management raised concern about the water quality in the bottom layers of the dam, which became depleted of oxygen and thereby presumably led to increased iron levels in the outgoing irrigation water.

Table 2.4: Project history since 1993

Start	Location	Stopped	Reason
1993	Ganskraal	1997	Farm sold – new owner not interested
1996	Rustenberg	2006	Oxygen problems
1996	Genadendal	1998	Theft and vandalism
1997	Nietvoorbij	operating	
1998	Mount Joy	1999	Concern about water quality (oxygen depletion at bottom)
1999	Worcester	operating	
2000	Suurbraak	2001	Changing water levels, high TSS
2001	Cape Olive	operating	(No operation in 2005, high TSS)

2.1.3.3 Formation of the co-operative and development since 2003

In 2003, there was a call from the remaining fish farms to merge their efforts to ensure greater advantages to the farmers. After two series of workshops with personnel of the Department of Agriculture Economics and the Department of Agriculture, members were briefed on forms and functions of different legal entities, as well as the operation of a co-operative. The Hands-On Fish Farmers Co-operation Ltd was registered in September 2002 for the small-scale farmers, primarily to address issues such as marketing, bulk buying, juvenile fish supply, financing, and training. In 2004, the first marketing agreement with "The Flying Trout Processors in Franschhoek" was reached.

In late 2004, Hands-On was approached by the Department of Science and Technology (DST). DST proposed using the small-scale fish farming system and the co-operative model to expand the programme in the Western Cape. In the process, partnerships were formed with Three Streams Smokehouse, the Division of Aquaculture and New Farmers Development. In 2005 Hands-On grew to include a number of thirteen projects and in 2006 there already were 23 projects with a collective production of above 100 tons. However, 29% of the produce did not meet the product quality for smoked fish demanded by the processing industry due to inadequate meat coloration and algal taint (off-taste). In 2007, only six projects could be stocked with juvenile fish due to supplier problems.

Currently, Hands-On has dedicated itself completely to the production of trout. The alternating production of tilapia in the irrigation dams during the warmer summer months has only been looked at from late 2006 onwards.

2.2 Production methods

In terms of practicability and cost-efficiency, net cage production was chosen to be most suitable for small farm dam systems with trout production.

2.2.1 Description of floating net cage aquaculture

The to net cage systems in KwaZulu-Natal and the Western Cape setups differed in size and volume and are described in the following two subheadings.

2.2.1.1 KwaZulu-Natal

In the Makhathini pump-house dam, a cage system with four cages was introduced. The cage system consisted of a 4 by 4 meter platform with supportive wooden planks and four 2 by 2 meter net units. The nets were assembled in the form of a square and were suspended to a depth of 2 metres (8 m^3 volume per net; a total of 32 m^3 net volume in the system) (Figure 2.7). The production at the site was not driven as an independent business as with the Hands-On trout project in the Western Cape situation, but was initiated for the WRC project to test its feasibility and promote aquaculture in the area. The effects of catfish and tilapia net cage aquaculture on the water quality of the pump-house dam could hereby be evaluated.

The sampling at the station started in November 2003, during which summer season the first small trials with ornamental fish were attempted. The first year (2004) can be regarded as a control year in which no considerable aquaculture was taking place at the production site (pump-house dam). In January 2005, the dam was stocked with 4500 tilapia (Tilapia rendalii) of an average individual size of 20 g Two hundred days later, in August 2005, a total of about two tons of tilapia with an average individual weight of about 450 g were harvested at the site. The stocking density was 60 kg/m^3 in the cages or about 8 tons per ha of total dam size.

Figure 2.7: Picture of the floating net cages in the Makhathini pump-house dam with walkways and predator netting (floating on surface); the four net cages reach two metres under the surface.

In January 2006, about 500 catfish (*Clarias gariepinus*) were inserted into two of the cages (4 m^3) with an initial average weight of about 100 g per individual. Sixty-two days later, 455 fish with an individual weight of about 500 g and a total of 228 kg of fish (0.2 tons) were harvested. After this first trial, the stocking amount was increased and in August 2006 about 4 000 catfish were introduced into 3 of the cages (some more into the fourth cage, which were lost due to a hole in the net) with an initial average weight of 35 g per individual. In October 2006, the fish had reached an average weight of about 200 gram per fish and a total of 750 kg of fish was harvested (0.75 tons). The catfish density was about 25 to 55 kg/m^3 or 1 to 2.2 tons per ha total dam surface.

2.2.1.2 Western Cape

In the three Western Cape sites, a floating cage farming system consisted of two square units of 10 by 10 metres each. Each cage was surrounded by a 45 cm-wide walkway to provide adequate access to the net cage and working space for production management tasks such as feeding, sampling, grading and harvesting. The nets were suspended from the walkways to depths of four metres and more. Suspension depth of nets could be adjusted according to the water profile, as trout usually dive to deeper, cooler water if the surface temperature reaches 21ºC and more. One standard size cage can produce two to three tons of trout. Each dam was supplied with two units, called a cage system, and therefore produced five to six tons of trout (see Figure 2.8 for photograph). With the volume of 400 m^3 per net, the density of trout (*Oncorhynchus mykiss*) was 6 to 7 kg/m^3 at harvest time.

Anchor ropes from cages can be fixed to moorings on the dam bottom or to the dam wall. Anti-predation netting has to be installed on the sides and over the top. A float is used for human access to and from the cages.

The Western Cape section of the given WRC study was embedded into the "small-scale farming programme" launched by the University of Stellenbosch. In contrast to the KwaZulu-Natal site, operational procedures and structures were well established.

Cage farming of trout is based on the growth of juvenile trout (100 to 250 g) to market size. Due to the temperature requirements of rainbow trout, the production cycle falls during the colder winter months. The cycle usually starts in May and continues until October/November. The number of months available for growth is subject to the water temperature. The ideal temperature for the production cycle of trout is 16 to 18 ºC. As soon as the water temperature reaches 21ºC and above, the fish are placed under stress and production problems occur. Ideally the farmer wants the fish to be market-ready before temperature problems set in.

The required sizes for markets depend on the end-product:

- Fresh plate-sized fish = 300-400 g
- Whole smoked fish = 400-600 g
- Fresh fillets = 600-800 g
- Smoked, sliced = 1 kg and more.

Figure 2.8: Picture of the floating net cages operated in the Western Cape. Walkways with anti-predator netting visible. The net pens housing the fish are under water, reaching a depth of four metres.

The biggest segment of the undersupplied South African market is for smoked products, consisting of sliced trout fillets that cover approximately 80% of the processed product. This market also requires the flesh colour of the fish to be of a specified rating on the Roche Colour Scale for salmonids (28 and more). The colouring of flesh is obtained by introducing natural colouring pigmentation into the feed. This is usually introduced when the fish reach about half of the market weight (600 g).

After the stocking of the juvenile trout of 150 to 250 grams, commercial feeds are fed on a daily basis. The daily amount of feed can be calculated according to a feeding programme based on the average weight and number of fish as well as the water temperature. Once a month, measurement of a subsample of the fish population is undertaken to determine the average growth increase. This information is used to adjust the feeding tables. Once in the production cycle, fish are graded to ensure uniform sizes in the cages. The fish have to be harvested within a brief period of time at the end of the season if destined for the smoked fish market.

2.3 Materials and methods

2.3.1 KwaZulu-Natal – Makhathini Research station

2.3.1.1 Frequency of sampling

The commissioned sites were visited on a fortnightly basis from November 2003 (at the control site from August 2004) until December 2006, during which time relevant environmental data, water samples and phytoplankton samples were collected. The time of the sample collection was early morning and the same order was maintained.

2.3.1.2 Water sampling

Samples at the cage site were taken by accessing the floating boards around the cage. The mid-canal water was sampled from a bridge crossing the canal. Water of the balancing dam was sampled from the shore at an position where there was a steep inclination.

Plastic bottles (250 mL) were used to collect the samples and were rinsed out with water from the respective sites prior to collection. The sampling bottles were filled to the top, leaving no headspace, to prevent oxygenation of samples. Laboratory analyses were carried out on the same day as the sample collection.

2.3.1.3 Sample analyses

Physical and chemical parameters were measured on-site or back at the laboratory and included water temperature, dissolved oxygen, pH and transparency (for a detailed listing refer to Table 2.5). The water temperature was determined by means of a mercury thermometer. Dissolved oxygen was determined colorimetrically by using a HACH DR/850 colorimeter. A Secchi disk with a diameter of 25 cm was used to qualify the transparency of the respective water bodies (Lind, 1979; Wetzel & Likens, 2000). The pH was determined with a SensION 1 pH meter.

At Makhathini Research Station, alkalinity and hardness were measured using the digital titration method. Nutrient analyses were done with a HACH DR/850 Colorimeter, without filtering samples prior to analyses.

Phytoplankton of Makhathini samples was analysed on one occasion, which was in early September 2005.

Table 2.5: Summary of physical/chemical parameters and analytical methods followed

Parameter	Unit	Method	Reference
Field measurements			
Temperature	°C	thermometer	
Transparency	cm	0.25 m Secchi disk	(Wetzel & Likens 2000)
Laboratory analyses			
pH		SensION 1 pH meter	
Dissolved Oxygen	mg/L	AccuVac Ampul colorimetric determination with HACH DR/850 Colorimeter	HACH water analysis handbook
Total ammonia	mg/L	Salicylate method followed by colorimetric determination with HACH DR/850 Colorimeter	HACH water analysis handbook USEPA approved
Total nitrate	mg/L	Cadmium reduction method followed by colorimetric determination at 500 nm with HACH DR/850 Colorimeter	HACH water analysis handbook
Total nitrite	mg/L	Diazotization method followed by colorimetric determination at 500 nm with HACH DR/850 Colorimeter	HACH water analysis handbook USEPA approved
Total reactive P	mg/L	Molybdo-vanadate method followed by colorimetric determination at 810 nm with HACH DR/850 Colorimeter	HACH water analysis handbook USEPA approved
Total Alkalinity	mg/L	Digital titration	HACH water analysis handbook USEPA approved
Hardness	mg/L	Digital titration	HACH water analysis handbook USEPA approved
Total suspended solids (TSS)	mg/L	Photometric method of determination at 810 nm with HACH DR/850 Colorimeter	HACH water analysis handbook

2.3.2 Western Cape – Cape Winelands Sites

2.3.2.1 Frequency of sampling

The commissioned sites were visited on a fortnightly basis from November 2003 (the control sites since August 2004) until December 2006, during which relevant environmental data, water samples and phytoplankton samples were collected. The sampling started at the same time on each sampling day and the order of dam visits was kept the same. The time ranged between 10:00 and 16:00.

2.3.2.2 Water sampling

In non-production dams used as control sites, water samples were collected from a single mid-impoundment site situated at approximately the deepest part of the respective dams. This site was indicated by a plastic buoy and accessed by means of a rubber boat. In fish production dams, net-cage structures were placed at the deepest section of the water body and therefore samples were collected from the cage structure.

Water samples for chemical analyses were collected only from surface water (30 cm from the surface). Plastic bottles (250 mL) were used for the collection and were rinsed out with water from the respective sites prior to collection. The sampling bottles were filled to the top, leaving no headspace, to prevent contamination of samples. After collection, water samples were placed in a cooler box with ice bricks to remain cold during transportation to avoid chemical changes within the sample between the time of collection and time of analysis. At the laboratory, water samples were stored at 4°C overnight until analysis commenced the following day. Chemical analyses of samples were carried out within 24 hours of sample collection (Lind, 1979; Wetzel & Likens, 2000).

2.3.2.3 Sample analyses

Physical and chemical parameters were measured during the collection of water samples at the study sites and included water temperature, dissolved oxygen and transparency (for a detailed listing of the methods applied, refer to Table 2.6). Temperature (°C) and dissolved oxygen (mg/L, %sat) were measured with a portable Oxyguard MK III oxygen meter. A Secchi disk with a diameter of 25 cm was used to qualify the transparency of the respective water bodies (Wetzel & Likens, 2000; Lind, 1979). Conductivity (µS/cm) and total dissolved solids (mg/L) of unfiltered samples were measured at the laboratory by means of a conductivity meter (HACH CO 150) and total suspended solids (mg/L) of unfiltered samples with a HACH colorimeter (DR/700 and DR/890 colorimeters).

Prior to nutrient analyses, water samples were left to reach room temperature and filtered through Sartorius cellulose nitrate filters with a pore size of 0.45 µm. Nutrient analyses included nitrate (NO_3-N), nitrite (NO_2-N), ammonia (NH_3-N), orthophosphate (PO_4-P) and total phosphate. Analyses were carried out according to the methods of the HACH water testing handbook. Other chemical constituents examined included pH and alkalinity. Additionally, water samples from the Western Cape sites, preserved with mercury chloride, were sent to the Department of Water Affairs and Forestry for analysis of trace elements and major inorganic determinants during December 2005 and July 2006. The duplicate analyses allowed external control of the water quality results.

Table 2.6: Summary of physical/chemical parameters and analytical methods followed

Parameter	Unit	Method	Reference
Field measurements			
Temperature	°C	Oxyguard MK III oxygen meter, OxyGuard Polaris	
Transparency	cm	Secchi disk (diameter 25 cm)	(Wetzel & Likens, 2000)
Dissolved Oxygen	mg/L	Oxyguard MK III oxygen meter, OxyGuard Polaris	
Oxygen saturation	%	Oxyguard MK III oxygen meter, OxyGuard Polaris	
Laboratory analyses			
pH		Hanna pH 211 microprocessor with automatic temperature compensation, one point calibration against pH 4 and 7	Hanna pH 211 microprocessor manual
Conductivity	mS/m	HACH CO 150 Conductivity meter with automatic temperature compensation	HACH SensION 5 Conductivity meter manual
Total dissolved solids (TDS)	mg/L	HACH CO 150 Conductivity meter with automatic temperature compensation	HACH SensION 5 Conductivity meter manual
Ammonia	mg/L	Nesslerisation method followed by colorimetric determination at 420 nm with HACH DR/700 Colorimeter Salicylate method followed by colorimetric determination with HACH DR/890	HACH water analysis handbook USEPA approved (only Nesslerisation)
Nitrate	mg/L	Cadmium reduction method followed by colorimetric determination at 500 nm with HACH DR/700 & DR/890	HACH water analysis handbook

Nitrite	mg/L	Diazotization method followed by colorimetric determination at 500 nm with HACH DR/700 & DR/890	HACH water analysis handbook USEPA approved
Soluble reactive phosphate	mg/L	Molybdo-vanadate method followed by colorimetric determination at 810 nm with Hach DR/700 Colorimeter & Hach DR/890 Colorimeter	HACH water analysis handbook USEPA approved
Total phosphorus	mg/L	Acid digestion, determination of soluble reactive phosphorus (srp) via molybdo-vanadate method.	Hach water analysis handbook
Total Alkalinity	mg/L	Burette titration method with 0.02 N H2SO4	HACH water analysis handbook USEPA approved
Hardness	mg/L	Burette titration method with 0.01 M EDTA	USEPA approved
Total suspended solids (TSS)	mg/L	Photometric method of determination at 810 nm with HACH DR/700 & later DR/890	HACH water analysis handbook

2.3.2.4 Phytoplankton

Phytoplankton samples were collected from November 2004 until November 2006 in all commissioned sites in the Western Cape. Samples for phytoplankton were collected at each sampling station by using a plastic pipe sampler (2 m by the diameter of 4 cm) to extract a water column from the surface to a depth of 2 metres (Harding, 1992) by inserting the pipe vertically. By creating a suction force, the content was transferred to a 250 mL plastic bottle.

Phytoplankton samples were immediately fixated by adding Lugol's solution at a ratio of 1:100 of Lugol to the water sample (Lind, 1979; Entwisle et al., 1997; Hötzel & Croome, 1999). Phytoplankton samples were clearly labelled and stored in a dark place on return to the laboratory.

The keys used for the determination of phytoplankton taxa, were those of Huber-Pestalozzi (1938, 1941), Huber-Pestalozzi & Hustedt (1942), Huber-Pestalozzi (1950, 1955, 1961), Huber-Pestalozzi & Fott (1972), Ettl (1978, 1983), Prescott (1978), Ettl & Gärtner (1988), Rieth (1980), Häusler (1982), Komárek & Fott (1983), Kadlubowska (1984), Mrozinska (1985), Krammer & Lange-Bertalot (1986, 1988), Popovský (1990), Krammer & Lange-Bertalot (1991a, 1991b), Joska & Bolton (1994) and Van den Hoek et al. (1995) were used for determination of phytoplankton taxa.

For the determination of composition and biomass of the phytoplankton samples, the conventional Utermöhl inverted microscope method was applied (Utermöhl, 1958; Lund et al., 1978). Self-constructed sedimentation chambers of different volumes (1 mL, 5 mL, and 10 mL) were used for cell counting and identification (Hötzel & Croome, 1999). Samples were examined using a Zeiss inverted microscope with magnification ranging from 125 times to 787.5 times. Individual cell biovolumes were calculated by applying measured cell dimensions to fixed geometrical figures that matched the shape of the cells (Wetzel & Likens, 2000). Individual biovolumes were then used to calculate the biomass (Young, 1986).

2.3.2.5 Zooplankton

Samples for zooplankton analyses were collected from December 2005 to December 2006 in all commissioned sites in the Western Cape. Collection took place by means of a Schindler-Patalas device of 10 ℓ volume which was lowered to a depth of 2 metres (Wetzel & Likens, 2000). The volume of 10 litres of dam water is hereby reduced to 200 mL by being filtered through a mesh with a pore size of 0.63 µm and increasing the density of occurring specimens and facilitating representation and quantification. After filtration, the contents were transferred to a plastic bottle and immediately fixed with formaldehyde to a final concentration of 5% (Edmondson, 1971; Van Ginkel, 1987; Galbraith &

Schneider, 2000; Paterson, 2001). The samples were transferred to a phenoxetol medium (Steedman's solution) for long-term preservation (Steedman, 1976) within the next three days. The volume of the solution was recorded.

To count the individual organisms, samples were left overnight to allow the animals to settle to the bottom of the bottles. After settling, the volume of the samples was further reduced to an end volume of 50 mL. For quantitative analyses, three subsamples of 2 mL were extracted and counted in a plexi-glass Bogorov counting chamber. Subsamples were examined using a Leica stereomicroscope with a magnification ranging from 6.3 times to 50 times. Wherever possible, zooplankton was identified to genus and species level according to the keys suggested by Day et al. (1999), Thirion (1999), Day et al. (2001) and Day & De Moor (2002).

2.3.3 Statistical tests

Before further analysis, each single data set was tested for normal distribution. Normal distribution could in no case be detected and all tests subsequently applied to the data were non-parametric tests.

To test if significant differences occurred among sets of data, the data sets of the sites had to be treated as one group over the whole study period or were grouped into four groups for each season (summer, autumn, winter and spring). The Kruskal-Wallis ANOVA for multiple comparison was then applied, and the results expressed by the respective H- and p-values.

To test for trends within a time line of data, Kendall's tau trend test was applied and the results indicated by the respective τ- (tau-) and p-values.

3 ASSESSMENT OF THE FITNESS-FOR-USE OF THE STUDY SITES FOR AQUACULTURAL PRODUCTION

3.1 Introduction

Optimised site selection for aquaculture in natural environments has many components. There are operational and logistical issues, as well as limitations in contrast to optimal growth under controlled conditions that have to be considered.

At the beginning of the Hands-on trout project, selection of sites was undertaken on a random basis, with some knowledge of other farmers having been successful in the area. The site at Makhathini was similarly chosen. Steer (2006) investigated options of aquaculture site selection via GIS. Variables such as proximity to the hatchery, road access, site security and dam size were considered in the study, concentrating on trout cage farming. Water quality information could not be included in the GIS-based site selection process because of a lack of available information on impoundments in the Western Cape. Overall, the results of the GIS approach proved to be impractical, due to the lacking linkage of the final computer-selected sites to actual information on property ownership, property names or deed numbers.

Sites continued to be chosen on an ad hoc basis, as well as according to criteria similar to those fed into the GIS approach, plus the willingness of the dam owners to cooperate. To date, the decision-making is also supported by analyses of water quality samples of surface water collected from the shores. These shore water quality reports stated the suitability of the water for trout production by single parameter observation, though; the underperformance of many production sites in 2005 and 2006 shows that these reports have not been conclusive enough to understand and estimate the production risks deriving from the environment enclosing the cages. Risk management is especially important in this kind of trout cage aquaculture production because of the marginal profits and heterogeneity in dam dynamics from site to site.

To assess whether the water quality of water bodies is suitable for fish production, given water quality conditions and production performance can be indicators for fitness of the systems to support fish growth successfully. The optimum growth requirements for most species are known and well covered in the literature and can be compared to the existing water quality situation. Additionally, once production has set in on a trial basis, some indicators for fish health and wellbeing within the given water situation would be mortality rates, feeding rates (food conversion ratio) and the absence of diseases and other production difficulties.

The KwaZulu-Natal site was perceived to be optimal for warm water species throughout the season because of having some of the mildest winter temperatures in the country. The Makhathini Research facility provided past experience with aquaculture as well as sufficient infrastructure for the analyses.

In the Cape Winelands situation, it was known that optimal fish production of certain species is restricted to certain seasons in a stagnant, natural environment, cold water species during the winter months and warm water species during summer, both preferably hardy enough to survive year-round conditions. Rainbow trout, therefore, can only be cultivated successfully during the winter season because of its temperature requirements. The aforementioned project with the Stellenbosch University investigates the suitability of tilapia, a warm water species, to be produced in rotation with trout to make optimal use of net-cage structures and allow better return on investment.

Water quality parameters that mostly reduce growth or increase mortality in aquaculture are temperature, pH, oxygen and ammonia (Molony, 2001). Information on the water quality of small irrigation dams (< 20 ha) is scarce in South Africa, mostly due to their large number and private property status. Recent freshwater research in the Western Cape has focused on information from river systems and large drinking water reservoirs. Overall, research into standing water bodies within the country has investigated large dams (> 1 km^2). In the current study, processes driving the nutrient household and influencing oxygen and ammonia distribution patterns, as well as algal growth in smaller dams were found to be similar to the large dams, yet there are some peculiarities concerning smaller dams (e.g. absence of thermoclines or disturbance of stratification during summer). Some insight into drivers of oxygen and nutrient distribution patterns have been gained during the present WRC study, which was made necessary by the large number of incidents related to oxygen decline in the upper water body becoming a severe threat to successful trout production.

Next to oxygen depletion or high ammonia content, diseases, predation and net fouling can become production problems with cage aquaculture. Some water quality parameters, such as higher temperatures, favour the spread of diseases. Others, such as low hardness, can lessen fish immunity or facilitate the availability of pollutants. There is also little knowledge on historical and recent dam contents concerning fertilisers and pesticides and their impact in general as well as their possible accumulation in food fish (e.g. trout, tilapia). Some studies have touched on pesticide accumulation in dams (London et al., 2000; Schulz, 2001; Capkin et al., 2006) and Davies (1997) found that several impoundments in the Caledon region (including Grabouw) are above the critical effect values for endosulfan on fish (with trout as the most susceptible species).

In this chapter, given water quality conditions are compared with the requirements of rainbow trout and tilapia species in the Cape Winelands as well as with tilapia and catfish requirements at Makhathini and conclusions for production management and improved site selection are drawn.

3.2 Materials and methods

3.2.1 Range data for comparison with literature data

To estimate the general suitability of the water quality of the Cape Wineland sites for trout and tilapia and of the Pongolapoort canal system for catfish and tilapia, tables with tolerated and optimal water quality requirements of the species were compiled (from data in literature) and compared with the ranges of given water quality conditions recorded at the sites studied from 2004 to 2006. The water quality data were derived from the data obtained at the five sites studied in the Western Cape and the three sites studied at Makhathini (for methodology refer to Sections 2.3.1 and 2.3.2). The detailed seasonal patterns obtained from the data (not only ranges) are presented in Chapter 4 A and B.

More abundant data were available for the Western Cape sites where not only the five studied sites (including three production sites), but an additional eighteen production dams (monitored by Hands-On) could be considered in 2006 to evaluate the suitability of farm dam conditions for trout production. At the Makhathini Research Facility in KwaZulu-Natal, only one production site was under inspection.

3.2.2 Oxygen and temperature profiles

To understand the frequent occurrence of surface oxygen depletion at the Western Cape sites, oxygen and temperature patterns of surface and deeper water layers were taken (additionally to the methods described in Chapter 2) at the five Winelands sites (three production and two control sites). The water from deeper water layers was hauled with a 1.5 ℓ water sampler with a single-line triggering mechanism and directly measured at the sites. The depths of 2 m, 6 m and near-bottom (maximum of 50 cm from sediment surface) were chosen for the additional oxygen and temperature readings.

3.2.3 Production performance

Data on maximum fish size at harvest, growth rates and mortality rates were made available by the Hands-On Fish Farmers Co-operative for the grow-out season of 2006 (winter 2006). The mortality rate was determined by the fish number inserted (initial fish number) less the fish number at harvest, divided by the initial fish number. Information on presence and duration of surface oxygen problems with trout production were also made available.

3.3 Results and discussion

There were differences in climatic and general conditions and hence species cultivated and methods applied between the KwaZulu-Natal and Western Cape sites, so that the two setups will be discussed in separate subchapters.

3.3.1 Are the general water quality conditions suitable for the chosen aquaculture species?

The climatic conditions given in the respective regions as well as the requirements for optimal growth for the respective species cultivated were compared. The achieved growth parameters were also taken under consideration.

3.3.1.1 Makhathini site

The species produced at the Makhathini study site were Sharptooth catfish (*Clarias gariepinus*) and *Tilapia rendalii*. Both species are warm water fish that can tolerate wide ranges of conditions.

According to the comparative data in Table 3.1, the water bodies in the Makhathini flats irrigation scheme are suitable for tilapia farming, however, their growth will subside to one third or less of the optimal growth rate during the periods of cooler temperature. Temperatures that are cooler than 22°C will be reached from the months May to August (Figure 4.1 in Chapter 4) when tilapia will still feed, but only grow slowly.

The pH levels in the canal system fed by the Pongolapoort Dam have a tendency to be alkalinic, but still seem to be suitable for tilapia production. Tilapia are not sensitive to low oxygen levels and oxygen in the flowing channels is sufficiently abundant.

The unionised (toxic) ammonia levels in the canal system shifted in June 2004 (see Section 4.2.1), but do not exceed the feeding behaviour or wellbeing of the tilapia species raised in the net cages.

Table 3.1: Compilation of most important water quality parameters affecting *Tilapia* spp./*Oreochromis* spp. wellbeing as well as tolerated and optimal growth parameters. All information in columns 2 and 3 according to Popma and Masser (1998); synergistic effects are excluded. Increased mortality risks outside the optimal ranges of the parameters have not been quantified.

Water quality Parameter	**Tolerated levels of *Tilapia* spp. & *Oreochromis* spp.**	**Optimal growth of *Tilapia rendalii***	**Range of conditions at the Makhathini site 2004 to 2006**
Temperature (°C)	< 17 stop feeding < 22 growth 1/3 of growth at opt T	29 to 31°C	18 to 30°C
pH	5–10	6–9	8.6 to 8.8
Oxygen (mg/L)	0.7–10 mg/L	> 1 mg/L	9 to 13 mg/L
Unionised ammonia (mg/L)	0–3 mg/L	< 0.08 mg/L (otherwise food consumption affected)	0.028 to 0.053 mg/L

Catfish are very tolerant of waters with high suspended solid levels, high ammonia or very low oxygen levels; in contrast to tilapia, they are more sensitive to elevated salinity levels.

The optimum temperatures for catfish growth (> 25°C) are only reached during the summer months November to April, but they are less sensitive to lower temperatures than tilapia and feed longer under cooler conditions (see Table 3.2).

The pH levels of the Makhathini flats canal system are higher than would be optimal, but are well tolerated by African catfish. The species is an obligatory air breather that can tolerate very low oxygen levels in water. The oxygen levels measured at the Makhathini site are therefore abundantly sufficient.

Conductivity and salinity levels were not measured at the site, but DWAF data from the Pongolapoort Dam suggests that the conductivity levels vary between 22 and 34 mS/m in the canal system. The corresponding salinity levels would therefore not exceed the range preferred by the catfish.

Catfish can tolerate very high ammonia levels and would therefore even endure values 20 times higher than the measurements at the study site in Makhathini.

Table 3.2: Compilation of most important water quality parameters affecting *Clarias gariepinus* wellbeing as well as tolerated and optimal growth parameters. All information in columns 2 and 3 according to Teugels (1986), Bruton (1988), Gunder and Fink (2004); synergistic effects are excluded. Increased mortality risks outside the optimal ranges of the parameters have not been quantified. Column 4 contains own data as presented in Chapter 4.

Water quality parameter	**Levels tolerated by Sharptooth or African catfish (*Clarias gariepinus*)**	**Optimal growth of *Clarias gariepinus***	**Range of conditions at the Makhathini site 2004 to 2006**
Temperature	8 to 35°C	28 to 30°C	18 to 30°C
pH	5.0 to 9.5	6.5 to 8.0	8.6 to 8.8
Oxygen	> 0.5 to 10 mg/L	> 0.5 mg/L	9 to 13 mg/L
Salinity %	0–1.2 %	0–0.25%	0.1–0.15% (DWAF data)
Ammonia	4–8 mg/L		Since June 2004: 0.13 0.22 mg/L

With cautious and adapted feeding strategies during the cooler winter months to avoid overfeeding, both species are highly suited to grow almost optimally for a period of 4 to 5 months in summer, with good toleration of the winter temperatures and reduced growth for 3 to 4 winter months. Other than the temperature, no other restrictions to possible optimum growth have been found through comparing literature data and ideal growth to the measured conditions at the sites. The pH of 8.7 is fairly alkaline, though most warm water fish species prefer higher alkaline water to acidic conditions.

Overall the water quality of the canal system is highly suitable for aquacultural production. Especially given the water renewal period and low retention time of the pump-house dam, nutrient accumulation by aquaculture can be assumed to be minimal.

The only risk of aquaculture under the given conditions would come from sudden changes in water quality due to uncontrolled waste water inflow into the canal. Fish diseases would mainly play a role if waste water from fish farming upstream would contaminate fish farms further downstream.

3.3.1.2 Cape Winelands sites

So far, most attempts with net cage aquaculture in the Western Cape have concentrated on trout. Trout is a very sensitive species in terms of temperature, oxygen and ammonia requirements, but is highly tolerant towards changes in salinity. Table 3.3 highlights the most prominent water quality parameters known to affect *O. mykiss* growth performance and wellbeing. The single parameters are discussed separately in the following.

The optimal temperature for trout cultivation would be around 18°C (Molony, 2001; Boyd, 2003). In the Cape Winelands, due to climatic conditions, this optimal temperature is only reached for a narrow window period of some weeks (see Figure 3.1). Otherwise, the water temperatures oscillate between a minimum of 12.5°C in winter (May to August) and a maximum temperature in summer (October to March) with a plateau of between 23 to 28°C (depending on dam location). Only for the transitional periods in between will the water temperature actually be optimal for trout. Levels lower than 16°C and higher than 20°C lead to gradually stagnating growth and higher temperatures, especially, can lead to greater susceptibility to diseases and temperature stress. In stagnating water bodies, higher temperatures are often linked to reduced oxygen levels. Lower temperatures are better accepted by the species. As a result, trout production can only take place during the winter months and temperature needs to be closely monitored in most Western Cape dams before insertion of juvenile fish and again at harvest time, before the water body heats up. Despite the suboptimal temperature conditions in most dams in the studied area, the production of rainbow trout during the winter period has been shown to be economically viable and successful. Survival rates over summer, with fish confined in the net cages, are, however, very low in most dams.

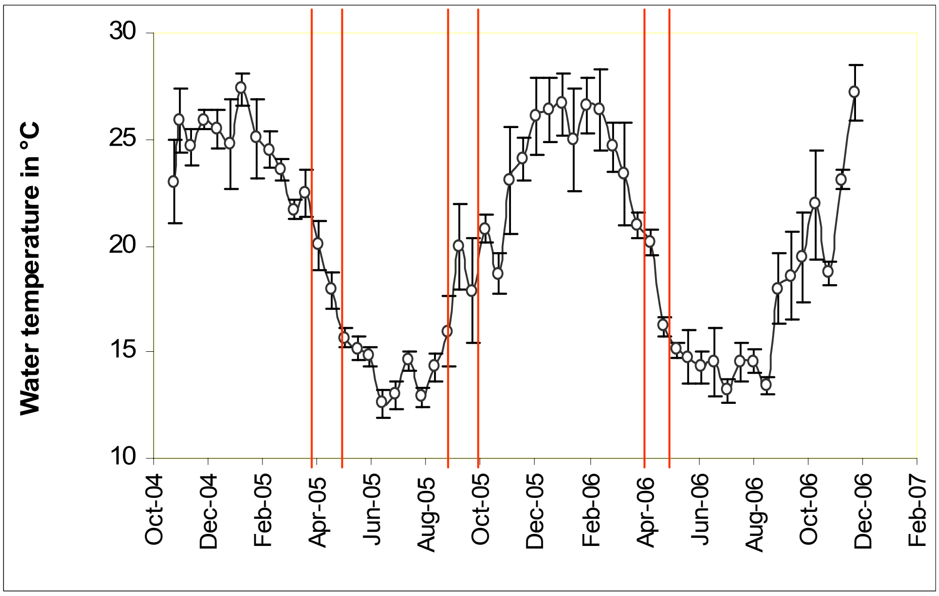

Figure 3.1: The average water temperature of the five Western Cape study sites with standard deviation. The vertical lines represent the narrow time windows in which the optimum temperature for trout production (18°C) equals the given water temperature conditions.

The pH of the sample sites varied from slightly acidic to strongly alkalinic. The highest pH levels occurred during the spring and summer months when excessive algal growth affected the pH levels (see Table 3.3). The soil texture in the catchment area of the Stellenbosch sites is mainly influenced by granite (60%) and Malmesbury shale (40%), whereas the catchment area of the Drakenstein sites consists of a granite basis (60%), alluvial soils (20%) and shale (20%) (Intersect overlay between catchment boundary data with the New Vegetation Map of South Africa, Lesotho and Swaziland (2003) using ArcView 3.1). The $pH_{(KCl)}$ of the soils of the agricultural land surrounding the water bodies is often monitored on the farms and $pH_{(KCl)}$ levels were mostly varied between five and six, according to data collated by Brown (2006). However, processes affecting the soil $pH_{(KCl)}$ are diverse and influences of the mostly alkaline irrigation water on soil pH can be disregarded.

The oxygen levels at the surface of the dams decreased to below 6 mg/L on two occasions only, but with additional data from deeper water layers it could be shown that they declined rapidly with increasing depth once lower oxygen levels were reached at the surface and this could lead to oxygen stress with the high densities of trout confined in the cages.

The hardness of the Western Cape dams is generally low and the water therefore is regarded as soft (0–75 mg/L $CaCO_3$ indicates soft water, 75–150 mg/L $CaCO_3$ moderately hard water; USEPA definition). Hardness levels above 200 mg/L could buffer highly acidic water, can reduce the toxicity risks of most ions (e.g. copper or zinc) and can reduce the disease risk (Wedemeyer, 1996).

Table 3.3: A comparison between measured Western Cape water quality conditions and the tolerated and optimal growth levels of *O. mykiss*. (All information in columns 2 and 3 according to Molony (2001); unionised ammonia by Boyd (2003); synergistic effects are excluded. Higher mortality rates outside the optimal ranges of the parameters are not quantified.)

Water quality parameter	**Levels tolerated by *O. mykiss* (Molony, 2001)**	**Optimal growth of *O. mykiss* (Molony, 2001; Boyd, 2003)**	**Range of conditions in the Western Cape dams 2004 to 2006 (compilation of data presented in Chapter 4)**
Temperature	5 to 24°C	14 to 21°C (18°C)	12.8 to 29°C 12.8 to 23.9°C (April to October) 19.9 to 29.0°C (November to March)
pH	3.5 to 9 (juveniles and adults only)	6.5 to 8.5	6.3 to 10.4
Oxygen	2.6 to 13 mg/L	6 to 9 mg/L	4.2 to 20.0 mg/L
Hardness		> 200 mg/L	8 to 86 mg/L CaCO3
Salinity	0 to 3.5 %	No sudden changes	0 to 2%
Conductivity			5 to 48 mS/m
Ammonia	0.07 to 0.39 mg/L (LC50)	< 0.1 mg/L	0.01 to 0.93 mg/L
Unionised ammonia		< 0.025 mg/L	0 to 0.19 mg/L

No extreme salinity changes would be expected within one dam and therefore the salinity levels are providing stable conditions; the same applies to the conductivity levels.

The ammonia content of all three production dams exceeded the sub-lethal effect range at times. Occurrences of high ammonia levels at the surface occurred mostly during the turnover phase in winter when the partly extremely high ammonia levels (> 3 mg/L NH_3-N) of bottom water are mixed throughout the water column (Maleri, 2008).

To increase the cost-efficiency of the infrastructures established and investment made for trout production, a new project was commenced to investigate the suitability of tilapia production in the same net cages as the trout by rotational production.

Table 3.4 shows water quality parameters whose effect on tilapia has been investigated and the data from the literature are compared to the measured water quality conditions at the five studied sites (also see Chapter 4).

Tilapia as warm water fish species grow optimally at temperatures between 29 and 31°C, levels that dams hardly ever reach in the study area. Temperatures of around 26 to 28°C can be achieved in the Stellenbosch area for one to three months during the summer. Further observations revealed that most trout sites of the Hands-On co-operative are situated in Grabouw or towards Worcester and Ceres and only reach maximum temperatures of 25°C in summer (Maleri, 2008).

The measured pH levels are suitable for tilapia production with possible growth inhibiting effects during periods of extremely alkaline pH values (> 9) in summer.

Tilapia are very tolerant to conditions of elevated toxic (unionised) ammonia levels. However, some studies have shown that food consumption might already be affected at very low toxic ammonia levels (Popma & Masser, 1999). Therefore, ammonia levels might affect tilapia growth rates in some dams.

Table 3.4: Compilation of most important water quality parameters affecting *Tilapia* spp./*Oreochromis* spp. wellbeing as well as tolerated and optimal growth parameters. All information in columns 2 and 3 according to Popma and Masser (1999); synergistic effects are excluded. Increased mortality risks outside the optimal ranges of the parameters have not been quantified.

Water quality Parameter	Tolerated levels of *Tilapia* spp. & Oreochromis spp.	Optimal growth of *Tilapia* spp. & Oreochromis spp.	Range of conditions in the Western Cape dams 2004 to 2006
Temperature	< 11 lethal < 17 stop feeding < 22 growth 1/3 of growth at opt T	29 to 31°C	14 to 29°C 12.8 to 23.9°C (April to October) 19.9 to 29.0°C (November to March)
pH	5 to 10	6 to 9	6.3 to 10.4
Oxygen	0.7 to 10	> 1 mg/L	4.2 to 20.0 mg/L
Salinity	0 to 15	0 to 5	0 to 2‰
Unionised ammonia	0 to 3 mg/L	< 0.08 mg/L (food consumption affected)	0 to 0.19 mg/L

The challenge of a rotational grow-out scheme with trout and tilapia in the same net cage structures would be to optimise the length of each grow-out phase to enable sufficient growth within one season. Less than 21°C is an experienced requirement for successful trout production and more than 21°C would be necessary for viable tilapia production. As a result of the temperature conditions in the Cape Winelands study sites, trout could be kept in the cages for 7 or 8 months, tilapia for 4 to 5 months (see Figure 3.).

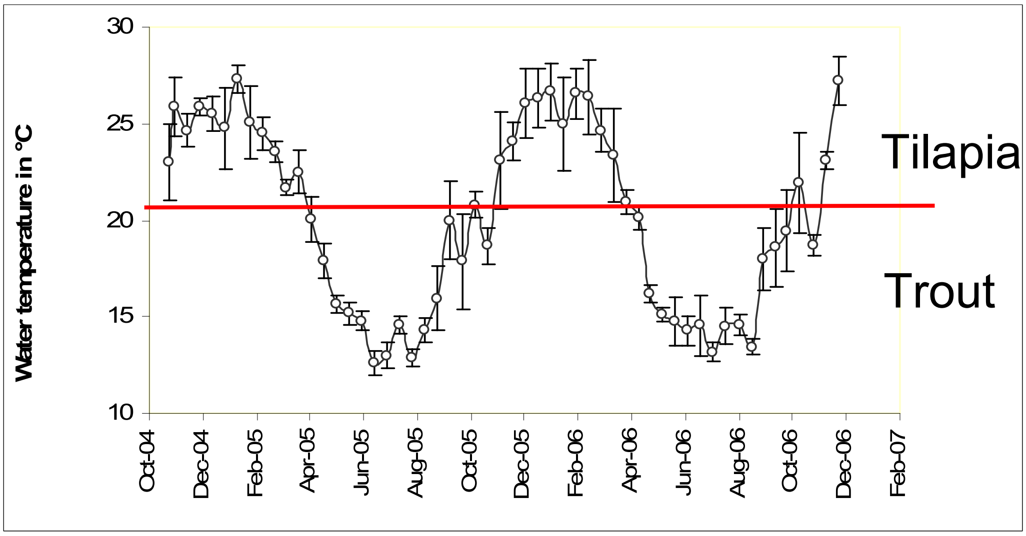

Figure 3.2: Average water temperature development at the five study sites in the Western Cape with the 21°C line differentiating between the most suitable temperatures for trout and tilapia. The standard error with the temperature measurements was 0.1°C for each single data point.

3.3.2 Problems with surface oxygen depletion at the Cape Winelands sites

During the grow-out season 2006, some Hands-On production sites showed production problems that caused economic losses, the most severe being surface oxygen depletion (29% of 21 dams) and consequent increased mortality rates (up to 40% of population). These problems also affected one of the three production sites included in this study, namely Rondawel Dam on Rustenberg farm, where these problems had been encountered in previous years as well and had led to the discontinuation of production in that dam in the year 2005, as well as for half the production season in 2006.

Within the canal system of the Pongolapoort irrigation scheme, oxygen problems would not be expected. The constant flow of the canal system creates turbulence and oxygenation and the retention time of the pump-house dam (only production site) was noted as 24 times per day or higher, so that natural stagnation and decomposition processes are overruled. Oxygen levels in the system did consistently remain at levels higher than 9 mg/L.

Section 3.3.2 of this chapter is therefore restricted to understanding of the conditions favouring surface oxygen depletion at the Cape Winelands sites. Knowing the causes of surface oxygen depletion will help to avoid critical sites and put oxygen depletion in context with the suitability of net cage farming in those dams.

To understand the patterns of oxygen depletion and nutrient accumulation and distribution (a closely related factor), an investigation of deeper and bottom water conditions became necessary.

The subtropical dams of the Western Cape follow a warm monomictic and holomictic regime, which means that there is one winter turnover phase per year, with complete mixture of the water column.

The coldest surface water temperatures per year lie in the range of 12 to 14°C in the Stellenbosch and Drakenstein area. When hypo- and epilimnion temperatures approach each other towards winter, density differences decrease and the water body is able to mix, usually strongly driven and supported by prevailing wind action. Depending on depth at full capacity, depth at lowest annual level, degree of groundwater influence and the given weather conditions, the turnover phase can last from February to August, and as a core period from March to July (concurring with the trout production season). During that phase, available nutrients at the bottom will be mixed into the water column and most ammonia that is present can be converted to nitrate because of sufficient oxygen supply. In addition, hydrogen sulphide becomes oxygenated to sulphate, which is an innoxious compound.

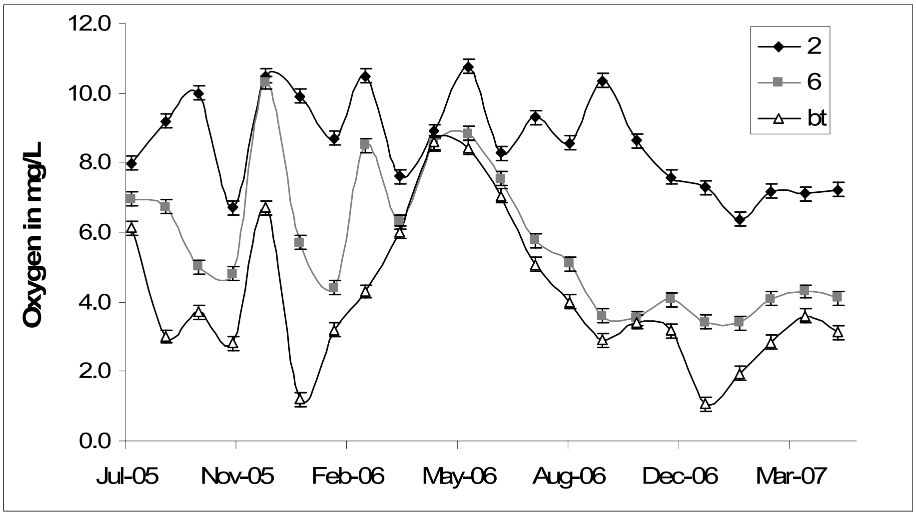

Figure 3.3: Average oxygen levels at the five sites studied from July 2005 to August 2007 at three depths (2 m, 6 m and near the bottom)

As visualised in Figure 3.3, below, the average oxygen levels at two and six metres, as well as near the bottom of the five studied sites, it can be observed that from September onwards, when stagnation sets in, the oxygen levels in the bottom water start to decline. There is an extraordinary peak in December 2005, when strong winds caused an intermittent destabilisation of the thermocline. The dams develop oxygen levels of less than 1 mg/L at some stage during the summer stagnation and experience hypolimnion oxygen consumption through decomposing processes consuming oxygen. Figure 3.4 presents the detailed oxygen pattern of the two Rustenberg sites at a depth of two metres. It is clear that both dams experience stages with relatively stable oxygen levels and patterns of rapidly increasing oxygen levels that decline just as fast. Those patterns can most likely be explained by excessive algal growth followed by a crash of the population with subsequent decomposition of phytoplankton debris. Those events mostly took place between August and October when high nutrients from the later turnover phase were kick-started by increasing temperatures. High biomasses of algae with sufficient nutrient supply plus supporting weather conditions (extended cloudy period after a series of sunny days) are assumed to play a role in the sudden die-off of these algae, with subsequent decomposition by bacteria with high oxygen consumption rates. These drops in oxygen levels were observed in late October 2005 at the John Smith site and in mid-August at the Rondawel site in 2006.

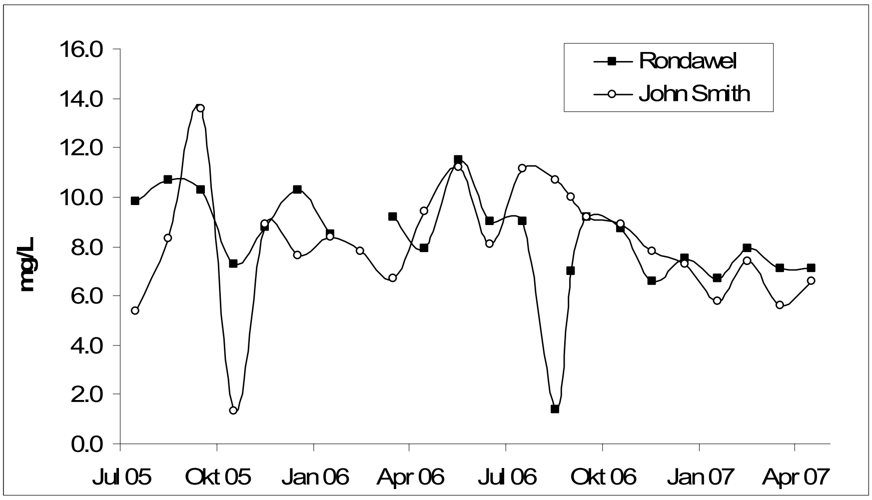

Figure 3.4: Oxygen development at two Rustenberg sites from July 2005 to April 2007. Rondawel is the production site included in this study. John Smith was the alternative site for fish production on Rustenberg farm when production at Rondawel was suspended. The dams are of similar size and depth.

Smaller dams (< 3 ha) with collected organic debris (leaves, runoff, aquaculture) at the bottom are most likely to experience highest nutrient levels during the turnover phase (smaller dilution effect) that cause excessive algal bloom during extended sunny periods. If the weather conditions change too suddenly into shaded conditions, the phytoplankton cells relying on light as energy source, will die.

3.3.3 Production performance

Production performance can be influenced by environmental conditions as well as managerial factors.

3.3.3.1 Makhathini

Production at Makhathini was irregular and organised on an ad hoc basis. Tilapia were produced for 200 days from January to August 2005, catfish for about 60 days from January to March 2006, as well as from August to October 2006.

Table 3.5 summarises the growth parameters of tilapia and catfish in the cages of the pump-house dam. Catfish production in winter affected the achieved FCR rates drastically and overall growth was much reduced (maximum fish size in same period and weight gain per day). The mortality rates were not far from the natural mortality rates and higher during the winter production.

The tilapia were grown to a good market size with a suboptimal mortality rate (production over winter) and relatively high FCR values. The mortality rate was very low.

With expansion of production sites, more knowledge and exchange of experience would be attracted to the area. The FCR values possibly came about by overfeeding during cooler weather conditions and the failure to adapt the amount fed to the number of fish present (that fish escaped through holes was detected only after an extended period of time). Better training in techniques to improve feeding would most likely have avoided the high FCR.

Table 3.5: Production performance parameters at the Makhathini production site (pump-house dam) from 2004 to 2006 with catfish and tilapia production.

Parameters in catfish production	**Optimum according to De Graaf & Janssen (1996), Yong-Sulem et al. (2006) and Haak (1987)**	**Achieved at the production site in Makhathini**
FCR	0.98 to 1.54	0.9 (summer) and 2.4 (winter)
Mortality rate %	0.2 to 2% (natural)	4.4 and 6.2%
Maximum fish size	Up to 1500 g in cage production	500 g and 200 g
Specific growth rate (% body weight per day)	3 to 4% (from 100 g) and 9 to 11% (from 20 g)	2.8% and 2.9%
Parameters in tilapia production	**Optimum according to Popma & Masser (1999)**	**Achieved at the production site in Makhathini**
FCR	0.9 to 1.2	1.9
Mortality rate %	1 to 3% (natural)	1.1%
Maximum fish size	500 g good market size	456 g
Specific growth rate (% body weight per day)	2 to 2.5% (starting with 20 g fish)	1.55%

3.3.3.2 Cape Winelands

Production-wise, the three production sites in the Boland area (Cape Winelands) performed below the optimum, but represent average sites within the Hands-On production scheme in the year 2006 (Table 3.6).

The FCR of the three sites ranged between 1.8 and 2.2, which suggests that, with a combination of unskilled feeding and adverse water quality conditions, double the amount of feed optimally necessary was applied.

The mortality rates at Cape Olive varied around the average while the Nietvoorbij site achieved lower mortality rates. The highest mortality rates within this WRC project was attained by the combined production sites John Smith (early season 2006) and Rondawel Dam (late season 2006), both located on Rustenberg farm. Those cage systems lost 27% of the original fish population inserted into the cages throughout the season, most of them during a period of low oxygen levels at the surface.

The three dams achieved maximum fish sizes above average, however, at two of the sites only by leaving the fish in the cages for longer. The average growth rates were below average at two of the sites.

Especially at Rustenberg (John Smith and Rondawel), the high mortality rate could be accounted for by water quality problems rather than managerial problems, as would the extended holding of the fish in the cages (162 days) and the still reduced maximum size of the fish at harvest time, as well as the overall growth rate.

Table 3.6: Production performance parameters for the 2006 season for the three production sites in the Cape Winelands. Optimum FCR according to Beveridge (1996).

Parameter	**Optimum for trout cage farming in natural waters**	**Achieved at Cape Olive, Nietvoorbij, Rustenberg (production sites) in 2006**			**Average of all 21 Hands-On projects (and range)**
		CO	NV	Rust	
FCR	Around 1.0	2.2	2.0	1.8	1.6 (1.1 to 2.5)
Mortality rate %	0 to 5 %	18%	13%	27%	19.9% (4.5 to 54%)
Maximum fish size	1360 g	1300	1150	1050	1050 g (420 to 1360 g)
Average growth rate over time in the cages (Ø 143 days)	9.1 g/day (124 days)	5.5 (147)	3.5 (175)	4.1 (162)	5.2 g/day (1.4 to 9.1 g/day)
Surface oxygen depletion	Avoidable by improved site selection	Occurred in 1 of 3 dams			Occurred in 6 of 21 dams

The FCR can be affected by unfavourable water conditions. However, feeding strategies can be adapted to most conditions (e.g. low temperature, weather, low oxygen levels) and high values should therefore not be reached. Cape Olive experienced relatively low visibility (high TSS values) during the 2006 season. Such conditions make feeding more difficult than other water quality conditions, as trout are more dependent on visual cues for food. The cost of higher FCR levels was outweighed by good achievements in maximum fish size and growth rates at Cape Olive farm.

At Nietvoorbij, the relatively low growth rate and maximum fish size were most likely caused by bad feeding practice (own observation) which would be managerial rather than water quality related.

3.4 Conclusions

The water in the canal system supplying irrigation water in the Pongola Flats is suitable for the production of warm-water fish species, with minor restrictions due to temperature during the winter period.

The fish species chosen for the Makhathini site within the Makhathini Flats irrigation scheme seem to be very suitable for the conditions that prevail. Possible reduction of growth performance caused by the surrounding water quality conditions could not be detected from the parameters measured in this study. Due to the temperature regime, adaptations that involved attempting to restrict the grow-out to one season and stocking in spring and harvesting in autumn were advisable. This was partly inhibited by irregular fingerling supply which would need to be organised better with expansion of aquaculture in the area.

Fish production is highly suitable in the canal systems of the Jozini dam, especially during the periods in which high water flow is guaranteed (with irrigation taking place). Major problems were encountered at the project through theft of fish and vandalism, which could be attributed to socio-economic conditions and poverty in the area. Another problem concerned FCR during the winter period. Improved feeding strategies and better knowledge of the fish species could help to overcome these problems in the future. The high FCR levels achieved could not be explained by water quality monitoring and has to be ascribed to feeding management procedures.

Problems with oxygen would not have been expected at the pump-house dam due to the very high water exchange rate of the water body (3600 times per year in contrast to a maximum of 3 to 5 times per year within most Western Cape irrigation dams). The accumulation of nutrients in the pump-house dam is therefore highly unlikely with nutrient accumulation being the major contributor to eutrophication, excessive algal bloom and subsequent problems.

The suitability of the balancing dam for aquaculture was not studied extensively. The results for hardness levels and TSS levels provided in Chapter 4A indicate that most water in the case of the study setup flows into the pump-house dam, whereas the water in the balancing dam is different; sediments have time to settle down and hardness levels are lower (by Ca and Mg taken up by phytoplankton or settling down as well). This indicates that the water retention time is much higher in the balancing dam and its suitability for aquaculture would have to be studied in a newly designed study.

It seems that the Pongolapoort Dam as water source for the canal system provides sufficient water quality levels for successful aquacultural production. The ammonia levels show an increase from earlier levels and should be monitored closely. Sudden changes in the water quality due to events in the canal could occur and add some risk especially to aquacultural operations at the dead end of a canal. However, during the study period, no cases of sudden fish kills or unease were observed.

The single parameter evaluation indicates that rainbow trout can be produced successfully in the Western Cape impoundments during winter months. Care has to be taken in dams with an elevated eutrophic level (total phosphorus > 60 to 80 µg/L) because of the effects of excessive algal growth on pH and the subsequent ammonia effects by conversion of the concurrent nitrogen inputs. The soft water increases the risk of diseases and effects from sudden water quality change caused by inflowing water (however, the size of the dams to a large degree allows dilution of inflowing water).

Shallow dams with high phytoplankton abundance especially are at risk of sudden oxygen depletion in the surface water due to a complete crash of the phytoplankton population or oxygen consumption of excessive algal occurrence during night-time. The problem is extremely intensified in dams that are void of a thermocline due to a depth of less than five metres in early winter. As a measure of improvement, through-flow of water in such dams should be guaranteed and optimised at all times by keeping the nets clean from algal growth (mostly filamentous algae) and consequent net fouling.

Consequently, large dams with sufficient depth (more than six metres at lowest level), exposed to wind action to stimulate turbulence, high water exchange rates and relatively cool summer temperatures would be most suitable for successful trout production.

Tilapia have a relatively short period with temperatures that allow sufficient growth in natural standing water bodies of the studied area. They are hardier, on the other hand, and tolerate the ambient water quality of most dams without the stress levels easily experienced by trout. Oxygen levels below 3 mg/L are rarely reached in the dams and then only for short periods in summer and tilapia would endure these conditions much easier than trout, without serious impacts.

In contrast to dams suitable for trout production, optimal sites for tilapia would be water bodies with a high water exchange rate (to avoid organic build-up from production waste) and high summer temperatures. Such conditions would most likely be available in smaller dams in sheltered locations.

4 THE IMPACT OF CAGE AQUACULTURE IN CANAL SYSTEMS AND STORAGE DAMS ON WATER QUALITY

4A PONGOLAPOORT CANAL SYSTEM

4.1 Introduction

In KwaZulu-Natal at present, there are 16 large state-owned dams ranging between 9 and 2300 million cubic metres in volume at full capacity (DWAF, 2007). The largest of these dams by far is the Pongolapoort Dam, also known as the Jozini Dam, which is fed by the Pongola River. The wall damming the Pongola River to the east has led to the filling of a formerly narrow gorge within the Lebombo mountains. The Jozini Dam wall was built in 1972 and is 89 metres high. The original river as well as a canal system is supplied with water beyond the dam wall. The main canal is from 5 to 7 metres wide, whereas secondary canals have a width of 2 to 3 metres. The high hydrological variability of the dams in KwaZulu-Natal (Schulze, 2000) made it difficult to decide on a site for an exemplary net-cage setup in the area. Eventually a setup within the canal system with a pump-house dam and a balancing dam fed by the Pongolapoort Dam was selected. An attempt was made to grow catfish and tilapia within this setup. As there are many of these pump-houses in the area, the setup could easily be replicated.

The advantage of the canal system is the constant supply of water. Despite the small size of the pump-house dam (0.25 ha), the low retention time (fifteen minutes to one hour during irrigation) and location of the cage assured constant nutrient removal. The disadvantage is that any single incident along the canal or chronic water change from the large dam can influence the water quality. Informal settlements established along the canal make this a likely risk as household waste could pass through at any time.

The water temperature of this subtropical area with summer rainfall was expected to be above 17°C throughout the year, so that warm water species were opted for production, namely Sharptooth catfish (*Clarias gariepinus*) and Tilapia (*Tilapia rendalii*), as well as ornamental fish.

The three-year period of the study was used to investigate the feasibility of aquaculture within the area along the canals on the downstream side of the dam wall, as well as to monitor and evaluate water quality changes along the same route.

4.2 Results

4.2.1 Physical and chemical parameters

The water quality parameters collected at the Makhathini Research Station included water temperature, dissolved oxygen, pH, transparency, alkalinity, hardness and the content of total suspended solids.

Makhathini has a warm, subtropical climate with hot and humid summers (rainfall period) and warm, dry winters. The water temperature varied accordingly between 18°C in winter (June and July) and 30°C in summer (January, February). The temperature was practically the same at all sites (see Figure 4.1). When grouped seasonally into spring, summer, autumn and winter, the temperature levels of the three sites did not differ significantly when tested with the Kruskal-Wallis Anova (all four H values were smaller than 3 and all p levels above 0.05).

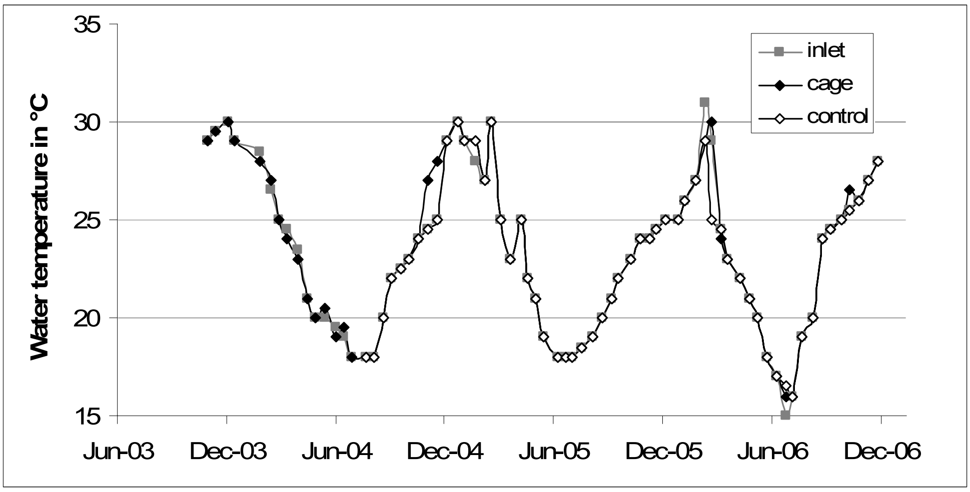

Figure 4.1: Temperature development at the three sampling sites near the Makhathini Research Station from November 2003 to December 2006. The standard error for each data point is 0.5°C.

The pH of all sampling sites, canal (inflow), production dam and balancing dam (control), showed little variance and consistently fluctuated around 8.7.

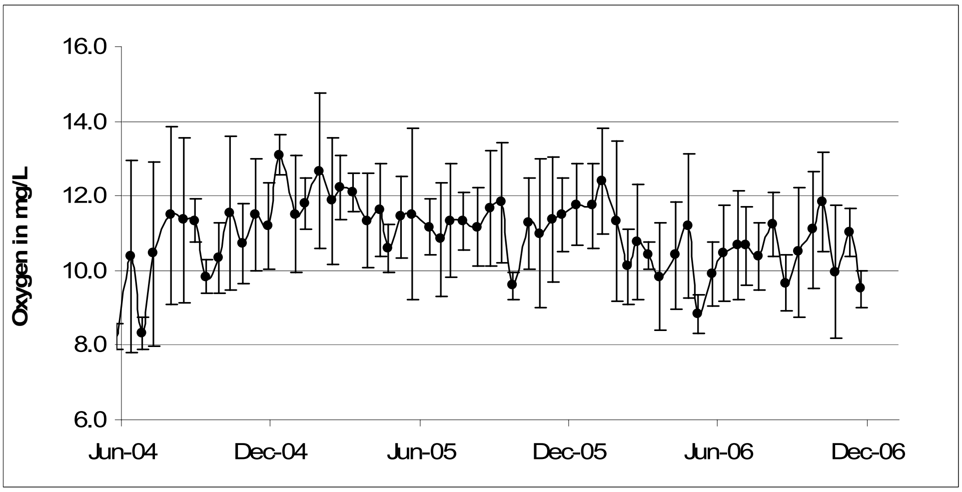

Figure 4.2: Average dissolved oxygen levels at the three sampling sites near the Makhathini Research Station from June 2004 to December 2006. All three sites fluctuated within the same range in a fuzzy pattern.

Dissolved oxygen levels showed similar stability that constantly fluctuated between 10 and 12 mg/L with some outlying values down to 8 and up to 14 mg/L. The graph shows the average oxygen level of the three sites per point in time (see Figure 4.2). When the data were sorted into site classes with all data points per site being grouped independent of time, there was no significant difference between the sites ($H = 2$, $p > 0.05$). According to the Kruskal-Wallis ANOVA, the oxygen levels recorded at the production site were not significantly affected by fish production. These oxygen levels were highly suitable for fish production at all times.

Transparency and total suspended solids tend to be related to each other. Transparency expresses the visibility through the water column and the total suspended solids (TSS) mainly represent the solid sediment particles present in the water (see Figure 4.3). The visibility measured by means of the Secchi disc varied between 65 and 70 cm in the canal and control dam and was slightly higher at the production site, with 80 cm recorded almost throughout. Little variability is shown by the values. The total suspended solids levels were slightly lower at the control site between February 2005 and May 2005 as well as between October 2005 and November 2005, which could indicate that the water hydrology of the balancing dam is following a different pattern, with less water exchange so that sediments have more time to settle down. Overall, the TSS values were quite low, with levels between 0 and 8 mg/L, mainly, and the water clarity was good.

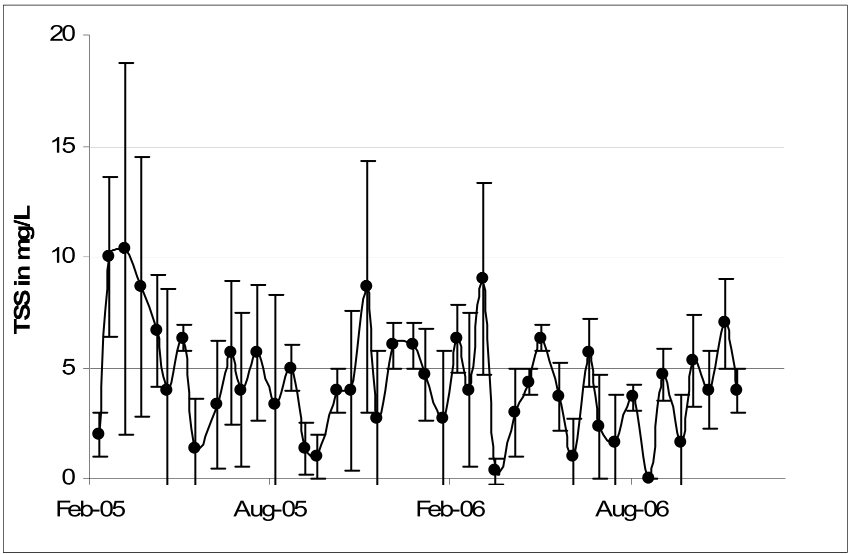

Figure 4.3: Average total suspended solid (TSS) levels at the three sampling sites near the Makhathini Research Station.

Water hardness and alkalinity give an indication of the calcium and magnesium as well as carbonate and bicarbonate content of the water.

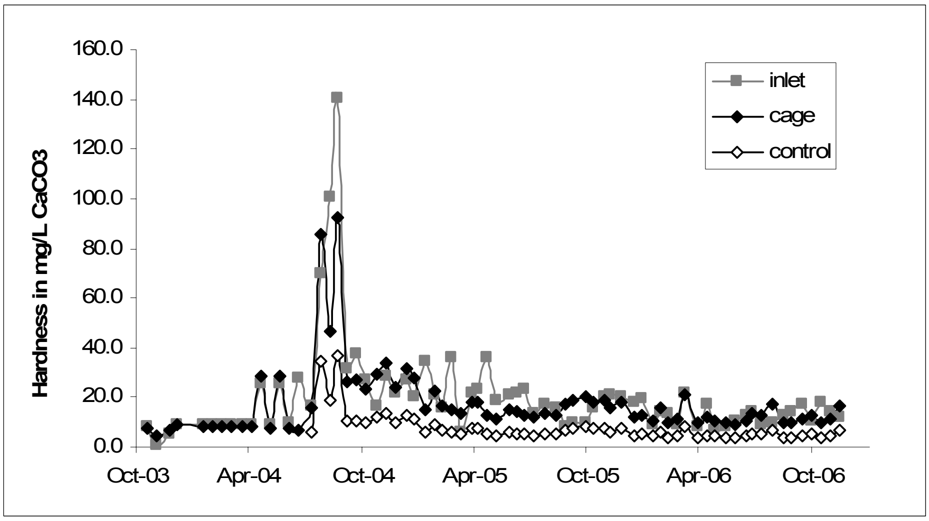

Figure 4.4: Hardness levels in mg/L $CaCO_3$ at the three sampling sites near the Makhathini Research Station

Results indicated that alkalinity and hardness of the water body in July and August 2004 showed fluctuating readings (see Figures 4.4 and 4.5). Since then, both alkalinity and hardness have stabilised at levels of around 10 to 15 mg/L. Such water can be described as soft to moderately soft (according to DWAF, 1996b), with low buffering control against acidic influence. At the control site (balancing dam), the hardness was significantly lower than at the two other sites ($H = 73$, $p < 0.01$). No difference was found between the production site (cage) and the canal (inlet).

The alkalinity did not show significant differences among the sites ($H = 4$, $p > 0.05$) when grouped either into pre-January 2005 or after January 2005.

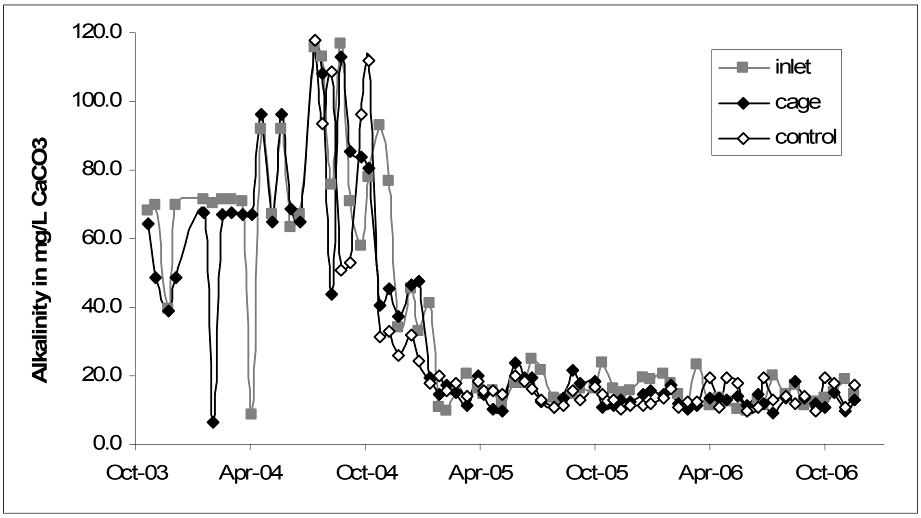

Figure 4.5: Alkalinity levels in mg/L $CaCO_3$ at the three sampling sites

4.2.2 Nutrients

There was no significant difference among the three sampling locations (grouped as pre-January 2005 and after January 2005; $H = 6$, $p > 0.05$), however, a significant increase in ammonia-nitrogen between the period of November 2003 to June 2004 and the period of June 2004 to December 2006 was detected at all the sites (see Figures 4.6 and 4.7). The ammonia development opposed the trend in nitrates, which decreased. A major change in the source water can be postulated.

With ammonia, the levels reached from November 2005 to December 2006 were significantly higher ($H = 63$, $p < 0.01$) with regard to the control site than the canal and production site with application of the Kruskal-Wallis Anova for non-parametrical data sets.

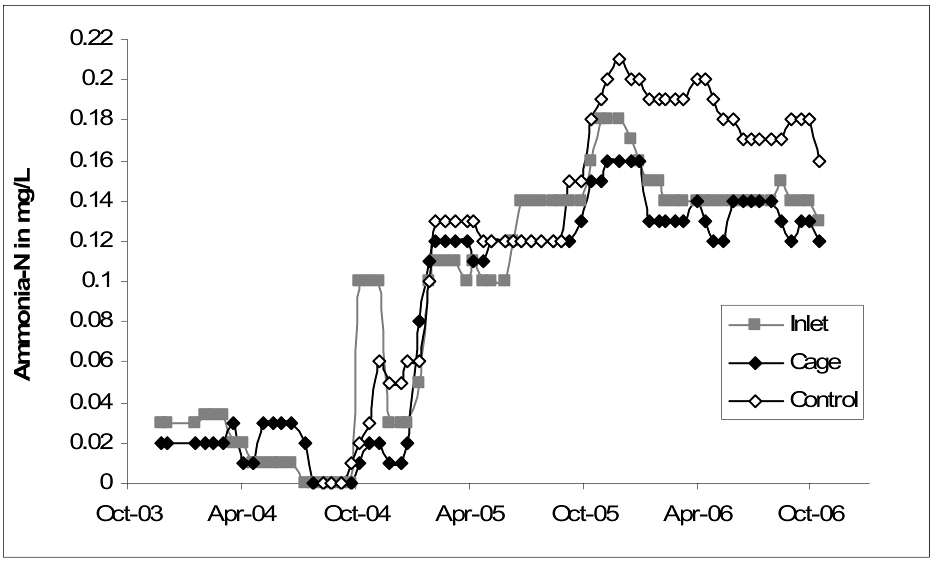

Figure 4.6: Ammonia-N levels in mg/L with smoothed data created by using a running average of each two adjacent data points.

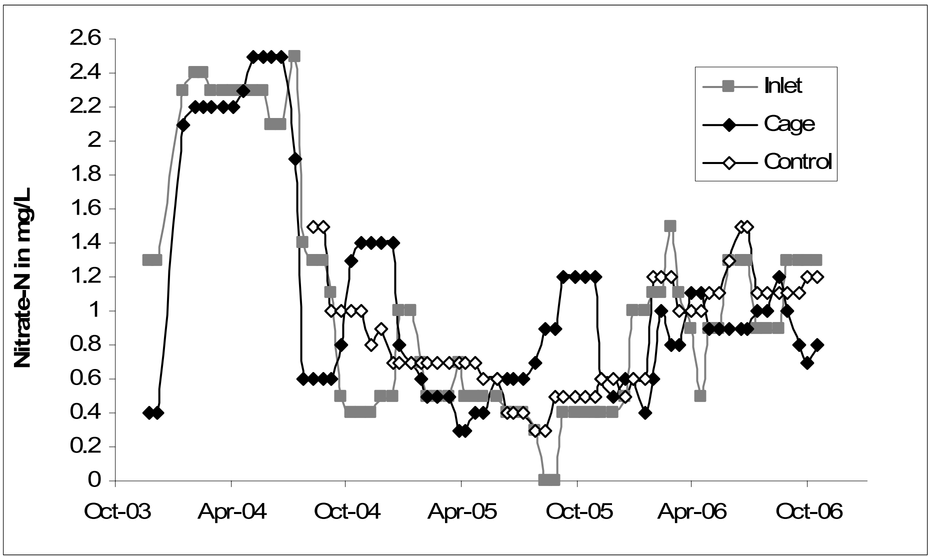

Figure 4.7: Nitrate-N levels with smoothed data created by using a running average of each two adjacent data points

The nitrite levels show no significant differences among the three different sample locations when grouped over the whole study period and vary consistently between the values 0.005 and 0.040 mg/L nitrite-N (see Figure 4.8) ($H = 9$, $p > 0.05$).

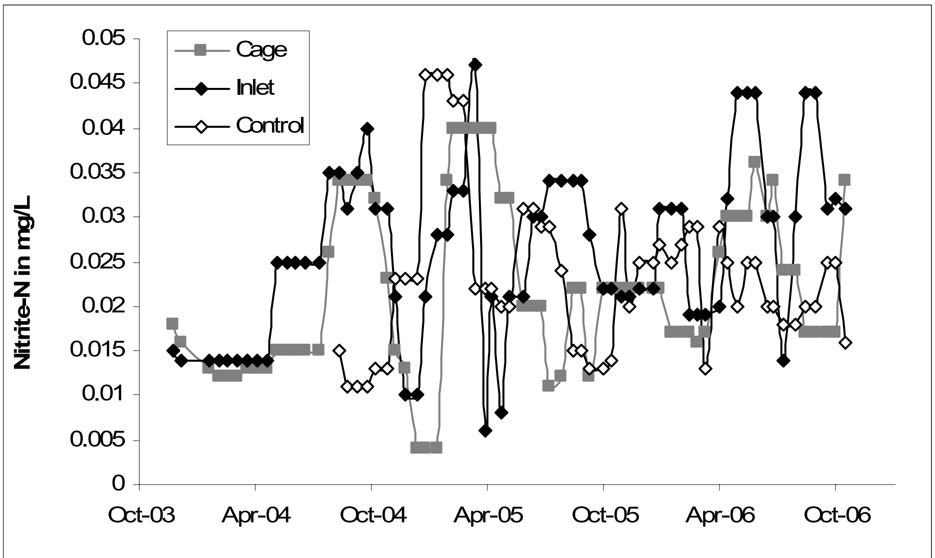

Figure 4.8: Nitrite-N levels in mg/L with smoothed data created by using a running average of each two adjacent data points.

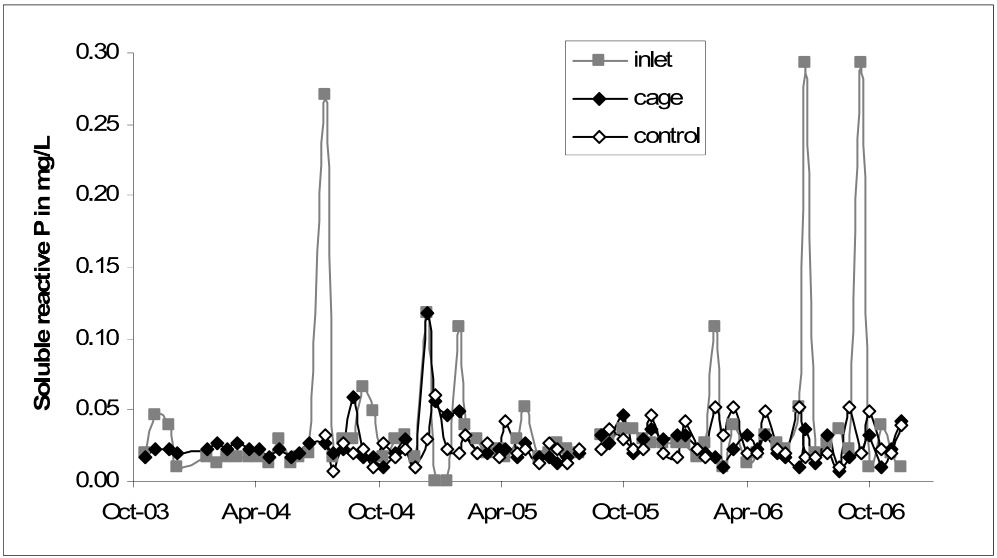

Figure 4.9: Soluble reactive phosphorus levels in mg/L as P

The phosphorus levels in the canal showed a significant increasing trend (2D range plot $\tau = 0.26$, $p < 0.01$), the balancing dam (control) had fairly stable phosphorus levels and the pump-house dam (production dam) even showed a tendency towards phosphorus decline (see Figure 4.9). The average levels ranged between 0.01 and 0.04 mg/L soluble reactive phosphorus as P. There were no significant differences among the sites (Kruskal-Wallis Anova) or over time.

The measured phosphorus levels are fairly low and high phytoplankton or macrophyte abundances are not expected in the dams, especially due to the flow-through rate of incoming water. The phytoplankton sample also reflects the flowing character of the system, but is of little significance due to its isolated status.

4.2.3 Phytoplankton

Phytoplankton samples were only determined for early September 2005. The dominant species were bacteriophyceae as well as chlorophyceae in little abundance. The biomass was below 0.05 g/L at the time. It is likely that the flowing character of the canal and the low retention time of control and pump-house dam (production site) can explain the low phytoplankton biomass of that time.

4.3 Discussion

The most important deduction from the Makhathini Research Station data is that no differences were evident for the three sites for most of the chemical and biological parameters and there were no differences among the sites that could be attributed to the aquacultural activities. The water entering the balancing dam and the pump-house dam via the canal showed the same chemical and nutrient levels and development. The ammonia levels would even indicate that the water quality at the production site is better than in the balancing dam. This could be because of a slower turnover rate in the balancing dam (situated in a dead end) in contrast to the high exchange of water in the production dam (pump-house dam) through constant water extraction for irrigation purposes.

There is also no noticeable seasonal pattern in the canal system. It seems that the quality of water released from the Pongolapoort Dam into the canal system strongly dominates the canal. The short retention time of the pump-house dam is reflected in the similarity of measurements taken in the aquacultural system. The balancing dam (retention time not known) is also completely determined by the incoming water from the canal. It seems, however, that an event upstream from the canal or within the Pongolapoort Dam caused a major change in the dead end of the secondary canal formed by the balancing dam and the pump-house dam (see Figure 1.3 in Chapter 1) in the course of 2004.

In that year, the alkalinity, which ranged around 60 mg/L at all sites at the beginning of 2004, rose to levels around 80 mg/L during July and finally settled down slowly until it reached an average of around 15 mg/L in January 2005, where it remained for the rest of the study period until December 2006. Hardness peaked to six-fold levels during August and September 2006, but otherwise remained at levels of 20 mg/L. Nitrate levels peaked in early 2004 and later settled down from above 2 mg/L to around 1 mg/L. The opposite pattern was observed with ammonia levels, which increased in the course of 2004 to values four times that of the initial study measurements at around 0.16 mg/L. The conductivity was not measured at the station, but revolved around 20 to 30 mS/m in the surface water of the Pongolapoort Dam (DWAF data).

The generally high pH of the canal and dams at the end of the secondary canal system would be unusual for a river system fed by a natural source, but the Makhathini Flats canal system is fed by the dam. The pH of the large state reservoir has slowly increased from fairly natural levels ranging from 6.5 to 7.5 in the years 1976 to 1981 and was therefore at neutral pH for at least 10 years after its construction in 1972 (see Figure 4.9). In the 1990s, especially, the pH level stabilised at levels almost constantly above a pH of 8.0.

The shift in the nitrate concentration was mirrored by the ammonia levels. Nitrogen is usually converted to ammonia by organisms that gain oxygen in the process under otherwise almost anoxic conditions. This is an indication that the change in the major type of inorganic nitrogen compound took place in the Pongolapoort Dam and not in the canal.

Within the canal system, the sudden change of alkalinity, hardness and nutrient levels in the course of 2001/2002 are not expected to have derived from irregular events, but rather from a more substantial change. The water layer from which water at the Pongolapoort dam is fed into the canal system and the river was probably changed for a deeper level. Alternatively, the same water level was retained for extraction, but ongoing eutrophication has raised the anoxic layer at the bottom right at the dam wall due to higher decomposition rates, so that it now reaches the level of water extraction. The eutrophication process postulated is indicated by the increase in surface water pH since 1976 (see Figure 4.10).

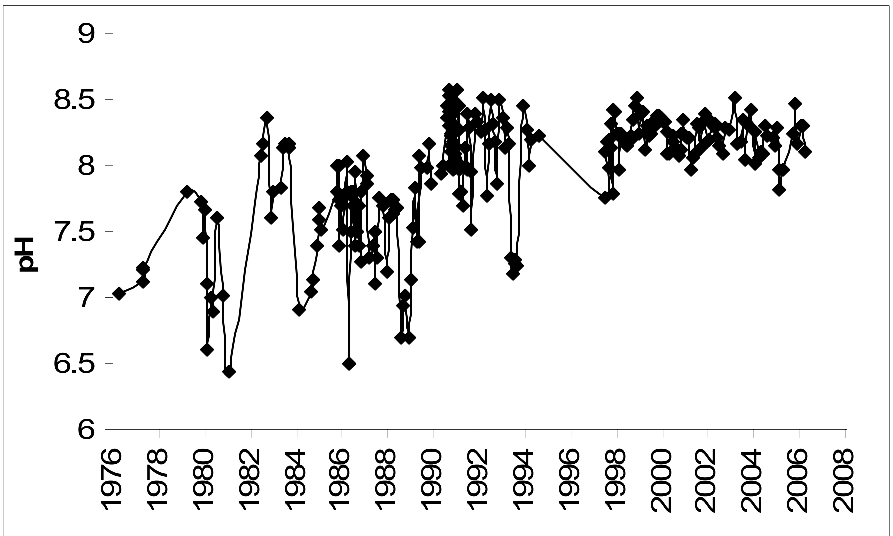

Figure 4.10: pH levels of the surface water (0 to 2 metres) of the Pongolapoort Dam. Data kindly provided by DWAF, Pretoria.

Oxygen levels of canal water are expected to recover fully due to turbulence created while flowing through the canal system. However, ammonia levels will not have enough time to be converted to nitrate before reaching the pump-house dam. The higher ammonia content in relation to nitrate might derive from an organic source or from water at a deeper level of the dam where oxygen is absent for most of the year. To reach the pump-house dam, water from Pongolapoort dam has to travel for about 16 km. At a speed of approximately 1 m/s, travelling time could therefore be roughly 5 hours (probably faster due to a more rapid flow of water in the main canal).

The quality of inflowing water should be controlled continuously. An explanation for the change in the quality of the canal water (monitored through the shift in nitrate and ammonia levels) could possibly be found through conferring with dam authorities. The alteration may be reversible and water with lower ammonia levels could be fed into the canal system.

4.4 Conclusions (Makhathini)

Aquaculture in the monitored pump-house dam of the Makhathini Flats irrigation scheme did not affect the given water quality conditions in any measurable way. These positive results correspond to the waste load entering the system, which was produced by at most 1 000 kg of catfish and 500 kg of tilapia, achieving an FCR of 1.6 (yearly average). Additional waste reduction by improved FCR values should be aspired to.

The amount of feed added over the 2-year production period to the pump-house dam totalled about 2900 kg residual feed released into the pump-house dam. Most likely all of that residue was washed out via the water extraction for irrigation. However, should the total amount remain in the system, with the high water exchange rate about 40 µg feed per litre dam water per year would be retained, of which only a fraction would be phosphorus or nitrogen. Improved FCR values could reduce that amount even further, by 85 to 90%, especially with tilapia production.

The main reason for the stable water quality of the production site is the high water exchange rate of these small pump-house dams (more than 3 000 times per year). The results do not allow an estimation of whether the balancing dams would also be suitable for long-term cage production.

The quality of the Pongolapoort Dam water mainly influences the quality of water in the canal and there are strong indications that the ongoing eutrophication of the dam has changed the quality of the extracted water feeding the canal. Ammonia levels of the Pongolapoort deep water as well as the water entering the canal system, should be monitored closely.

4B CAPE WINELANDS STORAGE DAMS

4.5 Introduction

For this report, the smaller irrigation dams (< 20 ha) located in the Cape Winelands district are on trial for their suitability for winter trout production. Small bodies of standing water in cool areas with hot summers are borderline areas for fish production, with limitations either for cold or for warm water species. Experience with trout in small bodies of water in temperate or subtropical areas is limited. Worldwide, many trout production sites are mainly marine based (Norway and Chile), while other countries use the resources of their large natural lakes, e.g. France, Italy and Spain, as well as Canada and the United States when temperature changes are balanced by the large water mass. Nonetheless, the impact of cage production has been observed in marine and large freshwater dams and some processes in smaller water bodies are similar. In Iran, small ponds (0.4 ha) are used as main production systems for trout and the water exchange rate is kept high by direct through-flow or rivers (Coad, 2007). In South Africa, trout production in raceways fed by cool mountain springs or perennial rivers has been established with success, as well as in larger dams in the mountains (Western Cape Trout Association general meeting 2007). First production cycles in small dams were promising but further information is needed to monitor the impact and to be able to direct future research for improved management of the systems.

The ambient water quality has a strong impact on fish growth and production, and fish production influences the overall ecology of the dams. Many studies have shown the adverse impact of cage farming, usually undertaken in sheltered marine areas (with restricted water exchange) as well as in large shallow lakes. Oxygen depletion at the bottom level, reduction of benthic living communities and changes in the phytoplankton and zooplankton structures could be identified in most of the studies (Longgen & Zhongjie, 2003; Clerk et al., 2004). The risk of oxygen depletion at the surface level is also increasing with increasing nutrients in an ecosystem. However, every system is unique as is the input of nutrients, the timing of the input and the hydrological background of each production site.

The results presented in this chapter can help to understand the current ecological status of the numerous small water bodies (< 20 ha) in the Western Cape. The obtained information can serve as a baseline for further recommendations on stocking densities, minimum dam sizes and threshold eutrophication levels, all important information for site selection. Ecological knowledge on these water bodies, including information on historical phosphorus or nitrogen levels or phytoplankton communities, is limited in this region. Research since the 1970s has concentrated on the need to understand the river systems and the quantity and quality of water resources and supply in the country. Larger dams, however, have been investigated and the main focus was on Mpumalanga and KwaZulu-Natal. However, some observations made in these dams can support findings obtained during the current study.

This present study provides necessary baseline material for future comparative studies on changes in irrigation dams caused by cage aquaculture, in particular.

4.6 Results and discussion

The results section is grouped into physical and chemical water quality conditions as well as the quantity and quality of the phytoplankton and zooplankton communities.

4.6.1 Physical and chemical parameters

The temperature in the Western Cape dams varies from 13 to 28°C (see Figure 3.2 in Chapter 3). The oxygen distribution follows seasonal patterns and oxygen depletion in the hypolimnion or near-bottom water is very common in the dams that were investigated (see Section 3.3.2 in Chapter 3).

As for the pH, Cape Olive and Calais Dam fluctuated mainly between 7 and 8 (see Figure 4.11). For the first part of the study period (September 2004 to July 2005), no significant difference between the production site (Cape Olive) and the control site (Calais) was recorded. From July 2005, a significantly higher pH was established in Calais Dam ($H = 35$, $p < 0.01$) than in Cape Olive Dam. Over the whole period, the pH at Cape Olive followed a significant decreasing trend ($\tau = -0.34$, $p < 0.01$).

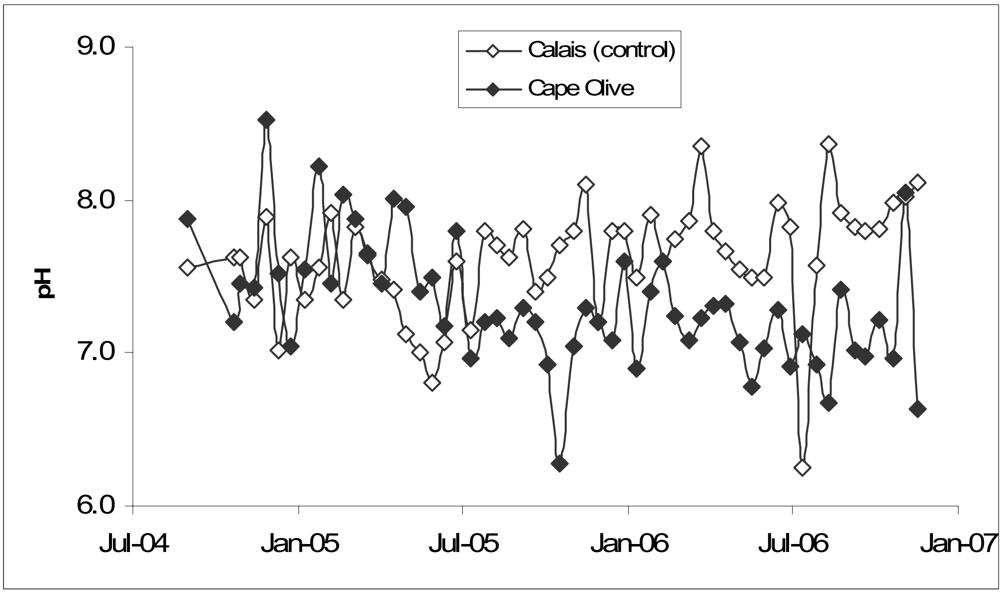

Figure 4.11: pH development in two dams in the Drakenstein district (Western Cape) from September 2004 to December 2006

The reason for the pH difference at the two sites could be derived from the difference in quality of the inflowing water. Considerably more sediment material enters Cape Olive Dam (also see Secchi depth results). The soils in the area are typically acidic (Chapter 7).

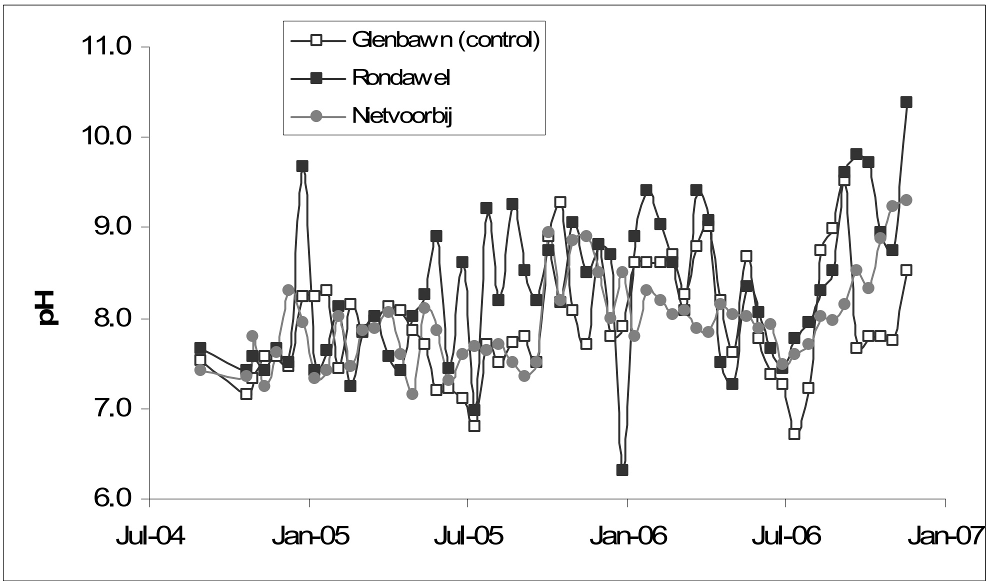

Figure 4.12: pH development of three Stellenbosch dams (Western Cape) from September 2004 to December 2006

The pH of Glenbawn, Rondawel and Nietvoorbij oscillated between 7 and 9, with Rondawel often even exceeding 9 (see Figure 4.12). Overall, an increasing pH tendency was noted at the two production sites: Rondawel ($\tau = 0.38$, $p < 0.01$) and Nietvoorbij ($\tau = 0.43$, $p < 0.01$), with the pH values of Glenbawn (control site) being more stable (no significant increasing tendency). Nietvoorbij was producing fish throughout the study period, whereas no fish were introduced into Rondawel Dam in 2005 and early winter 2006. The pH-increasing effect of phytoplankton is linked to the periods in which dam mixing is strongest (stronger winds and temperature assimilation of the water body), which is in autumn and spring. During these times, nutrient-rich sediment that collects at the dam bottom (naturally and additionally through aquaculture) mixes into the surface water and enhances phytoplankton growth.

The high pH values are directly linked to the corresponding excessive phytoplankton abundance in these dams (see phytoplankton results) and cause a biologically produced alkaline pH (López-Archilla et al., 1984). The reduction of CO_2 via photosynthesis raises the pH (Talling, 1976), especially in the soft water (soft water of low hardness containing 5 to 40 mg/L $CaCO_3$, according to DWAF, 1996b) of these dams. Higher calcium levels would be able to bind carbonate and change the carbonate (CO_3) to carbon dioxide ratio.

The alkalinity expresses the ability of the dam water to neutralise acids. Alkalinity values are low in the Western Cape dams and fairly stable over the course of the year (see Figure 4.13). In Nietvoorbij, carbonate and bicarbonate, the main contributors to alkalinity, reach increased levels during winter. In winter, the dams experience a mixing period and constituents from the bottom of the dams can be mixed into the water body. This seasonal increase is also present in Rondawel, another fish production dam. The third fish production site, Cape Olive, does not follow the pattern, however, which is most likely due to the high total suspended solids (TSS) load of that dam. Shading by suspended solids decreases the phytoplankton biomass and hence limits pH fluctuations. The results suggest that carbonates and bicarbonates, like other nutrients and inorganic constituents, settle into the hypolimnion during stagnation and are stirred up and mixed into the surface water with the turnover period in winter.

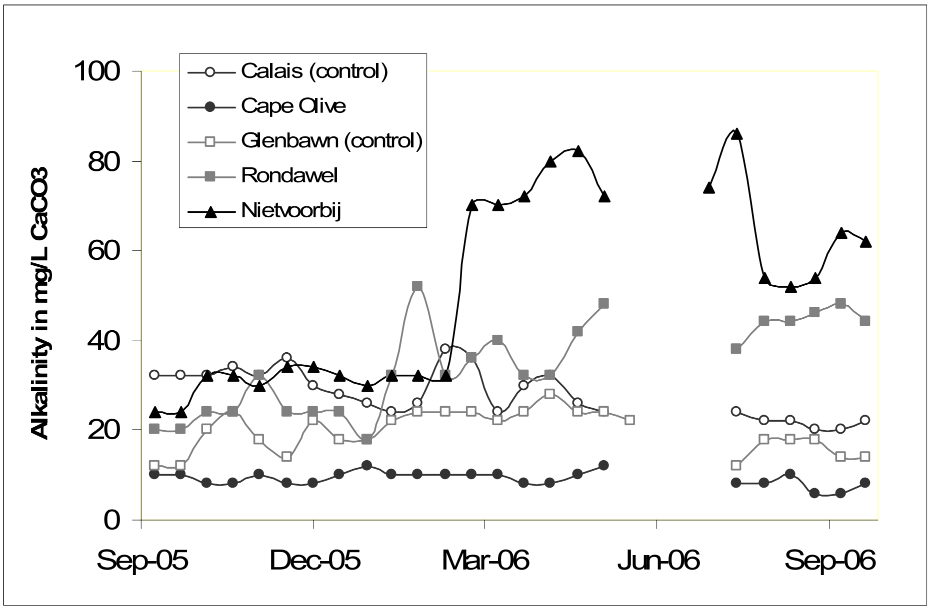

Figure 4.13: Alkalinity development in the five Cape Winelands dams – September 2005 to October 2006

The Secchi depth reflects the clarity of the water body and how far into the water column the human eye can still make out a rotating black and white disc. At Cape Olive, the visibility became extremely low with the winter season at the beginning of April 2005 (see Figure 4.14). Much sediment material was washed into the water body and the visibility decreased from values between 100 and 200 cm to values between 5 and 15 cm for a period of 3 to 4 months. Over the whole period of study, Cape Olive exhibited a significant trend to reduced visibility (τ = -0.24, $p < 0.01$). For the whole period after April 2005, the visibility was therefore significantly higher at the Calais site (H = 79, $p < 0.01$).

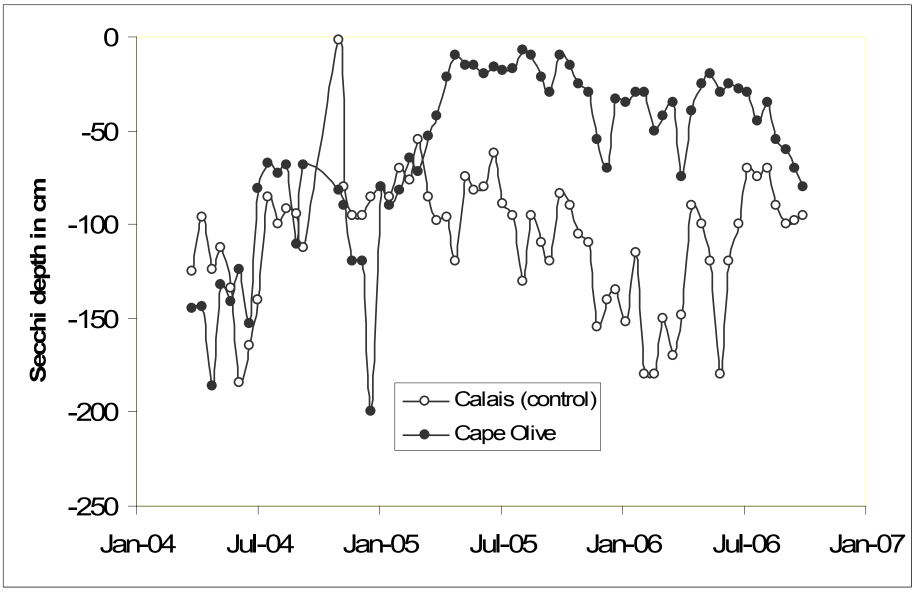

Figure 4.14: Secchi depth visibility of two dams in the Drakenstein district (Western Cape) from April 2004 to December 2006

At the Stellenbosch sites, the Secchi visibility was lowest at the control site, Glenbawn, with this effect also having been most prominent since the winter season 2005 (from June 2005) (see Figure 4.15). From that time on, there was a significant difference between the clarity of Glenbawn and Rondawel ($H = 58$, $p < 0.01$) and Glenbawn and Nietvoorbij ($H = 39$, $p < 0.01$). In both dams, Glenbawn and Rondawel, the clarity of the water decreased significantly over the study period ($\tau = -0.42$, $p < 0.01$; $\tau = -0.37$, $p < 0.01$) with the values at Nietvoorbij Dam not showing a clear tendency.

It seems that Nietvoorbij Dam's visibility is not that strongly influenced by sediment inflow and runoff, whereas Glenbawn, as the upper dam, receives water with higher sedimentation levels. Rondawel is also influenced by sediment inflow, but not as severely.

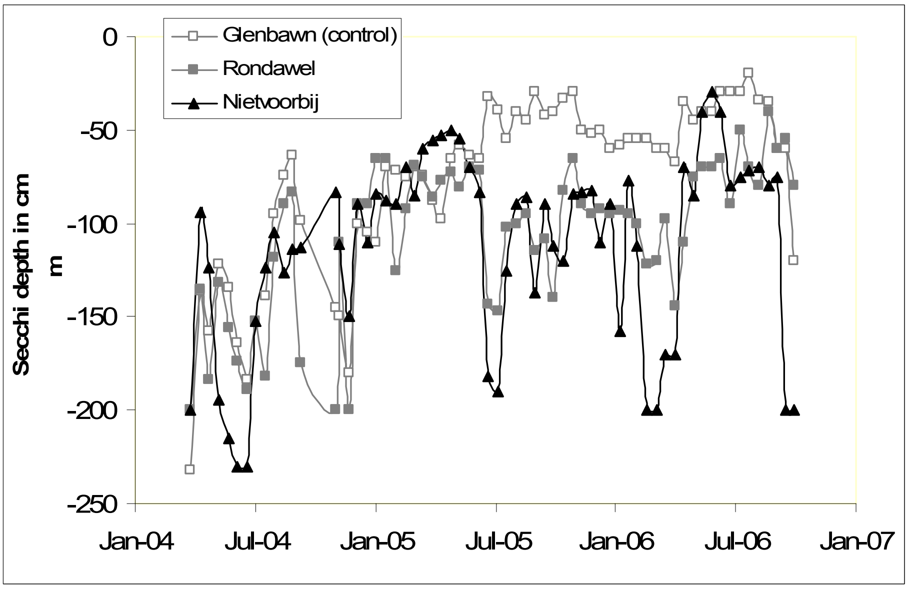

Figure 4.15: Secchi depth visibility of three Stellenbosch dams (Western Cape) from September 2004 to December 2006

Phytoplankton biomass did not reduce the visibility as strongly as the sediment inflow did. This was mostly verified by the overall dam colour which, was light, or darker brown in cases of lowest visibility, and not green or yellow-green.

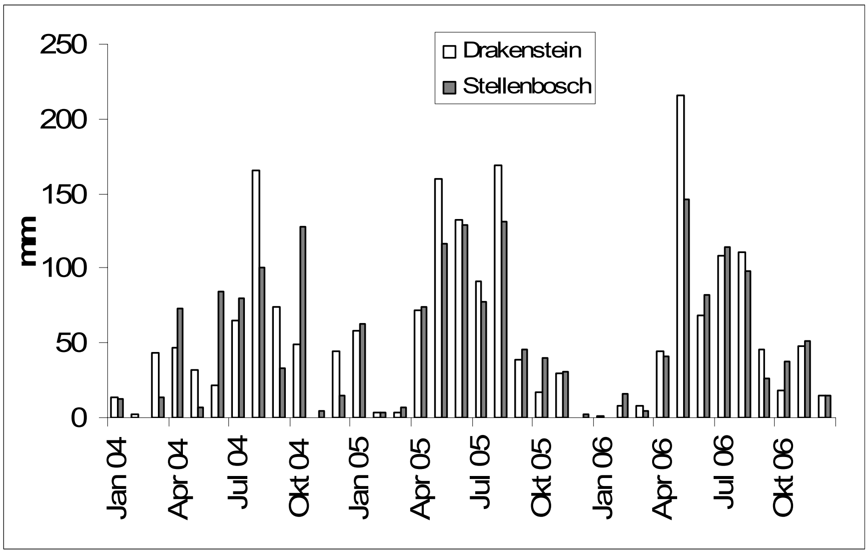

Figure 4.16: Monthly rainfall at a weather station in the Drakenstein district close to Cape Olive, and at the Nietvoorbij farm weather station, Stellenbosch district (SAWS data)

The compilation of monthly rainfall records at two stations closest to the two Drakenstein and three Stellenbosch sites respectively shows that winter rainfall in 2005 and 2006 was higher than in the previous year, 2004 (see Figure 4.16). The number of rainy days that brought more than 10 mm of rain in one day also increased in the years 2005 and 2006. In Stellenbosch, the first strong rain of the 2005 winter season brought 46 mm of rain on 10 April, which was similar to the Drakenstein site, where 49 mm of rain was recorded. In 2006, above 20 mm of rain fell in the middle of April on one of the first noteworthy rainy days, while the highest rainfall in one day in Drakenstein occurred on 17 May, with 63 mm of rain.

Figures 4.17 and 4.18 represent the TSS values of the two Drakenstein and three Stellenbosch sites. Total suspended solids can comprise of sediment particles, phytoplankton and other water constituents, however, when the water was not clear, the colour of the water bodies in early winter were tinted in shades of brown and towards spring (August or later) green or yellow-green tinges prevailed.

The TSS levels (see Figure 4.17) which were already showing in the clarity (Secchi disc) measurements were distinctly higher at Cape Olive ($H = 65$, $p < 0.01$) than at Calais, the control site, in the 2005 and 2006 seasons. Cape Olive water is fed directly by the river and the river water to a large degree, contains high TSS levels itself, while even more sediment seems to be whirled up in the process of the water flowing in to the dam (in the early season when the water level was low, the water was cascading over a small rocky wall, avoiding turbulence at the point of entry). At Calais, water flowing in through the pipe is often equally loaded with sediment particles, but the water enters the dam at the bottom level and therefore turbulence and high TSS values at the surface level of the water body are avoided and significantly reduced.

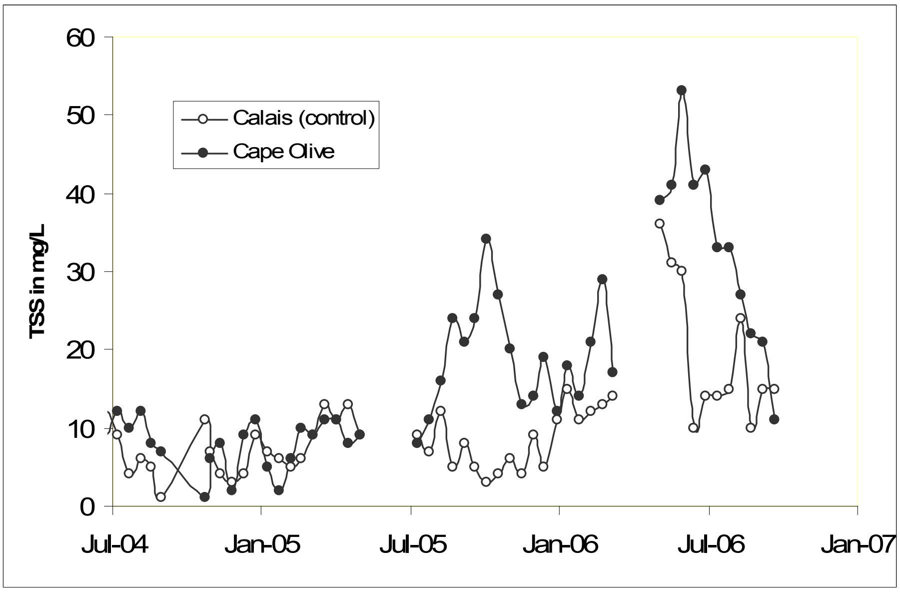

Figure 4.17: Total suspended solids levels of two dams in the Drakenstein district (Western Cape) from April 2004 to December 2006 (surface water)

At the Stellenbosch sites, TSS levels at Glenbawn again are significantly different from the two production sites (H = 42, p < 0.01) (see Figure 4.18). Glenbawn is mainly fed by runoff and to some degree by pipe water deriving from the Theewaterskloof tunnel system or, sometimes, from other dams on the farm. As with Cape Olive, the heavy rain in April 2005 caused a much higher TSS load in the surface water of the affected dams. Rondawel is fed by bottom water of Glenbawn and the water enters the dam at a deep water level, therefore reducing settling time of particles. Nietvoorbij is mainly fed by runoff water as well, but apparently at a location less inclined to favour sediment input.

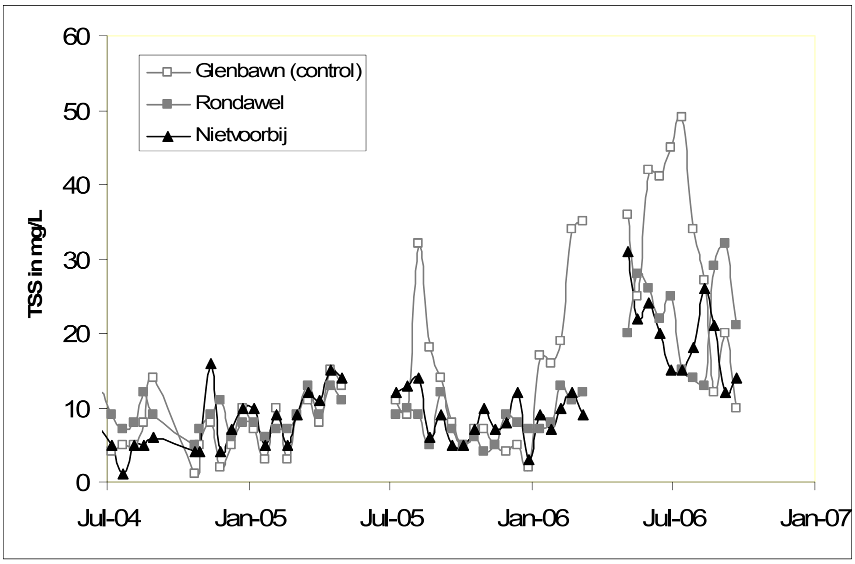

Figure 4.18: Total suspended solids levels of three Stellenbosch dams (Western Cape) from September 2004 to December 2006 (surface water)

The conductivity levels of the dams were stable throughout the study period (see Figure 4.19). The natural conductivity of lakes reflects the underlying geology of the catchment area, as well as the quality of the inflowing water, which explains the relatively low conductivity levels in the water bodies included in this study. Additional influences are usually related to human activity such as agricultural runoff and wastewater. Climatic factors (rainfall, maximum temperatures), in addition to frequently changing water levels, influence storage dam water quality as well.

The summer of 2004/2005 brought extreme changes in conductivity levels, with lower than usual levels at Nietvoorbij and raised levels in all other farm dams. The extreme heat and dryness of that summer (SAWS temperature data 2004 to 2006) and consequent evaporation and low dam volumes due to increased water demand could explain the intensification of electrical conductivity for most dams.

Conductivity levels are higher at Calais (control site) than in Cape Olive (higher water retention time at Calais), but higher at Rondawel than in the Glenbawn Dam (control site). Nietvoorbij has the highest conductivity levels, which result from a different inflow pattern or the influence of salt from the cellar water being released into the dam occasionally.

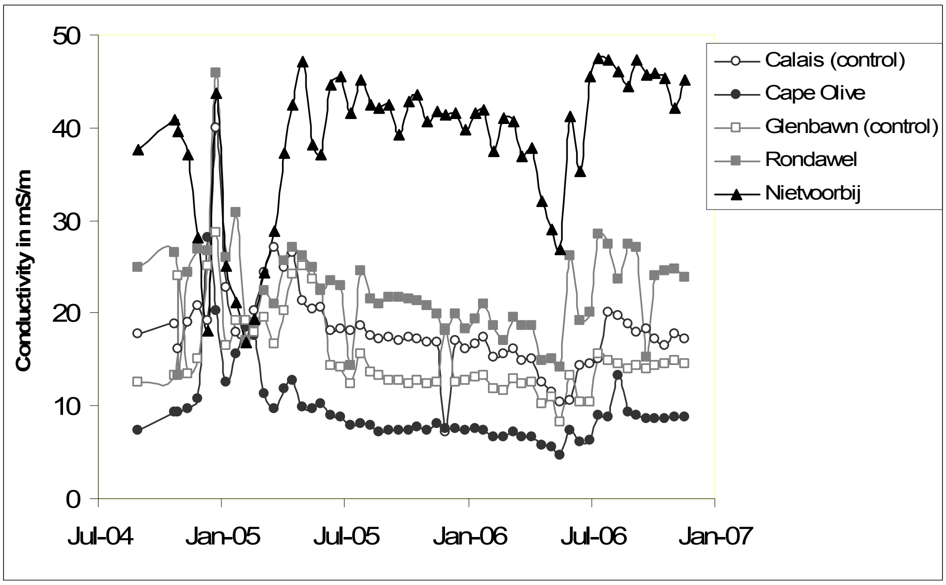

Figure 4.19: Conductivity levels in mS/m of the surface water of the five studied sites between September 2004 and November 2006

4.6.2 Nutrients

The soluble reactive phosphorus levels in the Drakenstein and Stellenbosch dams do not show any clear pattern that easily follows the stratification process. Turnover and uptake by phytoplankton and zooplankton and other biota during winter and spring would be the main influencing processes, together with settling and mixing processes of particles or during turnover (the mixing of nutrients collected at the bottom of the dam) in the water column.

Control and production sites maintained similar ranges of soluble reactive phosphorus, with no significant differences among sites and similar ranges for all sites. There seemed to be a seasonal tendency towards soluble reactive phosphate level reduction towards autumn and winter. This, however, was not statistically confirmed. In winter, phosphorus could be taken up by phytoplankton, which usually peaks in winter and early spring when the overall abundance of nutrients allows sufficient growth.

In Figure 4.20, the reactive phosphate levels of Nietvoorbij are documented for the period end of November 1997 to December 2006. The diagram (turnover phase and stagnation phase respectively are summarised) and comparative statistics did not indicate any significant increase of the soluble reactive phosphate levels when comparing seasons (e.g. to verify the perceived tendency towards lower levels in winter). Statistical analyses could only be undertaken for the years 1998 to 1999 and 2005 to 2006. The statistical comparison revealed that the phosphorus levels had increased significantly (about 50% higher) only for the winter of 2005, compared to the winter season of 1998 and of 1999.

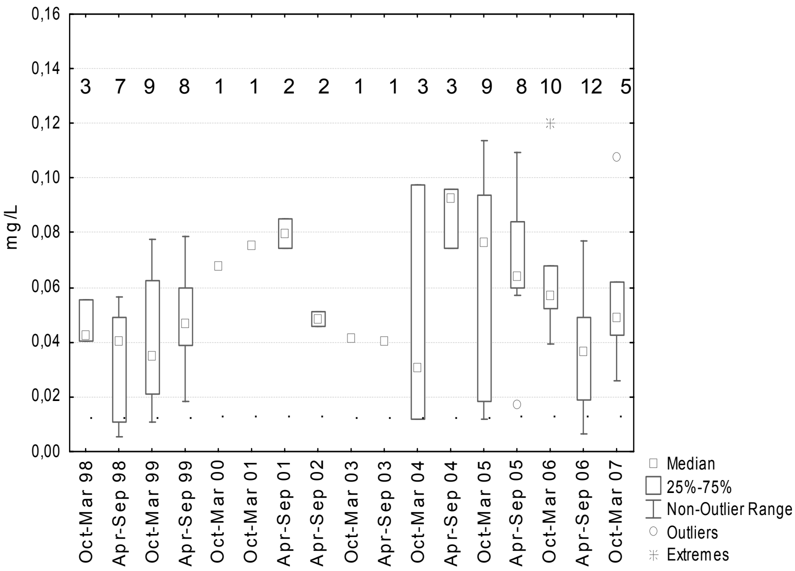

Figure 4.20: Diagram of soluble phosphorus-P levels in mg/L at Nietvoorbij. Data are averaged for winter (April to September) and summer (October to March), representing the turnover and the stagnation phase at the same time. The small numbers above the bars represent the number of data points that went into the respective bars. Data points for winter 2000 and summer 2001/2002 are missing.

Total phosphorus is a more accurate indicator of nutrient content in water samples because it includes organically bound phosphorus, as well as the dissolved and particulate inorganic components. Hence, the TP content is independent of organic biomass and seasonal changes. The method applied, however, tends to underestimate phosphorus bound to sediment particles.

The total phosphorus levels of the five dams have been found to be about 20 to 100% higher than the soluble reactive phosphorus levels, with a tendency toward the highest total phosphorus abundance during the turnover phase in winter (April to September), especially at Calais, Cape Olive and Glenbawn.

As shown in Figure 4.21, the Cape Olive and Calais Dams contained similar average total phosphorus levels over the study period, with Calais containing 0.084 mg/L P as total phosphorus (medium eutrophic dam as defined by DWAF, 1996c) and Cape Olive 0.070 mg/L (see Table 4.1). The tendency is clearly towards Cape Olive being the dam in which less total phosphorus was measured on most occasions, with significant differences especially in winter periods such as July to September 2005 ($H = 51$, $p < 0.01$) and May 2006 ($H = 55$, $p < 0.01$), as well as in the summer from January to March 2006 ($H = 37$, $p < 0.01$).

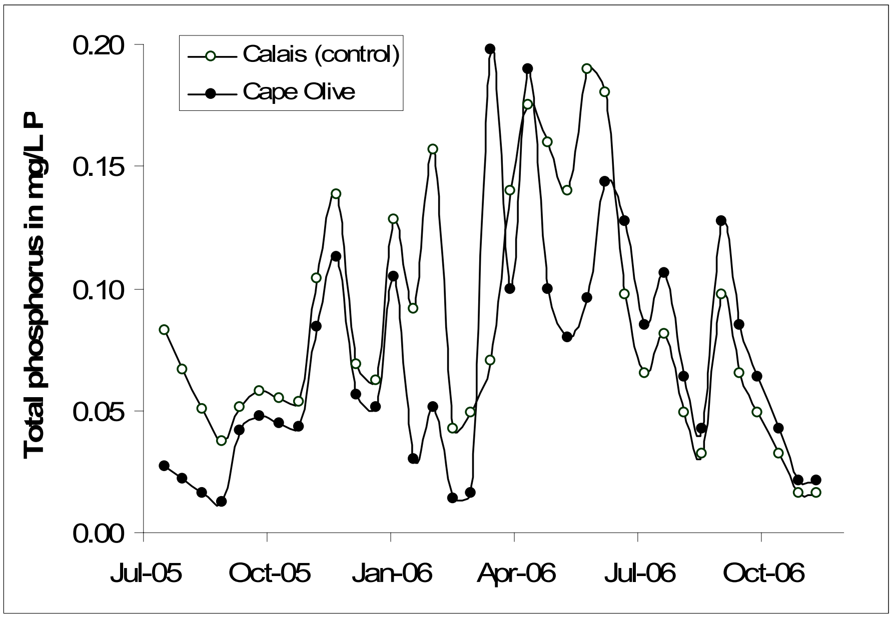

Figure 4.21: Total phosphorus levels in mg/L P for the two Drakenstein dams

The production season of April to October 2006 obviously does not have a direct effect on the phosphorus levels in the surface water, but is overruled by the mixing regime and other factors.

Table 4.1: Average total phosphorus levels in mg/L P for the study period July 2005 to December 2006 – Sediment data from Maleri (2008)

Dam	**Cape Olive**	**Calais**	**Glenbawn**	**Rondawel**	**Nietvoorbij**
TP in mg/L P	0.070 ± 0.048	0.084 ± 0.49	0.075 ± 0.044	0.073 ± 0.039	0.076 ± 0.055
TP in dry sediment in mg/kg	267 ± 8	315 ± 37	(2043 ± 372)	(2043 ± 372)	8184 ± 2000 (cage) 2744 ± 424 (ref. position)
Readily available P in dry sediment (mg/kg)	17 ± 13	20 ± 3	(78 ± 11)	(78 ± 11)	115 ± 27 (cage) 45 ± 31 (ref. position)

The levels of phosphorus in the two dams will be most influenced by the given total suspended solids conditions (probably more phosphorus carried into Cape Olive via sediment, but also unavailable through being absorbed into the sediment particles), phosphorus levels in the sediment that can be re-suspended during the turnover phase and the overall water retention time, which is higher in Calais Dam (water replaced less than once a year in Calais Dam, but three to four times per year in Cape Olive). As for the phosphorus levels in the sediment, a study by Maleri (2008) showed that 267 ± 8 mg/kg total phosphorus as P was found in the dry sediment of Cape Olive (below the cages) and 315 ± 37 mg/kg of total phosphorus as P in the dry sediment of Calais. These two total phosphorus levels of the dry sediment are fairly similar as is the sediment texture at the two sites and therefore the sediment capacities to bind phosphorus permanently. Only about 17 (Cape Olive) and 20 (Calais) mg/kg P adsorbed in the sediment are readily dissolvable in water (Maleri, 2008) and available for plants (see Table 4.1).

At Glenbawn and Rondawel, the total phosphorus levels of both dams show no significant differences in their averages over the study period (see Table 4.1). In Glenbawn, the main peak develops from the end of March to mid-August and therefore coincides with the turnover period of the dam, which suggests that nutrients are introduced by inflowing water or stirred up from the bottom of the dam. The water exchange rate of the Glenbawn Dam would be less than once a year. The dry sediment content of a dam nearby Glenbawn and Rondawel, on the same farm and of similar size, contained 2043 mg/kg P as total phosphorus content, with 78 ± 11 mg/kg readily available P.

The water surface TP levels of Rondawel (see Figure 4.22) showed no clearly seasonal trends, with three major peaks over the study period (October 2005, January 2006 and July 2006), and the presence of fish production also not showing clear effects (from the end of August 2006; there was no production in 2005).

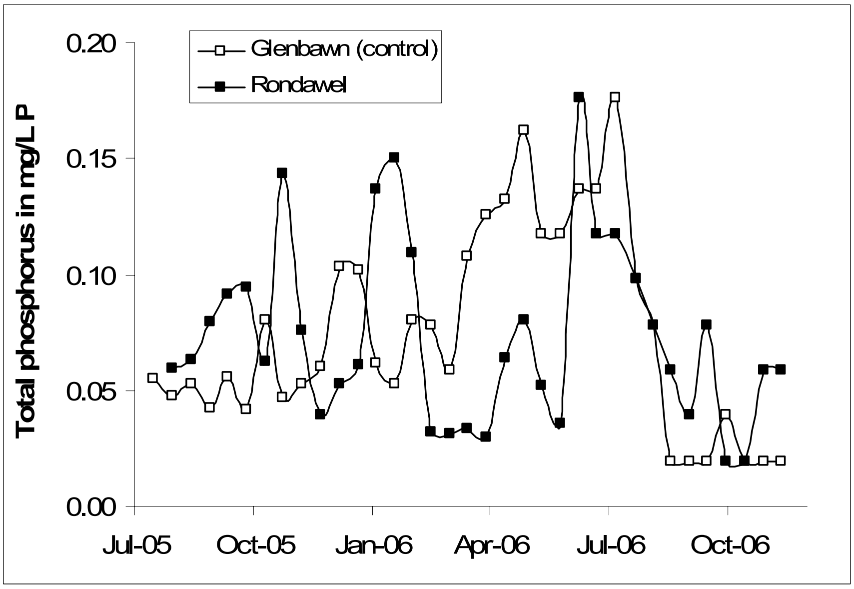

Figure 4.22: Total phosphorus levels in mg/L P for Glenbawn and Rondawel, the two Rustenberg sites at Stellenbosch,

At Nietvoorbij Dam, no clear seasonal pattern could be discovered for the total phosphorus content (see Figure 4.23), which fluctuates between 0.02 and 0.18 mg/L with average levels of 0.08 mg/L (see Table 4.1). The main peaks fell in October 2005, March 2006 and August 2006 and might have been caused by infrequent turbulence and nutrients being carried to the surface from the deeper dam layers.

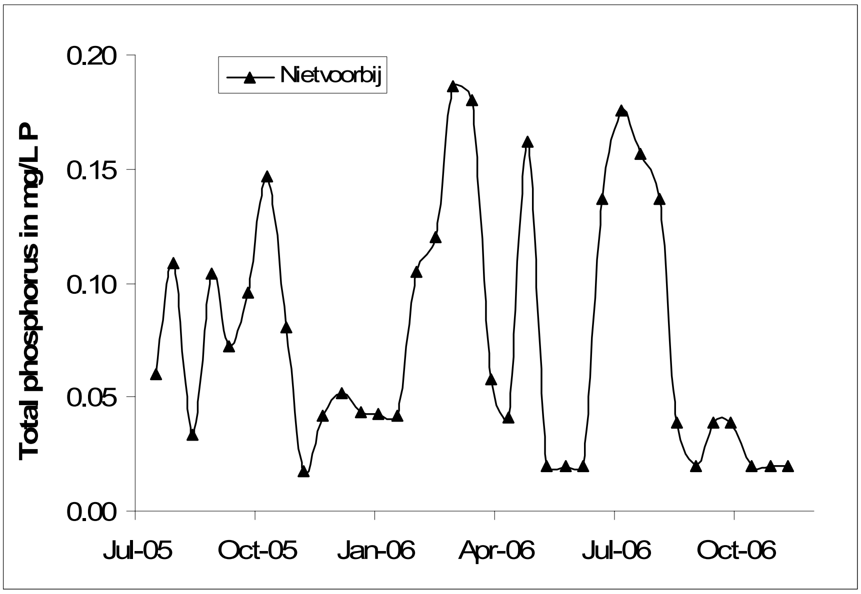

Figure 4.23: Total phosphorus levels in mg/L P for the Stellenbosch Nietvoorbij Dam

The dry sediment phosphorus content of Nietvoorbij Dam is much higher below the cages after 10 years of aquaculture and in the deepest dam area (11 m) and triple the amount found at a reference location within the dam (25 m from the cages at a depth of 7 m). The phosphorus, which is readily dissolvable from the dry sediment and which amounts to 115 mg P/kg, is about five times as high as at the Drakenstein site, Cape Olive, but is surprisingly low relative to the total phosphorus content (see Table 4.1). Of the 115 mg P/kg, 30 mg P/kg occur in the water-satisfied sediment, which theoretically adds about 43 µg P/L to the total phosphorus content of Nietvoorbij when diluted into its total water body.

Fish production at the Nietvoorbij Dam took place in the winter of 2005 and 2006, but no direct effect of fish presence and feeding on TP levels could be discovered.

The nitrite levels were negligible. The data ranged from 0.00 to 0.04 mg/L, with average levels around 0.01 mg/L NO_2-N. Rapid transition from ammonia to nitrate and vice versa can be assumed due to sufficient microbacterial activity by *Nitrosomonas spp.* and *Nitrobacter spp.*. The presence or absence of oxygen triggers either nitrification or denitrification.

The nitrate levels showed a tendency to increase during the turnover phase and slowly decrease again during the stagnation phase, by either settling to the bottom or being lost to the atmosphere (see Figure 4.24). All dams showed similar patterns, with increasing nitrate levels at the surface during the turnover period and decreasing nitrate levels during summer when most water constituents tend to settle into the hypolimnion. The time taken for nitrate to disappear from the epilimnion in summer differs, however, in taking much longer in Calais and Cape Olive where finer sediment particles prevail. Clay particles bind inorganic nitrogen and phosphorus and keep them in the water column.

The nitrate levels at Calais were fairly similar to the levels at Cape Olive, with no significant difference between the two sites for most of the study period. In winter 2006, however, the nitrate levels were much higher in Cape Olive ($H = 56$, $p < 0.01$), which may have been due to production taking place in that year and not in 2005. In addition, the high TSS levels of 2005 did not seem to stimulate nitrate differences.

Cape Olive shows a slight increasing nitrate trend overall ($\tau = 0.18$, $p < 0.05$).

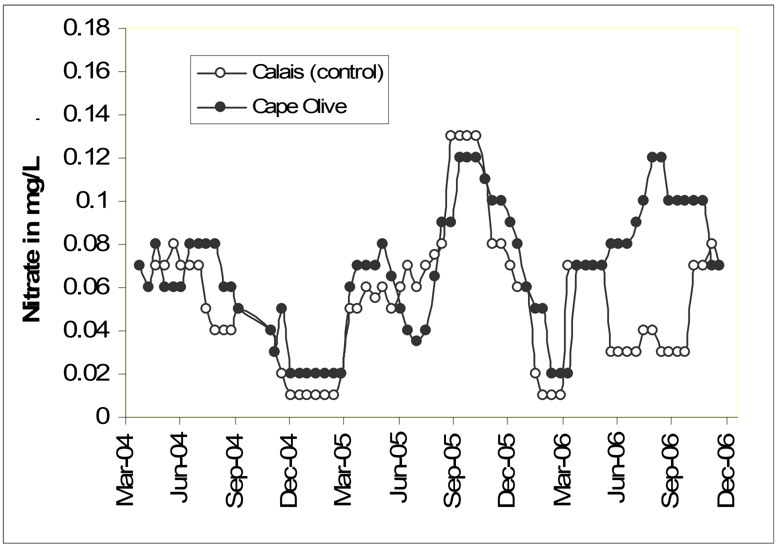

Figure 4.24: Nitrate-N levels in mg/L at the two Drakenstein sites, April 2004 to December 2006 – smoothed data (each two adjacent data points)

At Glenbawn and Rondawel, the control site (Glenbawn) usually showed higher nitrate levels than the production site (see Figure 4.25). Nietvoorbij had a delayed peak in 2005 and similar nitrate levels as Glenbawn Dam. Rondawel, the production site below Glenbawn Dam, has a decreasing nitrate trend (τ = -0.29, p < 0.01).

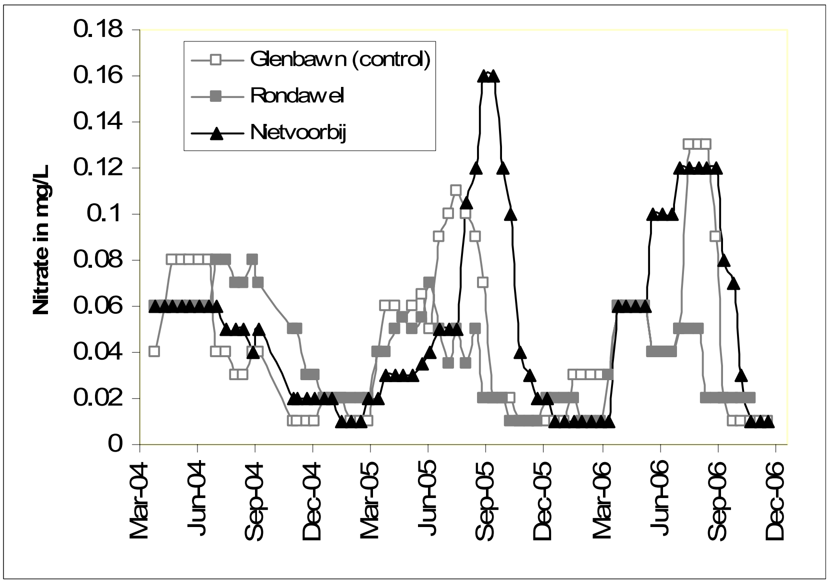

Figure 4.25: Nitrate-N levels in mg/L at the three Stellenbosch sites, April 2004 to December 2006 – smoothed data (each two adjacent data points)

The ammonia levels were fairly stable and overall even had a decreasing trend in the surface samples collected during the study (see Figures 4.26 and 4.27). Cape Olive showed a short seasonal increase in ammonia between July and November 2005 and again in July and August 2006. The tendency towards decreasing ammonia levels was more significant in Cape Olive (τ = -0.23, p < 0.01) than in Calais Dam (τ = -0.20, p < 0.05). However, Cape Olive showed a clear seasonal pattern of higher ammonia levels during the winter season, probably caused by ammonia being brought to the surface from the bottom area of the dam (aquacultural and organic waste) or the pattern was caused by the presence of fish and feeding material.

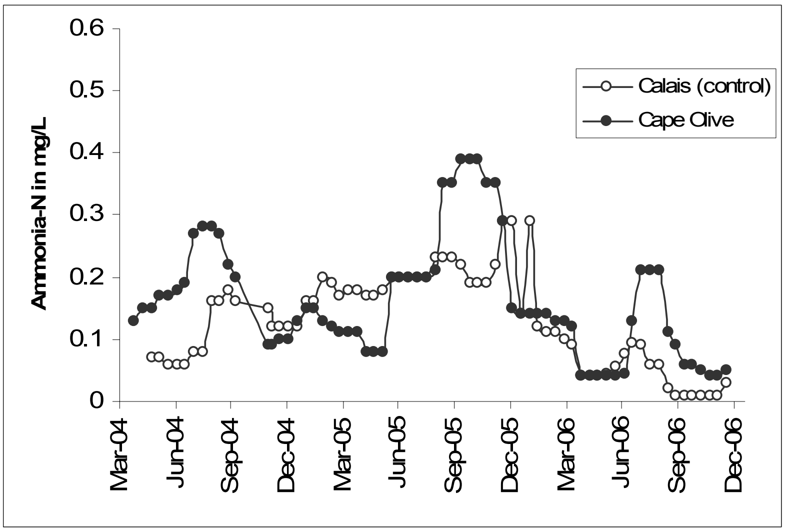

Figure 4.26: Ammonia-N levels in mg/L at the two Drakenstein sites, April 2004 to December 2006 – smoothed data (each two adjacent data points)

Nietvoorbij surface water showed the clearest tendency towards reduction ($\tau = -0.47$, $p < 0.01$) and no seasonal variability. Glenbawn had elevated ammonia levels during winter 2005, but also significantly lower ammonia levels in 2006 than in 2004 ($H = 39$, $p < 0.01$). Rondawel, like Nietvoorbij, had no seasonal pattern. Ammonia is most often an end product of nitrogen breakdown and is mostly accumulating when there is a lack of oxygen (when denitrification serves as oxygen source).

Fish excrete urea and ammonia and their presence could also increase the ammonia levels, but this was not detectable during this study at the Stellenbosch sites.

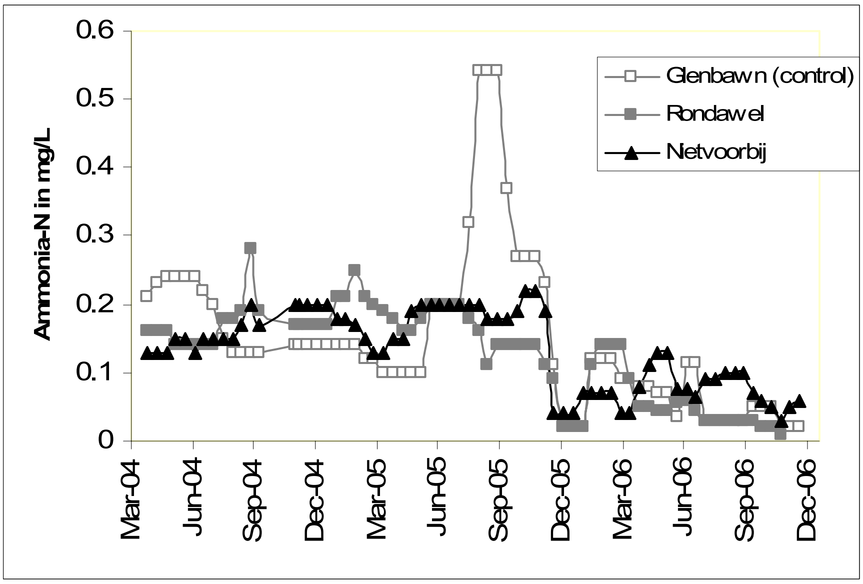

Figure 4.27: Ammonia-N levels in mg/L at the three Stellenbosch sites, April 2004 to December 2006 – smoothed data (each two adjacent data points)

According to Maleri (2008), the ammonia levels in the near-bottom water reveal a very distinct trend towards ammonia accumulation during the stagnation phase and towards transformation to nitrate when oxygen becomes available during the turnover period.

4.6.3 Phytoplankton

By comparing the five study dams for total biomass, strong differences become apparent among the different sets, but also between the control and production sites. Where total biomass at Calais did not exceed 1 g/L in peak situations, the total biomass of Cape Olive reached up to 2.5 g/L. At the Stellenbosch sites, biomass levels of more than 10 g/L were common. There were also differences in the speed by which biomass is increased, as well as broken down and in the species composition among the different sites. The main triggers for phytoplankton growth are nutrient availability and light conditions.

The two Figures, 4.28 and 4.29, summarise the phytoplankton biomass at the five study sites with the Drakenstein graph presented in one tenth of the scale of the Stellenbosch figure and therefore much lower total biomass levels overall. The fact that the steady-state inorganic nutrient pool (see Section 4.6.2) does not share the variances in these proportions proves that phytoplankton biomass and, probably, composition is a much better indicator of overall nutrient availability and abundance than chemical constituents only.

At the Drakenstein sites, the phytoplankton biomass of Cape Olive is significantly higher during the winter period ($H = 47$, $p < 0.01$), March to October 2006. This could have been caused by higher nutrient levels overall during winter with more nutrients being abundant at Cape Olive due to aquacultural waste from below the cages being mixed into the water column. Or the higher biomass could have resulted from more abundant nutrients introduced directly by fish feed and by faeces being abundant near the cages. As seen in Section 4.6.2, the inorganic nutrient steady state was quite similar at those two sites.

At Cape Olive, high TSS values were monitored for the dam, starting in the winter season of 2005 and continuing every winter since. Before that time, extreme blooms that have, according to the farm management, not been experienced in the years before aquaculture, were reported for this dam (unfortunately without documentation), most probably during the years 2001 to 2004.

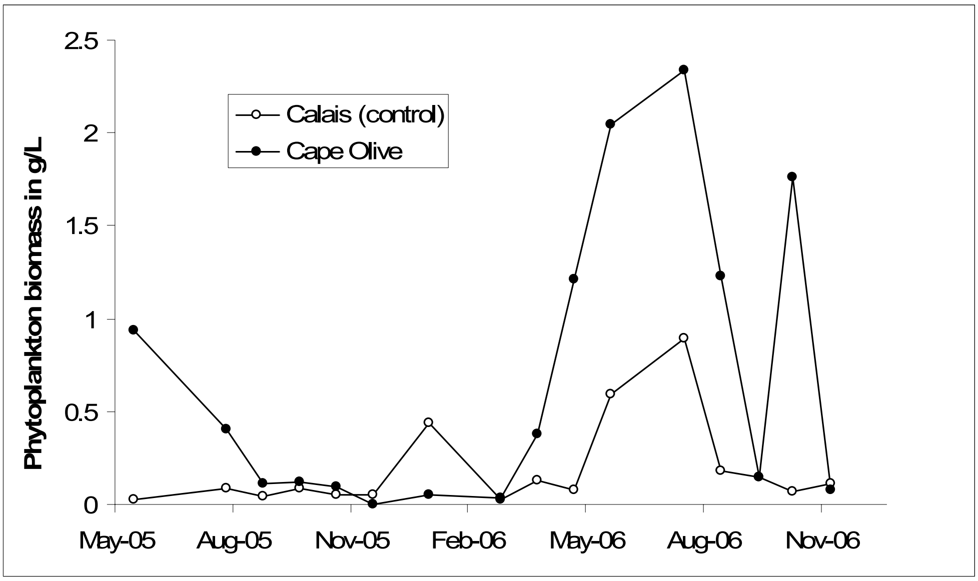

Figure 4.28: Phytoplankton biomass overview – Drakenstein sites

The Stellenbosch sites had much higher biomass levels overall, partly caused by the smaller volume of the dams (see Table 2.2 in Chapter 2) and the resultant reduced effect of dilution. The water exchange rate also happened to be greater at the Drakenstein sites. Lastly, all sample dams in the Stellenbosch area are not sourced by mountain water, like Cape Olive and Calais, but by Plankenbrug River water of known poor water quality (Gosling, 2006), Theewaterskloof Dam water with well-known water quality problems (blue-green algae) or water originating from other dams. Standing water bodies tend to accumulate nutrients over time so that nutrient accumulation in the Stellenbosch dams that are mainly sourced by other dams is even more pronounced.

Figure 4.29 shows that Rondawel Dam has much higher phytoplankton biomass levels than the control site Glenbawn, an effect that could have been caused by the accumulated nutrients entering Rondawel via Glenbawn bottom water plus the aquacultural activities of the past years (2003, 2004 and 2006). The biomass at Rondawel varied between 6-fold the control sites biomass in summer 2004/2005 to double and triple the biomass in autumn and winter 2006.

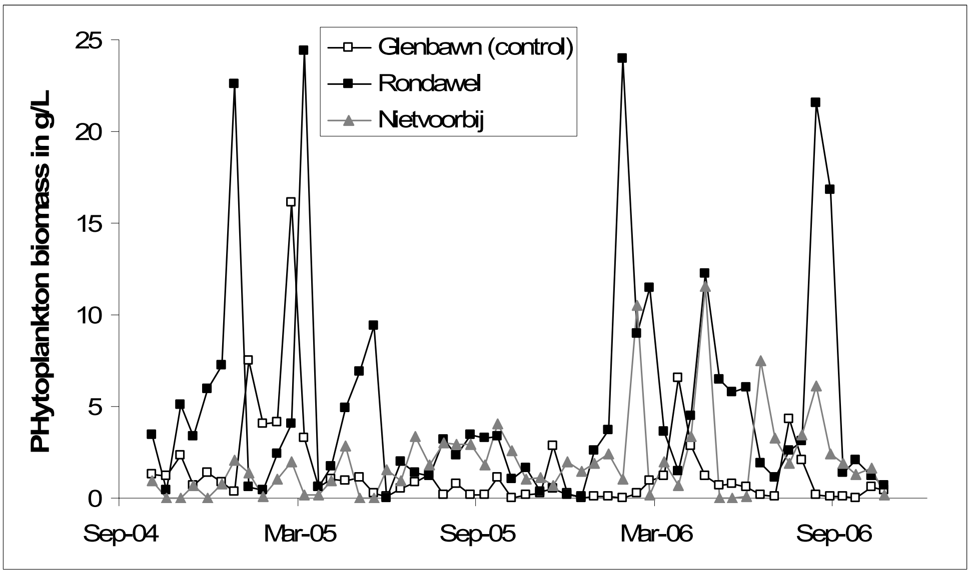

Figure 4.29: Phytoplankton biomass overview – Stellenbosch sites

The phytoplankton community of Calais could be the illustration of a phytoplankton population in a mesotrophic to eutrophic storage dam (see Figure 4.30). The main peak is seen to occur during the turnover phase when nutrients become available. Main families during that period are diatoms (Heterokontophyta), later joined by *Gymnodinium* spp*.* (Dinophyta) and *Eudorina* spp*.* (Chlorophyta), as well as *Anabaena circinalis* (Cyanophyta). The peak from May to August 2006 was formed by 4 to 11 species of which the above-mentioned dominate the succession.

The smaller peak in February was formed by two diatom species, namely *Fragilaria* spp*.* and *Gyrosigma* spp*.*

At the production site (Cape Olive), the phytoplankton situation is quite different when peaks were only observed during the two turnover phases and only included two cyanophyte species: *Microcystis* spp*.* and *Aphanothece* spp*.* (see Figure 4.31). Cape Olive Dam therefore reflected a moderately eutrophic character with its phytoplankton succession and total biomass, except that cyanobacteria dominated. This can partly be explained by the prevailing TN:TP ratio (refer to Table 5.4 in Chapter 5) in that the ratio was less than 10 at Cape Olive, whereas it was greater than 16 at Calais. Plants take up nutrients in a certain balance: the more nitrogen available, the more phosphorus becomes the limiting nutrient and vice versa. At Cape Olive, the TN:TP mass ratio can decrease below 10, which favours algae that can fixate nitrogen from air, such as blue-green algae.

Additionally, the introduction of feed into the water body can shift the nutrient ratio. In more acidic waters, as in Cape Olive, the phosphorus release rate was discovered to be at its maximum (Kibria et al., 1997). Therefore, aquaculture could have influenced the current phytoplankton conditions together with other factors (The impact of the nearby Buchu factory is unknown).

More importantly, most cyanophyte species have a light-harvesting mechanism which favours their growth in shaded conditions such as provided by the high TSS levels at Cape Olive (Shapiro, 1990).

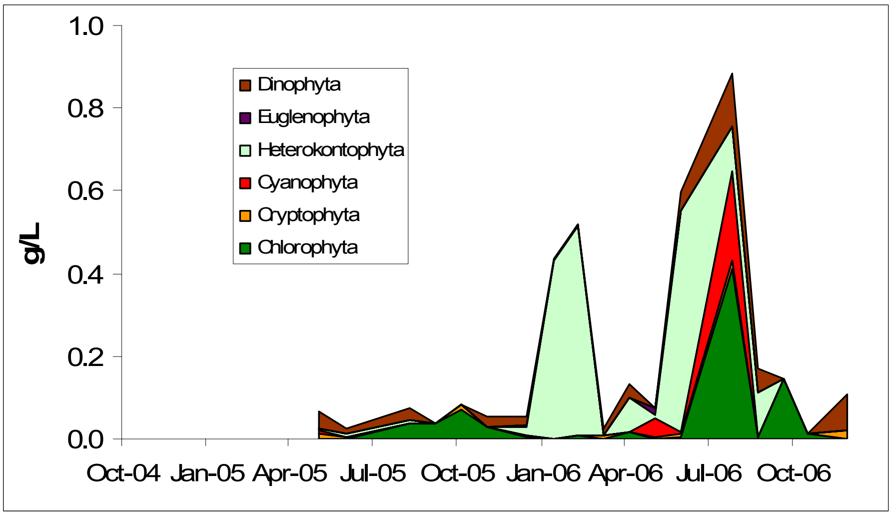

Figure 4.30: Phytoplankton biomass and composition by classes for Calais Dam, May 2005 to December 2006. Scales differ among the phytoplankton composition figures.

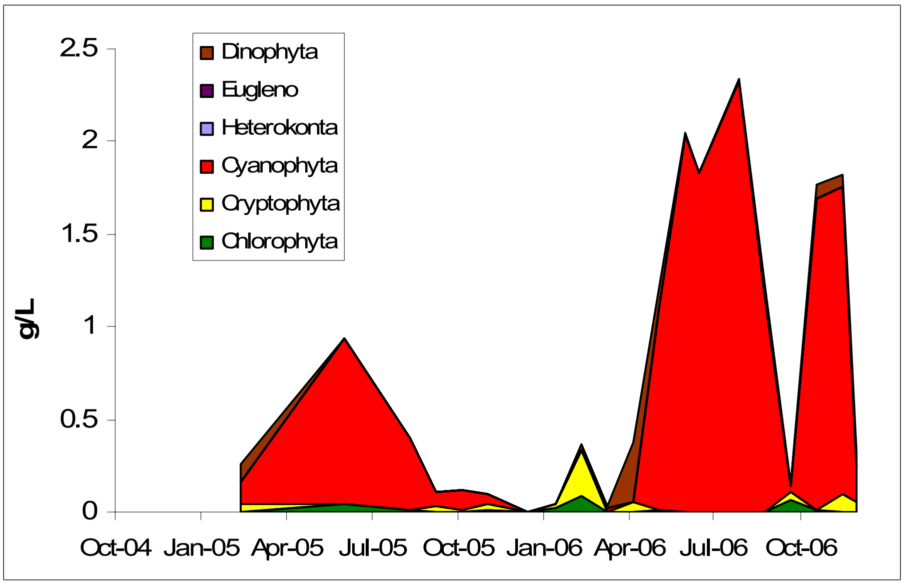

Figure 4.31: Phytoplankton biomass and composition by classes for Cape Olive Dam, February 2005 to December 2006. Scales differ among the phytoplankton composition figures.

At the Stellenbosch sites, the stability of peaks was very acute. Phytoplankton populations built up and crashed shortly afterwards. Glenbawn, the non-production site, showed slightly lower peaks than the other two sites, especially in 2006. Higher bacterial presence, instead, could not be excluded.

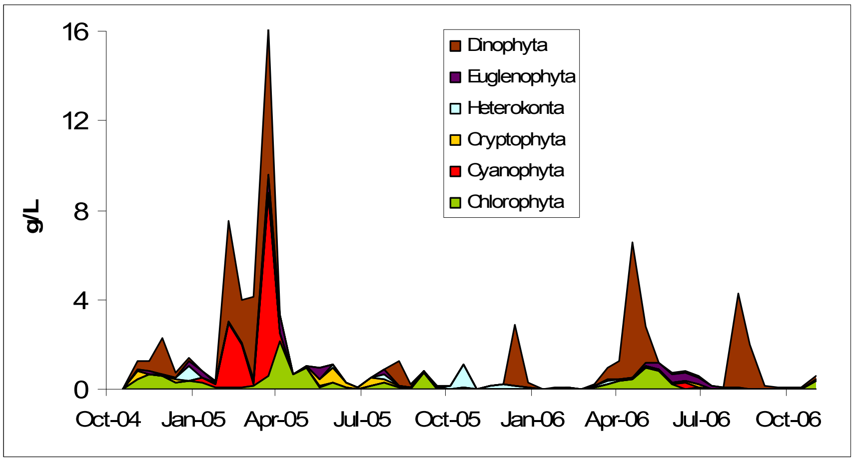

Figure 4.32: Phytoplankton biomass and composition by classes for Glenbawn Dam (control site), November 2004 to December 2006. Scales differ among the phytoplankton composition figures.

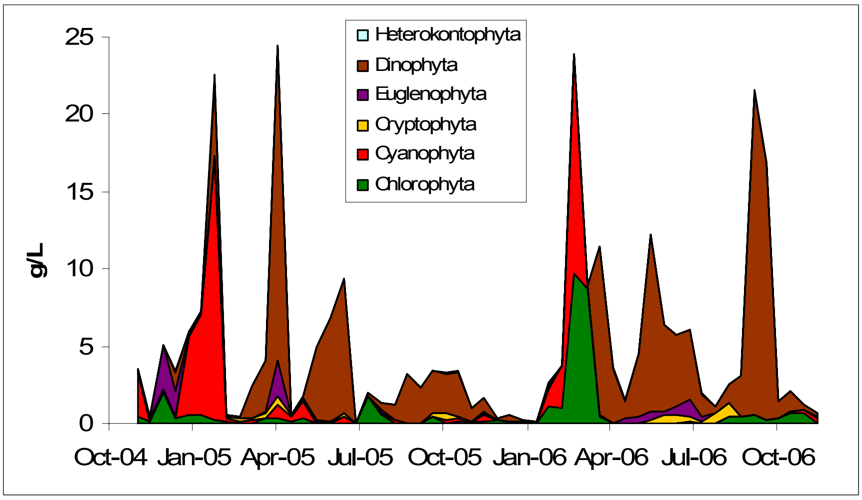

Figure 4.33: Phytoplankton biomass and composition by classes for Rondawel Dam (production site), November 2004 to December 2006. Scales differ among the phytoplankton composition figures.

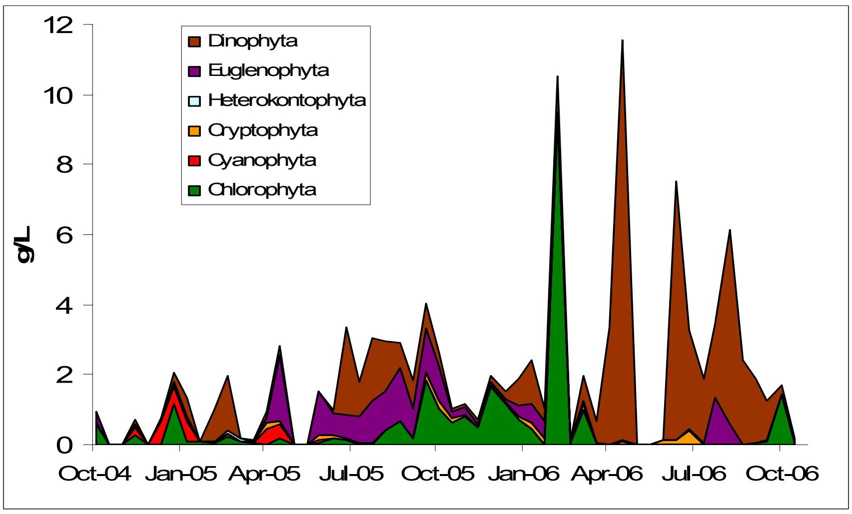

Figure 4.34: Phytoplankton biomass and composition by classes for Nietvoorbij Dam, November 2004 to December 2006. Scales differ among the phytoplankton composition figures.

At Nietvoorbij, the peaks in 2005 were smaller than in 2006, possibly because of less turbulence in the dam and a lesser nutrient supply from the bottom water in 2005.

Glenbawn's peaks mainly occurred during the turnover period (see Figure 4.32). The single dinophyte species that dominated was *Gymnodinium* spp*.,* whereas the cyanophyte adding to that biomass would have been *Microcystis* spp*.*

At Rondawel, the dominating dinophytes were *Ceratium hirundinella* and *Peridinium* spp*.,* and the dominating cyanophytes *Anabaena circinalis* and *Microcystis* spp*.* (see Figure 4.33). The chlorophyte species adding to that was *Staurastrum* spp*.*

The dominating species of Nietvoorbij were similar to the species in Rondawel, with *Ceratium hirundinella* and *Gymnodinium* spp*.* as the dinophyte representatives (see Figure 4.34). Cyanophytes were not very abundant in Nietvoorbij Dam. However, euglenophytes, represented by *Euglena* spp., as well as *Staurastrum* spp*.*, a chlorophyte species, were more present than in other dams.

Apart from the biomass differences between Rondawel and Glenbawn Dam, the composition and species present were fairly similar, with Rondawel being reduced to one dominating species at most times in contrast to several at Glenbawn. Rondawel showed strong of overabundant nutrients which would partly be attributable to aquacultural activities.

The algal composition in Nietvoorbij Dam was strongly dominated by a few species and reflected an environment high in nutrient for phytoplankton species, which increases the risk of eutrophication problems (bad odour, blooms, surface oxygen problems, skin rashes).

4.6.4 Zooplankton

The zooplankton biomass corresponded well with the total phytoplankton biomass, having been roughly in the same range for most dams. In Glenbawn and Rondawel, zooplankton was underrepresented. The dominating phytoplankton species in these dams were very bulky and therefore unpalatable for zooplankton.

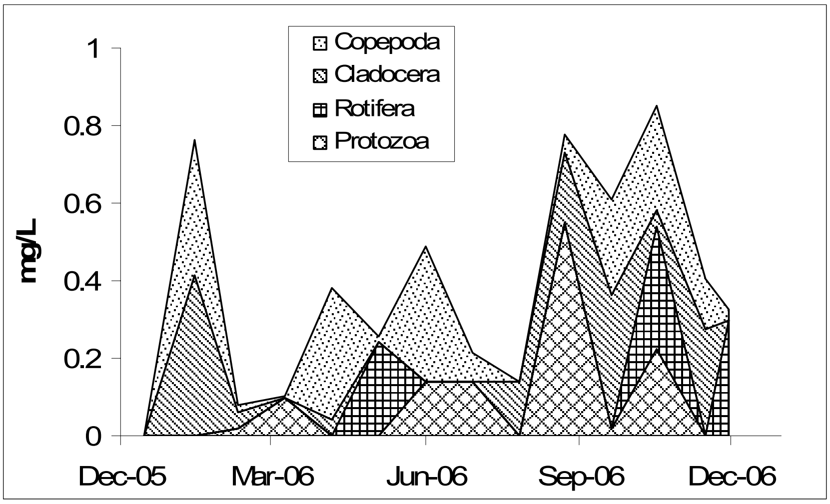

Figure 4.35: Zooplankton biomass and composition for Calais Dam, December 2005 to December 2006

In Calais, the dominant zooplankton composition was varying throughout the year, though peaking with a time lag, in contrast to the corresponding phytoplankton peak two months earlier (see Figure 4.35). Within the zooplankton successions (starting February 2006 with the minor peak and July 2006 with the major peak), the protozoans *Mesodinium* spp*.* and *Strombidium* spp*.* seemed to take the lead.

From there, copepods and, at the major peak, cladocerans alternated with rotifers. The main copepods were nauplius larvae and *Cyclops* spp. Cladocerans were represented by *Daphnia* spp. and rotifer species were *Hexarthra* spp., *Polyarthra* spp. and *Trichocerca* spp., with equal representation.

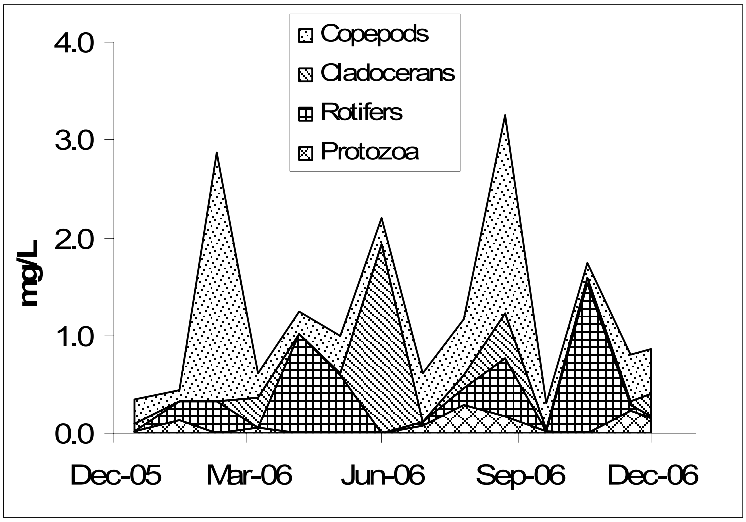

Figure 4.36: Zooplankton biomass and composition for Cape Olive Dam, December 2005 to December 2006

In Cape Olive, the zooplankton peaked four times during 2006 (Figure 4.36). Copepods (*Cyclops* spp.) and *Keratella cochlearis* (Rotifera) were present almost throughout the year in varying abundance. In June, *Daphnia* spp. (Cladocera) was able to develop briefly, however, the advantage of copepods being able to graze on *Microcystis species* prevailed soon thereafter.

The zooplankton biomass of Cape Olive and Calais reflected the ranges of the phytoplankton biomass in these dams.

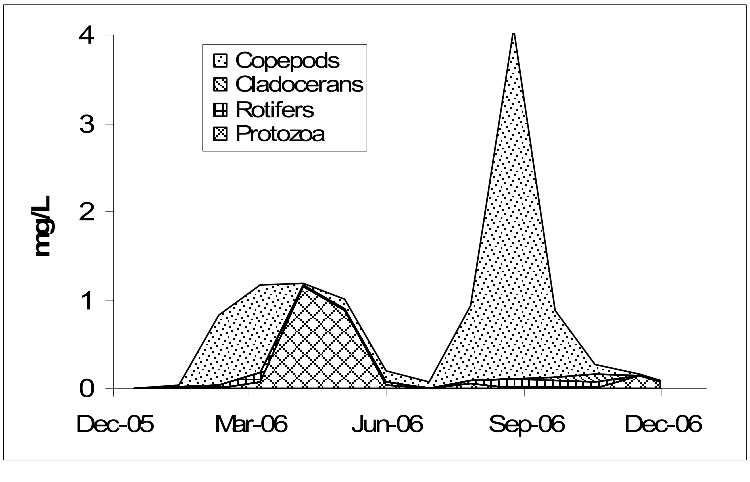

Figure 4.37: Zooplankton biomass and composition for Glenbawn Dam, December 2005 to December 2006

At the Stellenbosch sites, Glenbawn's zooplankton occurrence was in concordance with the total phytoplankton peaks (see Figure 4.37) and in winter 2006, as well as with the phytoplankton biomass (the zooplankton biomass was about 1/1000). The main zooplankton species between February and June 2006 first were copepods and later protozoans, mostly consisting of *Mesodinium* spp. and *Holophrya* spp. During the September 2006 peak, copepods made up most of the zooplankton.

Copepods filter small particles or feed from decaying matter (e.g. crushed phytoplankton population or fish feed).

At Rondawel, *Vorticella* spp. developed a peak in March 2006 (see Figure 4.38). Shortly afterwards, a zooplankton composition of crustaceans, *Bosmina longirostris* (Cladocera), and copepods built up. In late September, *Keratella cochlearis* peaked in conjunction with the heterotrophic phytoplankton species *Ceratium hirundinella*. In contrast to the phytoplankton biomass, the zooplankton abundance was much lower, probably due to rapid changes, unfavourable conditions for the zooplankton duration stages in the sediment or other unmonitored factors. The lack of a zooplankton structure can be seen as another sign of degradation of the dam, its high nutrient status and disrupted ecology caused by excessive nutrient abundance resulting from its source water, agricultural runoff and aquaculture.

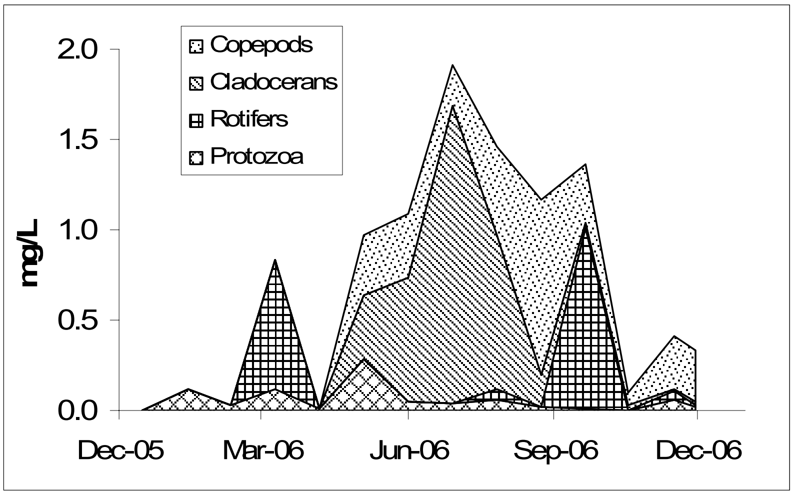

Figure 4.38: Zooplankton biomass and composition for Rondawel Dam, December 2005 to December 2006

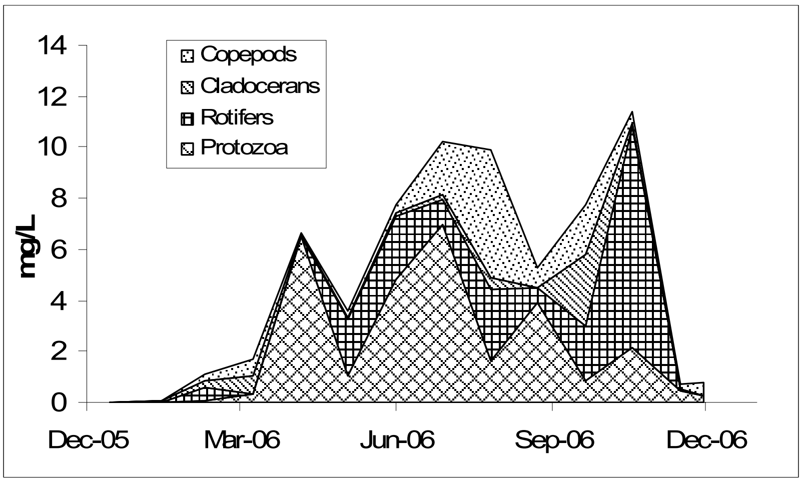

Figure 4.39: Zooplankton biomass and composition for Nietvoorbij Dam, December 2005 to December 2006

Nietvoorbij has developed very high zooplankton biomasses at times (see Figure 4.39). Except for the late summer months, zooplankton species were present throughout the year. The composition, as well as the dominant species, changed often. In April, *Vorticella* spp. (protozoa) established the first peak, followed by *Keratella cochlearis* (Rotifera) and *Strombidium* spp. (protozoan). The protozoans peaked in June, with *Holophrya* spp. as the dominant species. Copepods intermitted in July and in

August *Holophrya* spp. took over again. During the turnover period, many particles and nutrients were available. In September, *Keratella cochlearis*, *Daphnia* spp. and copepods (mainly *Cyclops* spp.) occurred in almost equal abundance; in October, *Keratella cochlearis* took over, before the zooplankton structure diminished at the end of November.

The zooplankton structure in Nietvoorbij was much more dominated by protozoans and rotifers than in the other dams, whereas copepods did not occur as in the control sites (Longgen & Zhongjie, 2003). While higher zooplankton taxa also feed on bacteria and organic debris (detritus), which seem to be abundant throughout in the dam and especially during the winter period, protozoans do this exclusively. The abundance of protozoans therefore was indicative of the eutrophic character of Nietvoorbij Dam.

Overall, the phytoplankton composition and biomass most accurately represents the conditions of the respective dams during the study period (November 2004 to December 2006). The eutrophic level and overall ecological status of the dams could be estimated, as well as more accurate indicators for future monitoring specified (such would be bottom water oxygen and nutrients and their accumulation during the stagnation phase). To get to know the historical dynamics of the dams and obtain data from before aquacultural introduction would be very important, due to the high heterogeneity of the Western Cape dams and the difficulties encountered in comparing them.

Despite the many similarities between Cape Olive and Calais Dam, they do not share the same water source. River water is diverged into a canal to feed the Calais Dam whereas Cape Olive is fed by the river, with the water accumulating more suspended solids before entering Cape Olive Dam. In addition, a Buchu factory's release of organic waste material into the river and runoff water also affects Cape Olive, but not the Calais inflow water.

The smaller dams in the Stellenbosch area, especially, showed a trend towards pH increase that would be caused by excessive phytoplankton growth (Talling, 1976). Phytoplankton converts carbon dioxide into oxygen in the process of photosynthesis and the balance of carbonates and hydrocarbonates is altered, which again affects the pH by removing protons from the water ($H_2O + CO_2 \leftrightarrow H_2CO_3 = H^+ + HCO_3$). The smallest dams, Glenbawn and Rondawel especially, as well as Nietvoorbij, showed high pH levels. The alkalinity of Nietvoorbij was influenced by the turnover period bringing carbonates and hydrocarbonates from the sediment to the surface water. The high phytoplankton biomass, therefore phytoplankton debris, is the most likely explanation for the changes in alkalinity. These parameters already suggested extreme phytoplankton biomass turnover in some of the dams.

That Cape Olive had the lowest pH levels could be explained by the high total suspended solids in the water that are only slowly settling out due to the fine character of the particles (clay). The TSS levels of Cape Olive also strongly influence the visibility of the water and therefore limit algal production, but also lower the pH by introduction of proton-donating constituents (especially clay and mineral compositions low in calcium and magnesium).

Phosphorus levels of the dams vary between 20 and 180 µg/L for all dams and confirm the elevated trophic level of the dams (Vollenweider, 1968; Carlson, 1977; DWAF, 1996c). Eutrophic to highly eutrophic bodies of water are defined by 25 to 250 µg/L P (DWAF, 1996c). The consequences of eutrophic conditions are that phytoplankton biomass grows and the low buffering capacity of the water (low alkalinity), allows pH levels to fluctuate. Another consequence of these eutrophic conditions will be oxygen depletion in the hypolimnion during stagnation, which was first described for temperate regions (Thienemann, 1921), but seems to be an even more likely effect of subtropical and tropical lakes (Diaz-Pardoa, 2007; Townsend, 1999).

Another indicator for elevated eutrophication levels is the absence of diatoms in most dams. Calais was the only dam in which algal biomass stayed below 1 g/L, in which the biomass peaks of phytoplankton developed slowly and where a diverse species composition developed during winter when nutrients were available. Cape Olive, partly due to the shading effect of the suspended solids, had fairly low total biomass levels at 2.5 g/L, but cyanophytes were in the majority.

The three other sites were on the way to become hypereutrophic. Phytoplankton peaks develop quickly and crash fast. This favours the presence of zooplankton species, protozoans first, that feed on organic debris (protozoa) and enhances bacterial activity and decomposition processes. The biological oxygen demand (by bacteria) during times of phytoplankton crashes will increase dramatically and consume surface water oxygen.

Zooplankton biomasses correlated with the total biomass of phytoplankton for most dams. The zooplankton biomasses in Glenbawn and Rondawel were low, which might have been due to the total depth of these two dams (no refuge for zooplankton cysts during stagnation because there is no hypolimnion), unfavourable sediment texture or higher bacterial populations. Calais, again, showed the typical character of a lightly eutrophic dam with higher zooplankton biomass in winter when nutrients and phytoplankton is present. The protozoans give way to the larger zooplankters by breaking the phytoplankton substance, therefore cladocerans and copepods as well as rotifers are present after them (Porter et al., 1979). The cladocerans mostly were not abundant in the other dams except for a peak in June 2006 in Cape Olive and a peak around the same time in Rondawel. They may have been able to feed on chlorophytes present in about the same biomass as the cladoceran biomass (1 to 2 g/L) during that time. Due to the single sampling depth of two metres, the zooplankton biomass also might also have been underestimated. At times during the year most zooplankton would be found within the region of the thermocline where temperature and nutrient conditions are most favourable during stagnation in summer (Vuorinen et al., 1999).

Unfortunately, no historical or pre-aquaculture data are available for Western Cape dams. Calais and Cape Olive might have shared the same water quality historically, but Cape Olive's water quality is different due to total suspended solids loaded into this dam at a much higher rate at present. Phytoplankton total biomass was two-and-a-half times higher in Cape Olive. The TN:TP ratio also was different for Cape Olive, hence advantaged cyanophytes dominated the phytoplankton composition.

Glenbawn and Rondawel, which are fairly similar in their physical, chemical and biological water quality properties showed that aquacultural influence will probably enhance the eutrophication levels. However, the initial eutrophication stages of the dams already give cause for concern.

Nietvoorbij is has a larger volume than the other Stellenbosch sites, but showed the same degree of trophic degradation. High total phytoplankton biomass and biomass fluctuations reigned, as well as a small number of dominating species. Protozoans to break up organic matter introduced by Plankenbrug River water, runoff water and aquaculture to unknown proportions mostly were abundant.

4.7 Conclusions (Cape Winelands)

The water quality of the five study sites was assessed and related to the presence of trout cage aquaculture at three of the sites to determine likely effects on the overall dam ecology. The impact of fish production could be detected from the total amount of phosphorus present in the sediment below the cages, as well as from the phytoplankton composition and biomass, the latter influencing pH levels. The change in phytoplankton composition and biomass could act as a source of oxygen problems for fish production, block irrigation filter systems and taint sensitive crops.

The pH levels of the Stellenbosch sites showed a tendency to increase during the mixing phases of the dams (September/October or March) when more nutrients are available. These phases also coincided with higher phytoplankton biomasses (at Rondawel and Nietvoorbij). With the low alkalinity (carbonate and bicarbonate content) and low hardness conditions that prevailed at the studied sites, algal growth had a strong impact on pH levels. These effects were stronger at the two production sites in Stellenbosch than at the control site. At the Drakenstein sites, high sediment inflow into the production site had a powerful effects on pH and shadowed algal growth. Increasing tendencies to sediment inflow not caused by aquaculture were noted, especially in early winter. These had a negative impact on production performance.

Nutrients are in a steady state within a dam and their level is affected by the regime and nature of inflow and outflow of water, by sediment binding capacities and overall accumulation in the sediments, as well as by biological processes (bound into phytoplankton). Few effects, either seasonal or among sites could be discovered from the nutrient levels. The average dissolved phosphorus components indicated that all dams experienced roughly the same eutrophic level. The Drakenstein and Stellenbosch sites showed strong differences between the total phosphorus contents of the dry sediment, with much higher levels at the Stellenbosch sites. Accordingly, levels of readily available phosphorus that could be released into the water column were four to six times higher. These findings, rather than the total phosphorus content of the surface water, was reflected in the phytoplankton biomasses at the sites. Phytoplankton biomass was up to ten times higher at the Stellenbosch sites than at Drakenstein. In addition, the sediment TP levels were four times higher below the cages in the Nietvoorbij Dam, compared to a reference location within the same dam.

Tendencies toward higher phytoplankton biomass were also present at the respective production sites, in contrast to the control sites. Rondawel Dam, especially, showed disconcerting phytoplankton patterns that led to population crashes and sudden surface oxygen depletion in every winter or spring season. The experience with Rondawel Dam showed that dams with this initial nutrient load are to some degree affected by aquaculture (phytoplankton biomass), but overall are not suitable for trout production (despite the argument that additional loading into such a dam would cause less damage than in a more pristine reservoir).

It seems that Cape Olive Dam coped very differently with the incoming nutrient load from aquaculture than the sites at Stellenbosch, which could have been due to the different hydrology and higher water exchange rate, as well as the overall much greater volume and the binding capacities of the sediment. The sediment showed no elevated phosphorus levels after five consecutive aquacultural production years (the cages, moreover, were moved around in the dam and the production waste did not accumulate in the same area every year).

This suggests that trout aquaculture has a lesser effect on water ecology, and is also itself less negatively affected, if undertaken in reservoirs of a certain minimum size and volume with a water exchange regime favouring nutrient dispersion.

4.8 Overall conclusions

The impact of aquaculture on standing water bodies and canal systems seems to greatly depend not only on the chemical and biological state of the dam, but primarily on its morphometric and hydrodynamic conditions. Size and depth as well as water exchange rate are the main parameters to consider before operations start. Models can help to determine whether production at a site would lead to its long-term degradation (for irrigation and aquaculture) or would have an acceptable effect (also see Chapter 5). Nutrient levels bound into the sediment need to be ascertained to judge the real eutrophication tendency in a dam and its likely phytoplankton community.

The water exchange rate played a major role at Makhathini. This was reflected in the fact that no effects of aquaculture whatsoever were detectable at the pump-house dam. The full amount of water in that dam is replaced more than 3000 times per year; the dam, in fact, has the properties of a body of flowing water. The low impact results can confidently be transferred to other pump-house dams with equally good water exchange, but should only be applied to adjacent balancing dams such as the one that served as control site at Makhathini with caution. These dams might be nutrient traps whose state would deteriorate with the introduction of cages (but could, on the other hand, still be very suitable for catfish and tilapia production despite deteriorating water quality, since both species are herbivorous and tolerate low oxygen levels).

A stable nutrient balance is of very extreme importance in the case of small irrigation and drinking water reservoirs in the Cape Winelands district (as well as the rest of the Western Cape). The smaller dams (< 5 ha) of the Stellenbosch area that were included in this study could all be described as nutrient rich (in terms of ecological response) with extremely fluctuating phytoplankton levels and the consequent negative effects on oxygen levels and pH. Trout aquaculture in that kind of reservoir involves risks for the environment and for successful production.

In contrast, the short- and medium-term effects (five years) of aquaculture at the Drakenstein production site seem to be limited, with the possibility of influencing the presence of cyanophyte species. The sediment inflow and consequent high TSS levels literally overshadowed the possible effects of aquaculture on phytoplankton quantity and quality.

Within the framework of careful site selection, using size, depth, water exchange and accumulation of nutrients in the bottom water as indicator, aquaculture with a minimised negative impact on storage dams will be possible in dams similar to Cape Olive (having a water exchange rate of once or twice per year, 8 ha of surface area or more, and a minimum depth of 7 to 8 metres).

5 MODELLING AND FORECASTING AQUACULTURE IMPACT ON WATER QUALITY OF SMALL-SCALE CAGE AQUACULTURE IN THE WESTERN CAPE

5.1 Introduction

Trout cage farming has been introduced into various irrigation dams within the Western Cape over the last 20 years. The average production size per cage system (usually one per dam) lies between five and six tons. The exemplary sites for estimating environmental capacity within this WRC programme comprised three dams within the Boland region, each loaded with approximately five tons of trout per season for the past three to ten years.

A primary concern of these production sites (irrigation dams < 20 ha) is the potential environmental impact on their water quality, as well as a negative throwback on irrigation water use (sometimes even drinking water use) or aquacultural use itself. In terms of aquaculture, it is important to facilitate sustainable production. Site selection as well as suitability should be established upfront by means of water quality tests and subsequent determination of long-term carrying capacity for trout production without noticeable water quality deterioration (deriving from aquaculture). As recommended by the South African guidelines for aquatic ecosystems (DWAF, 1996c), the inorganic phosphorus levels (soluble reactive phosphorus) should not be changed by more than 15% from the unimpacted conditions at any time of the year, the trophic status of the water body should be maintained or improved and the amplitude and frequency of natural phosphorus cycles should not be changed.

One of the models successfully applied for similar problems (to determine carrying capacity and environmental suitability of water bodies for cage farming) is the model introduced by Phillips and Beveridge (Beveridge, 1984; Philipps et al., 1985; Beveridge, 1996), which is itself based on assumptions and conclusions drawn by Vollenweider (1968) and Dillon & Rigler (1974, 1975) on water bodies with different eutrophication levels.

Some of the assumptions made by the model require caution with regard to smaller water bodies such as irrigation dams, which will be commented on in the discussion. Beveridge (1996) states that models for predicting the production capacity of cage culture are in the initial stages of development and should be used as guides rather than precise calculations.

The model outcome has to be seen and discussed in the context of each particular site's characteristics. The presence or absence of a thermocline during summer stagnation can change the dam capacity through impacting nutrient availability and phytoplankton compositions.

Further support for understanding the model outcome is obtained from comparing it to recommendations from other trout or small-scale cage production systems. The specie's trophic level (herbivorous or predator) and the climate will also play a crucial role. The best trout producing countries for comparison with South African conditions are Australia, the south-eastern United States (e.g. North Carolina) and Iran. Quantitative guidelines are available from the FAO and for Australia (Gooley & Gavine, 2003; FAO, 2007) as well as recommendations for water through-flow in tank systems of the Southern United States (Hinshaw, 2000) and the current production levels of Iran (Coad, 2005).

Another component that will have a considerable impact on the carrying capacity of these dams is determined by the degree of management applied to support the self-cleaning ability of the systems. Options for management could be the setting up of aerators, polyculture with species withdrawing nutrients (e.g. crayfish, mussels, water hawthorn), structures below the cages to collect waste or removal of the sediments collected from below the cages by mechanical dredging or suction.

5.1.1 Rationale behind the Phillips and Beveridge Capacity Model

The Phillips and Beveridge Capacity model can serve as production capacity model to determine stocking densities of rainbow trout in cages without aggravating the nutrient status of the water body.

The major concern with enclosed water bodies is nutrient enrichment, which is often referred to as eutrophication. Awareness of anthropogenically accelerated eutrophication was created in the past decades and the main contributors were defined as agricultural runoff and domestic as well as industrial waste water and litter (DEAT, 1999).

Similar to agricultural input, the main impact of fish production on water quality concerns the addition of nutrients, in this case through loss of uneaten feed and excretion. Additional nutrients stimulate productivity (primarily algal growth) and ultimately alter the abiotic, as well as the biotic characteristics of a water body. Organic enrichment, organically enriched sediments, excessive algal growth, toxic algal blooms, extreme oxygen variation at the surface (0 to 20 mg/L dissolved oxygen), oxygen depletion of the near-bottom water, loss of biological diversity, loss of self-regulation of the water body and fish as well as other animal kills can be events occurring during the medium to extreme stages of eutrophication. Climatic and hydrodynamic conditions of the water body trigger the timing and proportions of these possible events.

The component singled out to summarise eutrophication effect is phosphorus. Firstly, total phosphorus content can be an indicator for overall nutrient input. Secondly, provided that the nitrogen to phosphate ratio is greater than twelve, the chlorophyll *a* content of a water body will closely correlate with the concentration of total phosphorus (Vollenweider, 1968). In providing such an N:P ratio, phosphorus will be the most important limiting factor in algal growth and therefore decide the extent of primary production. In a study attempting to classify 98 South African impoundments by eutrophication level, it was found that phosphorus was the most limiting resource in non-eutrophied dams and nitrogen in highly eutrophied ones (Toerien et al., 1975). Due to the capability of certain algal species to fixate atmospheric nitrogen, the control of phosphorus also offers a better long-term solution for eutrophication problems. Excessive primary production leads to changes in the ecological balance as well as causes extreme variations in dissolved oxygen contents. Oxygen-sensitive species become threatened or will disappear. High-nutrient demanding species will replace several other species and dominate the present biota.

The advantage of one single parameter that represents most processes related to eutrophication (the biggest impact of aquaculture) eases the data collection prior to the assessment of environmental capacities and, consequently, the determination of production limits.

Information and clarification is therefore required with regard to the following:

- Does P determine the productivity of the environment (TN:TP ratios)?
- What do the farmed fish consume (respectively, produce as waste) in forms of P?
- At what P levels does the environment respond to P waste loadings?
- How much change is therefore desirable and thus allowable?

5.2 Materials and methods

5.2.1 Experimental sites

In the Drakenstein area the experimental site was Cape Olive farm dam. In the Stellenbosch region, the experimental sites were the production sites Nietvoorbij Dam and Rondawel Dam (see Section 2.1.2).

5.2.2 Formulas applied in the Phillips and Beveridge model

In the Phillips and Beveridge model, the production capacity is estimated as follows:

The development (production) capacity of a water body for cage culture is the difference between the P-related productivity of the water body prior to exploitation and the final desired/acceptable level of productivity. The capacity of the water body for cage culture is thus the difference, $\Delta(P)$, between P prior to exploitation, $(P)_i$, and the desired/acceptable P once fish culture is established, $(P)_f$. Therefore, $\Delta(P)$ is equal to $(P)_f - (P)_i$.

The allowable increase $\Delta(P)$ is the result of:

- P loading from the cages (L_{fish})
- the average depth of the water body (z), where z is the volume divided by the surface area (V/A)
- the flushing rate $\rho(y^{-1})$, which is the average volume flowing through the water body (total inflow or total outflow) divided by the average total volume (in m^3) of the water body (therefore Q/V)
- R_{fish} which is the ability of the water body to absorb the loading (i.e. the fraction of L_{fish} retained by the sediments)

Therefore $\Delta(P) = L_{fish}(1-R_{fish})/z\rho$ or $L_{fish} = \Delta(P)\, z\rho/(1-R_{fish})$.

R_{fish} is the most difficult parameter to determine. Using the arguments proposed by Phillips et al. (1985c), at least 45-55% of the total-P from caged rainbow trout is likely to be permanently lost to the sediments as a result of solids deposition, and thus only 45-55% of the total-P loadings are in the form of dissolved P. A fraction of the dissolved P component will also be lost to the sediments, and R_{fish} values are therefore greater than R for conventional P loadings when $R_{fish} = x + ((1 - x)R)$, where x equals the net proportion of total phosphorus lost permanently to the sediments as a result of solids deposition (i.e. 0.45-0.55), and R is the proportion of dissolved total-P lost to the sediments calculated from published data (Beveridge, 1996).

Once the permissible total phosphorus loading, L_{fish}, has been calculated, the intensive cage fish production (tons per year) can be determined by dividing L_{fish} by the average total phosphorus wastes per ton of fish production.

5.2.3 Additional data

Whether phosphorus was the limiting nutrient within the system was verified by determining total nitrogen to total phosphorus ratios (TN:TP). Water samples of all three dams were collected on a biweekly basis and analysed for their physical and chemical water quality. Total nitrogen and total phosphorus were sampled four times at irregular intervals in 2006 and analysed by DWAF, Pretoria.

The main source of trout fish feed for the grow-out phase within the Western Cape dams (AquaNutro trout grower 6 and 9 mm) contains an average of 1.54% of phosphorus, whereas trout biomass consists of 0.48% of phosphorus on average. Together with the food conversion ratio, the total amount of phosphate released into the water body per ton of produced fish can be evaluated. The food conversion ratio is a term applied in animal production and describes the proportional gain in the wet body weight of the fish to the amount of feed fed. Low FCRs are more economical as well as more environmental friendly and can be achieved by optimal feeding strategies and practices. Assuming an average FCR for trout production of 1.4:1, the total phosphorus (TP) loading to the water body per ton of produced fish (no mortalities) is approximately 16.76 kg of phosphorus (as P) and therefore about 80 kg of P for the Hands-On production unit. The real food conversion ratio was determined for the test dams in this programme. The FCRs experienced in the three experimental sites were 1.8, 2.0 and

2.2. The best FCR achieved with a Hands-On project was 1.06. The average of 27 projects was an FCR of 1.6, the majority (10 to 90% percentiles) of which varied between 1.2 and 2.3.

Allowable P levels were obtained from the South African Water Quality Guidelines for Aquatic Ecosystems and the Guideline for Agricultural Water Use: Aquaculture (DWAF, 1996b; 1996c) and the upper limit was set at 100 µg/L allowable inorganic phosphorus.

A portion of the dissolved phosphate will be bound to the sediments (expressed as R). This loss depends, among other factors, on the rate of water displacement. Empirical constants for the calculation of this sedimentation rate have been taken from Beveridge (1984), who used data from various European, US American and other studies. Using this published data, the sedimentation rate was calculated by means of an average empirical value of 0.617352 for R (this being the average obtained from 1138 empirical studies re-quoted by Beveridge (1996).

Hydrological information on the three test dams such as a depth profile, area and volume estimations was collected. Inflow and outflow information was recorded with every visit and samples were taken and analysed for total phosphorus. Water was sampled whenever water was carried by the inflowing canals or pipes, while outflowing water was measured at the overflow (Cape Olive, and once at Rondawel) or at the floating device that keeps the suction pipe for the irrigation water afloat, which was only done during the irrigation periods.

Speed of water flow and area of flow were estimated. See Section 2.3.2 (in Chapter 2) for the determination of total phosphorus.

The water exchange rate is the ratio between the amount of water exchanged per year and the water volume at full supply level.

Rondawel is mainly supplied through a pipe extracting bottom water from Glenbawn Dam and runoff water (see Figure 2.6 in Chapter 2). On occasion, the dam has a low volume overflow for some weeks during winter. In summer, 60% of the water volume is extracted from the surface level when the dams stagnate and the phosphorus levels are higher in the bottom water than at the surface, intensifying the nutrient content of the dam.

The inflowing water volume of Nietvoorbij Dam is estimated at 1200 m^3 per day for 1 to 2 months (which amounts to a total inflow of approximately 108,000 m^3 per year). The mean total water volume of the dam fluctuates between 160,000 and 210,000 m^3 (De Groeve, 2003) or 190,000 m^3 at full supply level as calculated by Maleri (2008). The quality of the incoming water is poor in that it brings in more phosphorus per volume unit than already present in the dam.

At Cape Olive, the inflowing water volume was estimated at 5000 m^3 per day for the months of June to August and at about 2000 m^3 per day in May, as well as in September, which amounts to a total inflow capacity of between 500,000 and 700,000 m^3.

5.3 Results

Nine variables are fed into the Phillips and Beveridge version of the Dillon and Rigler model, which allows many possible results within the range of some of these variables. Out of the plethora of possible outcomes, three scenarios were chosen to represent the highest environmental impact to the minimum impact caused by cage aquaculture in storage dams (1.5 to 7.5 ha).

Some of the variables remain relatively constant (such as the empirical sedimentation constant for P, the P content of the fish feed and the P content bound in the fish flesh). The FCR for 2006 was determined on the respective farms and varied from 1.8 to 2.2. These FCRs were applied to the worst case scenario as well as the average scenario; an optimised FCR was fed into the calculation for the best case scenario.

The levels of historical P (data from October 2004 to December 2006 were available to build an average) fluctuate seasonally. The phosphorus level at springtime in the temperate Northern

Hemisphere (lake turnover) is usually chosen for the model. With the given mixing regime in the studied dams (valid for all South African dams), the highest measured phosphorus content at turnover time was taken for the worst case scenario and the lowest value during turnover time (during winter) for the best case scenario.

The allowable P was based on a maximum 10% increase of original inorganic phosphorus levels per year. All water bodies should stay below levels of 100 µg/L phosphorus suggested in the South African Water Quality Guideline for Aquaculture (1996b). Eutrophic water bodies are indicated by phosphorus levels of 25 to 250 µg/L (DWAF, 1996c), but the protection of all aquatic organisms (including trout) can only be ensured under a target level of 100 µg/L (DWAF, 1996b). The results reflect the carrying capacity that supports sustainable dam use for aquaculture for years, whereas the number in brackets symbolises the amount of fish that could be produced in one year, after which the limit of 100 µg/L phosphorus would have been reached.

The volume and surface of these water bodies are known. Due to the introduction of fish in May when water levels are not replenished by the rainy season yet, the model works with an average water level for the whole grow-out season from May to October. In a worst case scenario, the dam will not be completely filled after a rainy season due to rain shortage, though water translocation from other dams can sometimes take place. This would also lengthen the time period needed to replace the total dam volume. Water exchange often only takes place when the highest water levels are reached and water can leave the dam via overflows. In Cape Olive, for example, 20,000 to 85,000 m^3 of water was replaced per day in the late rainy season (August and September). In the other dams, the yearly inflow was estimated to be less than half of these values.

The worst case scenario reflects simultaneous high historic phosphorus levels, poor climatic conditions (rainfall), poor dam conditions (low volume) and poor project management (high FCR).

5.3.1 Rondawel (representing < 2 ha dams)

Rondawel was a production site in 2003, 2004 and the second season of 2006.

Table 5.1: Environmental (full production) capacity of Rondawel Dam for cage trout production. Results in brackets represent the total tonnage that could be produced by adding phosphorus to the capacity limit in one season.

Variable	Worst case scenario	Average scenario (likely)	Best case scenario
Historical (P)i in µg/L	107	81	55
Allowable (P)f in µg/L	100	89 (100 µg/L)	61 (100)
Surface (A) in ha	1.5	1.7	1.8
Volume (V) in m3	30,000	65,000	80,000
Displacement (ρy-1)	0.5 times per year	1 time per year	2 times per year
P sediment (%P)sed	50%	50%	50%
P in feed (%P)feed	1.54%	1.54%	1.54%
P in fish (%P)flesh	0.48%	0.48%	0.48%
FCR	1.8	1.8	1.5
Capacity	0 tons of fish per year	0.1 (0.3)* tons of fish per year	0.2 (1.7)* tons of fish per year

*) in brackets: the amount in tons that could be added in one season, misjudging the 10% increase per year rule, but not exceeding the allowable $(P)_f$ of 100 µg/L.

5.3.2 Nietvoorbij (representing 2- to 5-ha dams)

Nietvoorbij Dam was a production site for 10 years, from 1997 to 2006 throughout.

Table 5.2: Environmental (Full production) capacity of Nietvoorbij Dam for cage trout production. Results in brackets represent the total tonnage that could be produced by adding phosphorus (feed) to the capacity limit in one season.

Variable	Worst case scenario	Average scenario	Best case scenario
Historical (P)i in µg/L	127	111	84
Allowable (P)f in µg/L	100	100	95 (100)
Surface (A) in ha	3.7	4	4.2
Volume (V) in m3	150,000	190,000	209,000
Displacement (ρy-1)	0.5 times per year	1 time per year	2 times per year
P sediment (%P)sed	50%	50%	50%
P in feed (%P)feed	1.54%	1.54%	1.54%
P in fish (%P)flesh	0.48%	0.48%	0.48%
FCR	2.2	2.2	1.5
Capacity	0 tons of fish per year	0 tons of fish per year	1.0 (1.6)* tons of fish per year

*) in brackets: the amount in tons that could be added in one season, but with which the allowable $(P)_f$ would already be reached.

5.3.3 Cape Olive (representing > 5 ha dam)

Cape Olive was a production site from 2001 to 2004 (for four years) as well as in 2006.

Table 5.3: Environmental (Full production) capacity of Cape Olive Dam for cage trout production. Results in brackets represent the total tonnage that could be produced by adding phosphorus (feed) to the capacity limit in one season.

Variable	Worst case scenario	Average scenario (likely)	Best case scenario
Historical (P)i in µg/L	40	35	31
Allowable (P)f in µg/L	44 (100)	39 (100)	34 (100)
Surface (A) ha	5.5	6.5	7.5
Volume (V) in m3	350,000	450,000	555,000
Displacement (ρy^{-1})	0.5 times vol / yr	1.5 times vol / yr	4 times vol / yr
P sediment (%P)sed	50%	50%	50%
P in feed (%P)feed	1.54%	1.54%	1.54%
P in fish (%P)flesh	0.48%	0.48%	0.48%
FCR	2.0	2.0	1.5
Capacity	0.25 (3.8)* tons of fish per year	0.5 (7.2)* tons of fish per year	1.3 (29.2)* tons of fish per year

*) in brackets: the amount in tons that could be added in one season, but with which the allowable $(P)_f$ would already be reached.

5.3.4 Fulfilment of assumptions made by the model

The simplified Phillips and Beveridge model is based on several assumptions (Beveridge, 1996):

- Any substance (nutrient) is completely mixed throughout the entire lake/water body
- Phosphorus is the limiting nutrient for primary production (TN:TP ratio > 12)
- The phosphate entering or leaving the lake is equal to the concentration in the water mass
- The proportion of phosphate bound by the sediment is seasonally equal.

Samples from the three sites analysed by DWAF for April, May and July 2006 were used to feed the model (total phosphorus, as well as total nitrogen to determine the TN:TP ratio). The data period corresponded with the requirements of the model to use phosphate levels of the turnover period. During the turnover event (which also happened to coincide with the grow-out period of the trout), the overall mixture of nutrients within the water masses was at its best and assumption one (complete water mixture) was served.

A related study (Maleri, 2008) showed that the turnover period in the sample dams (temperature difference of surface to bottom water less than 3°C) occurred between March and September (autumn and winter) for Cape Olive, whereas only in winter, from May to August, for Nietvoorbij. The difference in the climatic conditions of these two dams was responsible for those results (air temperature as well as local wind dynamics). There is only intermittent set of information on Rondawel Dam bottom water quality that suggests that the main turnover phase also occurs from May to September, as well intermittent mixture in summer due to the shallow character of the dam.

Consequently, the bottom water of Cape Olive was only oxygen depleted (less than 1 mg/L dissolved oxygen content) for one month (January), whereas Nietvoorbij's bottom water was oxygen depleted from August to May throughout (Maleri, 2008). Rondawel Dam is very organically enriched (which enhances fast oxygen depletion at the bottom, with the onset of the stagnation phase) and can be expected to be oxygen depleted throughout spring and summer. A short turnover phase in January could bring nutrient mixture, but only a very short-lived oxygen supply for the bottom water because of very strong decomposition processes in the organically enriched upper sediment.

Table 5.4: TN:TP ratio (mg/L:mg/L) calculated from total nitrogen and total phosphorus data provided from own samples analysed by DWAF, Pretoria.

		19.12.2005			**10.04.2006**	
	TN	**TP**	**TN:TP**	**TN**	**TP**	**TN:TP**
Glenbawn	0.68	0.05	14	0.96	0.043	22
Rondawel	0.94	0.054	17	1.1	0.055	20
Calais	0.27	0.014	19	0.33	0.023	14
Cape Olive	0.47	0.024	20	0.36	0.031	12
Nietvoorbij	0.8	0.034	24	1.34	0.084	16
		08.05.2006			**27.07.2006**	
	TN	**TP**	**TN:TP**	**TN**	**TP**	**TN:TP**
Glenbawn	0.81	0.045	18	1.17	0.113	10
Rondawel	1.25	0.107	12	1.6	0.191	8
Calais	0.27	0.018	15	0.41	0.019	22
Cape Olive	0.45	0.04	11	0.38	0.042	9
Nietvoorbij	3.47	0.127	27	2.18	0.111	20

The TN:TP mass ratio sometimes decreases below 12; this happened on three occasions in Cape Olive Dam and also in Rondawel Dam and Glenbawn (see Table 5.5). The lower ratios coincide with the turnover phase. It seems that nitrogen settles into the hypolimnion to a higher degree than phosphorus, so that the ratio changes between summer and winter. During phases of low TN:TP, nitrogen-fixating algae attain the advantage and become more abundant. Phosphate-limited dams, with nitrogen being overabundant, tend to develop *Ceratium hirundinella* blooms during winter (Whittington et al., 2000; Van Ginkel, 2001).

Inflowing and outflowing phosphate levels are difficult to integrate into the model. Outflowing water quality depends on timing as well as given structures (surface or bottom water withdrawal). The same applies to inflowing water quality. The gross nutrient budget of Rondawel is expected to be highly positive. Bottom water at Glenbawn comes in (this is best done during winter when at least the bottom water nutrients are less accumulated through turnover) and lower nutrient surface water is extracted. Aquacultural waste has a relatively high impact due to the small size of the impoundment (1.8 ha).

Nietvoorbij Dam receives mainly runoff water that is on an ecological scale and by means of the phytoplankton response highly concentrated in nutrients, mainly due to the influence of the surrounding agricultural land use. Other water sources are cellar water that comprises Nietvoorbij Dam water plus tap water, as well as Plankenbrug River water. This water has not been tested yet, but would be expected to dilute or meet the overall nutrient content of the Nietvoorbij Dam. The Plankenbrug River has a known history of bad water quality (nutrients, *E. coli*). Outgoing water for irrigation is extracted from deeper areas of the dam and will reflect the overall nutrient content of Nietvoorbij Dam. Nietvoorbij's nutrient budget, excluding aquaculture, could be of a slight or medium nutrient-accumulating tendency.

Cape Olive's outflowing water derives from the surface water body and is mainly extracted during layered water body conditions. The inflowing area and the overflow are close to each other so that inflowing water of diluting quality might be washed directly to the overflow without mixing with the whole water body in between, and without much chance to wash nutrients out of the system. However, the wind dynamics of this dam are in favour of a long lake turnover phase. The nutrient budget of Cape Olive is estimated to range from neutral to a slight tendency to nutrient accumulation.

Phosphates that are trapped in the sediments are more likely to be released under anoxic conditions. The dam that is able to tolerate and trap a higher phosphate load will therefore be Cape Olive, whereas Nietvoorbij and Rondawel release high portions of phosphorus into the lower water body during the stagnation phase, which, in those two cases, is almost synonymous with concurrent oxygen depletion conditions (high accumulation of nutrients at the bottom that attract oxygen-consuming bacteria and favour decomposing conditions), a factor that either reflects the initial dam conditions, with natural eutrophication plus agricultural influence, or the conditions created by fish farming.

5.3.5 Comparison of model with simplified calculation

A model independent calculation of phosphorus retention by trout cage aquaculture is attempted on the basis of the mixing pattern of South African storage dams and observations on outflowing mechanisms.

The waste production of 5 tons of trout consists of about 80 kg of net phosphorus input into the water (Beveridge, 1996) if a FCR of 1.5 with commercial trout feed is achieved. The phosphorus retained by the fish and removed during harvesting is not included in this figure, which includes waste resulting from uneaten pellets, faeces and excretion.

The 80 kg of P dilute into a winter mixing water body and can therefore probably be assumed to be mixed evenly. Without further water extraction and nutrient removal (which happens via overflow in winter or irrigation activities in summer), the addition of phosphorus to the existing phosphorus content of the water body will be extremely high, as is shown in Table 5.5. The total phosphorus value of Rondawel (73 µg/L) would be augmented by an additional 49 µg/L; in Nietvoorbij, 8 µg/L of phosphorus released from aquaculture remain in the winter as dissolved component in the mixed water body, and 11 µg/L remain at the Cape Olive site.

The calculations for the net P addition was undertaken stepwise. Water level changes could not be considered, but timing of inflow and outflow as well as the different phosphorus levels was considered. One assumption that was still required was that the inflowing water mixes completely with the water body before it is extracted, which is the case at Rondawel and Nietvoorbij, but not at Cape Olive where both inflow and outflow occur during winter, in close proximity to one another.

Table 5.5: Theoretical addition of diluted P to the water body with five tons of trout production. Data of rows 1 to 3 as in model. Data of row 4 from Table 4.1 in Chapter 4. Data for rows 6 and 7: see Material and Methods, Chapters 2 and 5 (own data). The inflowing water TP levels represent an average of six measurements at Rondawel and Nietvoorbij and fourteen measurements at Cape Olive (2006 and 2007). The outflowing (overflow) water TP levels are based on an average of ten measurements at Rondawel, eight measurements at Nietvoorbij and six measurements at Cape Olive). Rows 5 and 8 to 12 are calculations following rules of basic mathematical operations (sums, ratios, percentages).

	Rondawel	**Nietvoorbij**	**Cape Olive**
Average volume in m^3	65.000	190.000	450.000
Surface	1.7 ha	4.0 ha	7.5 ha
Existing TP levels (study period average) in µg/L	73 µg/L	76 µg/L	70 µg/L
% of P retained by sediment (ratio of the water dissolvable P fraction to the TP in sediment)	96%	98%	94%
80 kg P dissolved in dam volume with x% retained by the sediments (in µg/L) without water exchange	49 µg/L	8 µg/L	11 µg/L
TP levels of inflowing water	90 µg/L	95 µg/L	57 µg/L
TP levels of outflowing water (majority)	50 µg/L	55 µg/L	60 µg/L
Water exchange rate	0.60 /yr	0.56 /yr	1.34 /yr
P gain dam independent of aquaculture	1 µg/L	1 µg/L	-4 µg/L
P gain total	50 µg/L	9 µg/L	7 µg/L
Percentage of P gain that can be attributed to aquaculture	98%	89%	100%
% of TP gain in relation to the TP steady state	+ 68% (of which 67% by aquaculture)	+ 12% (of which 11% by aquaculture)	+ 10% (of which 100% by aquaculture)

At the Rondawel Dam Stellenbosch production site, 60% of the dam water is exchanged annually and the incoming water enriches the water by a net gain (the difference between in- and outflow) of 40 µg/L. The reason for this is the winter addition, but summer extraction of water, with different nutrient distributions within the dam during these two seasons. As a result, the nutrient rich bottom water during summer does mostly remain in the dam whereas water of a lower nutrient content is extracted. Most of the 40 µg/L was assumed to disappear in the sediment trap as was assumed for the aquacultural waste. The total net gain of nutrients per year (related to the full water body) would be 68% (see Figure 5.5) of the steady state level, 67% of which, according to the outcome of these simple computations, could be attributed to aquaculture (this increase could unfortunately not be compared to the one-year period in which total phosphorus levels were monitored – see Table 4.21 Chapter 4).

At Nietvoorbij Dam, the second site in Stellenbosch, the net gain of nutrients entering the dam is much lower (dilution effect of greater total volume and better adsorption of phosphorus by the sediment), so that a 12% addition of TP to the average TP levels per year seems to take place, most of which ascribable to the aquacultural input.

At Cape Olive, the natural phosphorus balance of the dam appears to be negative, which automatically suggests that any further addition shifting the balance to phosphorus gain would be attributed to aquaculture or changed quality of inflowing water. The total addition of phosphorus in relation to the average TP levels in the dam would be 10%.

These results indicate that the production of a 5-ton unit of trout at Nietvoorbij and the Cape Olive Dam respectively adds about 12% and 10% TP to the levels of the dams per year, which gives them a few more production years before the 100µg/L threshold suggested by DWAF regulations would be reached (DWAF, 1996b). At Rondawel only the results clearly suggest that the project should be ceased because of the high impact aquacultural waste seems to have on such a small body of water.

5.4 Discussion

Models are simplified tools to simulate complex systems. The weakness of the Phillips and Beveridge model lies with its assumptions about equally distributed nutrients throughout the water body through water exchange that brings in and takes out the given steady state phosphorus levels. These assumptions would probably fit most easily in natural lakes with low water exchange rates. If inflowing water quality and outflowing water quality differ exceedingly from the average steady state conditions, which seems to be the case with most of the irrigation dams investigated during this study, the model can over- or underestimate.

Caution should be applied with the outcome of the model in the sense that the model was not originally intended to serve as predictive tool for aquacultural impact. The precautionary principle should always overrule the result of the model and would therefore suggest even lower stocking rates than the model outcome does.

5.4.1 Rondawel

The model's results (see Table 5.1) postulate clearly that production to the scale of five tons of trout in a dam with the water exchange rate of the Rondawel Dam is not ecologically viable. Even under idealised conditions, the maximum carrying capacity of the dam would allow a production of less than 0.2 tons per year (which is not cost-efficient from an economic point of view) if production only added 10% to the existing phosphorus levels per year (precautionary rule) (see Table 5.1). Even if the calculation from the model allowed phosphorus introduction from aquaculture to a limit of 100 µg/L in one season, instead of gradually over years, production of only 1.7 tons of fish would be recommended.

Rondawel's carrying capacity has clearly been exceeded in the past. The consequences involve a high total phosphate load (although still similar to most other dams), as well as a generally high nutrient load at the sediment level.

The surrounding water quality conditions in Rondawel, such as the oxygen depletion in the bottom water (and in the surface water during low water level phases), the high nutrient load from inflowing water, the relatively lower nutrient load of outflowing water, the second turnover in summer induced by very low water levels and the phytoplankton composition that is dominated by cyanobacteria (Maleri, 2008) confirm that the dam is highly unsuitable for cage trout production on the scale applied in the past.

The issue of whether the present conditions have resulted from past trout production or had been established before the project was started, when site selection was not optimised and supported by water quality controls yet, was unfortunately not documented in existing water quality data. The sustainable production of Rondawel was estimated to be 100 to 200 kg per year (average and best case scenarios).

These results are confirmed by the phytoplankton biomass and composition in the dam as well as the surface oxygen problems encountered during production in this dam, with mortalities of 30% of the stocked fish in the season of 2004. The additional calculation suggests that 67% of phosphorus added to the total phosphorus content within Rondawel per year is caused by aquacultural waste.

5.4.2 Nietvoorbij

Nietvoorbij is the oldest trout cage project of the Hands-On cooperative that is still in production and would therefore be expected to be the most likely one to show accumulative effects. In comparison to most other dams, the phosphate levels of Nietvoorbij during the turnover phase are indeed among the highest that were measured. The scope for further phosphorus addition into the water body is therefore small and would not allow grow-out of trout on a cost-effective scale if the upper limit (100 µg/L TP) should not be exceeded. Production of only one ton of trout per season is suggested by the model, and only under idealised conditions if water quality should not reach the limit of 100 µg/L total phosphate during turnover phase on a permanent basis (see Table 5.2)

Data from 1999 show that soluble reactive phosphate levels during the turnover phase in that year (average for May to September) were about 43 µg/L P, while the levels were 37 µg/L on average during the same time period in 2006. Unfortunately, total phosphorus levels for 1999 are not available and srp levels are influenced by many factors, such as uptake and release by bacteria, phytoplankton, macrophytes and zooplankton.

Observations on phytoplankton and zooplankton assemblages in the dam confirmed the relatively high eutrophic level of the water body (high phytoplankton biomass, low phytoplankton species diversity, many microzooplankton species, such as protozoans, instead of meso- and macrozooplankton). Severe oxygen problems could so far not be observed during trout production, but critical levels were reached briefly (3.8 mg/L at the surface in September 2006). Production in the dam had been doing fairly well, and continuously so over the last 10 years. The relatively high FCR of 2.2 in 2006 was attributed to suboptimal feeding and introduced a lot of additional unused food into the dam. Despite that, the growth rate of the fish was among the slowest 20% of the 21 Hands-On production sites, maybe indeed a sign of the water quality conditions affecting fish wellbeing. Optimal pigmentation was also not reached in 2006 (a score of 27 with the Salmo-Fan, while 28 is requested by the processing industry).

The results of the additional calculation seem to reflect the 10-year production success that Nietvoorbij has generated, as well as the finding, in Chapter 4 (see Figure 4.20), that the soluble reactive phosphorus content had increased significantly over the last 10 years when stating that the TP levels introduced by aquaculture were still at an acceptable level.

5.4.3 Cape Olive

Cape Olive is the most suitable of the three exemplary dams for trout production and also the one with the best overall water quality. According to the model, only 1.3 tons should be produced per season to add only about 10% of P to the existing total phosphorus level (precautionary principle applied). Overall, the dam has a capacity to produce another 29.2 tons of trout before the upper limit of 100 µg/L inorganic phosphorus is reached on a permanent basis (see Table 5.3).

The current water quality situation must be described as lightly eutrophic. Due to high TSS levels and the TN:TP ratio, the phytoplankton is dominated by cyanobacteria in great abundance and low species richness. The dam suffers at times from a high total suspended solids level and consequent low visibility due to the sediment load (due to the nature of inflowing water as well as inflow mechanics).

The results of the additional calculation are in accordance with the results of the model. The 10% threshold is reached by aquacultural waste introduction, which is an acceptable level within the application of the precautionary principle, and the full capacity of the dam will therefore be limited by the reaching of TP levels of 100 µg/L on a permanent basis.

Dams like Cape Olive can confidently be used for trout cage production if ambient water quality conditions and long-term effects are consistently monitored. The model outcome suggested lower production levels than 5 tons, however, after 5 years of production, no phosphorus accumulation was manifested in the sediments (see Table 4.1).

Given the natural phosphorus balance of the dam, what seems very important is that gap years in production could really improve the water quality of the dam.

5.5 General discussion

Great caution has to be applied in site selection (ecology as well as hydrology of the dam) for trout cage aquaculture to maintain sustainable water quality levels to fulfil environmental requirements as well as secure future water use for irrigation and aquaculture itself. Only optimal site conditions combined with low feed conversion ratios and an adapted production size can ensure sustainable long-term trout production. Compliance with the present regulations is crucial.

The results of the model are fairly similar to stocking recommendations from different other entities. The Australian guideline for trout aquaculture in unmanaged irrigation dams with a low water exchange rate (no active aquacultural waste removal) recommends growing a maximum of 375 kg trout per ha of dam surface size (Gooley & Gavine, 2003). Accordingly, Rondawel would be recommended to grow a maximum of 565 kg per year, Cape Olive would be able to support about 2 tons and Nietvoorbij 1.4 tons. These guidelines are aimed at long-term sustainable production conditions. The Beveridge and Phillips model outcomes resulted in 200 kg, 1.3 tons and 1 ton respectively (35%, 65% and 71% of Australian levels) and therefore seems to be estimated more cautiously than the Australian recommendations.

In Iran, 2 to 4 tons of rainbow trout were produced in mountain ponds of 0.4 to 0.75 ha n size (Coad, 2007). However, the water exchange rate in these water bodies was 10 to 20 days. This would translate into 200 to 400 kg/ha in dams with an exchange rate of less than once to twice per season. These are no regulations, but current sustainable production levels in that country. A dam with a retention time of 90 to 360 days (like the three production sites in the Western Cape) should therefore have a size of at least 10 ha (320 by 320 m) to carry 5 to 6 tons of trout sustainably. This, again, would suggest that, despite the low cage stocking density of about 6 kg/m^3 (compared to 30 and 40 kg/m^3 in intensive marine cage farms), 50% of the small-scale farmers' projects (Hands-On) have been overstocked to different degrees with regard to the self-cleaning capacity of the dam environments and are not sustainable over the long term at present. This is mainly due to the high water retention times of most irrigation dams.

For rainbow trout production, the FAO (2007) recommends only using sites that allow a year-round (production season) supply of 1L per min per kg trout in systems without additional aeration. For the production of 5 to 6 tons of trout, a continuous inflow of 5 m^3/min would therefore be required, which amounts to a total inflow of about 1 million m3 of water during a 5-month grow-out period. This would require a water retention time of 10 days for Rondawel, 55 days for Nietvoorbij and 128 days for Cape Olive. In the case of aerated systems, the water inflow, by a recommendation released by the FAO (2007), is permitted to decrease to 1.5 m^3/min for the production of 5 tons of trout, or a total of about 320,000 m^3 inflow during a 5-month production period.

Rondawel and Nietvoorbij experience production problems or reduced growth rates and some indications of suboptimal water quality conditions affecting the trout. They also happen to be the two dams not recommended for aquaculture if the model outcome is adhered to, with Nietvoorbij showing better suitability for production according to the additional calculation. The model results for Cape Olive suggest reduced production levels, but indicate that production is feasible in that dam if it is undertaken with caution.

5.6 Conclusions

According to the model and other calculations and comparisons, only two of the three production sites would be suitable for the applied level of trout cage production, a result evident from practical production experience. According to an Australian guideline, the conditions pertaining to successful production levels in Iran and FAO recommendations, only Cape Olive Dam would be able to support the grow-out of 5 to 6 tons of trout per year, and Nietvoorbij would do so with more caution and insecure long-term sustainability. Water deterioration was not proven directly during the study period (see Chapter 4), but reports have indicated conditions of risk involving production setbacks in the form of oxygen surface depletion or algal taint in trout at some sites (Rondawel). Successful production in terms of production figures was reported for Nietvoorbij and Cape Olive by Hands-On management (concerning target fish size achieved, no algal taint, low mortality rates).

Total dam volume (or surface area) and water exchange rates are factors that need serious consideration in site selection processes, as is the initial trophic status of the dam (this is most safely determined from bottom water conditions during the stagnation phase).

Cape Olive and Nietvoorbij, according to the model and, more specifically, an additional calculation, will be able to continue to produce fish for between 5 and 10 years before water quality conditions will most probably force production to be discontinued because of intensifying problems. After that period, sediment removal might be an option, or, in the case of Cape Olive, an extended regeneration period.

The production in smaller irrigation dams (< 10 ha) could be stabilised and restricting limitations further defused if strategies for efficient nutrient removal were followed. Surface water aeration and bottom water aeration are mitigating measures only; what should be aspired to, is nutrient removal from the systems. Nutrient-rich sludges can be applied as fertiliser elsewhere, which would provide a means of reducing the high cost of their removal. Less efficient, but of additional economic value would be the application of polyculture systems with nutrient-removing species such as freshwater mussels, waterblommetjies (water hawthorn – *Aponogeton distachyos*) or specific macroalgae.

6 INTERACTION BETWEEN AQUACULTURE AND IRRIGATION ACTIVITIES IN THE WESTERN CAPE, COVERING BENEFICIATION AND DETRIMENTAL EFFECTS

6.1 Introduction

With a highly unpredictable rainfall pattern and an average annual precipitation of less than 500 mm, South Africa is described as a semi-arid country and therefore relies on irrigation for consistent and reliable crop production (Davies & Day, 1998; Prinsloo et al., 2000). Apart from climatic conditions, a rapidly increasing population also puts pressure on the agricultural sector to provide sufficient food products and consequently increases the demand for irrigation. Currently, the annual water usage in South Africa is 22,400 million m^3, about 60% of which are applied for irrigation purposes (Van der Merwe, 2001).

Irrigation may refer to frequent and regular application of water or a single annual watering. Weisner (1970) defines irrigation as "the practice of applying water to the soil to supplement the natural rainfall and provide moisture for crop growth". Irrigation regimes can be divided into three categories: supplementary, complete (permanent) and protective (opportunistic). Supplemental irrigation is applied where rainfall is adequate but improved quality and quantities of crops are required. Complete irrigation is applied where rainfall is low and the bulk of crop needs must be met. Protective irrigation is implemented if there is a risk of inadequate rainfall. Currently, supplementary irrigation in South Africa comprises 14%, full-scale or permanent irrigation 78% and opportunistic irrigation makes up the rest (DWAF, 1996a).

As a major consumer of water, the irrigation sector should increasingly be involved in the development of efficient and conserving ways to use irrigation water. Possibilities include the development and implementation of low-volume water irrigation systems such as micro-irrigation (trickle, drip) systems. At present, about 18% (140,000 ha) of cultivated land is under micro-irrigation, with the majority of irrigation practices still comprising conventional sprinkler and flood irrigation methods (DWAF, 1996a). However, all the farms included in this study make use of micro-irrigation, a more and more applied irrigation practice, especially in the Western Cape region.

Micro-irrigation systems can be described as the frequent application of water at small flow rates directly to the root zone, on top or below the soil surface. This method of irrigation has many advantages, the most important being the smaller amounts of irrigation water required and the direct application of water to the root zone. Direct application to the root zone minimises loss of water through evaporation, which makes micro-irrigation especially suitable for warm and dry regions where water supplies and rainfall are limited. A typical micro-irrigation system layout consists of an extensive network of distribution lines and pipes. Water is distributed from the water source via a main line to the sides of the block of crops to be irrigated. From there the water is delivered to the specific part of the field via submains (manifolds) and then to the lateral lines (water delivery pipes). The outflow is through emitters or nozzles that are located along the lateral lines (water delivery pipes). The emitters or nozzles are placed either above or below the soil surface.

Due to the small emitter sizes of low-volume water irrigation systems, components are more sensitive to problems arising from poor water quality than other conventional irrigation system components. Currently, various treatments are used to ensure water quality improvement before it reaches sprinkler nozzles and emitters. Treatments are implemented to ensure optimum water quality despite continuing year-round changes in the physical and chemical characteristics of the source water. These treatments include settling basins, centrifugal separators, disc filters, screens, sand media filters and chemical treatments with chloride or acid (Phillips, 1993).

Micro-irrigation systems are also more sensitive to encrustation, clogging and corrosion. The risk of clogging of the micro-sprinklers or drip-emitters is a major maintenance problem in micro-irrigation, even without the additional influence of aquaculture. Clogging is caused by various contaminants that can be categorised as physical factors (e.g. suspended solids), chemical precipitation (e.g. iron oxide) and biological factors (e.g. aquatic plants, bacterial growth). The degree to which clogging occurs, depends on the quality of the water source regarding the presence of these clogging factors. Poor water quality resulting from higher loads of suspended solids and algae numbers requires higher filtration capacities and calls for more frequent back flushing. This increases operational and maintenance costs. Capital expenses are also increased by the replacement of components that are affected by the abrasive action of particles (Capra & Scicolone, 1998).

Physical components such as suspended solids can disable an irrigation system by clogging emitters. Sand particles (50–250 μm) in irrigation water will be removed through filtration but smaller clay (<2 μm) particles will pass through, causing damage to emitters (Koegelenberg et al., 2002). During fish production, large amounts of organic matter in the form of unconsumed feed and metabolic waste are deposited directly into the water, adding to the suspended solids concentration. The optimal target water quality range for suspended solids pertaining to clogging of irrigation components is 50 mg/L (DWAF, 1996a).

Table 6.1: Classification of micro-irrigation clogging factors and their clogging potential according to Bucks et al. (1979).

Clogging factor	Unit	Hazard rating Minor	Moderate	Severe
Physical				
Suspended solids	mg/L	< 50	50–100	> 100
Chemical				
pH		< 7	7–8	8
Dissolved solids	mg/L	< 500	500–2 000	> 2 000
Manganese	mg/L	< 0.1	–1.5	> 1.5
Total Iron	mg/L	< 0.2	–1.5	> 1.5
Hydrogen sulphide	mg/L	< 0.2	–2.0	> 2.0
Hardness (CaCO3)	mg/L	< 150	150–300	> 300
Biological				
Bacterial number	Ind./mL	< 10 000	10 000–50 000	> 50 000

Chemical clogging occurs due to the interaction between dissolved ions to form precipitates in the water. The major dissolved solids to form precipitates include calcium and magnesium carbonates, as well as iron and magnesium components. Calcium and magnesium carbonate occur naturally in water and are related to the underlying geology and bottom soil characteristics of the catchment area. Scaling or encrustation is the precipitation of calcium or magnesium carbonate within the closed irrigation system and the degree to which scale forming takes place is strongly related to the pH of the water. If the pH of the water exceeds 7.5, calcium and magnesium (concentrations exceeding 50 mg/L) are likely to precipitate out of the water, forming calcium or magnesium carbonates. The scale forming potential of irrigation water can be predicted by the Langelier Saturation Index and Ryznar Index and are based on calcium concentration, alkalinity and other relevant factors such as pH and temperature (DWAF, 1996a; Koegelenberg et al., 2002). Iron is known to cause problems as a greyish precipitate, especially in the presence of iron-reducing bacteria. Under anoxic conditions, iron oxides are reduced to ferrous iron, the dissolved form of iron. Iron contents of less than 2 mg/L will not cause problems with irrigation systems (Bucks et al., 1979; DWAF, 1996a).

When the water source is under saturated of calcium and magnesium, it is known to be corrosive or aggressive. Aggressive water attacks unprotected irrigation structures and results in premature replacement of metal irrigation components. The Aggressiveness Index can give an indication of the water's corrosive character (DWAF, 1996a; Koegelenberg et al., 2002). The degree of aggressiveness is subjected to the reigning pH values of the water source. During the day pH levels will rise as aquatic plants and phytoplankton remove carbon dioxide and produce oxygen during photosynthesis. During night time the pH levels drop as photosynthesis ceases and the production of CO_2 by all aquatic organisms and plants continues. The higher fish stocking densities of fish farming and greater inputs of organic material by fish feed and metabolic waste require more oxygen for decomposition. Higher decomposition rates, fertilisers entering the aquatic environment and chemical additives ultimately result in great fluctuations in the pH of the water source. All effects on pH are also enhanced by the overall low alkalinity levels.

Another potential source of emitter clogging includes biological factors such as aquatic organisms (insects, algae, zooplankton), bacteria and microbial activities. Algae are found naturally in all aquatic environments and occur as single cells, as groups of cells (colonies) or as intricate branched filaments. Algal growth is mainly dependent on the availability of nutrients (nitrogen and phosphorous) in the water. If nutrient concentrations become excessive, epilimnetic total algal biomass increases. During fish production additional nutrients are added to the water in the form of uneaten fish feed and metabolic waste. Apart from the advantages of utilising nutrient enriched water for irrigation, this enrichment can have a stimulatory effect on the growth of nuisance plants and algal blooms. Nitrogen concentrations exceeding 0.5 mg/L inorganic nitrogen-N can begin with occasional growth of nuisance plants and blue-green algae within irrigation structures (valves, pipelines, sprinklers, filtering equipment) (DWAF, 1996a). When washed through filters, lateral lines and emitters, high algal biomass gives rise to clogging problems. In a technical report by Eurodrip (1999) an investigation found that the main genera to cause clogging included *Cyclotella* spp., *Cymbella* spp., *Fragilaria* spp., *Melosira* spp., *Navicula* spp., *Synedra* spp., *Spyrogyra* spp., *Mougeotia* spp., *Oscillatoria* spp. and *Peridinium* spp. (Koegelenberg et al., 2002). Current methods for controlling and minimising clogging by algae and bacterial growth include filtration, chlorination and acid treatments of irrigation water (Nakayama & Bucks, 1991; Koegelenberg et al., 2002).

Cage aquaculture is on the way to be adapted for its application in Western Cape irrigation dams. During the irrigation season after the introduction of aquaculture in several trial dams, farmers complained about blocked filters, the more frequent necessity for backwashing and cleaning of filters and failing filter systems. Approximately 23% of the 21 Hands-On production sites reported filter blockage in their irrigation systems in the season following fish production (which was randomly collected information and might be underrepresented). Frequent changes on the managerial level voiding experience and knowledge as well as missing records on filter cleaning and backwashing frequencies hinder a scientific comparison of historical with present conditions. The present study therefore concentrates on likely effects of aquaculture on water quality and the translation of these changes to prevailing difficulties with irrigation systems.

This chapter reports on the suitability of irrigation water dams containing cage aquaculture, with the main focus on the influence on irrigation equipment. The emphasis will be on factors that are both responsible for corrosion and clogging effects and that may be influenced by the presence of fish production. The objective is to evaluate whether water quality characteristics from current aquaculture projects fall within target water quality values suggested in the studies by Bucks et al. (1979), Koegelenberg et al. (2002), and DWAF (1996a) (see Table 6.1). A secondary aim was to identify the phytoplankton communities present that could cause blocking of irrigation filters and emitters.

The Impact on irrigation water has not been quantifiable, but independent reports on 30% of all small-scale farming projects (more than 20 dams) provided anecdotal evidence of negative changes in water quality to levels that have not been experienced before aquaculture was introduced. Tainting of drinking and irrigation water (by hydrogen sulphide or bottom cyanophytes as well as food residues) has been observed.

6.2 Materials and methods

All the study sites in the Western Cape (see general introduction) make use of ring filters that are implemented both as primary and as secondary filters or in conjunction with sand filters as primary filters (personal communication with farmers). On the research sites in the Western Cape, irrigation water is extracted at a fixed level of one to two metres below the water surface at the studied sites. An alternative practice, more common in newly constructed dams, is bottom water extraction. In both cases, water is withdrawn and then pumped to a nearby pump-house where filtration takes place. The filtration process is composed either of sand filters (filtration potential of 75–80 µm) as primary filters and ring filters as secondary filters, or two consecutive ring filters. Ring filters are often distributed at various points between fields of crops or vines. From the ring filters, water is directed to the lateral pipes for water delivery to the respective fields.

Irrigation activities are only in place during warmer summer months when rainfall becomes irregular. From October, irrigation commences with two to three hours per day. The duration of irrigation is slowly increased up to 24 hours per day in the months from November to March. Irrigation activities are terminated with the harvesting of crops or when the winter rains start in May. Backwashing of sand filters takes place approximately four times a day, whereas ring filters are cleaned after each irrigation interval during peak irrigation season (personal communication from farmers).

6.2.1 Sample collection and preservation

Water samples from production sites (key sites) and control sites in the Western Cape were taken and analysed for factors that may have an influence on the irrigation water quality. Water samples were taken at a fixed sampling station in the dam at approximately 30 cm below the surface of the water. After collection, samples were stored at 4°C until further chemical analysis continued on the following day (Lind, 1979; Wetzel & Likens, 2000). Additional water samples were preserved with mercury chloride ($HgCl_2$) and analysed by the Department of Water Affairs and Forestry for trace metals and major inorganic determinants.

Phytoplankton samples were collected during the irrigation season between October 2005 and March 2006 (see Chapter 4). In November 2005, samples were taken from the inside of various ring filters to determine the types of algae that could contribute to rapid clogging of filters. Samples were obtained by scraping the surface of individual rings within the ring filter and were preserved with Lugol's solution (Lind, 1979; Entwisle et al., 1997).

6.2.2 Sample analysis

Water samples were analysed for water quality parameters that could lead to clogging, corrosion and encrustation of micro-irrigation components. Water quality parameters included suspended solids, dissolved solids, iron and pH. Total suspended solids (mg/L) were determined using a HACH colorimeter (DR/700 and DR/890 colorimeter). The pH values were measured by means of a Hanna pH 211 microprocessor and dissolved solids were determined using a HACH CO 150 conductivity meter (see Table 4.1). Major inorganic determinant and trace metal content was determined by DWAF laboratories in Pretoria. The Langelier Saturation Index, Ryznar Index and Aggressiveness Index were used to calculate and predict the likelihood of scale formation and corrosion (DWAF, 1996a; Koegelenberg et al., 2002) (see respective formulas in Appendix Table 10.1). Water quality classifications proposed by Bucks et al. (1979), Koegelenberg et al. (2002) and DWAF (1996a) were used to evaluate the suitability of source water for irrigation applications.

The Langelier Saturation Index (LSI) provides an indicator of the degree of saturation of water to release protons by using the equilibrium between the following equations: $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ and

$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$. Calcium and magnesium carbonates are the main contributors to scaling and protons the main contributors to corrosion. Parameters influencing the Langelier Saturation Index were pH, TDS, calcium content, alkalinity and temperature. The Ryznar Stability Index (RSI) correlates scale thickness observed in municipal water systems to water chemistry and therefore predicts scaling. It is based on the Langelier Saturation Index, laying more emphasis on the given pH. The Aggressiveness Index (AI) is based on alkalinity, hardness and pH, and gives an indication of the likely degree of scaling or corrosion.

With all three indexes, the pipe or water flow material has to be considered as well. Farms with metal or concrete structures are more likely to experience the water effects predicted by the three indicators.

Phytoplankton samples from ring filters were investigated by using a Zeiss inverted microscope with magnification ranging between 125x and 787.5x (Hötzel & Croome, 1999). Due to the high pressure created within the ring filters during filtration and the presence of particulate matter, most of the phytoplankton species were distorted. Intact species were analysed qualitatively and identified to genus level. The keys refer to the methodology section of Chapter 4.

6.3 Results

6.3.1 Rondawel

Rondawel's water analysis shows that iron and manganese contents are very low and prohibit clogging of irrigation components (see Tables 6.1 and 6.2). Table 6.2 shows that the calcium and magnesium content of the water was less than 50 mg/L, ranging between 11–13 mg/L (or less than 20 mg/L, as accumulative scaling risk) and promoting the low hardness levels of less than 100 mg/L $CaCO_3$. Even the high pH readings during December 2005, April 2006 and January 2007 could not promote the formation of chemical precipitation due to these cation levels. Total dissolved solids ranged between 83 mg/L and 134 mg/L, which indicated only a minor hazard of clogging (< 500 mg/L).

Table 6.2: Water quality parameters of Rondawel Dam contributing to corrosion or scaling of irrigation systems.

Date	TSS	pH	Fe	TDS	Mg	Ca	Mn	Hardness
	mg/L		mg/L	mg/L	mg/L	Mg/L	mg/L	mg/L
Dec–05	9	8.8	0.01	83	5	11	0.002	48
Apr–06	12	9.1	-	103	7	11	-	56
May–06	20	7.3	-	98	8	11	-	63
Jul–06	15	7.8	0.06	134	7	13	0.001	61
Jan–07	-	9.2	-	121	-	12	-	50

The Langelier Saturation Index shows that the water of Rondawel was balanced during the sampling events of December 2005 and April 2006, with a possibility of pitting corrosion in the irrigation season 2006/2007. Although the pH values during these two samplings exceeded 7.5, low hardness values and calcium and magnesium content of the water inhibit scale-formation, while overall low cation contents increase the risk of corrosion. During May 2006 and July 2006 the index predicted water of slightly corrosive character (corrosion in the sense of degradation).

The Ryznar Index for all the sampling events confirmed a rather corrosive character of the irrigation water (dam water) in summer, and an even more corrosive character in winter (when irrigation is not taking place). A positive tendency was shown towards the summer of 2006/2007, when irrigation water was less corrosive.

January 2007 experienced a high pH of 9.2, which would actually make the water more prone to scale formation. The Aggressiveness Index for Rondawel indicated that the water was moderately aggressive during the irrigation season 2005/2006, but non-aggressive one year later, when the Ryznar index had also decreased.

Table 6.3: Likelihood of Rondawel Dam irrigation water causing scale formation or corrosion. Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressiveness Index (AI).

Date	LSI	RSI	AI
Dec–05	-0.02	8.84	11.86
Apr–06	0.26	8.54	12.33
May–06	-1.45	10.2	10.75
Jul–06	-0.98	9.76	11.17
Jan–07	0.81	7.59	12.71

6.3.2 Glenbawn

Table 6.4: Water quality parameters of Glenbawn Dam contributing to corrosion or scaling of irrigation systems.

Date	TSS	pH	Fe	TDS	Mg	Ca	Mn	Hardness
	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dec–05	4	8.8	0.027	85	5	10	0.002	46
Apr–06	28	9.0		69	5	7		38
May–06	24	7.6		65	4	6		31
Jul–06	12	6.7	0.106	73	4	5	0.001	29

The iron, manganese and especially calcium and magnesium levels were similarly low in Glenbawn and Rondawel, which therefore also showed inhibition of the likeliness of scale formation or clogging at Glenbawn (see Table 6.4). The indicators for corrosiveness were rather more distinct (Langelier Index and Ryznar Index), especially in winter 2006. Accordingly, the Aggressiveness Index suggested higher aggressiveness during the winter months.

Table 6.5: Likelihood of Glenbawn Dam irrigation water enhancing scale formation or corrosion. Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressiveness Index (AI).

Date	LSI	RSI	AI
Dec–05	-0.12	9.0	11.8
Apr–06	-0.03	9.0	12.1
May–06	-1.59	10.8	10.6
Jul–06	-2.70	12.1	9.5

6.3.3 Nietvoorbij

Table 6.6: Water quality parameters of Nietvoorbij Dam contributing to clogging, corrosion or scaling of irrigation systems.

Date	TSS	pH	Fe	TDS	Mg	Ca	Mn	Hardness
	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dec–05	8	8.8	0.04	83	11	20	0.002	95
Apr–06	9	7.8	-	213	12	21	-	102
May–06	31	8.0	-	196	13	22	-	108
Jul–06	15	7.6	0.1	225	11	21	0.001	98
Jan–07	-	9.0	-	224	-	20	-	84

The physical and chemical conditions of Nietvoorbij are summarised in Table 6.6. The alkalinic pH levels in summer indicate increasing problems with foliar damage from pH levels higher than 8.4 (DWAF, 1996a). Over the long term increasing problems with unavailability of micro- and macro-nutrients in plants could be experienced with alkalinic pH levels (DWAF, 1996).

From the water analysis it appears that the iron and manganese concentrations fell below the proposed standards and may have a minor clogging potential. The calcium and magnesium concentrations (11–13 mg/L) that were measured did not exceed 50 mg/L and would not give rise to calcium carbonate precipitation and clogging of equipment, not even with pH levels higher than 8 as during December 2005. The hardness of the Nietvoorbij Dam was below 110 mg/L during all the sampling events and supported the low clogging potential. The suspended solids content of the water may cause a minor hazard of clogging, especially of emitters, and especially in connection with phytoplankton growth.

Table 6.7: Likelihood of Nietvoorbij Dam irrigation water enhancing scale formation or corrosion. Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressiveness Index (AI).

Date	LSI	RSI	AI
Dec–05	0.18	8.44	12.2
Apr–06	-0.38	8.56	11.7
May–06	-0.28	8.56	11.9
Jul–06	-0.69	8.98	11.5
Jan–07	0.79	7.22	12.78

The results of the three indicator systems for Nietvoorbij are collated in Table 6.7. During the December 2005, April 2006 and May 2006 sampling the Langelier Saturation Index was seen to fluctuate between -0.7 (winter) and 0.8 (summer), specifying that the water was slightly favourable to corrosion in winter.

The Ryznar Index for all the sampling events was always higher than 7, therefore suggesting and confirming the rather corrosive tendency of the water. After additional calculation of the Aggressiveness Index it was found that the water was non-aggressive (≥ 12) in summer, and moderately aggressive (10.1–11.9) during winter when irrigation is usually discontinued.

6.3.4 Cape Olive

Table 6.8: Water quality parameters of Cape Olive Dam contributing to clogging, corrosion or scaling of irrigation systems.

Date	TSS	pH	Fe	TDS	Mg	Ca	Mn	Hardness
	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L $CaCO_3$
Dec–05	14	7.2	0.03	35	2	2	0.003	13
Apr–06	17	7.3	-	38	2	2	-	13
May–06	39	7.1	-	38	2	3	-	16
Jul–06	33	7.1	0.01	42	1	3	0.001	12
Jan–07	-	8.5	-	84	-	3	-	14

From Table 6.8, we can extrapolate that the iron and manganese levels in Cape Olive are within the proposed water quality standards and may only pose a minor hazard for clogging. The results also indicate that the calcium and magnesium content of the water does not exceed 50 mg/L and poses no threat of clogging. The hardness of Cape Olive is very low; accompanied by very low calcium and magnesium levels, there will be have a minor hazard of clogging, while rather favouring corrosion.

Table 6.9: Likelihood of Cape Olive Dam irrigation water enhancing scale formation or corrosion. Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressiveness Index (AI).

Date	LSI	RSI	AI
Dec–05	-2.86	12.92	9.22
Apr–06	-2.84	12.98	9.32
May–06	-2.76	12.62	9.38
Jul–06	-2.94	12.98	9.08
Jan–07	-1.10	10.7	10.85

The Langelier Saturation Index calculated for Cape Olive indicated a highly corrosive character of the water with values smaller than -2 at all the sampling events (see Table 6.9). A slight improvement seems to have occurred towards the summer of 2006/2007.

This Ryznar Index confirmed these findings very strongly. The corrosive character of the Cape Olive Dam is brought on by the low calcium and magnesium concentrations, low hardness and neutral pH of the water. With the alkalinic pH measured in summer 2006/2007, the Langelier Index showed a lessened corrosive character. However, the corrosive impact of Cape Olive Dam water is intolerable at all times.

The results of the Aggressiveness Index also verify that the water of Cape Olive is highly aggressive (mostly < 10).

6.3.5 Calais

Table 6.10: Water quality parameters of Calais Dam contributing to clogging, corrosion or scaling of irrigation systems.

Date	TSS	pH	Fe	TDS	Mg	Ca	Mn	Hardness
	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L $CaCO_3$
Dec–05	9	7.2	0.015	33	4	7	0.001	34
Apr–06		7.8		85	5	6		36
May–06	36	7.5		81	2	2		13
Jul–06	14	6.2	0.130	80	4	6	0.023	31

Calais (control site) has lower TSS levels than Cape Olive and would therefore be less prone to causing clogging by soil or sediment particles (sand or clay) (see Table 6.10). Calais also showed higher calcium levels, as well as iron, in the winter of 2006. The hardness is higher than at Cape Olive. Still, the indices (see Table 6.11) suggest that the water character is corrosive rather than tending to scale formation, with especially higher corrosiveness during the winter months (mixing period). If water would be left to stand in the pipes over winter, they might degrade due to pipe dissolution processes (this is highly dependent on the material of pipes).

Table 6.11: Likelihood of Calais Dam irrigation water enhancing scale formation or corrosion. Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressiveness Index (AI).

Date	LSI	RSI	AI
Dec–05	-1.7	10.7	10.2
Apr–06	-1.3	10.4	10.9
May–06	-2.3	12.0	10.0
Jul–06	-3.1	12.4	9.1

6.3.6 Biological clogging at all three sites

Biological clogging due to nuisance plants is not highly likely at any of the five studied sites (see Table 6.12). Minor risks of occasional clogging start with inorganic nitrogen-N levels of 0.5 mg/L and higher (DWAF, 1996a).

Table 6.12: Inorganic nitrogen-N levels (study average) for the five study sites.

	Average inorganic nitrogen-N in mg/L
Rondawel	0.21 ± 0.22
Glenbawn	0.22 ± 0.16
Nietvoorbij	0.25 ± 0.27
Cape Olive	0.24 ± 0.11
Calais	0.22 ± 0.18

The risk of clogging caused by phytoplankton and bacteria seems to be more grave. Table 6.13 lists the phytoplankton species that were found within irrigation material, especially on filters.

Table 6.13: Phytoplankton species contributing to clogging of filters at Western Cape study sites.

Division	Genus	Size (μm)
Dinophyta	*Ceratium* spp.	180
Cyanophyta	*Anabaena* spp.	> 300 (threads)
Chlorophyta	*Spondylosium* spp.	> 550 (threads)
	Dinobryon spp.	> 200 (colony)
Heterokontophyta	*Tribonema* spp.	> 1700 (threads)
	Fragilaria spp.	80–400

Ring filters at studied sites in the Western Cape were inspected before back flushing and cleaning in order to identify species that were too small to be removed by sand filters but would cause a blockage on secondary ring filters and emitters. Samples were distorted and identification to genus level was done, where possible. The algal analysis of deposits on ring filters included species such as *Ceratium hirundinella*, various *Anabaena* spp., *Spondylosium* spp., *Dinobryon divergens*, *Tribonema* spp. and *Fragilaria* spp. All of the species present were larger than the filtration potential of the ring filters of 80 µm. Species such as *Spondylosium* spp. and *Tribonema* spp. observed during routine analysis of water samples reached lengths up to 1.7 mm. *Fragilaria* spp. and *Ceratium hirundinella* were found to be most intact during investigation.

Table 6.14 indicates whether these species were present in the five sampling dams at any time during the study period, primarily from December to March (the main irrigation season). According to presence during these months, the two production sites in Stellenbosch are much more likely to experience clogged filters than the control site (which was dominated by *Gymnodinium*).

At the Drakenstein sites, no species from Table 6.13 occurred during the irrigation months, but *Microcystis* spp. was very abundant, a species that could most likely clog filters temporarily without the possibility of the cause being retrieved and determined from the filters.

Table 6.14: Occurrence of clogging phytoplankton species at the five studied sites

	Species found in the water body
Cape Olive (production site)	*Microcystis*
Calais (control site)	
Rondawel (production site)	*Ceratium*, *Anabaena*
Glenbawn (control site)	
Nietvoorbij (production site)	*Ceratium*, *Dinobryon*

6.4 Discussion

The integration of aquaculture into existing irrigation systems is a relatively recent development in the Western Cape. This integration offers the opportunity for multiple water usage of storage dam water by using it to irrigate crops, to a smaller extent provide drinking water and to produce animal protein. The objective of this chapter was to evaluate the likely effects of dam water on irrigation systems in general (at the five studied sites) and estimate the input of aquaculture in adding to these effects.

TSS levels helped to estimate the potential of physical clogging. The potential of the water to be corrosive (or enhance scaling) was evaluated with the use of several indices to estimate the effects caused by the chemical character of the water. Biological clogging was evaluated via nitrogen content and phytoplankton presence in the water.

At the study sites, heavy rainfall in early winter often results in large amounts of suspended material being washed into the dams. These sediments can cause clogging of emitters and nozzles, but their presence is not enhanced or influenced by aquacultural activities. The suspended solids content measured at all the study sites was below 50 mg/L and consequently only has a minor impact on clogging. Higher measurements of suspended solids at all the sites in May 2006 and July 2006 could be associated with higher rainfall and subsequent runoff, but irrigation water withdrawal is not in place during that period. Clogging in these dams would then be expected to be caused by clay (< 2 µm) at emitter level and by silt (2 to 50µm) and fine sand (50 to 250 µm) in the filter systems (soil texture classes according to Van der Walt & Van Rooyen, 1995). The suspended solids values were especially high in winter when water is not extracted for irrigation and particles have usually settled down before water extraction for irrigation purposes commences.

Previous chapters (especially Chapters 4 and 5) have shown that fish farming leads to higher inputs of nutrients and organic wastes, which result in an increase in the eutrophication level of the dam and may change the dam ecology. Indicators of increased trophic conditions are frequent development of nuisance phytoplankton blooms, great fluctuations in oxygen and pH levels and the release of excess products of biodegradation (e.g. ammonia levels at bottom). Decomposition of excess organic matter depletes oxygen in the bottom layers, creating anoxic conditions. Anoxic bottom water results in a higher release rate of iron from the sediments which is mediated through microbial activity. Increased dissolved iron concentrations in the irrigation water will lead to precipitation of iron oxides in irrigation equipment and will subsequently form blockages in emitters and nozzles. Iron concentrations at the studied areas occurred within ranges that can only cause minor problems (< 0.2 mg/L) with precipitation of iron oxide (rust) and clogging in irrigation structures. The iron concentrations at all the sites showed a higher dissolved iron concentration in winter during the turnover period of the dam than during the summer months. The higher concentration therefore coincided with fish farming, but iron levels (and other nutrients, minerals and trace metals) had settled to the hypolimnion on the sediment during irrigation water withdrawal in summer. Manganese levels were very low (< 0.002 mg/L) at all the sites and therefore would not have added to clogging.

Generally, pH levels for all of the five projects ranged between 7 and 9, therefore also posing minor threats to clogging. Higher pH levels occurred in summer, especially during the stagnation phase; pH elevation caused by phytoplankton would usually be limited to the winter phase when nutrients allow phytoplankton activity in dams of moderate trophic status (lightly eutrophic). However, in hypertrophic dams, phytoplankton activity is high throughout the year, elevating pH levels towards levels between 9 and 10. The low hardness and alkalinity, as well as low calcium and magnesium content of the water do not favour encrustation or scaling even under these alkalinic pH levels.

With biological clogging, the nitrogen content as such does not encourage algal growth within irrigation equipment as indicated by the fact that no difference in inorganic nitrogen levels was detected between production and control sites. Elevated phytoplankton biomass and certain species, however, do increase the blocking of filters (shown in the increased necessity to backwash the filters), which took place at the two Stellenbosch production sites, but not the control site. With higher eutrophic status, the phytoplankton composition in a dam is usually dominated by few species with a tendency of high individual biovolume of the species and increased clogging potential. Rondawel and Nietvoorbij experienced extreme blooms of certain species during summer, with Nietvoorbij dominated throughout by *Ceratium* spp., and Rondawel also dominated by *Anabaena circinalis* and *Microcystis* spp. in summer. The occurrence of these blooms is usually sudden and unexpected and therefore is able to overwhelm filter capacity. Observations by several independent farm managers that backwashing and filter clogging increased with the establishment of aquacultural activity can not be confirmed with the help of scientific evidence, but these reports should not be neglected.

Phytoplankton changes were mostly reported for the smaller production dams (surface area) at the Stellenbosch site. These two dams (Rondawel and Nietvoorbij) have already been described as problematic (especially in Chapter 5). With larger dam volumes, the capacity of a dam to dilute and minimise the effects of aquacultural waste input increases considerably, as with increased water exchange (if inflowing water is less nutrient enriched than the water body).

6.5 Conclusions

Effects of aquaculture on irrigation systems could derive from changes in hardness, alkalinity, pH, increased algal biomass and changed composition, as well as changes in the oxygen conditions at the bottom and subsequent heavy metal and carbonate release. The effects of aquaculture on irrigation water quality were found to be very indirect, however, and not predictable from the given data. Information on activities related to irrigation equipment (the necessity to exchange parts and backwashing of filters) was not consistently recorded at the studied sites and did not allow comparison. The study period may also not have been sufficiently long. Changes that may be suspected to take place would be related to phytoplankton composition and biomass changes and consequent filter blockages.

With respect to inorganic constituents (magnesium and calcium levels) and heavy metal content (iron and manganese), as well as the respective anions such as carbonates (influencing alkalinity), the Western Cape dams contain fairly low levels due to geological background and release. These conditions rather favour the lightly corrosive character of the water (in terms of dissolution of equipment and its degradation). Additional effects from aquaculture influencing the given hardness and alkalinity are minor in comparison with the background levels.

However, pH and phytoplankton biomass can be affected by aquaculture. Elevated pH levels might support the dissolution of pipes, nozzles and emitters, especially if plastic parts are integrated. The Stellenbosch production sites showed phytoplankton compositions that favoured biological clogging. Aquaculture can therefore affect irrigation equipment and irrigation water quality negatively, but not necessarily at all dams, because site selection and the previous water quality history of a site also play a role.

Depending on dam size and water exchange rate, inflowing water quality and background nutrient levels, the input of feed and the waste that is produced can be of varying relevance and magnitude. Due to their small surface areas and volumes and low water exchange rates, filter systems supplied by Nietvoorbij and Rondawel water most likely experienced clogging problems caused by phytoplankton growth. It can therefore be concluded, according to the results presented in previous chapters, that initial site selection of dams with water quality conditions that, to some degree, are resilient to aquacultural input can avoid problems with additional biological clogging of filters. Shifts in pH and biological clogging can be avoided by choosing dams with initially non-clogging phytoplankton biomasses and species and monitoring their trophic levels and phytoplankton status.

7 ASSESSMENT OF THE SUITABILITY OF OUTFLOW WATER QUALITY AND QUANTITY FOR CROP IRRIGATION

7.1 Introduction

Aquaculture in open water systems such as small on-farm irrigation dams, is a relatively new development in South Africa and constraints and impacts of the industry are yet to be determined. Trout has been produced successfully in raceways and larger lakes (> 1 km^2), but experience with smaller production sites and their carrying capacity is limited.

The influence of aquaculture on the filters in irrigation systems were discussed in Chapter six. Relevant to crop quality, therefore, are those water components that bypass the filtering system. Suspended solids levels and phytoplankton biomass and composition as such will not have an effect on crop longevity. The impact of fish feed on conductivity levels and hardness cannot be excluded and will show effects, depending on the water exchange rate of the dam and its total volume in relation to fish production.

Some effects on crops attributed to aquaculture were foul (hydrogen sulphide) or fishy odours, as well as muddy odours, the latter usually caused by substances released from cyanobacteria. Due to a lack of baseline data on the conditions in the dams before aquaculture was introduced, the described effects could only be documented on the basis of anecdotal evidence. The turnover rates of employees are high (at managerial level) and written records of procedures, problems and impressions are scarce. However, the number of independent observations (27% of 21 different projects within Hands-On reported irrigation system problems unknown before aquaculture) is noteworthy.

Next to observations on odour and taste, available data that warranted inclusion into this study because it was useful (affecting soils and crops, with the possibility of being influenced by aquaculture) concerned: pH, inorganic nutrients (nitrogen and phosphorus) and exchangeable cations and the levels of total dissolved salts (indirectly measured as conductivity). Nutrients and dissolved salts are directly introduced via fish feed, whereas pH changes are caused secondarily by phytoplankton growth (triggered by the introduction of nutrients).

As explained before, the main effects of aquaculture amount to an increase in phytoplankton biomass, as well as the accumulation of decomposing matter (organic material, nutrients) below the cages, with subsequent oxygen reduction. Increased algal biomass would secondarily cause changes in surface water pH. Additional organic matter at the bottom of the dam seems to have an effect on oxygen depletion rates and the duration of anoxic phases. Oxygen composition of water will not affect crops, but secondary reactions will increase the amount of hydrogen sulphide in the anoxic zone, as well as enrich nitrogen in the form of ammonia. Location of water withdrawal from the dam will therefore play a crucial role in any effect on irrigation systems and crop quality. Irrigation takes place in summer when dams deeper than six to seven metres become stratified. Epilimnion and hypolimnion water quality were observed to differ greatly during that period (refer to Chapter 2).

Some observations were made concerning drinking and irrigation water quality on farms practising bottom water extraction. During the summer, nutrients and minerals accumulate on the dam bottom. The higher extraction of nutrients would be advantageous for the overall dam nutrient balance, but could also save costs as far as fertilisers are concerned. However, the positive effect of nutrient accumulation for irrigation is reduced by oxygen depletion and, therefore, the accumulation of hydrogen sulphide and the enhanced presence of filamentous cyanobacteria in the hypolimnion, causing muddy flavour.

Differences concerning root irrigation (vine, olives, and orchards) versus sprinkler irrigation (e.g. vegetables) are also to be expected. Much greater care has to be taken with the water quality of dams that supply direct irrigation to crops.

Brown (2006) has conducted a study on the impact of aquaculture on crops under irrigation. Estimations of the possible impact of irrigation water quality on soil properties were attempted on the basis of information on optimal soil requirements for vines (exemplary: Chenin Blanc) and olive trees.

In this chapter, the aim is to estimate the impact of aquaculture on the two predominant crops of the Western Cape by combining results from the honours thesis submitted by Brown (2006) and additional comparative information on the fertilising effect of irrigation dams (with and without aquaculture) with common fertilising practices applied by farmers on their fields.

7.2 Materials and methods

7.2.1 Study sites

Surface water extraction at the Cape Olive, Nietvoorbij and Rondawel Dams on which the study has focused (see Section 2.1.2) takes place from a depth of one to two metres. The crops cultivated on the farms are grapes and olives. Aquaculture has been taking place since 2003 in the Rustenberg dam, since 1997 at Nietvoorbij, and since 2001 in Cape Olive. No production has taken place at another Rustenberg dam mentioned in this chapter.

The water of the Cape Olive Dam is mainly used for the irrigation of olive trees and vineyards. Irrigation water is extracted at a constant level of one meter below the surface of the dam and pumped to a nearby pump-house where it is filtered. The water is filtered twice before it is distributed to the water delivery (lateral) pipes. At Nietvoorbij, only vines are irrigated with surface water extracted from the dam. Rondawel Dam water is used to irrigate pastures and vines. Here, water is also withdrawn from the surface of the dam.

7.2.2 Sampling method

Water quality information collected for the purpose of the study as recorded in Chapter 4, plus additional data for ammonia from the bottom water levels for the three sites was used.

Soil data for all three sites was obtained through acquiring the secondary data analysed by BemLab$^{(Edms)\ Bpk}$ (Somerset West) for different patches irrigated from the dams in this particular study.

7.2.3 Comparison of the fertilising effect of dam water with common fertilising practice

The data for the average irrigation water volume applied per ha and the nutrient content supplied by the dam water was compared with the commonly applied amounts of fertiliser added to their fields by wine and olive farmers.

7.2.4 Soil information

Soil data is summarised on a yearly basis and calculated by BemLab$^{(Edms)\ Bpk}$, and this is presented as a single data entry for each year. The results do not illustrate any trends or patterns in the accumulation of certain chemicals expected to derive from aquacultural practices in neither the soil nor the water. Plots that were irrigated only with water from the studied dams during the study period were selected for representation.

7.3 Results and discussion

The impact of irrigation dam water quality on crop irrigation will be estimated according to the following results. Out of the available data, nutrients, pH, dissolved ions and conductivity were chosen as parameters of most influence on crop health.

7.3.1 Irrigation water quality (with surface water extraction in summer)

Irrigation water at all five study sites is extracted via pumps through floating pipes with one end diverged to a depth of between one and two metres.

7.3.1.1 Nutrients

Figure 7.1 shows the average total inorganic nitrogen development during the years 2004 to 2006 for the four seasons and each single dam. At Cape Olive, Glenbawn and Nietvoorbij, the recorded levels were highest in winter, whereas the tendency at Calais and Rondawel was towards highest levels in summer.

Due to the fact that irrigation water is mainly extracted during summer and at surface level, an average total inorganic nitrogen level of 0.2 to 0.3 mg/L N is most representative for the two Drakenstein sites. At the Stellenbosch sites, the average TIN levels are seen to vary between 0.15 mg/L N at Glenbawn and Nietvoorbij and 0.4 mg/L N at Rondawel. The TN (total nitrogen) levels measured in these dams (own samples analysed by DWAF) during summer (see Table 5.5 in Chapter 5) were about 0.3 mg/L TN for Calais and 0.42 mg/L for Cape Olive, while 0.82 mg/L TN was recorded for Glenbawn, with Rondawel containing 1.02 mg/L and Nietvoorbij 1.07 mg/L TN by average of two values (December 2005 and April 2006). A large portion of the organically trapped nitrogen is removed during the filtering process, though, therefore the inorganic nitrogen content was used as the value that can be utilised by crops and soils.

As explained in previous chapters, the inorganic nitrogen levels at production and control sites are fairly similar, so no further distinction between the general effect of water nutrient content on crops and additional input from aquaculture can be made.

The phosphorus levels were expected to show a similar seasonal pattern to the nitrogen contents, but the soluble reactive phosphorus either was evenly distributed over the year or most abundant in autumn (see Figure 7.2), with the exception of Rondawel, where the highest srp concentrations could be found in summer.

The average level of srp, the representative of the inorganic phosphorus content of the summer months, varied between 0.05 and 0.07 mg/L P at the Drakenstein sites, between 0.05 and 0.08 mg/L P at the Rustenberg sites (Stellenbosch) and was recorded as 0.03 mg/L P at Nietvoorbij (Stellenbosch). Since these values are an underestimation of the total inorganic P content (including particle sizes larger than 0.45 µm – the filter size used before srp measurement takes place), these values will be doubled in further use in this chapter.

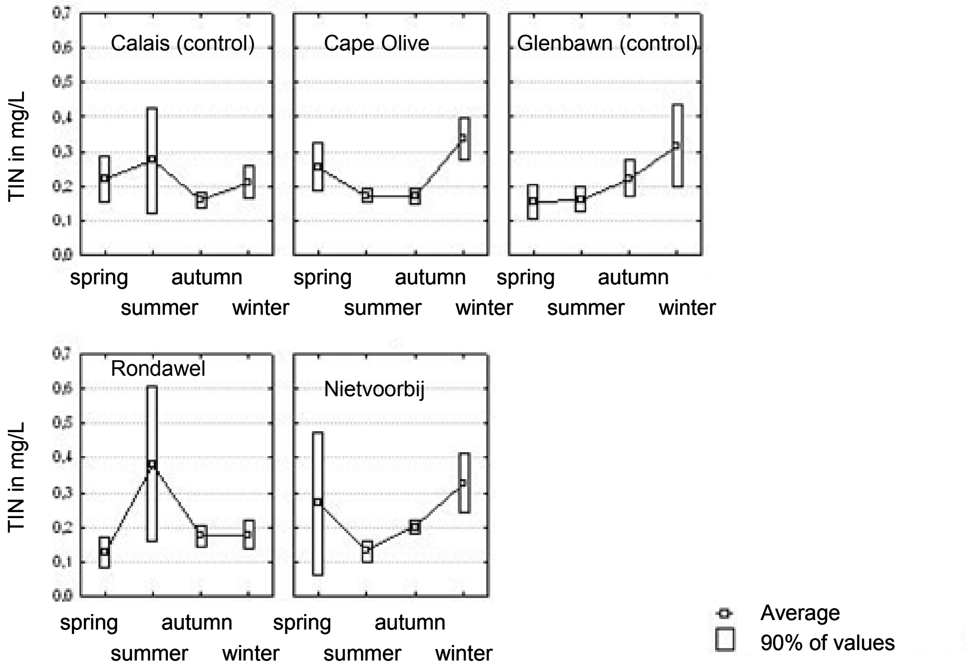

Figure 7.1: Average plot of the TIN (total inorganic nitrogen) values in mg/L N for the three Stellenbosch and two Drakenstein sites at the surface water level – Spring: Oct to Dec (n=17), summer: Jan to March (n=12), autumn: Apr to June (n=18), winter: July to Sept (n=18)

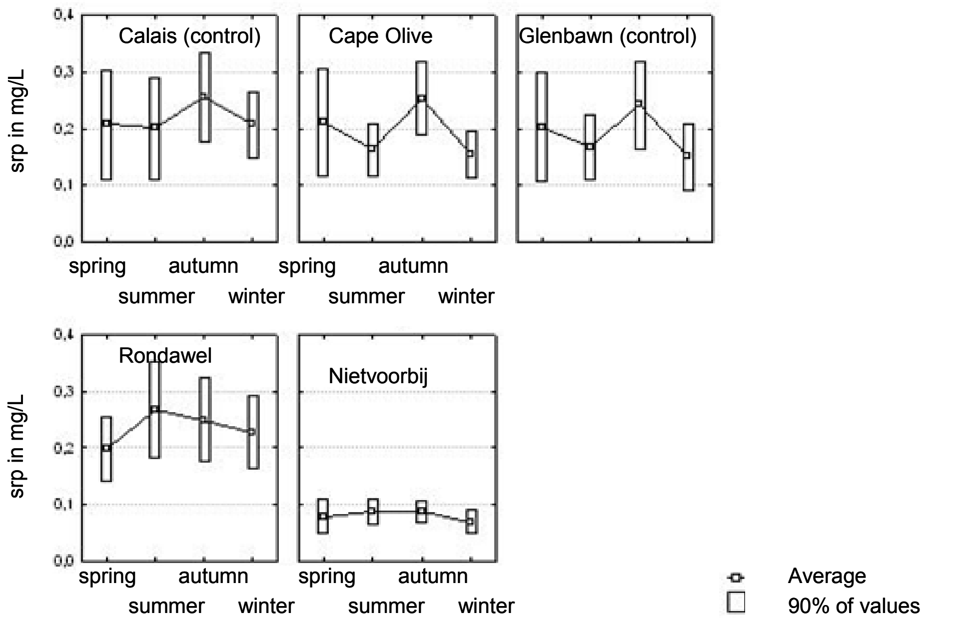

Figure 7.2: Average plot of the srp (soluble reactive phosphorus) values in mg/L N for the three Stellenbosch and two Drakenstein sites – Spring: Oct to Dec (n=17), summer: Jan to March (n=12), autumn: Apr to June (n=18), winter: July to Sept (n=18)

There is no clear indication whether summer inorganic nutrient levels are affected by winter aquaculture or rather by other factors within the overall nutrient balance of the dams. The general fertilising effect of these nutrients on crops and the effects of nutrient increase will be discussed in Section 7.3.2.

7.3.1.2 pH

As shown in Figures 4.11 and 4.12 (in Chapter 4), the pH levels of the five dams varied between 6.3 and 10.3. With the exception of Cape Olive Dam, where there was an oscillation around neutral pH, the remaining four dams had pH levels of between 7 and 8.3 in the summer of 2005 and higher pH levels that varied between 7 and 9 (maximum 10.1) in the following summer (2006). When pH levels are above 8.4 they can have a direct effect on the visual quality of crops (under sprinkler irrigation) and, in the long term, also affect general macro- and micro-nutrient availability in the soil (DWAF, 1996).

Nutrient input and subsequent changes in phytoplankton biomass definitely increases pH. The low recorded alkalinity cannot buffer the photosynthetic activities of the microalgae and daily fluctuations of pH are supposedly high, with maximum values measured during the day, when the dams were sampled.

7.3.1.3 Dissolved ions

Table 7.1 summarises the ion content of the dam water at the Stellenbosch and Drakenstein sites. The Calais dam contains more dissolved salts than Cape Olive, as can also be noted from the conductivity levels in these dams (see Figure 4.19, Chapter 4). The higher levels at Calais would be attributable to its longer water retention time. At the Stellenbosch sites, Nietvoorbij has the highest ion levels (and also the highest conductivity levels), with sodium and chloride as the most abundant ions. Glenbawn, the control site next to Rondawel, has lower ion levels than Rondawel. The salt contents in Nietvoorbij and Rondawel could have increased due to aquacultural activities and agricultural runoff. At Nietvoorbij, additional salts could enter the dam via the water loop into the wine cellar. However, the possible contribution by aquaculture to the given conductivity levels is not expected to bring about major changes and therefore affect soils or crops.

Table 7.1: Average ion content (n=4) in mg/L for the five study sites in the Cape Winelands area (own samples analysed by DWAF, Pretoria – Dec 2005, April, May and July 2006)

	Na	**Mg**	**K**	**Ca**	**Cl**	**SO_4**
Calais	21.0	4.0	3.2	7.0	31.0	4.0
Cape Olive	10.0	2.0	1.9	2.0	14.0	4.0
Glenbawn	15.0	3.0	2.1	5.0	24.0	4.0
Rondawel	24.0	5.5	4.3	10.0	46.0	4.5
Nietvoorbij	52.5	12.0	6.8	20.5	93.0	6.5

7.3.1.4 Conductivity

The conductivity levels at the dams run entirely parallel to the ion contents and are plotted in Figure 4.19 (Chapter 4). See Dissolved ions (7.3.1.3) for further explanation.

7.3.2 Fertilising effect of dam water (with and without aquaculture)

The application of fertiliser can be adapted and reduced, depending on irrigation water volumes that are applied and the content of nutrients in the water (nitrogen, phosphorus and potassium).

7.3.2.1 Drakenstein sites and olives

The planting density at the Cape Olive site is about 250 to 300 trees per hectare, with each tree requiring 80 to 120 litres of water per day. Optimal growth of olives begins from 600 mm irrigation per year, of which about 350 mm is supplied by the average yearly rainfall in the Western Cape (SAWS, 2007). Costa (1998) suggests an irrigation requirement of between 100 and 300 mm for olives in the Western Cape.

According to the information in Table 7.2, the dam water would only provide 0.3% to about 2.0% of the nitrogen requirements for optimal olive growth under lowest irrigation water applications and lowest TIN levels in the water. With higher volumes of irrigation water applied and higher levels of inorganic nitrogen, the supply from irrigation water can go up to 9.0% with surface water irrigation and 18.0% with bottom water irrigation (surface and bottom referring to the zone in the dam where water is extracted).

Table 7.2: Estimated fertilising effect of inorganic nitrogen in irrigation water in comparison with common olive fertilisation practice with the Cape Olive Trust, Drakenstein district. Nutrient content own information, data on irrigation water application and common fertilisation amounts by Cape Olive Trust farm management.

Nitrogen	N content of outflowing water	Irrigation water (average season)	Amount of dam water nutrients per ha	Amount of N added by common fertilisation practice per ha	% of nutrient level in irrigation water in comparison with fertilisation practice
Lower range (surface water)	0.2 mg/L	1,000 m^3/ha (100 mm)	0.2 kg/ha	10 to 60 kg/ha	0.3 to 2.0%
Higher range (surface water)	0.3 mg/L	3,000 m^3/ha (300 mm)	0.9 kg/ha	10 to 60 kg/ha	1.5 to 9.0%
Bottom water	0.6 mg/L	3,000 m^3/ha (300 mm)	1.8 kg/ha	10 to 60 kg/ha	3.0 to 18.0%

Depending on the water source and litres of irrigation water applied per hectare, phosphorus to the amount of 0.1% to 1.1% can be supplied by using surface water resources see (Table 7.3). By extracting bottom water, up to 2.4% of the phosphorus required for sufficient growth can be provided by the dam water. No specific time is regarded as more sensitive to oversupply of phosphorus, but it is recommended that only approximately 15% of the yearly phosphorus nourishment should be applied during the time of bud burst. With current levels of phosphorus, there is no risk of phosphorus over fertilisation at the Drakenstein sites, even if aquaculture would double or triple the given phosphorus levels.

Table 7.3: Estimated fertilising effect of inorganic phosphorus in irrigation water in comparison with common olive fertilisation practice with the Cape Olive Trust, Drakenstein district. Nutrient content own information, data on irrigation water application and common fertilisation amounts by Cape Olive Trust farm management.

Phosphorus	**P content of outflowing water**	**Irrigation water (average season)**	**Amount of dam water nutrients per ha**	**Amount of P added by common fertilisation practice per ha**	**% of nutrient level in irrigation water in comparison with fertilisation practice**
Lower range (surface water)	0.05 mg/L	1,000 m^3/ha (100 mm)	0.05 kg/ha	20-90 kg/ha	0.1 to 0.3%
Higher range (surface water)	0.07 mg/L	3,000 m^3/ha (300 mm)	0.21 kg/ha	20-90 kg/ha	0.2 to 1.1%
Bottom water	0.16 mg/L	3,000 m^3/ha (300 mm)	0.48 kg/ha	20-90 kg/ha	0.5 to 2.4%

In Table 7.4, the common fertilisation practices of potassium are compared to the existing contents of potassium in the dam water. Depending on the olive requirements (determined via the content in the leaves), 1.3 to 32% of potassium can be supplied by the surface dam water. Bottom water values of potassium were not available.

The sensitive period for potassium application would be the time of bud burst. Only 10% of the yearly total fertiliser application should take place during that period. The potassium contents of the water do not pose a problem of over fertilisation; however, potassium applications could clearly be reduced if dam water testing would be integrated into fertilisation planning. This is specifically true with bottom water extraction where the potassium levels can be expected to be higher than at the surface.

Table 7.4: Estimated fertilising effect of potassium in irrigation water in comparison with common olive fertilisation practice with the Cape Olive Trust, Drakenstein district. Nutrient content own information, data on irrigation water application and common fertilisation amounts by Cape Olive Trust farm management.

Potassium	**K content of outflowing water**	**Irrigation water (average season)**	**Amount of dam water nutrients per ha**	**Amount of K added by common fertilisation practice per ha**	**% of nutrient level in irrigation water in comparison with fertilisation practice**
Lower range (surface water)	1.9 mg/L	1,000 m^3/ha (100 mm)	1.9 kg/ha	30-150 kg/ha	1.3 to 6.3%
Higher range (surface water)	3.2 mg/L	3,000 m^3/ha (300 mm)	9.6 kg/ha	30-150 kg/ha	6.4 to 32%

7.3.2.2 Stellenbosch sites and vines

According to Green (1985), the annual irrigation requirements for wine vary between 466 mm with 5 mm design applications and 386 mm with 15 mm design applications at a study site in the Stellenbosch area. The lower value of 390 and the upper value of 470 will therefore be used for the following compilations.

Knowing the constituent content of the outflowing water makes it possible to estimate the amount of nutrients added to the soil directly through irrigation water. Table 7.5 shows the results of a comparison of the nitrogen added via irrigation water with the average fertilisation practice of nitrogen on vines.

Even if nutrient levels were doubled or tripled by aquaculture, surface dam water (irrigation water) would not provide a sufficient fertilisation effect on the plants. Should bottom water be extracted from some dams (e.g. Rondawel, with relatively high nutrient levels, for which refer to row 4 in Table 7.5), the ammonia content of this water would still not reach minimum satisfactory fertilisation levels, but could supply about 47.2% of the fertiliser requirements – almost half of the nitrogen added to the irrigation water.

Another concern arises from the varied application of fertilisation at different stages of growth in vines. The percentage of fertiliser added per season is usually lowest during the ripening phase of a crop. In the case of vines about 5% of the yearly fertiliser application should be applied during the ripening stage of the grapes. That percentage corresponds to a minimum of 5 and a maximum of 20 kg nitrogen being applied during the ripening phase, which will not be exceeded by the fraction of irrigation water that may be applied during that period. However, awareness of the nitrogen content is required in the case of bottom water application.

Table 7.5: Estimated fertilising effect of inorganic nitrogen in irrigation water in comparison to common vine fertilisation practice in the Cape Winelands area. Nutrient content own information, data on irrigation water application and common fertilisation amounts by the Pinotage Association.

Nitrogen	N content of outflowing water	Irrigation water (average season)	Amount of dam water nutrients per ha	Amount of N added by common fertilisation practice per ha	% of nutrient level in irrigation water in comparison with fertilisation practice
Lower range (surface water)	0.15 mg/L	3,900 m^3/ha (390 mm)	0.6 kg/ha	25–100 kg/ha	0.6 to 2.4%
Higher range (surface water)	0.4 mg/L	4,700 m^3/ha (470 mm)	1.9 kg/ha	25–100 kg/ha	1.9 to 7.6%
Bottom water	2 to 3 mg/L	4,700 m^3/ha (470 mm)	11.8 kg/ha	25–100 kg/ha	11.8 to 47.2%

With phosphorus, the effect of using water from smaller dams as irrigation water on crops was higher than with nitrogen (see Table 7.6). With surface water extraction, again, it is not expected that nutrients added to the dam via fish feed need necessarily be considered since only up to 23.7% of the total phosphorus fertilisation could be supplied by the irrigating water. But with the use of bottom water, phosphorus application via dam water could almost be sufficient for vines as up to 94% of the phosphorus requirements of the crop could be supported by bottom water application. However, if the phosphorus levels obtained from bottom water extraction are not considered in the irrigation design, a phosphorus oversupply is likely.

Table 7.6: Estimated fertilising effect of inorganic phosphorus in irrigation water in comparison with common vine fertilisation practice in the Cape Winelands area. Nutrient content own information, data on irrigation water application and common fertilisation amounts by the Pinotage Association.

Phosphorus	P content of outflowing water	Irrigation water (average season/year)	Amount of dam water nutrients per ha per year	Amount of P added by common fertilisation practice per ha per year	% of nutrient level in irrigation water in comparison with fertilisation practice
Lower range (surface water)	0.08 mg/L	3,900 m^3/ha (390 mm)	0.31 kg/ha	3–18 kg/ha	1.7 to 10.3%
Higher range (surface water)	0.15 mg/L	4,700 m^3/ha (470 mm)	0.71 kg/ha	3–18 kg/ha	3.9 to 23.7%
Bottom water	0.60 mg/L	4,700 m^3/ha (470 mm)	2.82 kg/ha	3–18 kg/ha	15.7 to 94%

In the case of the Stellenbosch dams, the potassium content of the irrigation water is almost satisfactory, depending on the potassium requirements of soil and crop (vines). Comparing the common potassium additions to vines made by farmers in the area, the supply of potassium by dam water can range between 6.8% and 32.8% in the case of Glenbawn (2.1 mg K/L) and between 26.7% and sufficient supply (to oversupply) in the case of Nietvoorbij Dam, with comparatively high potassium levels (6.8 mg K/L).

Table 7.7: Estimated fertilising effect of potassium in irrigation water in comparison with common vine fertilisation practice in the Cape Winelands area. Nutrient content own information, data on irrigation water application and common fertilisation amounts by the Pinotage Association.

Potassium	K content of outflowing water	Irrigation water (average season)	Amount of dam water nutrients per ha	Amount of K added by common fertilisation practice per ha	% of nutrient level in irrigation water in comparison with fertilisation practice
Lower range (surface water)	2.1 mg/L	3,900 m^3/ha (390 mm)	8.2 kg/ha	25–120 kg/ha	6.8 to 32.8%
Higher range (surface water)	6.8 mg/L	4,700 m^3/ha (470 mm)	32.0 kg/ha	25–120 kg/ha	26.7 to 128.0%

7.3.3 Bottom water extraction of irrigation water and effects on crops

Three independent observations by farmers stated that the water quality of their dams changed with the introduction of aquaculture operations. All had in common that irrigation water extraction from the bottom water level was employed on their farms. Even if the occurrence of tainted drinking and irrigation water was coincidental and not related to aquaculture, it created awareness of problems arising from aquacultural waste, the decaying processes of which add to the reduction of oxygen in the hypolimnion (and of secondarily built-up ammonia and hydrogen sulphide levels).

In two of the three cases, the taint could be accounted for by the presence of hydrogen sulphide. In the third dam, the taint was caused by a mass occurrence of a filamentous cyanophyte (*Oscillatoria limnetica*) only observed in the near-bottom waters of the dam at that time. This alga is a facultative anoxygenic species that can survive and even thrive under anoxic conditions that develop in most hypolimnia of the studied farm dams over summer.

7.4 General discussion

Aquaculture enriches the water with nutrients. This could have a negative effect on the dam ecology, but also provide these additional nutrients to the agricultural industry by allowing the reduction of fertiliser that needs to be applied. More specifically, feed introduction related to net-cage fish farming would more likely cause an increase in inorganic nitrogen levels and inorganic phosphorus levels in the water body, which could add the advantage of saving on fertilisers. Awareness of the existing nutrient concentrations in the water is therefore necessary, especially in the case of bottom water extraction.

High nitrogen levels can cause a stimulatory effect on plant growth and could also leach and contaminate groundwater sources (DWAF, 1996a). The amount of nitrate and ammonia added through irrigation is usually very small compared to the levels applied as fertiliser (DWAF, 1996a), but some of the results showed that when lower fertiliser application is needed for optimal growth of the crop, the fertilising effect of the dam water would almost be sufficient (mostly with bottom water extraction). With fertiliser applications usually at the high end of the requested ranges, nitrogen and phosphorus in dam water will mostly supply 10% or less of the total fertiliser amounts added. In the case of potassium, it seems that levels in the dams could be underestimated, which would eventually result in elevated potassium levels in the soils.

For more accurate estimations, it is suggested that the irrigation water quality should be measured after filtration and just before distribution onto the fields.

On observing the plotted conductivity levels, it seems that conductivity tends to be stable or undergo parallel development in all five dams, with and without aquaculture. Therefore, the total dissolved salts added by fish feed do not show trends or a significant effect at surface water level. The concentration of salts and nutrients that is present thus enters the dams via the inflowing water source or agricultural runoff.

Aquaculture can affect the pH in an irrigation dam. Irrigation water will cause soil pH to change slowly, but is seldom a problem in itself (DWAF, 1996a) when viewed in relation to other factors that affect the pH of the soil. Olives and vines both require rather lightly acidic soil conditions (e.g. olives with a $pH_{(KCl)}$ of 5.5) whereas most of the studied dams maintained elevated pH levels of 8 and higher during summer. It is possible that these alkalinic water conditions have long-term effects on soils.

Under the eutrophic and hypereutrophic conditions that are experienced in all the studied sites in the Stellenbosch (in ecological terms: providing more than sufficient nutrients for algal growth), algal blooms develop and break down regularly. Aquaculture could add to the problem and threshold limits of problematic algal growth may be reached earlier. Higher rates of algal bloom would be more likely to impact the overall dam ecology, increase the risk of oxygen depletion during winter and affect aquaculture itself or cause increasing problems with filter blockage than affect soil properties. With sprinkler irrigation of vegetables (overhead application of water), the situation would be very different when the crop is directly affected by odour or pH.

The accumulation of nutrients at the bottom of the dams will eventually lead to longer lasting and accelerated oxygen depletion. This has to be considered when bottom water extraction is the prevailing source of water. If the water is not dedicated as drinking water supply or not used for sprinkler irrigation, but rather for root irrigation, these effects will probably not affect crops. In the case of root irrigation, bottom water could indeed supplement existing fertilisation regimes as the nitrogen levels at the bottom of some dams could supply up to 100% of the crops' nutrient requirements (see Tables 7.2 and 7.5).

Irrigation water quality usually is not considered when fertiliser applications are planned according to soil and leaf samples. The laboratory results of a soil probe include recommended soil ameliorants, which indicate to the farmer how much of which chemical needs to be applied to a specific patch of soil. This can create complications for the integration of aquaculture and agriculture when the dynamics of each are not considered, especially when water is extracted from the bottom of the dam. To be able to fertilise the soil for optimal growing conditions, the irrigation water should also be chemically analysed periodically to apply the correct ratio of nitrogen, phosphorus and potassium to the crops.

7.5 Conclusions

The quality of outflow water in dams with aquaculture is suitable for irrigation crops, especially when surface water extraction is employed. With bottom water extraction, the water could become tainted with hydrogen sulphide or algal by-products as well as fish feed leftovers. The possibility of taint needs to be considered with sensitive crops (vegetables and salads) in the case of bottom water extraction.

Concerning nutrient content, the additional nutrients added to dam water by aquaculture will not cause changes in the fertilising effect of the water. The nutrient levels that are present usually supply less than 10% of the overall crop requirements. The potassium levels of dams are higher and can supply up to 30% with the use of surface water. With bottom water extraction and irrigation, the nutrient contents of the water may be high enough to fully satisfy the nutrient requirements of the crops, especially if extracted from smaller dams as at the sample sites in Stellenbosch.

The integration of aquaculture and agriculture is a positive step towards sustainable resource management in that it uses the same water resource for fish production as well as crop production. This is becoming increasingly important with the depletion of natural water resources. The results presented in this study indicate that no short-term detrimental effects on crop production occur from irrigation water extracted from dams used for aquaculture, and that it would be even safer to incorporate the irrigation water quality into fertilisation plans, which is a finding independent of aquacultural production.

In dams with a sustainable carrying capacity for aquacultural production, bottom water extraction could be the means to achieve a neutral to negative nutrient balance within the dam. However, in dams of hypereutrophic character (algal biomasses of 10 g/L and higher), bottom water extraction could have negative effects on crop health if sprinkler irrigation is employed (e.g. vegetables or salad tainted by hydrogen sulphide or algal by-products). Bottom water extraction for root irrigation would probably not cause any noticeable effect on crops and nutrient levels in bottom water could supplement or substitute fertilisation.

With surface water extraction, sufficient provision or even supplementation towards optimal fertilisation is only likely with very low-fertilisation schemes and requirements by the crops.

Other negative effects of surface water components are unlikely. Only with sprinkler irrigation could higher pH levels (> 8.4) have negative implications through affecting the visual appearance and longevity of crops.

8 OVERALL CONCLUSIONS AND RECOMMENDATIONS

The study was undertaken in two divergent geographical areas employing widely different irrigation water exchange rates. In Pongolapoort, temperatures are relatively high throughout the year and the water exchange rate within the canal system was very high. In the Western Cape, winter temperatures are low and the water exchanges in the irrigation dams are very slow.

8.1 Pongolapoort canal system

8.1.1 Overall conclusions

The Pongolapoort network has great potential to expand aquacultural activities in the area. The water exchange rate and total amount of water available allow direct removal of nutrients and faeces introduced from aquacultural production in the production dams. Therefore, physical, chemical and biological water quality parameters are not significantly affected by aquaculture, as all inputs are removed immediately (water exchange rate being than 3000 times per year).

The water quality of the canal system (supplied by the Pongolapoort Dam) is highly suitable for aquacultural production, however high in pH levels, as the rapid flow of the system, which creates turbulence and good oxygenation, prohibits denitrification of nitrate to ammonia. Pongolapoort Dam water at the Jozini dam wall seems to undergo a nutrient accumulation process, though, and water entering the canal is highly influenced by the conditions in the dam. This water source should be monitored closely in order to avoid production losses resulting from source water deterioration.

The condition of the water in the canal (which supplies the production site), as well as of the production site, was sufficient to support the growth of the warm-water species *Tilapia rendalii* and *Clarias gariepinus*. The largest constraint was temperature; two catfish production episodes (summer and winter 2006) showed that suboptimal temperatures caused considerable restriction in growth. Future fish production should therefore be concentrated on the summer season to benefit optimally. This will also decrease the FCR values and consequent feed input. The summer catfish production achieved almost optimal growth and optimal FCR levels and could be extended to achieve higher fish weight at harvest.

The major crops of the area are cotton and vegetables, which could be affected by feed residues and fish faeces (there is no filtering of water). However, most processes causing off-flavour in fish production need long retention times to allow biochemical conversion, or require anoxic conditions, both of which can be excluded for these dams as long as water flow is maintained by irrigation.

The input of feed into the pump-house dam amounted to a maximum of about 50 µg feed/L of dam water, producing about two tons of fish during the 2005 tilapia season. These levels of feed do not remain in the dam, but become distributed to the irrigated crops. Theoretically, about 2 µ/L P is hereby added to the phosphorus levels by aquaculture and supplied by the pump-house dam (which contains approximately 50 µg/L TP – twice the measured soluble reactive phosphorus levels). With five-fold intensification of the tilapia production (up to 10 tons in the 6000 m^3 pump-house dam) and concurrent improvement of the FCR levels to 1.2 and below, the introduction levels of additional nutrients by aquaculture would be reduced even further.

The results obtained are strictly valid for the production period of two years during which no effects of aquaculture could be established and could confidently be expanded into the long-term perspective. The additional nutrients entering the system from aquaculture are mostly removed from the pump-house dams and would only add about 5% to the nutrients already present in the irrigation water even under intensified conditions (10 tons production). Effects on crops and soil are not expected, even under long-term production. However, optimum production with very low FCR ratios (1.2 and lower) will be the most important factor in ensuring the long-term low impact.

All pump-house dams with a high water exchange rate will provide good production sites with no or low impact on the pump-house dam itself, and on aquacultural production, irrigation water quality and crop quality.

The results obtained with production in the pump-house dam should not be transferred to the adjacent balancing dams where the turnover seems to be slower. Accumulation of nutrients introduced by aquaculture could have a deteriorating effect on the ecology of these sites, with algal bloom and oxygen reduction as first effects. In addition, the pH regime of the canal system suggests that ammonia levels will rise under more stagnant conditions.

8.1.2 Recommendations

1) Adaptation of the aquacultural production season to the temperature conditions should be undertaken and the introduction of fish into the pump-house dam should be organised accordingly to optimise production. Good monitoring of water quality and production data in order to control and constantly improve the production success will be important.
2) The conductivity levels, as well as total phosphorus levels, should have been monitored in addition to the water quality parameters tested during the study.
3) To verify that the unfiltered irrigation water does not affect crop quality, monitoring and control of the water distributed to the fields would be advisable. TSS values, as well as visual and odour tests, may be sufficient. A comparison of water at the pump-house dam and nutrients in the irrigation water could also further consolidate the interpretation of the results of this study.
4) The exact flow-through pattern of these pump-house dams should also be established. During periods with little irrigation activity, waste could accumulate at the bottom of the dams, water quality could deteriorate rapidly and haphazard fish. These periods should be considered in the stocking schedule of these low volume dams.
5) The water balance and flow schemes of the balancing dams should be investigated to estimate the water exchange rate of these dams in order to expand aquacultural production. Cages would most likely be best positioned at the end, towards the canal inlet. The balancing dams should be accessed by a floating device in order to take samples from the centre of the dam.
6) Any production that takes place should be monitored in terms of inflowing water quality. The further the site is from the Pongolapoort Dam, the more likely it will be that differences in water quality will develop in the canal from the main dam. In terms of the high ammonia content of the Pongolapoort water, a longer travelling period might even ameliorate the ammonia levels by oxygenation to nitrate due to turbulence, which could enhance fish growth rates.
7) Spreading of information on household waste and its acute or chronic effect on water quality should be undertaken in case of project expansion.
8) Understanding the shift in water quality levels in the canal system during the year 2004 could become important in terms of overall irrigation water quality, as well as the possible addition of aquaculture to the canal system. As point of departure, the outlet of water released from the dam should be located and possible changes during that period ascertained.

8.1.3 Future studies

Further studies into the following aspects are recommended:

- Pongolapoort bottom water development
- Water quality of the irrigation water and effect on crops
- Monitoring water through-flow patterns of the pump-house dams over the seasons
- Potential of the balancing dams for aquacultural production and understanding the balancing dam ecology

8.2 Cape Winelands storage dams

The following conclusions are drawn and recommendations given for the Cape Wineland storage dam systems.

8.2.1 Overall conclusions

The dams in the Cape Winelands are more heterogeneous than the pump-house dams at the KwaZulu-Natal site and are not supplied by a large water source with a very rapid flow-through of water. The storage dams in the Western Cape, and therefore also in the study area around Drakenstein and Stellenbosch, differ greatly in volume, basin shape, source water (including catchment geomorphology and runoff), through-flow of water and microclimatic conditions. The major factor influencing the nutrient balance of these dams, however, seems to be the quality and quantity of the inflowing water, which has an impact on the water exchange rate of a dam.

Most of the dams in the study area are used for irrigation water supply, with some dams supplying drinking water as well.

Trout cage production in the small irrigation dams (< 20 ha) of the Western Cape also is of a more risky and problem prone nature when it comes to the climatic and environmental conditions. The Mediterranean climate, with dry and hot summers, limits the production period in which trout can be raised in standing water bodies, since fish in intensive stocks would mostly die under summer conditions. Because of their specific requirements concerning of water quality, trout often experience borderline environmental conditions in Western Cape dams, which hinders their optimal growth, the most fundamental parameter being the surrounding water temperature. The other main parameters putting trout under physiological stress were found to be alkaline pH (> 9.5), low dissolved oxygen levels (< 5.0 mg/L) and high free ammonia levels (> 0.05 mg/L). These conditions often occur in combination, therefore causing synergistic stress on trout wellbeing, as they signify water bodies with elevated trophic status. Naturally low hardness and alkalinity levels increase the effects of other water constituents, e.g. by reduced buffering capacity (alkalinity) and a weakening of the immune response of trout (possibly due to calcium deficiency). Other pollutants such as pesticides, heavy metals, etc. are also known to affect fish more readily at lower levels than with higher alkalinity or hardness backgrounds.

One problem observed in one production site was oxygen depletion caused by a massive die-off of an algal bloom under cloudy weather conditions following a period of extended hours of sunshine that enhanced algal biomass. By including additional study sites from related studies into the picture, this observation was repeated in connection with all smaller dams and dam size and depth therefore would seem to be seen a highly critical parameter to consider for avoiding sudden fish mortalities.

All the dams that were studied were stocked with five to six tons of trout per season because of economic viability. Carrying capacity calculations revealed that the low water exchange rates of the water bodies, the given phosphorus levels and the prevailing irrigation practices (surface water extraction in summer during stagnation when the nutrients are in the hypolimnion) do not remove sufficient nutrients from the system, so that nutrient accumulation inevitably occurs in most dams, with most effects taking place at the bottom water level and in the sediment.

In the Western Cape irrigation is practised during the dry summer months when dams deeper than six metres will be stratified. Problems with water quality and irrigation are not new to the Western Cape and are partly indicated by the prevailing practice of surface water extraction. Frequent backwashing of filters is a necessity in the area.

All Western Cape study sites used surface water extraction for irrigation or drinking water purposes, whereas related studies revealed that most of the adverse effects alongside aquaculture occurred in bottom water extracting setups. Factors influencing irrigation systems using bottom water will include anoxic water (affecting pipes), hydrogen sulphide, ammonia and filamentous cyanophytes in bottom water (facultative anoxygenic photosynthesis of *Oscillatoria limnetica*). *Oscillatoria limnetica* is known to produce high amounts of geosmin, a substance of unpleasant odour. Except for the removal of geosmin, oxygenation within the pumping system could remove these problems by converting the above-mentioned compounds to sulphate and nitrate which are not harmful (in the case of drinking water, total nitrate content has to be monitored). Aquaculture will add to the problem by increasing the organic substances on the dam bottom, which enhances oxygen removal and therefore the presence of suspended solids (faeces, uneaten pellets), ammonia, hydrogen sulphide and geosmin. Faeces and uneaten pellets can block the filters and exceed filter capacity. While ammonia is not a problem for irrigation (most fertilisers contain ammonia and nitrate in equal ratios), fishy odours, hydrogen sulphide (smelling like foul eggs) and geosmin (earthy-muddy odour) can become a problem with sprinkler irrigation (e.g. direct irrigation of vegetables) and, obviously, in drinking water dams.

With surface water removal, factors that inhibit irrigation can involve the phytoplankton biomass, through blocking of filters and nozzles, as well as extreme pH levels (mostly alkalinic through photosynthetic activity). Aquaculture can accelerate these problems as well as introduce an additional suspended solid load. However, the naturally low alkalinity and hardness levels in the study area in the Western Cape favour corrosion rather than scaling of pipes and equipment. Increased pH levels will therefore not cause problems as the low calcium levels already restrict the occurrence of scaling. More nutrients introduced by aquaculture will not only increase the biomass in phytoplankton, but also change the composition. In hypereutrophic dams, larger species (e.g. *Ceratium hirundinella*) prevail, in contrast with moderate eutrophic dams. Chlorophyll *a* levels only will therefore not give sufficient insight into possible blockage of filters. Increased problems with total suspended solids from aquaculture will probably depend on the location of the suction outlet in respect to cage location and prevailing wind direction.

With regard to crop health, it should be noted that the main impact of aquaculture on crops will come with direct sprinkler irrigation of crops, which could affect crop quality and longevity. With bottom water extraction, odour problems could be introduced with aquaculture; with surface water extraction, pH changes could affect crops negatively. Overall, nutrient additions from irrigation water are mostly minimal in relation to soil and crop requirements and can be ignored (with or without aquaculture).

In the case of irrigation applied to soil, the main additional impact of aquaculture will derive from pH and will only have long-term effects. Most crops require neutral soils and dam waters tend to become more alkaline at higher eutrophication levels. Since soils are buffered against pH changes, the effect of irrigating with high pH water will develop over longer terms and undesirable pH changes may be rectified. Olfactory effects of hydrogen sulphide and geosmin on roots might be mitigated by biochemical processes in the soils, but in the discussion of “terroir”, an impact on wine cannot be excluded.

Overall, the effect of aquaculture on irrigation and soil/crops specifically, as well as on water quality in general, will be negligible with appropriate future site selection based on dam hydrodynamics, ambient water quality and their combined effect, which is conveyed via carrying capacity models.

8.2.2 Recommendations

1) Good site selection is one of the major factors in successful trout cage farming in Western Cape storage dams. If the initial water quality is sufficiently good and the immediate impact from introduced feed and feed waste, as well as fish faeces, does not affect the water quality in the first season by the choice of large enough dams, there is a good medium-term scope for the production site. For trout farming, a site that is exposed to wind action and consequently has a longer mixing phase, especially while the overflow is supplied, will help to clear out the dam and avoid nutrient accumulation and oxygen depletion in the bottom water.
2) With site selection, the precautionary principle should be applied to avoid a long-term impact on the dam system as well as provide secure production for a long period. Dams with high water exchange rates (at least once or twice per year, if not more) and a minimum size of 8 ha should be preferred for the required minimum production of 5 tons per season per dam. Measures to improve water quality only by mitigation are not recommended in the long term (paddle aerators, bottom water aeration). They are costly, have to be repeated often and therefore do not offer real solutions to the risk of sudden mortalities.
3) In addition to the initial investigation of water quality, regular monitoring of the water quality should be undertaken. Suggested parameters to be continuously monitored to estimate aquacultural impacts and overall dam status are: total phosphorus, total nitrogen, surface and bottom water oxygen, surface and bottom water ammonia, as well as phytoplankton biomass (or chlorophyll *a* levels) or phytoplankton composition (which could be limited to a few dominant species). Sampling should be undertaken in mid-winter (with mixing of the dam water in June/July) as well as, and more importantly, in mid-summer when a thermocline separates the water body into two layers (December/January). Repetitions within a season will allow stronger cases. Long-term control of these parameters will give sufficient insight into water quality changes to monitor aquacultural impact, and water quality control for aquacultural production can reduce production risks considerably.
4) Drinking water dams should be avoided, as well as dams where the irrigation water supplies sensitive crops or vegetables directly, specifically if bottom water extraction is applied in the dam. On the other hand, if the dam water is extracted for root irrigation and the filter system is not too sensitive, bottom water extraction should be preferred to remove additional nutrients from the dams during the stagnation phase in summer, when more nutrients are accumulated in the bottom area of the dams.
5) Fertilisation programmes for irrigated lands should give consideration to the nutrient contributions of the irrigation water in the dam, especially if bottom water extraction is employed.
6) Trout is a predator fish that completely relies on additional feeding under cage culture conditions. Feeding programmes and best management practices for feeding have been developed, but have to be monitored better to prevent feed loss. The feed conversion ratios (FCRs) within the programme, varying between 1.1 and 2.5 (the optimum is an FCR of 1.0; 1 kg of feed needed to grow 1 kg of fish) suggest a strong tendency towards overfeeding that is not explicable by averse water quality (Maleri, 2008). Compliance with guidelines for the proper care of cage equipment could support the oxygen supply within the nets through constant removal of, for example, macroalgae from the nets to avoid bio fouling.

7) The cultivation of fish or aquatic organisms lower in the food chain than trout (feeding on algae) would seem much more feasible for Western Cape irrigation dams under the prevailing water quality conditions. A DST project including trials with tilapia cultivation in Western Cape dams commenced at the end of 2007.
8) Next to ensuring that the water quality conditions already permit risk-minimised trout production (improved site selection criteria for trout production as well as control and monitoring of the present state of the dam environment), a neutral or negative overall nutrient budget should be aimed at. Either the hydrodynamic situation enabling constant nutrient removal or means to remove aquacultural waste successfully through win-win situations could be applied (e.g. by selling the fertilising effect of the sludge below the cages). The accumulation of organochemical compounds and other pollutants would have to be verified beforehand to avoid bio amplification of these substances in the fertilised crop. If the water flow into and out of the dams during winter is high enough, the Mediterranean conditions in the Western Cape are actually ideal because of the concurrence of the rainfall season and turnover rate.
9) Polyculture with marketable species could provide relief to nutrient input, providing they can be added to the existing production system and be grown extensively (without further food introduction). Species under consideration could be water hawthorn (also waterblommetjies, *Aponogeton distachyos*), freshwater mussels, crayfish, carp or tilapia. However, the roughly estimated input of phosphorus into the dams by aquaculture (for 5 tons trout production per year, the FCR is 1.5) would be between 60 and 100 kg of total phosphorus per year, which would ideally have to be the amount that is removed from the system by alternative means.

8.2.3 Future research needs in the Western Cape setup

A wide range of studies could be undertaken to facilitate the successful extension of aquaculture in the Western Cape. Possible investigations could focus on the following:

- Impact of cage aquaculture on the bottom water level and on the sediment
- Long-term effects, continuing the research presented in this study
- Pollution prevention and minimisation
- Provision of environmental-friendly aquafeeds and elaboration of feeding techniques that avoid feed loss
- Mechanical nutrient removal methods and possible applications for the removed sludge
- Development of mitigating measures (e.g. gap years, influence of TN:TP levels)
- Implementation of a poly-culture farming system with complementary intensive and extensive production
- Integration of nutrient removers (plants, mussels)
- Before and after effects of aquaculture introduction. Water quality data collection would have to start at least one year before introduction of aquaculture into a dam.
- Fertilisation design in the Western Cape and how the given conditions of the irrigation water could be included

8.3 Combined conclusions and recommendations

Cage aquaculture releases waste into the aqueous environment and the most important criterion before starting cage aquaculture operations therefore is to determine the sink and accumulative effects of these nutrients, as well as their effect on the environment. These effects mostly depend on the water exchange rate, the hydrodynamic conditions and the dilution effect of the water volume in relation to the stocking rate of the cage.

Within the canal system, the pump-house dams are small entities with an expected high turnover and through-flow of water. In contrast, many storage dams exchange their overall volume less than once per year, depending on the access to and quantity of the source water. These dams are thus more prone to experiencing eutrophication and associated negative environmental effects.

Site selection for appropriate locations for cage aquaculture will have to include basic nutrient contents (total phosphorus) and an understanding of the water exchange taking place in the systems. The amount of waste introduced into the water with particular stocking rates of specific fish feed are known and can be considered when choosing a site.

Based on these considerations, pump-house dams are highly suitable for cage aquaculture and their use can be recommended if source water quality is continuously monitored and as long as the water extraction for irrigation does not cease for extended periods. The amount of nutrients added to the system by 5 to 10 tons of tilapia or catfish can be assimilated by the small pump-house dams (< 1 ha) if low FCR levels are maintained.

The situation in KwaZulu-Natal is much simpler than in the Western Cape due to a couple of factors. The water through-flow is so intensive in the canal system that no build-up of material is expected in the pump-house dams. The balancing dams or other standing water bodies with lower water exchange would only be recommended with caution for aquacultural production. There is no filtering of the extracted water, therefore no blockage of filter systems, and crops are mostly locally consumed and root irrigated. On the fish species level, warm water species are produced that are very undemanding with regard to oxygen requirements and highly tolerant to a range of water quality conditions.

In the Cape Winelands, effects on the phytoplankton composition and biomass by aquaculture were noticeable in the smaller dams within the Stellenbosch region. The phytoplankton situation enhanced the pH levels of these small dams, which could reach levels of alkalinity of 9 or 10. At the surface water level, no effects on other water constituents were measurable. Minimum sizes of 7 to 8 ha and good water exchange (twice to three times per year) would be recommended as minimum requirement for cold-water fish production.

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10 APPENDICES

Appendix A: Corrosion and scaling formulas applied in Chapter 6

Langelier Saturation Index

LI = pHa - pHs

where LI = Langelier Saturation Index

pHa = actual measured pH

pHs = saturation pH

For TDS, 200 mg/L

pHs = -0.014732 x t + 2.30149 + 0.00065 x TDS + 9.70167 – log(2.4972 x Ca) - log(alkalinity)

For 200 < TDS < 300 mg/L

pHs = -0.014732 x t + 2.30149 + 9.84 – log(2.4972 x Ca) – log(alkalinity)

For TDS > 300 mg/L

pHs = -0.014732 x t + 2.30149 + 0.00006786 x TDS + 9.8336 – log(2.4972 x Ca) – log(alkalinity)

where t = temperature (°C)

TDS = total dissolved solids (mg/L); Ca = calcium concentration (mg/L);

Alkalinity = total alkalinity (mg/ L)

Prediction of water characteristics following the Langelier Saturation Index

LI	Tendency of water
+ 2.0	Scale forming, non-corrosive
+ 0.5	Slightly scaling and non-corrosive
0.0	Balanced, but pitting corrosion possible
- 0.5	Slightly corrosive and non-scale forming
-2.0	Highly corrosive

(Koegelenberg et al. , 2002; DWAF, 1996)

Ryznar Stability Index

RSI = pHa – 2 x LI or RSI=

where RSI = Ryznar Stability Index

pHa = actual measured pH

LI = Langelier Saturation Index

Prediction of water characteristics by the Ryznar Index

RSI	Tendency of water
4.0–5.0	Heavy scale
5.0–6.0	Light scale
6.0–7.0	Little scale or corrosion
7.0–7.5	Corrosion significant
7.5–9.0	Heavy corrosion
> 9.0	Corrosion intolerable

(Koegelenberg et al. , 2002; DWAF, 1996)

Aggressiveness Index

AI = pH + log(A x H)

where AI = Aggressiveness Index

A = total alkalinity (mg/L $CaCO_3$); H = calcium hardness (mg/L $CaCO_3$)

Interpretation of the Aggressiveness Index

Appendix B: Outline of the BMP booklet

1) Site selection
2) Operational procedures
a) Water quality management
    b) Feed management
    c) Production
        i) Escapees
        ii) Mortalities
        iii) Grading, harvesting and transport of fish
        iv) Predation
        v) Cage maintenance
        vi) Animal welfare
    d) Disease monitoring, treatment and control
3) Monitoring and evaluation
4) Useful contact numbers