RISK-BASED AND SITE-SPECIFIC AQUACULTURE USE WATER QUALITY GUIDELINES

Volume 1: Description of a Prototype Decision Support System

P Moodley, CLW Jones, NC Mabasa and G Singh

WATER RESEARCH COMMISSION

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Volume 1: Description of a Prototype Decision Support System

Report to the
Water Research Commission

by

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This report forms part of a series of four reports. The other reports in the series are:

- *Development of a Risk-based Approach for Assessing Animal Watering Water Quality Guidelines Volume 1: Decision Support System* (**WRC Report No. TT 861/1/21**)
- *Development of a Risk-based Approach for Assessing Animal Watering Water Quality Guidelines Volume 2: Technical Support* (**WRC Report No. TT 861/2/21**)
- *Development of a Risk-based Approach for Assessing Aquaculture Water Quality Guidelines Volume 2: Technical Support* (**WRC Report No. TT 862/2/21**)

EXECUTIVE SUMMARY

In 2008, a national review by the Department of Water and Sanitation (DWS) recognized the need for the development of the South African Risk-based Water Quality Guidelines, leading to the following three phased approach being planned:

Phase 1: Development of philosophy
Phase 2: Application of philosophy and development of prototype guidelines
Phase 3: Development of tools for higher-tier site-specific guidelines

A number of specific issues came to the fore that made it necessary to re-examine the philosophical basis used for determining and applying water quality guidelines. These included inter alia the implementation of resource directed measures (the classification of water resources, Reserve determination and determination of resource quality objectives) and the application of source directed controls under the National Water Act (Act No. 36 of 1998), the concept of risk as potential common basis for decision making in various contexts, site specificity and advancements in guideline determination internationally. Additional factors that have influenced the optimal use of the 1996 South African Guidelines (SAWQGs) include the misapplication of the guidelines (e.g. guideline values are used interchangeably) or confusion in interpretation of terminology (e.g. guidelines versus standards).

The Phase 1 Needs Assessment and Philosophy document (DWS, 2008) led to the Water Research Commission (WRC) commissioning a series of projects developing risk-based approaches for water quality guidelines per user group, encompassing phase 2 of the process.

AIM AND OBJECTIVES OF THE PROJECT

The aim of this project was to develop a methodology for a risk-based approach for aquaculture water quality guidelines as part of the water quality guidelines series, presenting new approaches to expand the scope of water quality guidelines in terms of how they are presented, applied and decision support that is provided to the user. Risk-based approaches for irrigation, recreation and domestic use water quality guidelines have recently been developed, and the approach for animal watering has been undertaken concurrently with this project.

The project objectives included firstly, the development of the approach methodology based on risk principles and on supporting science, and secondly the development of a prototype technology demonstrator decision support system (DSS) that addresses the main decision contexts for the use of the guidelines.

SCOPE OF THIS PROJECT

The risk-based water quality guidelines need to be applied in manner that support site specificity and be based on a risked philosophy, whilst providing for a tiered assessment approach that caters for the level of use and that is specifically presented as a software-based decision support tool.

Unlike the other user water quality guidelines, for the aquaculture water use, no prior work or research has been undertaken since 1996, 2nd edition. Thus the 1996, Volume 6 Aquaculture User Water Quality Guidelines remained the departure point for this undertaking. The project has thus focused on identifying the fundamental aspects and defining a proposed concept for a risk-based approach to aquaculture water quality guidelines. The scope of the project of includes only freshwater fish (excludes marine) and has focused on three species to present the concept. The software decision support tool is a prototype technology demonstrator that includes a selected number of representative water quality constituents and scenarios to demonstrate functionality. The development of the risk-based water quality guidelines has also been limited by the lack of empirical evidence and the supporting science to extensively demonstrate the risk-based concept.

GENERAL RISK-BASED APPROACH

The proposed extension to current guidelines lies in that the fitness for use assessment now relates to hazard and exposure, rather than the hazard predominantly, as applied in the 1996 guidelines. "Risk-based" guidelines simply allow the suitability of the water to be interpreted in terms of risk of specific adverse effects.

The project was aimed at developing a software tool able to provide site specific and generic water quality guidance for aquaculture water use in South Africa. This was achieved in a two-step process, the initial phase focusing on the definition of the risk-based concept for aquaculture and the associated risk assessment methodology, and the second phase involving the design and generation of the informatics for the DSS based on the methodology defined and technical considerations. Both qualitative and quantitative expert information and the supporting science were consolidated into look up tables and form an integrated part of the decision support.

In defining a proposed risk-based approach for aquaculture, it has become apparent that, greater site-specificity, particularly in respect of the nature of the species exposed to the water, and the species' life stages, make the risk-based water quality guidelines much more relevant and widely applicable.

Three fish species were identified to demonstrate the concept of a quantified risk-based approach to water use in aquaculture. While the freshwater aquaculture industry in South Africa is small, relative to marine aquaculture, the three freshwater species selected here are the most appropriate freshwater representatives based on the current activities in the industry. The fish types included in the approach development are (1) trout (*Oncorhynchus mykiss*), because it is the only large-scale freshwater industry in South Africa, (2) Mozambique tilapia (*Oreochromis mossambicus*), although this subsector is very small with no large-scale production in South Africa, it has got some potential for growth and (3) African catfish (*Clarias gariepinus*), this aquaculture does not operate on any large scale close to those of trout and tilapia and does not show immediate potential for growth at this time. The approach to the DSS development comprised the following:

1) An inception phases that focused on understanding aquaculture as a user group and the nature of the water use, as well as a clarification of the project aims and outputs.

2) A definition of the key concepts and determination of the fundamental risk aspects associated with aquaculture as a water user (how would one assess risk of the adverse effects as it relates to aquaculture water use). This included of the selection of the aquaculture species to be included the approach development.

3) A literature assessment of the water quality hazards focusing on understanding the interactions of waterborne water quality hazards within the water medium and determination of the operating within the limits of these hazards, as these have a direct effect on fish productivity and influences optimal aquaculture production. A suite of hazards representing different categories of water quality hazards were selected to develop the concept that is presented here in the prototype decision support system.

4) Definition of the risk methodology to be applied in deriving the aquaculture risk-based guidelines. This comprised the risk assessment component of the development process, to define the relationships and interpretation of the assessment of risk of the adverse effects for a scenario to provide both qualitative and quantitative decision support. A source, pathway and receptor analysis approach was applied in the methodology development;

5) Development of a Technology Demonstrator, a pilot decision support system, as a preliminary demonstration of the most important features and the tiered approach to the tool for the water quality constituents selected.

6) A draft and final report documenting the approach development and the important feature of the demonstrator DSS.

Given the scope of this project it should be noted that the prototype does not offer a fully functioning DSS. However, the basic functionality presented does provide an indication of what the system is intended to look like from a user-interface perspective and the outputs the provided in terms of water quality guidance.

DEVELOPMENT OF THE TECHNOLOGY DEMONSTRATOR DECISION SUPPORT SYSTEM (DSS)

The Decision Support System (DSS) tool is a user-friendly tool that presents a concept approach to the user to assess risk to aquaculture water use at a generic and site-specific level. Guidance is provided in respect to:

- Water quality requirements for aquaculture production in respect of a selected fish species; and
- Site specific assessment on the fitness for use of source water and the operational conditions.

A simplified schematic representation of the DSS structure is shown in Figure 1. The DSS allows for a three-tiered system for water quality risk assessments. The difference between the tiers lies primarily in the degree of site-specificity required to produce an output, where:

- Tier 1 is largely equivalent to 1996 generic guidelines and is made available in the DSS. Tier 1 assessment does not involve any calculation methodology, however it does bring in the site specificity in terms of fish species. The DSS contains specific literature-based information about constituents under consideration, hazard characterisation and potential adverse effects. It requires minimal user defined input, and it is intended to reflect the most conservative set of conditions, even if these do not occur together.

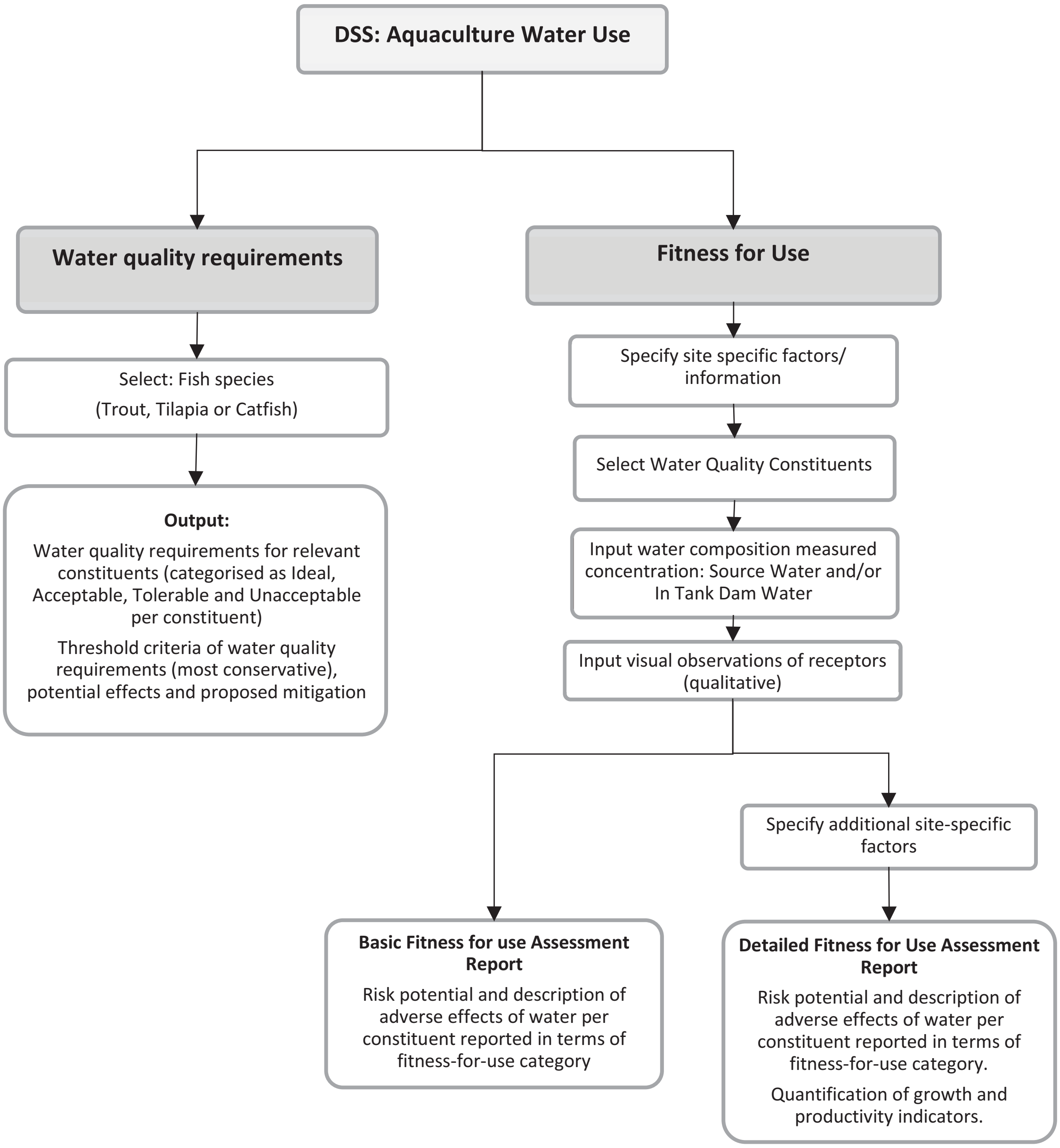

Figure E1: Functional structure of the DSS

- Tier 2 is a specific application level with increasing data inputs to the model occurring, as more site-specific detail is provided. It largely uses pre-defined water user scenarios and limited site characterisation choices with common field observation and or measurement input required from the user for the assessment.

- Tier 3 is reliant on additional specialist input (in addition to the site-specific data) with additional calculation methodology functionality. This tier addresses the quantification of selected growth and productivity indicators of aquaculture that serves as a measure of the risk present.

Based on the guidance required the user selects the required functionality, and then follows the instructions to complete generic and site-specific selections, information and water quality data inputs to obtain the decision support regarding potential risk posed by the water quality.

For purposes of the technology demonstrator the two site specific default scenarios addressed include fish species and life stage. Additional scenarios identified to be included at the next development phase include fish health, production system type, scale of operation, duration of exposure, fishing stocking density and water turnover rates.

Water is the most important resource in aquaculture since it determines the success of the aquaculture operation and ultimately the success of the industry. Fish are immersed in water and complete their entire life cycle in direct contact with it; they cannot avoid it by moving away or simply not ingesting it (as a terrestrial animal might be able to do) because they cannot remove themselves from the water and thus cannot avoid the hazard. So, in respect of aquaculture as a water user it is not only necessary to understand the water quality risk of the source water (raw water quality) but also of the system/tank/dam water quality. Thus, the tool provides the user the option to assess the suitability of the water to be interpreted in terms of risk of specific adverse effects for both source water (raw) and tank/dam water quality.

The Development Platform

The tool was developed in the Microsoft (MS) Excel Visual Basic for Applications (VBA) integrated development environment (IDE). The graphical user interface is developed using a series of 'User Forms' and results are displayed as reports using MS Excel worksheets. Custom dialog boxes, list boxes and message boxes are used to insert the input parameters and direct the user through the tool. The tool also has the ability to export results to a 'PDF' format for a more formal reporting method.

RISK REPORTING

The risk-based water quality guidelines are reported at two levels, as follows:

- For ***Water Quality Requirements***: a report of all risk threshold criteria and associated fitness for use levels for all relevant water quality constituents, for the specific fish species selected. This would guide the user on the requirements of the quality of water needed for the operation.
- For ***Fitness for Use***: only the fitness for use category of the input water quality constituents presenting the acceptability and implied risk (ideal OR acceptable OR tolerable OR unacceptable) together with the exposure concentration of the specific constituent, the description of the associated adverse effects and proposed mitigation measure is reported. This is presented for both source water (raw) and/or tank/dam water as selected.

The water quality guidance reporting in the DSS is categorised visually in a colour-coded manner that the user is able to immediately assess suitability and the level of risk posed. The reporting system includes a four category system which has been based on the classification system adopted by the Department of Water and Sanitation to categorize fitness for use ranges. In order to ensure that all the risk-based guidelines of the different South Africa Water Quality Guideline Series Water User groups are consistent and aligned, this system is employed in all these guidelines. The four-category system is in harmony with a risk-based assessment of water quality in that the 'Ideal' category represents a no risk scenario (safe level), while the 'Unacceptable' category represents a high-risk scenario (likely presence of the adverse effects). However, it must be noted that for aquaculture water use, the supporting science lends itself to three levels of risk, thus the distinction between the acceptable and tolerable ranges required a somewhat 'superficial' division of the middle range level of risk into two category ranges as a means to demonstrate the concept of this tool and to remain consistent with the other guidelines.

The generic categorization is shown below.

A generic description of the fitness for use categories used for reporting

Reported Category	Description
Ideal	A water quality fit for a lifetime of use.
Acceptable	A water quality that would exhibit minimal impairment to the fitness of the water for its intended use. No observed adverse effects.
Tolerable	A water quality that would exhibit some impairment to the fitness of the water for its intended use. Minor risk of adverse effects presenting themselves.
Unacceptable	A water quality that would exhibit unacceptable impairment to the fitness of the water for its intended use. Significant risk of adverse effects, presenting themselves.

Water Quality Requirements

Tier 1 requires very little input from the user and is accompanied generic guidance on the ranges of suitability (threshold criteria) of the relevant water quality constituents. The water quality requirements are presented once the species is selected.

Fitness for Use

At the higher tiers the fitness for use is determined by assessing the potential risk-based posed by a hazard for the selected exposure scenario. The assessment is carried out as follows:

- The exposure scenario is defined (*i.e.* species; life stage);
- The water quality analyses are entered for either for source water quality or tank/dam water quality or both;
- Qualitative information is entered based on visual observations of the fish;
- Production and growth indicators are entered.

The calculations are run in the model to generate the fitness for use report of both qualitative and quantitative outputs. In terms of quantitative outputs the following is calculated:

- The mean growth rate of the fish, measured as specific growth rate (SGR) which is a standard measure of the percentage body weight gain per day, and
- The mean food conversion ratio (FCR) of the fish (measure of the wet weight gained by the fish as a proportion of the dry feed eaten).

The potential risk of the adverse effect occurring is presented which would then allow the user to assess if the risk is an acceptable one in the specific context or to reduce the risk factors identified to an acceptable level.

CONCLUSION

The project has been successfully achieved, with the DSS as a product fulfilling the requirements of the prototype technology demonstrator for risk-based water quality guidelines for aquaculture water use. The concept approach developed form the foundation of the modelling and algorithms to the DSS and associated graphical user interfaces that will, for the first time, be used to determine the measurable risk that waterborne hazards have on water use in aquaculture. Further phases of the project will need to build on the concept model developed.

RECOMMENDATIONS

The following is recommended as key research needs to develop the product further to a fully functional system:

- A key gap identified in the development of the approach is a lack of sufficient site specific hazard/indicator-linked data for quantifying water quality risk in aquaculture. One of the outcomes of this exercise was the establishment that there were insufficient empirical data available in the literature and in the time that was available to do this comprehensively. For the purposes of the risk-based concept approach development, synthetic data sets were thus used to develop the concept for the quantification of water quality-based risk in aquaculture and the associated functionality in the DSS. Update of the model with real data will be required during future phases of the project, when the full functionality has been developed and more importantly when scientific data becomes available.

- Currently the modelling of the risk in the DSS is based on a weighting system which accounts for the impact the different water quality hazards and their relationships shall carry on the risk that the hazard is likely to have on the fish species. The weighting system used in the DSS tool has been based on current expert knowledge of aquaculture and a knowledge of interactions of the hazards with the different assumptions, which has been used to demonstrate the concept. These weightings will need to be adjusted, in time to come, based on a thorough literature review and based on stakeholder interactions, both of which will need to be taken forward in the next phase of this project.

- Extension of the DSS functionality is needed to include additional site specific scenarios such as:
    - Additional species of fish;
    - Scale of operation;
    - Type of production system;
    - Stocking density;
    - Fish health;
    - Water turnover rates;
    - Carrying capacity of system;
    - Factors related to the management of the system (pre-farming, farming operation; post–farming).

  Again, the challenge is availability of the supporting science to express the risk of the adverse effect in terms of a calculation methodology for these indicators. Further research and assessment are required to determine the appropriate methodologies that could applied to the modelling in quantifying the risk in terms of end-point effect (e.g. fish size, growth rate, behaviour). Much of the added functionality will support the assessment of water quality risk potential within the production aquaculture system. However, the source water would also influence these scenarios and the manner and extent to which the adverse effects result.

- The DSS has focused on the identified key physio-chemical water quality constituents selected for the purposes of the DSS development. Confirmation of additional water quality constituents to include those constituents relevant to aquaculture water use/production in the South African context is required. In respect of water quality constituents:
    - Extension to include additional physio-chemical hazards, biological parameters (indicator organisms) and constituents of relevance to the specific fish species,
    - Inclusion of empirical data related to the guideline values (end point adverse effect levels) for all hazards as relevant,
    - Inclusion of calculation methodologies that can account for the assessment of multiple constituents simultaneously, and
    - Investigations into the antagonistic and synergistic effects of the water quality constituents and approaches on how to incorporate these into the quantification of the risk.

- Further development of Tier 3 is required. This is reliant on additional specialist input (in addition to the site-specific data) with corresponding adjustments to the guideline values, using referenced modules of the DSS but also inclusion of subsequent methodologies based on, for example, the obtaining clinical biochemistry values, histopathological data and reproductive output.

- Further testing with the wider stakeholder user groups is required to refine the product and to update the DSS to improve user-friendliness and utility, based on feedback from users.

- The DSS tool has been demonstrated using MS Excel, however in going forward to full scale application, it is recommended that available on-line databases be tested to select a software suitable for the DSS for the guideline series.

- Next phases of the project require integration with the other water user groups' guidelines that needs to consider the selection of coding platform, intellectual property issues, controlled access to software system, version controls as well as processes and procedures on the updating of the methodologies and functionality of the DSS for the water user groups. There is also a real need in the aquaculture industry to expand the tool to include brackish-water aquaculture and marine aquaculture (mariculture).

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LIST OF ABBREVIATIONS

Abbreviation	Definition
DAFF	Department of Agriculture, Forestry and Fisheries
DSS	Decision Support System
DWAF	Department of Water and Forestry
DWS	Department of Water and Sanitation
FCR	Feed Conversion Ratio
IDE	Integrated Development Environment
LC_{50}	Lethal Concentration (50%)
NWA	National Water Act
PDF	Portable Document Format
RQOs	Resource Quality Objectives
SGR	Specific Growth Rate
SAWQGs	South African Water Quality Guidelines
VBA	Visual Basic for Applications
WRC	Water Research Commission

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1. INTRODUCTION

1.1. Background

The Department of Water and Sanitation's South African Water Quality Guidelines (SAWQGs) for Fresh Water (Second Edition) published in 1996 has been an extremely important contribution to water resource management in South Africa. It reflected the scientific thinking at the time that it was produced. Subsequently, the decision support function of water quality guidance has grown and become more complex. Increased scientific understanding of the complexity of water ecosystems and adaptive management processes has led to new ways of managing water quality. Traditional scientific and management approaches may not deal well with contemporary water quality issues. Since the evolvement of water resource management within South Africa, the SAWQGs have become decision support tools rather than just a list with limits.

Both application and scope issues have made it necessary to re-examine the philosophical basis used for determining and applying water quality guidelines. These included inter alia the implementation of resource directed measures (the classification of water resources, Reserve determination and determination of Resource Quality Objectives (RQOs)) and the application of source directed controls under the National Water Act (Act No. 36 of 1998) (NWA), the concept of risk as a potential common basis for decision making in various contexts, site specificity and advancements in guideline determination internationally.

The need for a quantifiable assessment system to judge fitness for use and suitability of water quality that moves beyond simple numeric values, that provides an assessment in terms of the nature of the resource and the nature of the water user, has been identified.

Against the backdrop of an evolution in water resource management and specifically water quality assessment and guidance the then Department of Water Affairs and Forestry (DWAF) in 2008 commissioned a project to critically investigate the need for a review of these guidelines, and the principles that govern them. This investigation, compromising Phase 1 of a broader project, concluded that there was a need for the review of the 1996 version of the SAWQGs.

The outcomes of the Phase 1 investigation had highlighted the necessity to extend the application of the water quality guidelines. The new envisaged guidelines would be different in a number of fundamental ways:

- They would be risked based (different to the 1996 guideline which was largely hazard based);
- They would allow for greater site specificity (a widely recognised limitation of the generic 1996 guidelines); and
- They would be made available primarily as a software decision tool to support decision making.

A key fundamental change in philosophy from the 1996 guideline series has been the concept of "acceptable risk" that now needs to be adopted by the user audience of the risk-based guidelines, from water resource managers to the actual water users, in order to allow for informed decisions to be made concerning water use that were sustainable. This is a paradigm shift in thinking and arguably the most important concept to adopt, as it represents a significant departure from the previous versions of the South African Water Quality Guidelines (DWAF, 1996) in which a “desired state” of a Target Water Quality Range was the goal and generally construed to imply a “no adverse effect” state.

The new goal may thus be stated as to adequately describe the outcome of a water use under a specific context in a manner which enables a more realistic decision to be reached regarding either accepting some degree of adverse outcomes or reducing the risk factors identified to an acceptable level. The decision support provided by the guidelines would need to relate to the assessment of fitness for use and water quality requirements in, primarily, freshwater resources

In light of these recommendations the Water Research Commission (WRC) initiated an overarching project that has seen the commissioning of a series of projects to revise the approach and guide the development of risk-based water quality guidelines and decision support tools for different water user groups. This project addresses the ‘Development of a Risk-based Approach for assessing Livestock Watering and Aquaculture Water quality Guidelines’ as part of the series, with this specific report addressing the development of the prototype decision support systems (DSSs) for the Aquaculture Water User. Previous recent projects have addressed risk-based water quality guidelines for the irrigation, domestic and recreational water user groups, that are aligned in terms of the philosophy and concept fundamentals, to this, the aquaculture water user group guidelines. The risk-based water quality guidelines for livestock (animal) watering have been developed in parallel with and as part of this project.

1.2. Project Objective

The objective of the project was to develop a risk-based approach for aquaculture water quality guidelines for assessing water quality requirements and fitness for use, enabled through a user-friendly decision support system (DSS). The scope of this project has addressed the development of a DSS technology demonstrator tool, and not on producing a fully functional decision support system at this stage.

The methodology for this project was designed to achieve the general aim of developing a software-based tool able to provide both generic and site-specific risk-based water quality guidelines. A DSS offers the advantage of improving the way in which the guidelines are used because the focus will be on supporting decisions in specific contexts.

1.3. A Risk-based Product

Guidelines reflect the scientific environment. The key components defining the nature of the envisaged revised guidelines are:

- Risk, and

- Site-specificity.

Risk can be defined as the expected likelihood or probability of undesirable (adverse) effects. It is a statistical concept that results from an exposure to an environmental concentration of a known substance or material. The risk is considered acceptable if the exposure levels to the substance or material are considered safe (EPA Victoria, 2004).

A risk is posed when there is a source, a potential exposure pathway and a receptor (receiving environment, for example, animals, fish: the so-called "population at risk"). It is important to note that risk is not a concentration, dose, other value-based point, or even non-value based levels. Risk is the probability that a particular adverse effect occurs during a stated period of time (DWAF, 2005). Risk-based can therefore be defined as recognising the risk factors in giving effect to risk objectives.

In the course of deriving the guidelines the risk refers to the probability of specific adverse/undesired effects to the fish species of "using" water containing a potential hazard, including the severity of the consequences. The hazard in this context refers to a range of water quality constituents that may be present in the water that renders it less fit for use, and its consequences based on the extent and manner the water is experienced or contacted by the fish. Thus, risk is a function of hazard and exposure. Where "*hazard* = physical, biological, chemical or radiological agent" that has the potential to cause harm, *hazard effect* = adverse impact on health that can result from exposure to a substance and *exposure* = contact between a substance and a population" (Leiss and Chiolco, 1994). The threat caused by a hazard depends not only on the severity of its effect but also on whether or not the effect is reversible (Leiss and Chiolco, 1994).

Description of the risk, therefore, requires an assessment that provides answers to the following three questions (Jooste, 2015):

- What can happen (the scenario) (dependent on the way/circumstances the water is experienced)?
- How likely is this to happen (probability)? and
- If it does happen, what are the consequences (adverse effects of the hazard on the fish population)?

In the development of the risk-based water quality guidelines, the adoption of the risk approach is that it can provide a common philosophical basis for decision-making in different contexts. This risk approach generalises the basis for decision-making by incorporating as much of the relevant site-specific evidence (the scenario) as possible.

1.4. General Approach

The risk-based guidelines must still present to the water user a source of information which allows them to determine the water quality requirements for the applicable water use. The guideline design must also ensure that the application thereof does not have an adverse impact on water resources in which the water use occurs.

At a fundamental level a risk-based guideline must provide both an analysis and management statement of risk. It should be considered that this approach differs significantly from the previous approaches adopted in that the output is not a statement on the quality required to be present without risk as was the case for the previous Target Water Quality Range approach, but rather as a method to arrive at an acceptable risk level.

A risk-based approach effectively implies that different water quality may be fit for use for the same water user (water use type) in a different setting or scenario (site or location). As the scope of guideline application includes multiple water source types ranging from municipal to raw surface water or groundwater, the guidelines must allow water users to make informed decisions relating to water quality, noting that this does not mean that risk is managed by only manipulating water to arrive at a suitable quality, but recognising that user and site-specific factor manipulation may also achieve an acceptable risk level.

Site specific factors for aquaculture production would for example extend to the fish species, the type of production system (intensive; extensive), life stage (eggs, larvae, juvenile, adult) and the environmental conditions of the systems as well stocking densities of site specific scenarios.

The guidelines would also need to account for direct or indirect response-indicators, for example responses of survival, changes in colour and behaviour, an impact on fish growth and the rate that fish convert feed into somatic growth, level of reproduction, etc.

The risk-based guidelines are intended to provide the user with a potential risk which may then be applied to a risk management process. The first step relies on a potentially variable range of user inputs, which will accordingly result in a varying degree of accuracy in the estimates generated.

As opposed to many of the other user group water quality guidelines having received attention over the recent decades, developments and improvements in the aquaculture water quality guidelines have been limited. The Phase 1 Philosophy and Needs Assessment report (DWAF, 2008) of the project also did not address aquaculture as a user to any extent. The 1996, Volume 6: Aquaculture Water Quality Guidelines thus remained the departure point for this undertaking, and which has required the definition of approach fundamentals and the development of a risk-based concept for aquaculture and associated methodologies that informs the decision support system design.

The proposed extension to current guidelines lies in that the fitness for use assessment now relates to risk, which combines hazard and exposure, rather than the hazard predominantly, as applied in the 1996 guidelines. “Risk-based” guidelines simply allow the suitability of the water to be interpreted in terms of risk of specific adverse effects. The project development process included the tasks as outlined below.

It is important at the outset to note that this initiative has focused on aquaculture in terms of the Freshwater Series of the 1996 South African Water Quality Guidelines and does not address mariculture that constitutes Volume 4 of the Coastal Marine Waters South African Water Quality

Guidelines series, DWAF, 1995. This is considered a fundamental gap, as the sector in South Africa is dominated by marine aquaculture.

Since there are numerous known species of freshwater fish, it was not realistic to cover all fishes as part of the approach development through this project scope, particularly since the effect of many water-borne hazards are species-specific among fishes. For that reason, this project has been limited to 3 fish species that represent the larger freshwater aquaculture industry in South Africa. The risk-based approach development is based on these target species as it relates to the fish as the receptor and the related aquaculture production activities. It is envisaged that that defined risk-based assessment approach for water use in aquaculture in South Africa that emanates from this project, would in future be easily adapted to other species and aquaculture systems through the incorporation of species specific and scenario specific information into the DSS.

The consideration of the receptor characteristics such as nature of the species exposed to the water and the species' life stages has introduced greater site specificity to the water quality guidelines.

The development of the DSS emanates from the key aspects highlighted as follows:

- Inception Phase:
  - Provided a description of the context and the risk- based approach development process as well as a clarification of the project aims and outputs. It further presented a baseline literature survey and proposed concept approach to the aquaculture water quality guidelines.

- Development of Risk Approach Fundamentals for Aquaculture:
  - Focused on creating an understanding of the aquaculture user group and the nature of the water use. This included:
    - Selection of the aquaculture freshwater fish species: trout, tilapia and African catfish,
    - Definition of the site-specific factors, drivers and environmental conditions; and
    - Definition of the norms and adverse effects associated with water quality hazards
  - Involved the definition of an approach incorporating the risk fundamentals on which the modelling approach could be based upon and a decision support system designed.

- Hazard Assessment for Risk Approach Guideline for Aquaculture:
  - An assessment of the water quality hazards was then undertaken focusing on understanding the interactions of waterborne water quality hazards within the water medium and determination of the operating conditions within the limits of these hazards, as a means to determine the effect on fish productivity and influence on optimal aquaculture production.
  - A range of adverse effects (end points) and indicators were then identified as a means to define the calculation methodology and risk assessment.

- Representative water quality constituents were then selected to demonstrate the concept approach in the design and generation of the informatics for the DSS.

- Risk Assessment Methodologies for Aquaculture:
  - The risk calculation methodologies to be applied to provide quantitative and qualitative risk-based guidance were defined which includes:
    - Specific growth rate (SGR) and feed conversion ratio (FCR) chosen as the end points, and
    - General relationship of the hazard to the probability of adverse effect described:
      - change in skin colour;
      - changes in behaviour;
      - change in the rate of survival; and
      - change in reproduction.

- Development of the technology demonstrator decision support system:
  - The risk calculation methodologies developed were used as the basis to define the informatics for the software application. The demonstrator tool programming was then undertaken to develop the functionality and presentation as required.
  - The definition of the levels of tiered assessment, the modelling of the generic and site-specific applications, collation of all the reference data and the development of graphic user interface were developed. Further to this an important aspect was the fitness for use assessment and reporting of the outputs that were required.

The DSS prototype that was developed addresses the specifications, business development and functional requirements, in terms of those that were envisaged in Phase 1 of the project (DWAF, 2008) with respect to what the risk- based water quality guidelines should be. The tool incorporates the tiers of assessment and the qualitative and quantitative assessment to express the risks associated with aquaculture water use done through a user-friendly graphical interface.

The risk-based approach remains a guideline process which by definition is not the application of an inflexible standard to a different set of sites. Thus, the DSS is supposed to guide the user which implies that it must do more than generate a guideline confined to a statement on risk following exposure, but it must also assist in the identification of key risk factors, which are by their very nature site-specific. It is relevant to note that this approach accords with the widely adopted source, pathway and receptor analysis for hazardous chemical investigations and represents a multidisciplinary approach to what is a complex field.

The final DSS risk-based guidelines are thus envisaged to be continually evolving as opposed to standards which are fixed and only subject to changes which coincide with planned revisions. This difference is fundamental to achieving guidelines which remain applicable as aquaculture production systems continually improve and new knowledge on the risk-hazard relationship is developed in the fish farming industry. The key to achieving this objective is a combination of data capturing fields on the one hand, and the provision of results calculations in a manner which enables risk factor identification, quantification and manipulation on the other. In other words, the end-user can enter site-specific information into the tool (*i.e*. both risk- and hazard related data as it becomes available), making the assessment increasingly applicable and the results that are generated more useful.

The fundamental objective of a risk-based approach is to optimally utilise the available water resources. The objective is thus not to remove all risk and provide safe water quality, but to accept that some risks are acceptable, can be mitigated, and for the specific intended purpose, remain fit for use without appreciable loss to the sustainability (and in this case profitability) of the water use.

This final report presents the DSS and provides an overview of its development for the evaluation of fitness for use and water quality requirements for aquaculture water use. It provides an indication of what the system looks like from a user-interface perspective and explains the functionality and modelling aspects of the technology demonstrator tool. This report consists of two volumes, Volume 1: Description of the Decision Support System (this report) and Volume 2: Technical Support.

2. OVERVIEW OF THE DECISION SUPPORT SYSTEM

As the risk-based models are fundamentally an analysis of risk enabling the management thereof, the design may be considered to equate to data flow (decision tree analysis). The DSS thus provides a structured approach necessary for addressing the main decision contexts for the assessment of risk in the aquaculture water use. The overall product allows for a three-tiered system with increasing data flow noted with higher tiers. The difference between the tiers lies primarily in the degree of site-specificity required to produce an output. The definition of the assessment levels that inform the basis of design for the DSS informatics are aligned with the philosophy specifications of Phase 1 (Table 1). The three tiers are as follows:

- Tier 1 is largely equivalent to 1996 generic guidelines and is made available in the DSS. Tier 1 assessment does not involve any calculation methodology however it does bring in the site specificity in terms of fish species. The DSS contains specific literature-based information about constituents under consideration, hazard characterisation and potential adverse effects. It requires minimal user defined input, and it is intended to reflect the most conservative set of conditions, even if these do not occur together.
- Tier 2 is a specific application level with increasing data inputs to the model occurring, as more site-specific detail is provided. It largely uses pre-defined water user scenarios and limited site characterisation choices with common field observation and or measurement input required from the user for the assessment.
- Tier 3 is reliant on additional specialist input (in addition to the site-specific data) with additional calculation methodology functionality. This tier addresses the quantification of selected growth and productivity indicators of aquaculture that serves as a measure of the risk present. It would provide the most site-specific guidance – probably a risk assessment protocol, requiring highly skilled input- and output interpretation. The tier would likely require considerable expertise and would be used occasionally in practice and in specific situations.

Table 1: An overview of the Tiered Assessment System

Tier 1	Tier 2	Tier 3
Most generic (and by implication the most conservative) approach to risk guidance. Minimum user input required and simple output provided. Simplified generic conservative assumptions used and totally reliant on the default datasets (worst case exposure). Does not involve rigorous calculation methodology.	Moderately site-specific, requiring some skills, but largely uses pre-defined water use scenarios and limited site characterization choices with common field observation and or measurement input required from the user for scenarios manipulation. Rule-based output interpretation.	The most site-specific guidance. A risk assessment protocol, requiring highly skilled input and output interpretation. Allows for the adjustment of the modelling and reference data. Default site-specific component options that can be changed to suit site specific circumstances (more specific models and parameters).

Whilst these descriptions conveniently demarcate tiers, these are in reality more flexible with increasing variations of site-specific detail use as the user moves from Tier 1 to Tier 3, with a general migration from reference documentation used in the calculations performed to user-defined site-specific input. In computing terms, this may be considered as moving from recursive algorithms to dynamic algorithms.

2.1. Water Quality Assessments

A simplified schematic representation of the aquaculture water use DSS structure is shown in Figure 1. Based on the tiered approach, the risk-based water quality guidelines operates at two levels of functionality. Guidance is provided in respect of (1) Water quality requirements for aquaculture production in respect of the selected fish species; and (2) Specific assessment on the fitness for use of source water and the operational conditions. The difference between the levels lies primarily in the degree of site-specificity required to produce an output. The two-level assessment system accommodates for the needs of the novice, intermediate and expert user, dependant on the decision support required. The risk-based water quality guidelines are reported as water quality requirements or as a fitness for use assessment both of which incorporating the analysis of the risk and the management guidance thereof.

The input needs, processing and outputs of the assessments in the DSS are different at the two levels of functionality. The science (reference data) and calculations that support them are however the same.

By selecting the either the water quality requirement assessment or fitness for use assessment in the DSS, at the Tier 1, Tier 2 and Tier 3 the following outputs will be produced:

- Tier 1 conservative water quality ranges of relevant constituents for a selected fish type required for aquaculture production, with proposed mitigation;
- Tier 2 calculations:
    - to assess the fitness for use of a given water quality composition of source water for a selected fish species;
    - to assess the fitness for use of a given water quality composition of in tank/dam water for a selected fish species;
    - qualitative assessments providing an interpretation of visual observation indicators and potential risk.
- Tier 3 as listed in Tier 2 above, and:
    - calculation to assess the fitness for use of a given water quality composition in terms of food conversion and growth rate of the selected fish species.

The outputs of the assessments are reported as PDF screens that may be printed or saved.

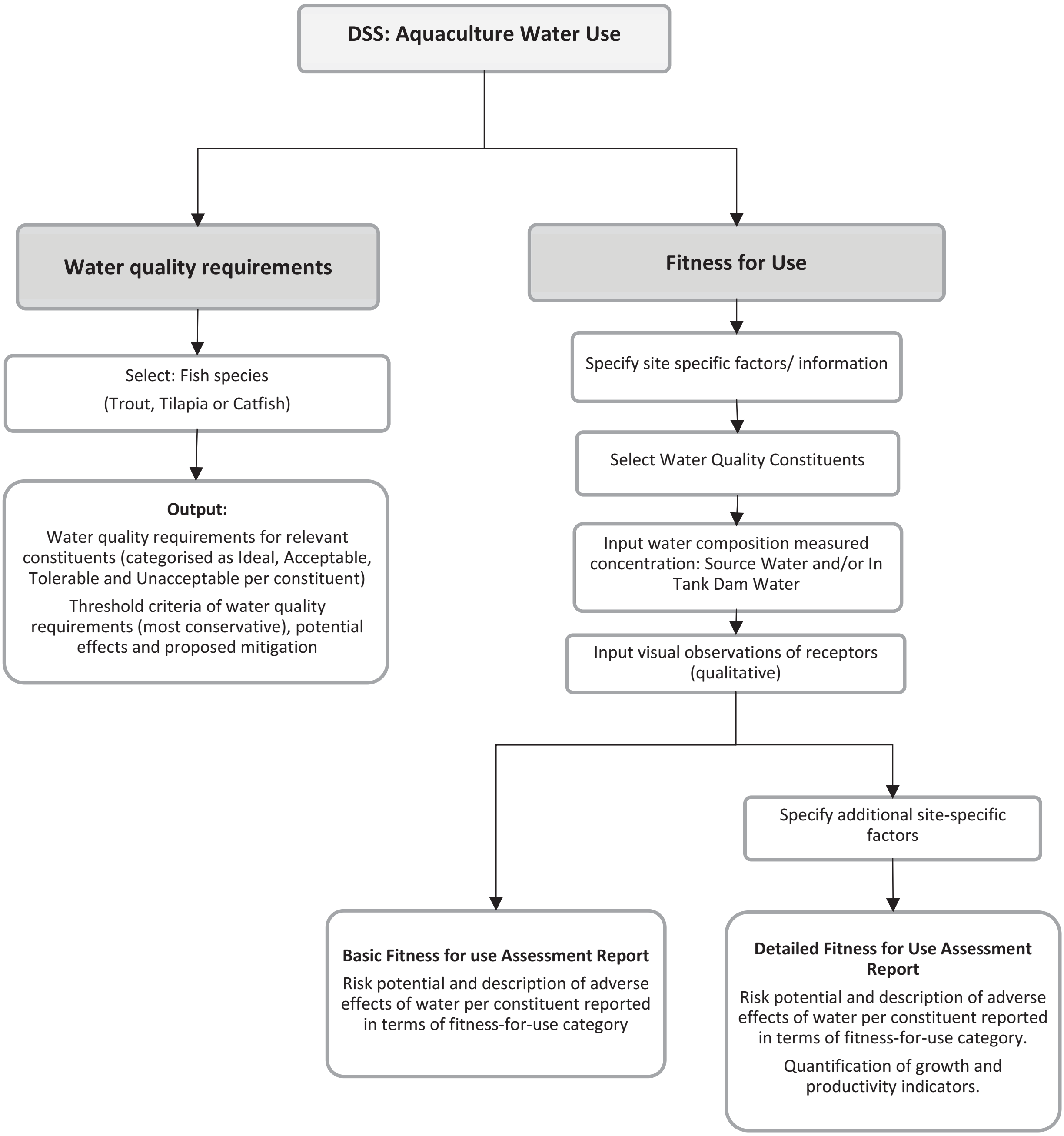

Figure 1: Schematic of functional structure of the DSS

2.2. Reporting in the Decision Support System

The risk-based water quality guidelines are reported at two levels, as follows:

- ***Water Quality Requirements***: a report of all risk threshold criteria and associated fitness for use levels for all relevant water quality constituents, for the specific fish species selected. This would guide the user on the requirements of the quality of water needed for the operation.
- ***Fitness for Use***: only the fitness for use category of the input water quality constituents presenting the acceptability and implied risk (ideal OR acceptable OR tolerable OR unacceptable) together with the exposure concentration of the specific constituent, the description of the associated

adverse effects and proposed mitigation measure is reported. This is presented for both source water (raw) and/or tank/dam water as selected.

The water quality guidance reporting in the DSS is categorised visually in a colour-coded manner that the user is able to immediately assess suitability and the potential risk posed. The reporting system includes a four-category system which has been based on the classification system adopted by the Department of Water and Sanitation to categorize fitness for use ranges. In order to ensure that all the risk-based guidelines of the different South Africa Water Quality Guideline Series Water User groups are consistent and aligned, this system has been applied. The four-category reporting system is in harmony with a risk-based assessment of water quality in that the 'Ideal' category represents a no risk scenario (safe level), while the 'Unacceptable' category represents a high-risk scenario (most likely presence of the adverse effects).

However, it must be noted that for aquaculture water use, the supporting science lends itself to three levels of risk, thus the distinction between the acceptable and tolerable ranges required a somewhat 'superficial' division of the middle range level risk into two category ranges as a means to demonstrate the concept of this tool and to remain consistent with the other guidelines.

The generic categorization is shown below.

A generic description of the fitness for use categories used for reporting

Reported Category	Description
Ideal	A water quality fit for a lifetime of use.
Acceptable	A water quality that would exhibit minimal impairment to the fitness of the water for its intended use. No observed adverse effects.
Tolerable	A water quality that would exhibit some impairment to the fitness of the water for its intended use. Minor risk of adverse effects presenting themselves.
Unacceptable	A water quality that would exhibit unacceptable impairment to the fitness of the water for its intended use. Significant risk of adverse effects, presenting themselves.

3. DEVELOPMENT PLATFORM

The prototype DSS is designed to present the graphical user interface of the modelling aspects that are assessed to determine the risk-based water quality guidance. The programming software selected would thus need to cater for the processing, modelling, data capture and evaluation, as well as an interactive user interface. A requirement of the project (and for all the user guidelines) is that open source software be used for the decision support system of the various guidelines.

The prototype aquaculture water use DSS tool has been developed in the Microsoft (MS) Excel Visual Basic for Applications (VBA) Integrated Development Environment (IDE). The use of Microsoft Excel is motivated by its global acceptance as a powerful calculation and graphing program. It is easily accessible to most users, simple to understand and can be updated on a regular basis. The graphical user interface is developed using a series of 'User Forms' and results are displayed as output reports using the back-end reference data. Custom dialog boxes, list boxes and message boxes are used to insert the input parameters of the tool. The tool also has the ability to export results to a 'PDF' format for a more formal reporting method. It is designed to guide users through a series of 'User Forms' at each assessment level to produce a relevant result based on the option selected.

At this stage there is no separate database that is being utilised since the MS Excel platform performs a pseudo database function for the demonstrator tool which for the purposes of this project, is at concept a level. The MS Excel VBA IDE adequately demonstrates the DSS functionality of aquaculture water use, since the risk analysis and associated calculations related to aquaculture use are still in an infancy stage not requiring complex computing and dynamic algorithms. The supporting science to assess risk in aquaculture water use is not readily available. More research and empirical evidence is required to develop the risk-based analysis to a further degree.

As the number of fish supported by the tool grows, the availability of scientific data on risk assessment of water quality hazards improves, the source pathway receptor analysis of hazards for fish increases, the quantification methodology of indicator responses are developed, and as the understanding of site specific aquaculture production conditions are built in to develop a fully functional DSS, the demand for separate databases will eventually grow. Microsoft Excel is limited as a database program and the vast amount of information that will be eventually developed (water quality data and linked in databases) will require a stronger software database management programs such as MS SQL, or MYSQL or similar.

Ultimately, once the DSS tool is developed to full scale application, an online database would be more suited for the programming software. This is a requirement for the DSS tools of all the respective user groups of the South African Water Quality Guidelines series which would need to be accessible via an integrated online platform.

4. CALCULATION METHODOLOGY

Risk assessment is a process by which the extent of exposure is compared against the hazard of the contaminant to determine whether it is likely to result in harm to the exposed individual(s)/situations, in this case to the fish population for the aquaculture operation. Risk is a function of hazard and exposure (Figure 2). The threat caused by a hazard depends not only on the severity of its effect but also on whether or not the effect is reversible. The risk assessment methodology accounting for exposure and hazard forms the basis of the calculation methodology applied in the DSS to provide water quality guidance.

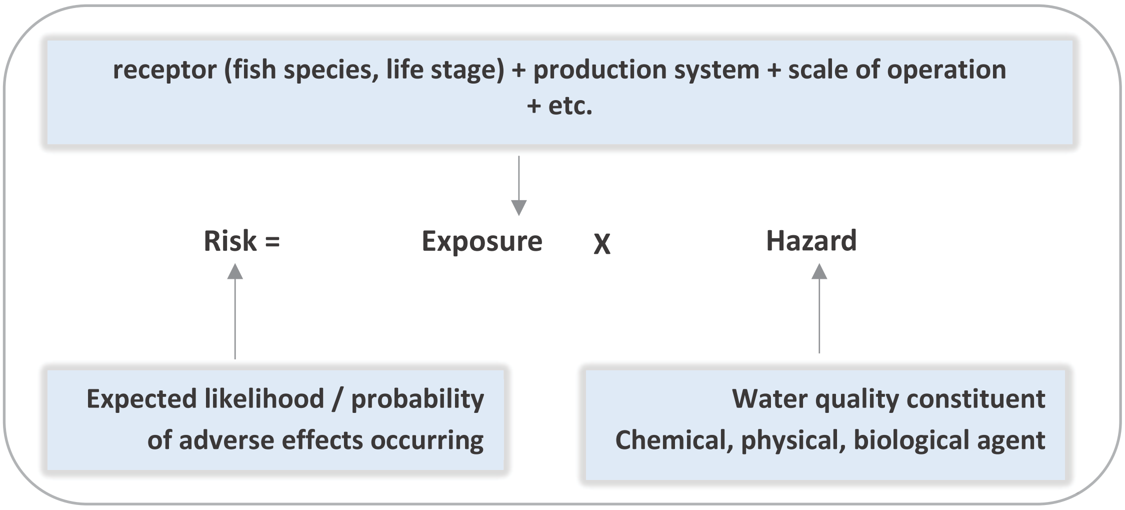

Figure 2: Risk assessment

4.1. Introduction

Water quality not only determines the health and growth of fish in an aquaculture system, but also their overall survival (Ajayi, 1971), and its changes can affect these responses (Ufodike & Garba, 1992). Furthermore, waterborne hazards can interact and must be within ideal limits for optimum production (Boyd, 1979). The importance of understanding these interactions and operating within the limits of these hazards has a direct effect on fish productivity. This risk-based methodology development has attempted to determine the hazards (species-specific), understand these interactions and present the adverse effects through the qualitative and quantitative response relationships indicative of fish health, quality and production.

The fish types that have been used here in the development of the risk-based water quality guidelines approach for aquaculture are as follows: the first species is trout. This is because trout is the only large-scale freshwater industry in South Africa. Rainbow trout (*Onchorynchus mykiss*) is produced on a large, commercial-scale in South Africa for human consumption and brown trout (*Salmo trutta*) are also produced to a smaller degree. Trout fingerlings are also produced for stocking recreational fishing waters, which supports the lucrative recreational fly-fishery in parts of the country (DAFF, 2016). The production of trout in South Africa was 1497 t/annum in 2015 (DAFF, 2017), and the majority of the farms are small-scale, family owned operations; the average production per trout farm in South Africa was 39.4 t tons/year (DAFF, 2017).

The second selected group included tilapia (*Oreochromis mossambicus*, *Oreochromis niloticus* and *Tilapia rendalli*). Although the tilapia subsector is very small with no large-scale production in South Africa, it has got some potential for growth, but this potential is limited due to climatic conditions in South Africa that restrict profitable, large-scale production to warm parts of the country only or to unique instances where the producer has access to inexpensive energy to heat the production system. Annual national production of tilapia was 325 t in 2015, with an average production of only 4.4 t per farm in that year (DAFF, 2017).

The third freshwater candidate considered for inclusion is African catfish (*Clarias gariepinus*). However, this aquaculture does not operate on any scale close to those of trout and tilapia and does not show immediate potential for growth at this time. Catfish production in South Africa started in the 1980s, with promise; but the industry collapsed in the early 1990s due to low market demand and high production costs relative to marker price (Hecht, 1993). There are currently 13 catfish farms in the country, none of which reported a harvest of fish for human consumption in 2015 (DAFF, 2017). The majority of the local catfish production focussed on fingerling exports to neighbouring states (DAFF, 2017), and for stocking recreational fishing waters in parts of the country. Catfish are grown in a range of production environments varying from extensive open ponds to highly intensive recirculating systems (DAFF, 2016).

The assessment of hazards completed as part the project aimed to provide examples of the water quality data that are available in the literature and how they correspond with responses such as growth, feed utilization or survival of various life-stages of three species of freshwater fish that are farmed in South Africa, rainbow trout, tilapia and African catfish.

The assessment did not include a definitive list of water quality hazards and a measure of their response in these fishes. Rather, it includes a few well-selected examples of hazards and associated responses that supported the development of the risk-based approach to water-use in aquaculture. Representative-hazards from the broader groups, such as the physical, biological, organic and inorganic-hazards and those from groups likely to be considered a waterborne hazard in South African aquaculture have been included. The water quality hazard assessment provided an idea of the volume of literature available on the selection of hazards and starts to uncover the gaps that exist in the literature that will need to be addressed before a complete revision of the water quality risk-based guideline numeric values for aquaculture water use can be achieved.

Fish in aquaculture are constantly exposed to waterborne hazards in their immediate environment. The intensity or severity of risk to fish production due to these hazards will vary for different fish species, the life stage of the animal and the production system in which the fish are cultured. The methodology presented here, to calculate the risk posed to fish production as a result of waterborne hazards, has been developed to take species (trout, tilapia and African catfish species), life-stage and production system into account as the site specific scenarios.

4.2. End Points for Risk Assessment

The suitability of water for fish production can have direct or indirect response-indicators. The effects are ultimately measured as “crop yield”; here the crop is the volume of fish produced. The most commonly recorded end point responses in aquaculture are the indirect responses of survival, fish growth and the rate that fish convert feed into somatic growth. In addition, the contact of fish with the water directly affects fish health and behaviour (feeding, reproduction, etc.) but aspects of health and behaviour are more difficult to quantify reliably so they are more often recorded using qualitative measures. However, these direct effects usually account for the indirect indicators since growth, feed conversion ratio and survival are often a result of the cumulative consequences of waterborne hazards on the direct response of health and behaviour.

The total volume of fish that is produced is difficult to record consistently and cannot always be compared reliably between studies because total volume is often not standardised. The method of recording specific growth rate (SGR) is, on the other hand, well-standardised and is the most commonly recorded yield-response in aquaculture literature. Furthermore, while it is positively influenced within ideal hazard ranges, SGR is usually compromised if water quality conditions are not suitable (Boyd & Tucker, 1998). As such, SGR is a suitable end point response-indicator of the influence that a potential water quality hazard will have on fish productivity. It is used to quantify the instantaneous growth per day of fish (Equation 1; Ricker, 1979):

SGR = [(Ln (final weight g) - Ln (Initial weight g) / no of days] x 100 (Equation 1).

Another response that is reliably quantified and recorded in aquaculture literature is food conversion ratio (FCR). This is the rate at which dry feed is converted into the final product, and this final product is included in the ratio as a measured as a wet-weight gained (Cowey, 1992). The importance of this parameter is linked to the economic viability of an aquaculture operation. In many aquaculture industries, feed is often the single most expensive variable running cost; therefore, the efficiency with which feed is converted into product can determine the economic viability of the aquaculture business. Furthermore, FCR is often highly sensitive to the environmental conditions under which the fish are produced; if these conditions are compromised, the FCR is often also compromised. For these reasons, FCR has been selected as a second end point response-indicator in this risk approach development (Equation 2; Cowey, 1992):

FCR = food intake (dry weight g) / body weight gain (wet weight g) (Equation 2).

Finally, the effect that inorganic compounds have on the survival of aquatic organisms is recorded as the concentration (C) that results in the death (L) of 50% of the population over a given period. This is termed LC50, also known as minimum lethal concentration (Stephan, 1977). Since some literature is limited to the rate of survival and does not record SGR and FCR, and since the method of determining mortality recorded as LC50 is well-documented and a reliably measurable/quantifiable response, the LC50 was also included as a response-indicator in this study.

The SGR, FCR and LC50 have been used as quantifiable end points for the risk analysis for the purposes of the methodology development, to define the concept approach. They have been selected because they are easily quantifiable and are used by fish farmers, aquaculturists and scientists to determine the growth and productivity in aquaculture, and because growth and FCR are the most commonly recorded and published indicators in the sector. Three water quality constituents were selected to demonstrate the quantification of SGR and FCR, *viz*. ammonia, sodium and lead.

The direct responses that cover changes in fish colour, changes in behaviour, reproduction and various changes in fish health have been included as a qualitative measure in the DSS; not because they are not important and not because they are not good response-indicators, but because they cannot always be reliably standardized and consistently quantified. The direct response indicators which have been included in the DSS to provide additional guidance, listed in an increasing order of magnitude are as follows:

- Change in fish body colour;
- Change in fish behaviour;
- Pathological indicators (both micro- and macroscopic health indicators);
- Compromised reproduction;
- Compromised growth;
- Poor feed conversion ratio; and
- Death.

The assessment of the risk associated with a particular hazard in the DSS therefore includes quantitative (can be reliably measured) and qualitative (visual) outputs of the response indicators, reported in the terms of the fitness for use and water quality requirements.

4.3. Modelling Aspects

While some very comprehensive aquaculture water-use guidelines have been published and there is an extensive body of literature to support these guidelines, in just about all instances the guidelines are limited to a single number above or below which the water is considered suitable or unsuitable for use in aquaculture. The reality it is not as simple because, in most cases, a hazard does not suddenly become unsuitable, since the level of risk that is imposed usually increases progressively, and most guidelines do not take this graded level of risk into account. That is, they do not consider that a particular hazard might have little to no effect at a concentration, but that the risk might increase moderately within a particular range, before posing a more serious risk within another range.

Furthermore, a particular water quality parameter might be considered unsuitable at a certain concentration for one species of fish, whereas the hazard at the same concentration might pose less of a risk for another species, or less of a risk for the same species of fish but at a different stage in its life or under a different set of production conditions. Most of the published water quality guidelines do not take the level of risk into account and none take the level of risk under a complete suite of biological and environmental conditions into account.

The modelling aspects of the concept approach and associated decision tree that forms the basis of the prototype tool, for the first time, measures the risk associated with water-use in aquaculture.

The prototype concept DSS tool has been designed at three levels specified to cater for the range of the target audience as well as the availability of aquaculture and water quality knowledge available to the user. Transition from Tier 1 to Tier 2, with Tier 3 representing a higher degree of user defined input and updates to the risk assessment as data capturing guides are implemented. This transition aligns with the objective of defining an acceptable risk level as new data captured, for example, histopathology results, could lead to a significant change in the risk posed under the specific site-conditions applicable.

The tool is designed to cater for specific exposure scenarios (the site specificity component of the DSS functionality). The site specificity aspects built into the modelling approach include fish species, production system and life stage (Table 2), in addition to the water quality data inputs of the sample composition for both source water and tank/dam water conditions of the operation. At this point additional aspects such as scale of operation and stocking densities are not yet enabled into the functionality, however this and other considerations will form part of the site scenario definition.

Table 2: Default Site Specific (Exposure) Scenarios

Fish Species	Life Stage		Production System	
Trout	Adult	Juvenile	Intensive	Extensive
Tilapia	Adult	Juvenile	Intensive	Extensive
Catfish	Adult	Juvenile	Intensive	Extensive

Aquaculture is unique in respect of other water users as the operation, is undertaken within the water environment. Unlike terrestrial animals, fish cannot avoid a hazard that contributes to the constituents that make up water that they are exposed to. This is because they cannot leave the water. The hazard will enter their body, primarily through the gills, but also across every membrane that is in contact with their aquatic environment (i.e. across the intestine, skin, eyes, etc.). They are immersed in water and when water carries a hazard they will be exposed to that hazard. Thus, there is no specific distinction for the fish in terms of input source water and the water in tank/dam operation as it ultimately becomes one in the same medium where the hazard exists. However, from the DSS user point of view the guidance required for fitness for use assessment may require a distinction in input source (raw) water quality and tank/dam water quality (i.e. within the culture environment) in order to assess risk potential of both, depending on the management objective or management requirement linked the water management. The DSS thus assesses the risk associated with both the input source water quality and the tank/dam water quality.

Fitness for use is determined for both scenarios, based on the input water quality composition that is entered. Using the built-in reference data in the DSS of the target ranges for a particular constituent, the tool highlights the results of the hazard assessment to the fish species in terms of the source water and culture system (tank/dam) conditions. The tool also reports on potential adverse effect that the unsuitable water quality conditions will have on the fish and if it is feasible to take remedial action or not.

The model at a first assessment level, accounts for the input measured water quality data to assess the potential risk of the water quality to the fish species based on the site-specific exposure scenario. As one progresses to the highest risk assessment level, the FCR and SGR are calculated as part of the modelling approach to provide the user with an indication of the aquaculture productivity and profitability. These outputs are based on the calculations linked to quantifiable dose response relationships discussed above.

In addition, risk-based guidance outputs are also reported for the direct response indicators of fish health, growth, reproduction and quality (e.g. colour, behaviour, macroscopic and microscopic health indicators, etc.) based on qualitative assessment of visual observations. The risk assessment result output is presented as a PDF report, which incorporates mitigation measures in instances where a risk has been noted.

The effect of different water quality hazards and their relationships have been weighted differently in the modelling approach in terms of the risk that the hazard is likely to have on aquaculture operation. For example, the interaction of pH and ammonia will have a greater impact on the risk of juvenile trout raised under intensive recirculating aquaculture culture conditions than it will have on similar fish raised under more extensive pond culture conditions where stocking densities are low. For that reason, the interaction of pH and ammonia has been weighted as having a greater influence on the risk under intensive culture conditions compared to extensive conditions. The weighting system used in the DSS has been based on expert knowledge of aquaculture and a knowledge of interactions of the hazards with the different assumptions and has been used to demonstrate the concept in this tool. These weightings will need to be adjusted, in time to come, based on a thorough literature review and based on stakeholder interactions (both of which will need to be taken forward in the next phase of this project). In the future the synergistic and antagonistic effects of water quality hazards will also need to be catered for in the DSS model.

A brief overview of the components and data flow, at the 3 tiers is provided below. It should be noted that this is an overview to highlight the key components, relating to the modelling aspects in the DSS tool.

4.3.1. Tier 3

Tier 3 calculations cater for the site-specific scenarios, exposure conditions and detailed assessments not covered by Tier 2 and is targeted at an expert user. This tier allows for more site specificity in other ad-hoc contexts. In addition to the hazard assessment of water quality composition entered and assessment fish species reproductive output, their growth and FCR, the user will apply additional protocols to assess histopathological evidence, growth and reproductive factors. The Tier 3 functionality is still to be developed further with the protocols and modules to be applied.

4.3.2. Tier 2

Tier 2 is seen as the more widely used applicability and functionality of the DSS tool. Tier 2 allows for site-specificity by selection of default-based site specific factors provided for in the DSS and for the input of water quality composition of source water (influent) and of tank/dam water quality.

- The exposure scenario is defined (*i.e*. species; life stage);
- The water quality analyses are entered for either for source water quality or tank/dam water quality or both;
- Qualitative information is entered based on visual observations of the fish;
- Production and growth indicators are entered.

The calculations are run in the model to generate the fitness for use report of both qualitative (colour, behaviour) and quantitative outputs (FCR and SGR). The potential risk of the adverse effects occurring is reported with mitigation measures. This allows the user to assess if the risk is an acceptable one in the specific context or to reduce the risk factors identified to an acceptable level.

4.3.3. Tier 1

Tier 1 requires very little input from the user and presents the water quality requirements for aquaculture water use with an account of associated risk to the fish species in question. It can be considered equivalent to 1996 generic guidelines. Tier 1 assessment does not involve any calculation methodology and contains specific literature-based information about water quality constituents of relevance to aquaculture, hazard characterisation and potential adverse effects. Ranges of threshold limits are presented in terms of the four-level categorisation from an ideal water quality (safe level) to an unacceptable level (highest risk level). Tier 1 however does allow for an input to be made by the user to indicate the species of fish that will be farmed. This is a fundamental difference to 1996 guidelines which adds significant value in terms of applicability as there is considerable variation in the risk-hazard relationship among different species of fish. It was therefore determined it that would be appropriate to have different risk-hazard relationships for different groups of fishes in terms of the specifications of water quality requirements for aquaculture water use.

For example, trout is a cold-water species and has a very different temperature tolerance range to warm water tilapia and catfish. Also, by way of example: trout are highly sensitive to low oxygen concentrations, whereas catfish have evolved an apparatus that makes it possible for them to obtain oxygen from the air if oxygen concentrations in the water are low. Similarly, catfish are less sensitive to an increase in total suspended solids as they have evolved to cope with muddy African floodplains, compared with trout which is highly sensitive to suspended solids as this fish is native to the upper catchment in mountain streams. The risk associated with these parameters differs considerably for different species of fish, and the DSS accounts for this at all levels of use, starting at Tier 1.

5. PROTOTYPE DEMONSTRATOR TOOL DESIGN

The DSS is designed as a user-friendly tool to assess the potential risk of site-specific water quality on aquaculture water use. Guidance is provided in respect of:

- Water quality requirements for aquaculture production in respect of a selected fish species; and
- Site-specific assessment on the fitness for use of source water and the operational conditions

The tool incorporates the colour-coded categorization to provide risk-based guidance as discussed in Section 2.2.

The DSS design presents the graphical user interfaces of the respective modelling aspects that are assessed to determine the risk as discussed in the previous section. The DSS system provides a structured approach necessary for addressing the main decision contexts for the use of the guidelines *i.e.* prescribing water quality requirements and fitness for use assessments and in future, water quality objective setting.

5.1. DSS User Interfaces

5.1.1. Home Page

When a user opens the application, the home page will appear (Figure 3). From this page, the user has the option to choose between the two types of assessment to obtain risk-based water quality guidance for aquaculture water use. The home page also provides the user with help via the 'Help' button. If the user wishes to exit the program, the 'Exit' button is provided. This allows the user to save their version of the tool as a macro-enabled MS Excel worksheet and will close the application thereafter.

Upon the selection of the level of assessment from the Home Page, the user is taken to the Water Quality Requirements page or Fitness for Use page. Once this is selected, the home page will automatically close and a series of relevant user interfaces will open allowing the user to continue with the selected application. If the user wishes to return to the home page, the 'Return to Home page' button is clicked.

Figure 3: DSS Home page

5.1.2. Data Reference Sheets

The calculations and modelling in the DSS draws on backend sheets of reference data stored in the database. These reference sheets include the exposure assessment data, quantitative definitions, the hazard characterisation and adverse effect endpoint threshold limits and descriptions derived for each constituent from the literature-based data and risk databases for each of the three fish species. These reference sheets are hidden and locked for editing purposes by the novice or intermediate user but will need to be password protected for the expert Tier 3 user who wishes to adjust the methodologies.

The reference data sheets are the source data on which the algorithms run in order to perform the modelling related to risk assessment for the identified scenario. The data reference sheets include:

- the threshold criteria ranges defined for each water quality constituent (hazard) (i.e. safe level, no effect level dose, lowest effect level dose, unacceptable level) for the relevant fish species type (an exposure scenario);
- Potential risk effects on aquaculture for the respective criteria ranges of the constituents of concern;
- The modelled relationships of site-specific criteria in respect of the water quality hazards; and
- Potential mitigation options to improve the water quality and reduce the risk where applicable.

At this point in the demonstrator tool development, the reference sheets are completed for a selected number of water quality constituents. Figure 4 presents the example of the database reference sheet.

5.1.3. Calculation sheets

Calculation sheets have been developed as separate worksheets in the tool. The main function of the calculation sheets is to extract data from the reference sheets, incorporate the user's input data and determine the potential risk from the information provided by the user for the scenario. This is done as per the calculation methodologies described in the previous section. Formulas are used in the development of the calculation sheets so that each equation can be viewed, and easy adjustments can be made to the modelling. "Index-match" searches are used to link the selected constituents of concern and the appropriate information in each sheet. Once the user selects the type of assessment and inputs, the site specific scenario factors and data, the program will then use these inputted values to quantify a potential risk.

Rainbow Trout: Categories / Risk Profiles			Ideal Risk Limit	Effect	Mitigation	Acceptable Risk limit	Effect	Mitigation	Tolerable risk limit	Effect	Mitigation	Unacceptable risk limit	Effect	Mitigation
Rainbow Trout	**Temperature**	°C	15-16	No effect	None	13-14, 17-18	reduced growth and feeding	heat or cool water down	12-13, 19-20	reduced growth and feeding	heat or cool water down	<12, >20	poor health / death	heat or cool water down
	Dissolved Oxygen	mg/L	6-9	No effect	None	5	behavioural changes, physiological stress	aerate water	6	behavioural changes, physiological stress	aerate water	<6, >9	physiological stress, death	provide aeration
	pH		6-9	No effect	None	4	physiological stress	increase pH	5	physiological stress	increase pH	<4, >9	death	increase/decrease pH
	Alkalinity	mg/L	100-150	No effect	None	96-99, 151-155	physiological stress	decrease pH	90-95, 156-160	physiological stress	decrease pH	<90, >160	death	increase/decrease pH
	Ammonium	mg/L	0.03	No effect	None	0.05	growth reduction	aerate water, do a water change	0.06	growth reduction	aerate water, do a water change	>0,06	death	aerate water, do a water change
	Sodium	mg/L	1000	No effect	None	1100	osmoregulatory stress	perform a water change	1200	osmoregulatory stress	perform a water change	>1200	reduced growth, death	perform a water change
	Lead	mg/L	0.002	No effect	None	0.005	ill-health	coagulation and precipitation with ferric salts	0.01	ill-health	coagulation and precipitation with ferric salts	>0,01	spinal deformities death	coagulation and precipitation with ferric salts
	Nitrate	mg/L	15	No effect	None	150	no effect	none	300	no effect	none	>300	osmoregulatory stress	water exchange
	Nitrite	mg/L	0.05	No effect	None	0.07	anoxia	dose with chloride	0.099	anoxia	dose with chloride	0,1-0,3	anoxia, death	adjust stocking density and feeding frequency
	Phosphorus	mg/L	10	No effect	None	12.5	growth reduction	run water through reed bed or constructed wetland	15	growth reduction	run water through reed bed or constructed wetland	>15	osmotic stress	run water through reed bed or constructed wetland
	Total dissolved solids	mg/L	200	No effect	None	230	reduced growth	desalinate to remove sodium and chloride, reverse osmosis	250	reduced growth	desalinate to remove sodium and chloride, reverse osmosis	>250	stunted fish	desalinate to remove sodium and chloride, reverse osmosis
	Total hardness	mg/L	150	No effect	None	175	reduced growth	soft water-add lime, hard water soften with deionised water, raise pH to 8,3	200	reduced growth	soft water-add lime, hard water soften with deionised water, raise pH to 8,3	>200	reduced growth, high feed conversion ratios	soft water-add lime, hard water soften with deionised water, raise pH to 8,3
	Total suspended solids	mg/L	1	No effect	None	5	limited oxygen uptake	mechanical filtration of water	20	limited oxygen uptake	mechanical filtration of water	>20	death	mechanical filtration of water
	Aluminium	mg/L	0.06	No effect	None	0.08	gill damage	raise pH	0.1	gill damage	raise pH	>0,1	death by anoxia	raise pH
	Arsenic	mg/L	0.05	No effect	None	0.07	gill damage	oxidation with chlorine or potassium permanganate	0.09	gill damage	oxidation with chlorine or potassium permanganate	>0,09	death by anoxia	oxidation with chlorine or potassium permanganate
	Cadmium	mg/L	0.8	No effect	None	1	ill-health	water change	1.2	ill-health	water change	>1,2	irreversible kidney and intestinal damage	water change
	Carbon dioxide	mg/L	14	No effect	None	18	nephrocalcinosis	lime addition, aeration	20	nephrocalcinosis	lime addition, aeration	>20	reduced growth, death	lime addition, aeration
	Chloride	mg/L	400	No effect	None	500	physiological stress	desalination, electrolysis	600	physiological stress	desalination, electrolysis	>600	reduced growth	desalination, electrolysis
	Chlorine	mg/L	1	No effect	None	2	physiological stress	aerate water	4	physiological stress	aerate water	>4	death due to anoxia	aerate water
	Chromium (IV)	mg/L	20	No effect	None	25	anaemia	decrease pH to 6.5	30	anaemia	decrease pH to 6.5	>30	organ damage	decrease pH to 6.5
	Copper	mg/L	0.005	No effect	None	0.007	physiological stress	flocculation with ferric salts, add lime to raise pH	0.009	physiological stress	flocculation with ferric salts, add lime to raise pH	>0,009	death	flocculation with ferric salts, add lime to raise pH
	Cyanide	mg/L	0.02	No effect	None	0.06	loss of appetite, histopathological damage	oxidation with metal hydroxides, filtration with activated carbon	0.1	loss of appetite, histopathological damage	oxidation with metal hydroxides, filtration with activated carbon	>0.1	death	oxidation with metal hydroxides, filtration with activated carbon
	Iron	mg/L	0.01	No effect	None	0.05	respiratory stress, gill damage	aeration, increase pH with lime	0.2	respiratory stress, gill damage	aeration, increase pH with lime	>0,2	death	aeration, increase pH with lime
	Manganese	mg/L	0.1	No effect	None	0.25	gill damage	increase pH	0.5	gill damage	increase pH	>0,5	anaesthetic effect on fish	increase pH
	Mercury	mg/L	0.001	No effect	None	0.002	metabolism disruption	treatment with activated carbon	0.003	metabolism disruption	treatment with activated carbon	>0,003	abnormal cell division	treatment with activated carbon
	Polychlorinated biphenyls	mg/L	0.04	No effect	None	0.075	fatty tissue accumulation	difficult to remove due to high stability	0.1	fatty tissue accumulation	difficult to remove due to high stability	>0,1	decreased reproductive potential	difficult to remove due to high stability
	Phenols	mg/L	1	No effect	None	1.3	growth reduction	treatment with ozone or activated carbon	1.7	growth reduction	treatment with ozone or activated carbon	>1,7	decreased reproductive output, compromised immune system	treatment with ozone or activated carbon
	Plasticizers	mg/L	0.01	No effect	None	0.03	growth reduction	change water	0.05	growth reduction	change water	>0,05	endocrine function disruption	change water

Rainbow Trout: Categories / Risk Profiles			Ideal Risk Limit	Effect	Mitigation	Acceptable Risk limit	Effect	Mitigation	Tolerable risk limit	Effect	Mitigation	Unacceptable risk limit	Effect	Mitigation
	Selenium	mg/L	0.3	No effect	None	0.37	weak young	coagulation and precipitation with ferric chloride at pH above 8,5	0.45	weak young	coagulation and precipitation with ferric chloride at pH above 8,5	>0,45	weak young, high mortality	coagulation and precipitation with ferric chloride at pH above 8,5
	Sulphide	mg/L	0.0001	No effect	None	0.006	growth reduction	aerate water, precipitate with iron salts	0.012	growth reduction	aerate water, precipitate with iron salts	>0,012	death	aerate water, precipitate with iron salts
	Total dissolved gases	mg/L	10	No effect	None	15	difficulty swimming and feeding	aerate water, expose water to atmosphere	20	difficulty swimming and feeding	aerate water, expose water to atmosphere	>20	haemorrhaging, death	aerate water, expose water to atmosphere
	Zinc	mg/L	0.1	No effect	None	0.25	impaired feeding	add salt, precipitate through filtration or sedimentation, Once zinc is removed, the pH must be return to neutral before entering the aquaculture facility.	0.3	impaired feeding	add salt, precipitate through filtration or sedimentation, Once zinc is removed, the pH must be return to neutral before entering the aquaculture facility.	>0,3	reduced growth, suffocation, death	add salt, precipitate through filtration or sedimentation, Once zinc is removed, the pH must be return to neutral before entering the aquaculture facility.

Figure 4: A screenshot of part of the database reference worksheet

5.2. Water Quality Assessment

The user is directed to one of two assessment types in the DSS tool.

5.2.1. Water Quality Requirements

Once the user clicks on the water quality requirement tab on the home page, the User Form requires the user to specify the species of fish of relevance. On doing so the information is collated under the respective reporting worksheets with the target ranges (defined as ideal, acceptable, tolerable and unacceptable) of water quality requirements reported for the species in question. The report is generated in an excel spreadsheet, with an option to save to a PDF. The water quality requirement's calculation sheet matches the data for the fish species selected by the user to the constituent database in the reference sheets. The information extracted and displayed presents the risk-based threshold limit criteria as a concentration for the relevant water quality hazard (Figure 4). The 'Return to Home page' button will direct the user to the Home page of the application. The 'Exit' button will give the user the option to save their progress and exit the application.

5.2.2. Fitness for Use

By selecting the fitness for use tab on the home page, the application will direct the user to the fitness for use input page. Here the user required to input site specific details and the input water quality composition of either influent source water or of tank/dam water or both. The user has the option to enter additional input data based on qualitative direct response indicator observations related to fish health, growth and reproduction (Figure 5). Based on the inputs provided, the tool will process the respective calculations and modelling to generate a user fitness for use specific report (Figure 6). The report output generated presents the fitness for use results of the risk analysis with potential effects (consequences) and recommendations on remedial action. This is presented for the water quality compositions that was inputted, the direct response indicators and for the FCR and SGR that is calculated. Here, the program differentiates between the different fish species types, life stage and production system based on available reference data to assess the risk present. The specific hazards of concern (those determined to be the highest risk) for the scenario are highlighted in the report. The report is generated in an MS Excel spreadsheet, with an option to save as a PDF file.

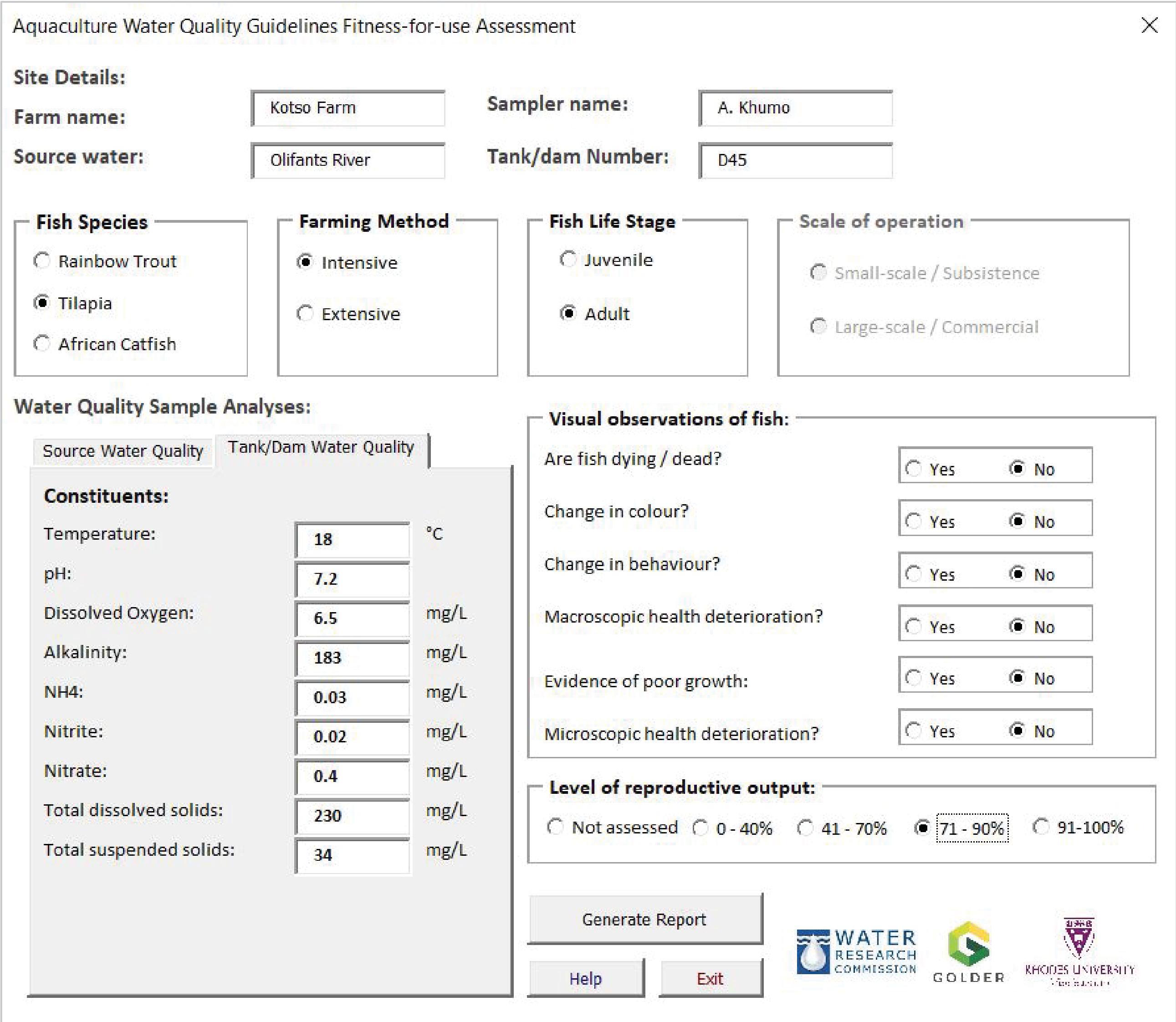

Figure 5: Fitness for Use Assessment input page

NOTE: Hypothetical data is used in this prototype version to demonstrate the conceptual report.

Risk-based Water Quality Guidelines for Aquaculture
Fitness-for-use Assessment Report

Site Information

Date of analysis:	3/7/2021	Source water description:	Olifants River	
User information:	Singh, Givarn	Farm Name:	Kotso farm	Farming method: Intensive
Sampler Name:	A.Khumo	Tank Number:	D45	Fish Life Stage: Adult
		Fish species:	Tilapia	

Source water Fitness-for-use:

Constituents:	Value	Units	Fitness-for-use	Effects	Mitigation
Alkalinity	50	mg/L	Ideal	No effect	None
Sodium	220	mg/L	Ideal	No effect	None
Lead	0.01	mg/L	Ideal	No effect	None
Selenium	0.5	mg/L	Unacceptable	weak young, high mortality	There are no known measures that mitigate against the effects of selenium toxicity in fish.
Iron	0.2	mg/L	Tolerable	respiratory stress, gill damage	Fish should be moved to water with a low iron content. Alternatively, the pH and alkalinity should be raised.

Tank/Dam Water Fitness-for-use:

Constituents:	Value	Units	Fitness-for-use	Effects	Mitigation
Temperature	18	C	Unacceptable	Poor health / death	heat or cool water down
pH	7.2	-	Ideal	No effect	None
DO	6.5	mg/L	Ideal	No effect	None
Alkalinity	183	mg/L	Unacceptable	death	increase/decrease pH
Ammonium	0.03	mg/L	Ideal	No effect	None
Nitrite	0.02	mg/L	Ideal	No effect	None
Nitrate	0.4	mg/L	Ideal	No effect	None
TSS	230	mg/L	Unacceptable	death	mechanical filtration of water
TDS	34	mg/L	Ideal	No effect	None

Visually observed adverse effects:

Indication	Result	Presence of potential water quality risk	Mitigation
Fish are dead?	No	Ideal	Unnecessary
Change in colour?	No	Ideal	Unnecessary
Change in behaviour?	No	Ideal	Unnecessary
Macroscopic health deterioration?	No	Ideal	Unnecessary
Microscopic health deterioration?	No	Ideal	Unnecessary
Evidence of poor growth?	No	Ideal	Unnecessary
Level of reproductive output	71-90%	Acceptable	Unnecessary

Fish growth Indicators:

Expected specific growth rate:	Result	Risk to Production	Growth rate	Mitigation
SGR	0.644	Ideal	Highly Profitable	No mitigation required
Expected food conversion ratio:				
FCR	2.606	Unacceptable	Unprofitable	Major changes required to improve water quality

RESULTS SUMMARY

Source Water:	**Flagged constituents**	**Potential adverse effect**	**Mitigation**
Unacceptable	Selenium.	Refer to the Unacceptable Risk effects above.	Refer to the Unacceptable Risk mitigation above.

Tank/Dam Water:	**Flagged constituents**	**Potential adverse effect**	**Mitigation**
Unacceptable	FCR. TSS. Alkalinity. Temperature.	Refer to the Unacceptable Risk effects above.	Refer to the Unacceptable Risk mitigation above.

Figure 6: Sample Fitness for Use Report

6. CONCLUSION AND RECOMMENDATIONS

The project has been successfully completed, with the DSS as a product fulfilling the conceptual requirements of the prototype technology demonstrator for risk-based water quality guidelines for aquaculture water use. The DSS is an engineered computational software system presented as a demonstrator. It incorporates the key features of risk and site specificity to provide risk-based guidance on water quality used for aquaculture use, using MS Excel as the user platform. The concept approach developed form the foundation of the modelling and calculations in the DSS and associated graphical user interfaces that will, for the first time, be used to determine the measurable risk that waterborne hazards have on water use in aquaculture.

Although the prototype DSS does present the concept user interface aspects and proposed functionality, a fully functional working software system is required to demonstrate the additional modelling aspects and site specific scenarios. Further phases of the project will need to build on the concept model that has been developed here.

The objective of the DSSs is to provide guidance by estimating risk, highlighting the applicable risk factors and providing a method for attempting to reduce them to an acceptable risk level. The ability to guide the user through to apply user-defined or selected approaches is a key aspect of functionality which does what the risk-based guidelines are intended to do, namely offer guidance.

For purposes of meeting the objective of this project, a risk-based concept presented for aquaculture water use has been based on synthetic data, three fish species and a selected number of relevant water quality hazards only. This has sufficed in presenting a concept approach and technology demonstrator. The approach for similar hazards is the same and can be added to the modelling approach as the DSS model is developed further.

The aquaculture user risk-based water quality guidelines represent a paradigm shift in the decision-making context to water quality management and in how water quality guidelines are used and applied. The functionality of the DSS tool presents a fundamental change from the use of simple numeric values to providing both regulators and water users with a quantifiable assessment of the risk. In doing so the user would need to make a judgement call based on the available information, context and influencing factors.

In addition, further site-specific functionalities will need to be built in and enabled as more empirical data becomes available on end point adverse effects and direct responses that are able to provide a quantifiable estimate of risk related to aquaculture production. At this point the lack of availability of such evidence and research, places limitations on the levels that can be assessed. Much of the guidance that exists is based on qualitative factors related to direct response indicators which are often reliant on level of expertise of the operator/farmer.

In some instances direct responses such as those that cover changes in fish colour, changes in behaviour and various changes in fish health, although essential for risk analysis, have been deemed less suitable for the risk analysis that requires quantification; not because they are not important and not because they are not good response-indicators, but because they cannot be reliably and consistently quantified. Thus, the challenge to the expanding the risk assessment for aquaculture use is to determine the relationships that are consistently and generically quantifiable.

The following is recommended to develop the product further to a fully functional system to be utilised within the aquaculture water use sector in South Africa:

- A key gap identified in the development of the approach is a lack of sufficient hazard/indicator-linked data for quantifying water quality risk in aquaculture. One of the outcomes of this exercise was the establishment that there were insufficient empirical data available in the literature and in the time that was available to do this comprehensively. For the purposes of the risk-based concept approach development, synthetic data sets were thus used to develop the concept for the quantification of water quality-based risk in aquaculture and the associated functionality in the DSS. Update of the model with real data will be required during future phases of the project, when the full functionality has been developed and when more importantly when scientific data becomes available.
- Currently the modelling of the risk in the DSS is based on a weighting system which accounts for the impact the different water quality hazards and their relationships shall carry on the risk that the hazard is likely to have on the fish species. The weighting system used in the DSS tool has been based on current expert knowledge of aquaculture and a knowledge of interactions of the hazards with the different assumptions, which has been used to demonstrate the concept. These weightings will need to be adjusted, in time to come, based on a thorough literature review and based on stakeholder interactions, both of which will need to be taken forward in the next phase of this project.
- Other risk assessment factors such as accounting for the sources of the water used for aquaculture systems such as springs, dams, irrigation canals, rivers, other ground water and treated effluent would also need to be incorporated in the risk equation so that guidance on the optimal use scenario can be provided the water user. Production factors such as fish stocking density, water exchange rates, level of expertise of the management and fish health are other site-specific factors of relevance that influence the risk to aquaculture production. In addition factors related to the management of the operation (pre-farming, farming operation; post–farming) bring in additional dimensions of water quality risk that would need to form part of the future integrated management approach.

  Again, the challenge is availability of the supporting science to express the risk of the adverse effect in terms of a calculation methodology for these indicators. Further research and assessment are required to determine the appropriate methodologies that could applied to the modelling in quantifying the risk in terms of end-point effect (e.g. fish size, growth rate, behaviour). Much of the added functionality will support the assessment of water quality risk potential within the production aquaculture system. However, the source water would also influence these scenarios and the manner and extent to which the adverse effects occur.

- The DSS has focused on the identified key physio-chemical water quality constituents selected for the purposes of the DSS development. Confirmation of additional water quality constituents to include those constituents relevant to aquaculture water use/production in the South African context is required. In respect of water quality constituents:
    - Extension to include additional physio-chemical hazards, biological parameters (indicator organisms) and constituents of relevance to the specific fish species,
    - Inclusion of empirical data related to the guideline values (end point adverse effect levels) for all hazards as relevant,
    - Inclusion of calculation methodologies that can account for the assessment of multiple constituents simultaneously, and
    - Investigations into the antagonistic and synergistic effects of the water quality constituents and approaches on how to incorporate these into the quantification of the risk.
- Further development of Tier 3 is required. This is reliant on additional specialist input (in addition to the site-specific data) with corresponding adjustments to the guideline values, using referenced modules of the DSS but also inclusion of subsequent methodologies based on, for example, the obtaining of clinical biochemistry values, histopathological data and reproductive output.
- Further testing with the wider stakeholder user groups is required to refine the product and to update the DSS to improve user-friendliness and utility, based on feedback from users.
- The DSS tool has been demonstrated using MS Excel, however in going forward to full scale application, it is recommended that available on-line databases be tested to select a software suitable for the DSS for the guideline series.
- Next phases of the project require the integration with the other water user groups' guidelines that needs to consider the selection of an online platform, intellectual property issues, controlled access to software system, version controls as well as processes and procedures on the updating of the methodologies and functionality of the DSS for the respective water user groups.
- There is also a real need in the aquaculture industry to expand the tool to include brackish-water aquaculture and marine aquaculture (mariculture).

This undertaking has highlighted the need for more research to be done on water quality requirements for freshwater aquaculture that is species, life-stage and production-environment specific. The aquaculture risk-based water quality guidelines approach will need to be developed further during subsequent phases of the project accounting for additional scenarios and factors indicated above. Further development of the approach will facilitate the development of a fully functioning decision support system.

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