# RISK-BASED AND SITE-SPECIFIC INDUSTRIAL USE WATER QUALITY GUIDELINES DEVELOPMENT OF A RISK-BASED APPROACH

P Moodley, C Pardesi, Y Vemblanathan, P Wille, G Singh, N Juggath, L Boyd and T Coleman

**Volume 2: Technical Support** 



# RISK-BASED AND SITE-SPECIFIC INDUSTRIAL USE WATER QUALITY GUIDELINES

Development of a Risk-based Approach

**Volume 2: Technical Support** 

A Report to the Water Research Commission

by

P Moodley, C Pardesi, Y Vemblanathan, P Wille, G Singh, N Juggath, L Boyd and T Coleman

Golder Associates Africa

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The outcomes of this project are presented in two volumes – this is volume 2. Volume 1 is the Decision Support System (WRC Report No. TT 874/1/21).

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# **EXECUTIVE SUMMARY**

The current series of South African Water Quality Guidelines (SAWQGs) (DWAF, 1996) has been an extremely important contribution to water resource management in South Africa. It reflects the scientific thinking at the time it was produced. Subsequently, the decision support function of water quality guidance has grown and become more complex. With the evolvement of water resource management within South Africa, the SAWQGs have become decision support tools rather than a list with numbers. Both application and scope issues related to risk, site specificity and guidance on an expanded set of water quality constituents have become more apparent.

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

In 2008, a national review by then Department of Water Affairs and Forestry (DWAF) on the 1996 SAWQGs recognised the need for the development of South African risk-based Water Quality Guidelines. The following three phased approach has been undertaken:

- 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

Phase 1 was completed culminating in the compilation of a Needs Assessment and Philosophy document (DWS, 2008).

In light of the review and recommendations of the Phase 1 outcomes, the Water Research Commission (WRC) initiated an overarching project to address Phase 2. A series of projects to develop risk-based approaches for water quality guidelines per user group was commissioned.

This project is part of the Phase 2 series of projects and addresses the approach development for *Volume 3 – Industrial Water Use* as part of the South African Water Quality Guidelines series. It attempts to present new approaches that will 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, animal watering, domestic use and aquaculture water quality guidelines have recently been developed.

The risk-based water quality guidelines need to be applied in a manner that support site specificity and be based on a risked philosophy, whilst providing for a tiered assessment approach presented as a software-based decision support tool. The proposed revision to the 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 quality to be interpreted in terms of risk of specific adverse effects.

The new goal may thus be stated as 'to adequately describe the outcome of a water use quality 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'.

#### **OBJECTIVE AIMS OF THE PROJECT**

The objective of this project was to develop a risk-based philosophy and site-specific methodology for assessing water quality requirements and fitness for use of water for industrial use. The specific aspects addressed include firstly the development of the basis of the risk approach and quantification methodology for the risk assessment; and secondly the development of the informatics for a technology demonstrator decision support system that addresses the main decision contexts for industrial water use.

The project aims included:

- Assessment of industrial use types and selection of relevant water quality variables in support of the approach development;
- Definition of a sound scientific basis for the risk assessment approach;
- Systematic review of relevant literature to identify and critically appraise best available evidence and information sources.
- Definition of the methodologies/calculations for quantifying the risk (quantitative and qualitative).
- Presentation of a prototype software decision support system to pilot the proposed approach and demonstrate the most important features (tiered system).
- Engagement with stakeholders to elicit comment and recommendations.
- Presentation of functioning decision support system for industrial water use.

#### SCOPE OF THE PROJECT

The project required that the revised water quality guidelines be risk based, support site specificity and be presented as a software decision support tool as aligned to the philosophy as defined in the Phase 1 document of 2008.

For purposes of the risk-based guideline development, the scope of this project has focused on the input water into an industrial process (irrespective of the source), as the intention of the South African Water Quality Guideline Series (Volumes 1 to 7) is to support users make informed judgements about fitness for use and for other water quality management purposes. The current approach has not focused on individual on industries *per se*. It focuses on well-defined problems occurring in industry, such as

scaling, corrosion, fouling, etc., and considers process applications in the larger manufacturing and processing industrial sectors in South Africa. By defining the context of the situation/site and the processing/manufacturing units a risk approach for assessing fitness for use has been developed.

While it is accepted that most industries use bulk water supplies as their source water or treat water to their requirements, there are some that rely on water extracted directly from the water resource. The tool supports either type of user to assess fitness for use. The tool easily lends itself to expansion in future to consider re-use applications.

The final product of the risk based approach is that the envisaged DSS should comprise a three-tiered system:

- Tier 1 is equivalent to 1996 generic guidelines;
- Tier 2 allows for site-specificity in generic specified contexts;
- Tier 3 allows for site-specificity in localised contexts, allowing the user to adjust the reference data in the coding modules. This would require significant expertise.

The DSS presents a functional tool for user application that can be extended as data becomes available. A user-friendly interface is presented providing water quality guidance outputs.

The determination of the risk and associated factors require that they are measurable to an extent and exhibit characteristics or outcomes that can be adequately described for the industrial use. At this point the limitation is related largely to the availability of this science and empirical data to support the risk based calculations related to industrial water quality use problems.

Unlike the other user water quality guidelines, for industrial use, no prior work or research has been undertaken since the 1996 edition. Thus the 1996, Volume 3 Industrial User Water Quality Guidelines, remained the departure point for this undertaking, and which has required as the basis, the definition of risk approach fundamentals.

#### **RISK BASED APPROACH**

Fundamental to the basis of the guidelines is what constitutes risk to the industrial water use(r).

The core of the proposed approach requires accounting for the end point adverse effects (key water quality problems) posed by the water quality constituents and the manner and extent to which they express themselves, and further within site specific scenarios of the water use. Water quality problems in industrial use and the constituents that cause them are largely known and well documented in literature.

The fitness for use assessment thus still forms the core technical requirement of the guidelines. The focus of this endeavour has therefore been to formulate a mathematical approach (modelling) to the

fitness for use analysis as the basis for derivation of the risk-based guidelines. The ability of the user to provide some input to the risk assessment process and contextualising the scenario, supports the presentation of the guidelines as a software product rather than a static document.

For the industrial user the risk-based guidelines serve the purposes,

- in a generic context evaluating the fitness for use of the source water, and
- in a specific context as a screening tool to guide and support decision-making regarding industrial water related problems (e.g. scaling, corrosion, fouling, foaming, abrasion).

While the generic guidance of the DSS addresses fitness for use objectives of source water in industrial uses irrespective of whether it is treated or devoid of treatment (similar to the 1996 guidelines), the site specific guidance defined by the risk factors associated with the industrial process (the processing application) and input water quality concentrations form the basis of risk based guidance. Based on the understanding of the chemistry and science associated with the commonly and most recurrent water quality end point adverse effects (e.g. scaling, corrosion), the probability of occurrence and extent of effect can be calculated for the industrial process in question. This is then report as the water quality risk in the DSS tool.

The materials of construction of the processing units and the key water quality problems, *viz*. corrosion, scaling and scaling were selected as the end points of the risk assessment quantification for the purposes of the methodology development, to define the concept approach.

It is well accepted that water quality problems within an industrial process or operation can often be addressed through some form of engineered solution. Thus it is the intention that the decision support tool also serve as a platform for industrial water users to account for potential water quality risks that could manifest and contribute towards improved and informed decision making regarding the timing, implementation and design options of the engineered solution or operational interventions.

The risk-based guidance may also account for waters incorporated into processes as part of water use efficiency or re-use measures by varying the source water as the input variable in the risk assessment to the use scenario, thus enabling its determination for "fitness for purpose'.

In defining a proposed risk-based approach for industrial water use, it has become apparent that greater site-specificity, particularly in respect of the nature of the characteristics of the material exposed to/contacting the water, and measured quality, make the risk-based water quality guidelines much more relevant and meaningful in terms of the guidance.

## **DECISION SUPPORT SYSTEM – TECHNOLOGY DEMONSTRATOR**

The objective of the DSS 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 prototype DSS available as a functional tool is presented as a standalone deliverable to be experienced in conjunction with this summary final report.

The DSS provides a structured approach necessary for addressing the main decision contexts for the assessment of risk in industrial water use. It serves as a predictive tool designed to assess the likelihood of the adverse effect and severity and present potential consequences of a water quality related to a specific industrial use context.

A software-based DSS offers the advantage to improve the way in which the guidelines are used because the focus is directly on supporting decisions in specific contexts; by applying the supporting science rather than producing simple numeric guidance. The DSS is done through a software prototype system for the purposes of this project using Python as the development platform. Python was selected since it is an open-source, cross-platform programming language well-suited for developing desktop applications

The DSS has been designed to assess:

- Water quality requirements for industrial related water quality problems; and
- Site specific assessment on the fitness for use of source water and the operational conditions.

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 assessment system accommodates for the needs of the novice, intermediate and expert user respectively includes three tiers. The following definition of the assessment levels informs as the basis of design for the DSS informatics.

Water Quality requirement	Fitness for Use		
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 characterisation 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).	
<i>Output:</i> Descriptions and risk- based thresholds of levels of water quality requirements (most conservative and generic) per water quality problem, applicable water quality constituent of concern and related to the material on construction of the processing unit.	<i>Output:</i> Presentation of the risk assessment of the water quality problems and associated fitness for use based on the water quality input and selection of the pre- defined exposure scenarios	<i>Output:</i> Presentation of the risk assessment based on the adjustment of site-specific exposure scenarios and methodology	

#### An overview of the Tiered Assessment System

This report presents technical support information to the DSS, which includes the approach development and the risk assessment methodologies applied as the basis to define the informatics for the software application. This report consists of two volumes, Volume 1: Description of the Decision Support System and Volume 2: Technical Support (this report).

# CONCLUSION

The intention of the guideline revision, *i.e.* the risk-based methodology development, was to present a product that provides a series of tiered assessment levels to support a greater diversity of guideline use which facilitates more accurate risk-based assessments on the fitness for use of water for industrial applications. The fundamental objective is to assist decision making by improving the science behind the assessments. The objective has been achieved through this project, by the development of a risk-based philosophy and site-specific methodology for assessing water quality requirements and fitness for use of water for industrial use within the scope of the intention of the SAWQGs series.

The prototype DSS presented allows for the fundamentals of a risk-based approach to be tested in order to assess and evaluate the accuracy of the risk assessment and risk mitigation methodology employed. More cause and effect data is needed to expand the functionality and application of the tool for the industrial water user sector.

The fitness for use assessment still forms the core technical requirement of the guidelines. The ability for a user to input a user-defined water quality composition to derive a computated risk output is a fundamental developmental in how water quality guidelines are presented, for South Africa and internationally as well. This adds significant value in terms of applicability and relevance of water quality guidelines.

Although various guidelines are available to assess water quality parameters for, e.g. potable water quality, the existence of any comparable tool for industrial water users in the world is not known and this is believed to be a world-first. Through the assessment of a range of input parameters as opposed to a single pollutant's risk in isolation, and consideration of interactivity between these parameters a holistic assessment approach is achieved that is a unique value added approach for this type of guideline.

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The contribution of all other stakeholders and the participation of industry representatives is gratefully acknowledged.

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# LIST OF ABBREVIATIONS

AI	Aggressive Index		
Al	Aluminium		
BOD	Biological Oxygen Demand		
С	Carbon		
Са	Calcium		
CaCO₃	Calcium Carbonate		
CaPO <sub>4</sub>	Calcium Phosphate		
CI	Chloride		
Cr	Chromium		
CSMR	Chloride to Sulphate Mass Ratio		
Cu	Copper		
COD	Chemical Oxygen Demand		
DSS	Decision Support System		
DWA	Department of Water Affairs		
DWAF	Department of Water Affairs and Forestry		
DWS	Department of Water and Sanitation		
EC	Electrical Conductivity		
Fe	Iron		
HI	Hazard Index		
HP	High Pressure		
LP	Low Pressure		
LSI	Langelier Saturation Index		
Mg	Magnesium		
Mn	Manganese		
Мо	Molybdenum		
MOC	Materials of Construction		
Na	Sodium		
Ni	Nickel		
NO <sub>3</sub>	Nitrate		
NO <sub>2</sub>	Nitrite		
NWA	National Water Act		
Pb	Lead		
PGM	Platinum and other Platinum group metals		
PO <sub>4</sub>	Phosphate		
PREN	Pitting Resistance Equivalent		
PTFE	Polytetrafluoroethylene		
PVC	Poly-Vinyl Chloride		

PVFD	Polyvinylidene Fluoride		
RI	Ryznar Index		
RO	Reverse Osmosis		
SAWQG	South African Water Quality Guidelines		
SI	Stability Index		
SDI	Silt Density Index		
Si	Silicon		
SO <sub>4</sub>	Sulphate		
TDS	Total Dissolved Salts		
Ti	Titanium		
TSS	Total Suspended Solids		
TWQR	Target Water Quality Range		
UDC	Under Deposit Corrosion		
WRC	Water Research Commission		

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# 1.0 INTRODUCTION

### 1.1 Background

Water quality issues are complex and dynamic in nature, presenting challenges to water security that demand urgent solutions from a local to global scale. As human populations grow, industrial, domestic and agricultural activities expand and climate change threatens to cause major alterations to the hydrological cycle, the availability of water resources as we have become accustomed to, will become strained (UN Water 2014). Declining water quality is a growing concern that will impact human well-being, environmental sustainability and economic performance.

A balanced mix of water supply and water demand management strategies is required to ensure water security for the future. Making water management more efficient through innovative and wise policies, regulations and guidelines is one way to achieve this goal.

The Department of Water and Sanitation's (DWS) South African Water Quality Guidelines (SAWQGs) for Fresh Water (Second Edition) published in 1996 have been an extremely important contribution to water resource management in South Africa. The guidelines reflect the scientific thinking at the time and are still widely used.

Subsequently, the decision support function of water quality guidance has grown and become more complex. Increased scientific understanding of the complexity of water resource systems and adaptive management processes have led to new ways of managing water quality, where water quality is defined as physical, chemical and microbiological properties of the water. Since the evolvement of water resource management within South Africa, the SAWQGs have become decision support tools rather than just a list with limits, and traditional scientific and management approaches may not be adequate to deal with contemporary water quality issues. In parallel water treatment technologies have been optimised and new technology developments continue to enter the market.

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.

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

- They would be risked based,
- They would allow for greater site specificity, 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 water users, in order to allow for informed decisions to be made concerning water use that is 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 outcome 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 the recommendations of the Phase 1 outcomes, the Water Research Commission (WRC) initiated an overarching project that has seen the commissioning of a series of projects to develop riskbased approaches for water quality guidelines per user group, encompassing phase 2 of the process. The water quality guidelines need to be revised in manner that support site specificity and be riskbased. It should further provide for a tiered assessment approach that caters for the level of use and degree of complexity of the output and specifically be presented as a software-based decision support tool.

This project addresses the Volume 3 – Industrial Water User Guidelines as part of the series. It attempts to present new approaches that will expand the scope of water quality guidelines in terms of how they are presented and applied, including decision support that is provided to the user.

# 1.2 Project Objective

The objective of this project was to develop a risk-based philosophy and site-specific methodology for assessing water quality requirements and fitness for use of water for industrial use. The specific aspects addressed include firstly the development of the basis of the risk approach and quantification methodology for the risk assessment; and secondly the development of the informatics for a technology demonstrator decision support system that addresses the main decision contexts for industrial water use.

The project aims included:

• Assessment of industrial uses, water quality problems and relevant water quality constituents in support of the approach development;

- Definition of a sound scientific basis for the risk assessment approach;
- Systematic review of relevant literature to identify and critically appraise best available scientific evidence and information sources.
- Definition of the methodologies/calculations for quantifying the risk (quantitative and qualitative).
- Presentation of a prototype software decision support system to pilot the proposed approach and demonstrate the most important features (tiered system).
- Engagement with stakeholders to elicit comment and recommendations.
- Presentation of functioning decision support system for industrial water use.

The current undertaking must also achieve the maximum possible synergy and compatibility with the approaches related to the revision of the other use volumes of the 1996 South African Water Quality Guidelines Series (*viz.* Recreation, Irrigation, Domestic, Aquaculture, Livestock and Aquatic Ecosystems) recently completed or which are currently underway.

## 1.3 The Rationale

Water quality guidelines form an important input into national and regional water resource management in South Africa. A water quality guideline is a numerical concentration or narrative statement recommended to support and maintain a designated water use. Its purpose is to provide basic scientific information about the effects of water pollutants on a specific water use.

They are used in their own right or in conjunction with process or industry specific guidance to protect or improve the quality of water resources or to meet the needs of water users. Without some knowledge of what the impact of a specific water chemistry or microbiology is, establishing whether water resource management has been achieved and meeting quality specifications for use has been successful would be very difficult, even impossible.

The initial focus of producing water quality guidance placed greater emphasis on producing guidance in terms of tables of numbers representing acceptability of constituent levels (target "cut-off" levels). Publications during and subsequent to the 1980s shifted toward producing information on which regulatory action might be based. Issues such as social relevance of resources, site specificity, sciencebased tools, state of the environment reporting and risk assessment became more apparent (S Jooste, 2015, unpublished). In the decades that followed, significant developments have taken place internationally with respect to water quality assessments and guidance for setting water quality objectives. A gradual shift toward a risk-oriented approach to water quality assessment has changed the way the guidelines are formulated and presented.

These developments have included verified reference dose values and concentration based values, risk characterisation, human and environmental risk assessment, consideration of assessment guidance as part of the management decision process as opposed to a start or end point, and the trigger value concept. These concepts take the process a step further by making the site-specific adaptation a part of the guideline rather than a separate process (S Jooste, 2015, unpublished).

Further to the above, in the current context of strained water resources, threats to water security and declining water quality, holistic, localised water-system level viewpoint and assessment is becoming necessary for improved understanding of use of alternate water sources and supply side options that allow for more efficient and optimised use of water resources and consider the best fit scenario.

The shift towards a risk-oriented approach and the need to address current and future water supply/source challenges presents an opportunity for countries, including South Africa, to make its water quality regulatory framework and management instruments, such as the SAWQGs "fit for purpose". This improves water security and more importantly delivering better water quality solutions for all users.

The SAWQGs (DWAF, 1996) which encompasses the Industrial Water User guideline as Volume 3 are essentially a user-needs specification of the quality of water required for different water uses. For industrial use, Target Water Quality Ranges (TWQRs) per constituent were determined in terms of definable water quality requirements related to water utilising processes and incorporate a margin of safety. The TWQRs were set as equal to the desired water quality range which is defined as the range of concentrations or levels at which the presence of that particular constituent would not result in any extraordinary requirements in terms of cost or any other requirements on the fitness of the water for the intended use (DWAF, 1996, Volume 3). A move towards a risk-based approach

It is against this background that the work on the South African Water Quality Guidelines is being undertaken to investigate the need for water quality guidelines and the principles governing them. The 1996 guidelines were risk-based to some extent, because risk (*i.e.* the probability of adverse effects occurring when exposed to a particular hazard) was considered in the development of the guidelines. However, the purpose of the current endeavour is not only related to what the risk posed is, in the development of guidelines (*i.e.* what is the scientific thinking), but also relates to the contexts in which they occur and how it is accounted for.

#### 1.4 Industrial Use Water Quality Guidelines

The 1996 Industrial Water User guidelines, published as Volume 3 (DWAF, 1996) were an improvement on the previous 1993 edition which did not account for the inherent differences between industries and included only a limited number of industry types. The second edition of 1996 saw the revision of the approach to focus on the description of general and specific industrial processes, and by doing so water quality guidelines could be specified for any industry based on the building block approach. By assigning industrial processes to categories, water related problems and related constituents could be identified. Based on an understanding of fitness for use water quality guidelines were then developed.

The DWAF 1996 Industrial Use water quality guidelines, industries have been defined as systems of water-using processes, in which fitness for use of water is defined by the following norms which are used as yardsticks for defining the basis of the effects of water quality constituents:

- impacts on equipment and structures
- interference with processes
- product quality and
- complexity of waste handling.

However, while the guidelines are easy to use and have a wider scale application with the specification of process categories, certain shortcomings have been identified. Many of these are fundamental in nature (DWAF, 2008 and S Jooste, 2015, unpublished):

- The limited range of constituents. The 1996 version contains some common constituents that were of local importance at the time. However, it has become necessary for a wider range of constituents to be included.
- Limited site-specificity. The use and applicability were broadened with the specification of water use process categories rather than different industries to account for water 'purity' required, but procedural guidance for the application of the guidelines to site-specific issues and local context is limited (catchment related, sector-related or on site).
- The guidelines have been misapplied, probably unintentionally, e.g.:
  - For a specific constituent, the numbers pertaining to the various user water quality requirements are used as if their contexts in the guidelines are interchangeable, e.g. aesthetic guidance numbers are used in direct comparison with desired range numbers – with clearly unwarranted consequences.
  - There appears to be confusion about interpretation of terminology such as the "Target Water Quality Range".
  - Guidelines verses standards (guidelines are Guidelines reflect the scientific environment, standards reflect the regulatory environment.
- They are generic and conservative in nature (one size fits all), providing limited guidance on the best fit scenario.
- They do not naturally facilitate informed use (providing a context and alternatives).
- No procedures were indicated for incorporating new data.
- They are limited in terms of wider local relevance, being based to a large extent on international information sources.
- They do not consider synergistic and antagonistic effects of water quality constituents.
- Environmental conditions and interactions pertaining to the use are not accounted for.
- While simple, being generic they are over-simplified thereby compromising wider functionality and presenting limitations in terms of the decision support for the water quality guidance required to address the current water challenges being faced and the greater need for holistic water system/site management, and
- The practical issues regarding the cumbersome nature of the hardcopy volumes in context of the digital age that we live in.

The 1996 guidelines also did not provide an alternative strategy to non-compliant water quality, with no clear communication of the concept of variances changing the outcome following exposure, or the key factors leading to effects with exposure.

# 2.0 KEY COMPONENTS OF THE RISK-BASED GUIDELINES

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.

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

- Risk, and
- Site-specificity.

# 2.1. Risk-Based Product

Risk is a statistical concept defined as the expected likelihood or probability of undesirable effects resulting from a specified exposure to a known or potential environmental concentrations of a material or contaminant. A material/contaminant is considered safe if the risks associated with its exposure are judged to be acceptable (EPA Victoria, 2004).

A risk is posed when there is a source, an exposure pathway and a receptor (receiving environment, 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 risk refers to the probability of specific adverse or undesired effects (e.g. corrosion) to the industrial application using water containing a potential hazard, including the severity of the consequences.

Hazard in this context refers to a range of water quality constituents and physical properties that may be present in the water that renders it less fit for use, and its consequences is based on how the water is used or how it is contacted. Thus, risk is a function of hazard and exposure, where,

- *hazard* = biological, chemical or physical agent that has the potential to cause harm,
- *hazard effect* = adverse impact on process/equipment/output that can result from exposure to the contaminant/ substance/property, and
- *exposure* = contact between a substance/contaminant and a "population" (industrial water use process/contact/outcome/product).

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 Chociolko, 1994) or in the case of industrial water use, whether it is recoverable. Description of the risk therefore requires an assessment that provides answers to the following three questions:

- What can happen (the scenario and effect) (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 (effects of the hazard, in this case to the industrial use, process and product)?

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 situational evidence (site scenario) as possible.

It is generally accepted that a risk-based approach can assist with decision-making and is a useful management tool. It is particularly useful in that it helps to set priorities on a comparative basis and can assist in allocating expenditure of capital and resources.

The estimation of risk (probability of the risk occurring) constitutes the risk assessment process, which would then have to be taken by the user into the risk management phase to assess if the estimated risk is an acceptable one in the context of the situation. The risk assessment supports the risk management process, but the decision making will further also need to be based on industrial application, processes and systems, operational, economic or other related considerations.

The differences between the processes of risk assessment and risk management are outlined Table 1 (DWAF, 2005).

Table	1:	Risk	Analysis
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	Risk Assessment (Risk-based decision support)	Risk Management		
Actions	Identify Describe Measure	Evaluate and Judge Decide Implement		
Influencing factors	Nature of effects Potency of agent Exposure Pathways Population at risk Average risk Cumulative risk	Importance of risk De minimis levels Acceptable risk – regulatory/operational Criteria/Policy Decision to reduce/not reduce risk Economics Priority of concern		
	Sensitive groups Uncertainties of science Uncertainties of analysis	Legislative mandates Legal issues Risk perception		

The intention is that the risk-based water quality guidelines provide the outcome of the risk assessment to the user who is then able to apply the result to the risk management process (decision making context). The water quality guidelines need to be an expression of science supporting a decision (illustrated in Figure 1).

International practice has shown that incorporating risk or risk-based approaches is the best method to manage and protect water resources. The fitness for use assessment forms the core technical requirement of the guidelines.



#### Figure 1: Decision context

The ability of the user to provide some input to the risk assessment process and contextualising the use scenario, supports the proposal of presenting the guidelines as a software product rather than a static document.

### Acceptable Risk

Risk is generally taken to be the probability of adverse effect, injury, disease, or death under specific circumstances. Acceptable risk decisions are rarely easy. The subject of what constitutes an acceptable risk is an extremely complex issue. In determining acceptability, it is however largely the perceived risk that determines the basis of what can be tolerated. Acceptable risk is highly location and scenario specific. For this reason, it plays an important role in adapting guidelines to suit local circumstances, where local stakeholder involvement and available data is vital. The new goal of 'acceptable risk' 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.

# 2.2. Site specificity

While not explicitly related to the concept of risk, a significant deficiency of the 1996 water quality guidelines is that they are generic and uniformly applied. Fitness for use water is dependent on its composition in relation to its intended use. This therefore implies that site specificity is necessary so that decision making on water fitness for use can be assessed accurately based on its character and context of the intended use. A further specification of the guidelines is that assessment should ensure that the experience of different use is the same, wherever they may be.

The envisaged guidelines addresses this by allowing the fitness for use assessments to account for specific scenarios/site circumstances. If the water quality guidance has been derived from an unrealistic base, then it could well mean that a socio-economic impact will be attributable to scientifically tenuous factors, which in turn, could have an impact on local sustainable development. These considerations place a heavy responsibility on the scientific integrity of the data and processes used in deriving the water quality assessment guidance (S Jooste, 2015, unpublished).

Strictly, a more appropriate philosophy for this will be "scenario specificity" because the word "site" implies that it refers to location only.

The site/ scenario specificity of the new guidelines is envisaged to manifest in the following ways (DWAF, 2008):

- *Nature of the water resource*: The water resource itself will determine the nature of the fate and transport behaviour of water quality constituents. For example, soft clear waters have very different characteristics from hard turbid waters.
- *Multiple exposure routes (the "pathways"):* It will be possible to take account of multiple routes of exposure (e.g. contact, process, outcome) of the target "material" and how it reacts to specific water quality constituents.
- The nature of the water use ("the receptor"): It will be possible to define water user/contexts (current or future) in considerable detail so that guidelines specific to that user can be developed (when the necessary data are available). It is the increasingly detailed description of the water user, and implicitly or explicitly the nature of the exposure of that use to the water, that makes the envisaged guidelines "risk-based" as opposed to "hazard-based" (e.g. sector, process, equipment, etc. in the case of the industrial user).

Site/ scenario specificity enables risk assessment to identify differences between background risk, incremental risk, and thus total risk, on a more realistic basis.

The inclusion of this functionality into the decision support system overcomes the shortcoming of the generic nature of the 1996 guidelines, expands its use to support the industrial user to a greater degree as well as facilitate more informed decision making related to water resource use and management (DWAF, 2008).

While site location is a major factor, the new guidelines would need to handle different scenarios or contexts at the same site. The site-/ scenario specificity of the new guidelines will relate primarily to the nature of the source water and the nature of the industrial user (sector/sub-sector/processes).

# 2.3. Tiered Decision Support System

The intention with the risk based guidelines is that the final product provides a series of tiered assessment levels that supports a greater diversity of guideline use and facilitates the decision making (DWAF, 2008).

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. Table 2 provides the definition of the assessment levels that inform the basis of design for the DSS informatics as per the Phase 1 philosophy specifications. The difference between the tiers lies primarily in the degree of site-specificity required to produce an output; and should not be equated to or confused with the tiers of risk assessment. All tiers must be categorised in terms of risk objectives.

Tier 3	Tier 2	Tier 1		
The most site-specific guidance. A risk assessment protocol, requiring highly skilled input and output interpretation. Allows for the adjustment of the algorithm and reference data. Default site specific component options that can be changed to suit site specific circumstances (more specific models and parameters).	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.	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.		

### Table 2: An overview of the Tiered Assessment System

When considered from a programming perspective, the objectives of the DSS may be considered to be:

- To provide a flexible management tool for decision making purposes concerning water quality for aquaculture to a wide user group;
- To provide a means for incorporating site-specific information in risk assessment for aquaculture water use;
- To provide supporting information regarding the various components and their interactions required for decision making;
- To provide a water quality guideline system than can be updated as new information becomes available.

# 2.4. General Approach

Fundamental to the basis of the guidelines is what constitutes risk to industrial water use.

The core of the proposed approach requires accounting for the end point adverse effects posed by the water quality constituents and the manner and extent to which they express themselves, and further within site specific scenarios of the industrial water use. Water quality problems in industrial use and the constituents that cause them are largely known and well documented in literature. Identifying these key water quality problems/adverse effects specific to the South African industrial sector has formed the basis of the risk-based guideline development.

The development of the industrial use risked based guidelines approach and prototype DSS emanates from the key aspects highlighted as follows:

- Understanding of the industrial user group, the sub-sectors and the nature and manner of the water uses and key water quality problems (through consultation with the sector).
- Identification and definition of the key concepts, fundamentals and components to be considered for determining the risk (on which the modelling approach could be based upon and a decision support system designed).
- An assessment of the water quality hazards focusing on understanding the interactions of water quality hazards and determination of the site scenarios and operating conditions, as a means to assess the effects;
- Definition risk calculation methodologies for determining the adverse effects for a range of industrial use scenarios.
- Development and design of the prototype DSS.

The determination of the risk and associated factors required that the effects are measurable to an extent and exhibit characteristics or outcomes that can be adequately described for the industrial use scenario.

The generic first tier guidance of the DSS is seen to address water quality requirements of source water in industrial uses irrespective of whether it is treated or devoid of treatment (similar to the 1996 guidelines). The site specific guidance defined by the risk factors associated with the industrial processes and input water quality concentrations form the basis of the higher tier fitness for use assessment. Based on the understanding of the chemistry and science associated with the commonly and most recurrent water quality end point adverse effects (e.g. scaling, corrosion) and the site scenario, the probability of occurrence and extent of effect can be calculated which would then be reported as the risk.

The risk-based guidance may also account for waters incorporated into processes as part of water use efficiency or re-use measures by varying the source water concentrations as the input variables in the risk assessment to the use scenario.

It is well accepted that water quality problems within an industrial process or operation can often be addressed through some form of engineered solution. Thus it is the intention that this decision support tool serve as a platform for industrial water users to account for potential water quality risks that could manifest and contribute towards improved and informed decision making regarding the timing, implementation and design options of the engineered solution or operational interventions. As a volume of the suite of the South African Water Quality Guideline Freshwater Series, the guideline is primarily intended to guide the fitness for use assessment for the more common adverse water quality effects associated with industrial water use.

### 2.5. Decision Support System

The DSS prototype 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 industrial water use done through a user-friendly graphical interface. The DSS presented is a prototype software system that demonstrates the key features of the tiers and the assessment methodology representing the risk outcomes.

This report presents technical support information to the DSS, which includes the approach development and the risk assessment methodologies applied as the basis to define the informatics for the software application. This report consists of two volumes, Volume 1: Description of the Decision Support System and Volume 2: Technical Support (this report).

# 3.0 INDUSTRIAL WATER USE

#### 3.1 Overview

The current distribution of water use per sector in South Africa is shown in Figure 2 (DWS, 2018). Agriculture is the largest water use sector in South Africa, accounting for 66% of the total water use, followed by municipal and domestic use at 27% (which includes industrial and commercial users provided from municipal systems). The remaining 12% of water use is collectively made up by power generation, mining and bulk industrial use, and conservation and afforestation. Power generation as a strategic water use is provided with the highest assurance of water supply (99.5%), with the level of assurance to the agricultural sector is at 90%, lower than that of the other sectors (90%) (DWS, 2018).



### Figure 2: Sectoral Water Use in South Africa (DWS, 2018)

The South African industrial sector in terms of the water requirements (quality and quantity) includes bulk industry, mining, power generation and urban-based industries. The sector accounts for approximately 16 per cent of the total water used, including water used by industries supplied by water services authorities (water boards and municipalities) (NWRS, 2013). Many of the bulk industrial, mining and power generation users rely of direct abstractions from water resources. Given the diversity of industry and types of mining, the nature of water use by the sector is highly varied. South African industries range from the processing of agricultural and forestry products, construction (such as iron and steel), food and beverage processing, textiles, manufacturing and commercial industries, in addition to the power generation and mining. The breakdown of the water use within the sector is presented in Figure 3 (M Steyn, *et.al*, 2020). A summary of specific water use (intake volumes) for some of various industry types in South Africa extracted from the Natsurv Series of documents is presented in Table 3 (<u>https://www.greencape.co.za/assets/Uploads/Natsurv-summary.pdf</u> – revised/updated based on the Edition 2 documents).



## Figure 3: Water Use breakdown within the broader Industrial Sector (adapted Steyn et al., 2020)

Year	Industry	Average	Minimum	Maximum	Unit
2017	Red meat Abattoirs				
	>100 SU	910	2050	500	l/cattle unit
	50-100	1040	2080	280	l/cattle unit
	20-50	2.04	2600	1480	l/cattle unit
2017	Edible oil				
	Extraction	4.1			l/kg
	Milling	2,60	2,10	3,10	l/kg
	Refining	3,80	3,20	4,60	l/kg
2017	Laundry				
	Rinse water recycle	8-18	-	-	l/kg
	No rinse water recycle	25-30	-	-	l/kg
2017	Poultry				
	>2000 birds	12.8	9	14	l/bird
	Leather Finishing				
2017	Tanning and Leather Finishing				
	Full tanneries		170	550	l/hide
2017	Sugar Cane				
	Sugar mill	0,37	0,04	1.13	l/kg
2017	Paper and Pulp				
	Pulp Mills	40.7	11.9	76.1	l/kg
	Paper Mills	15.6	3.5	33.8	l/kg
2017	Iron and Steel				
	Iron and Steel Plants	4.8	2.3	9.3	m <sup>3</sup> /t
2016	Malt beer				
	Small breweries	5,2	1,5	9,0	1/1
2016	Sorghum beer				
	Sorghum Malting	7850	-	-	l/t
	Brewing	3,54	3.19	3.9	1/1
2016	Metal finishing				
	Metal finishing Plants	95.02	4.23	399.57	l/m <sup>2</sup>
2015	Soft drinks				
	Soft Drink Factories	0,8	0,1	3,8	1/1
2005	Oil refineries & re-refineries				
	Refineries (Crude)	0,57	0,51	0,67	l/kg
	Refineries (Synthetic)	2,9	0,06	7,2	l/kg
	Re-Refinery	1,43	0,06	7,2	l/kg
2005	Electricity Generation				
	Recycling Water-Cooled Coal	1,95	0,51	0,67	l/kwh
	Once Through Wet-Cooled	6,5	0,06	7,2	l/kwh
		0.00	0.00	7.0	1/Lauda
	Dry Cooled Coal	0,09	0,06	7,2	I/KWN
	Nuclear	0,07	0,06	7,2	l/kwn

Table 3:	Summary	of specific	water int	take vo	olumes fo	r various	industry	types in	South	Africa

Year	Industry	Average	Minimum	Maximum	Unit
1993	Textiles				
	Textile factories	137	95	400	l/kg
2017	Textile factories	1	Not specified (va	ried)	
1989	Dairy				
	Unpacked milk	1,6	0,75	5,5	1/1
	Bottled milk	3	2	4,4	1/1
	Sacheted milk	1,7	1,1	3,2	1/1
	Cartoned milk	2,2	1,5	2,6	I/I
	Dairy Products				
	Cultured products	10,2	6,3	13,8	I/I
	Fruit juices and mixes	2,7	0,75	5,5	I/I
	Sterilised/UHT products	3,7	2	6,2	I/I
	Butter	1,5	1,3	6,9	l/kg
	Ice Cream	2,5	1,9	3,1	l/kg
	Skim Milk	3,6	2,1	5	l/kg
	Milk Powder	11,8	8,7	16,6	l/kg
	Cheese	23	16,4	29	l/kg
	Condensed milk	4,4	3,5	5,3	I/I
1987	Fruit & Vegetable Processing	7,13			
	Apples (canned)	6,62	4,3	11,25	l/kg
	Apples (juiced)	1,84	-	-	l/kg
	Apricots (canned)	5,5	2,5	11,5	l/kg
	Beans in Tomato Sauce(Canned)	20	20	70	l/kg
	Beetroot (Bottling)	8	8	24,8	l/kg
	Citrus (Canned & Juiced)	2,08	1,1	2,6	l/kg
	Corn (Canned)	9,25	6	11	l/kg
	Green Beans (Canned)	7,4	-	-	l/kg
	Guavas (Canned)	6,4	4	7	l/kg
	Peaches (Canned)	6,88	2,5	12	l/kg
	Pears (Canned)	12,7	4,5	29	l/kg
	Pears (Juiced)	1,91	-	-	l/kg
	Peas (Canned)	22,8	19	25	l/kg
	Pineapples (Canned)	2,94	2,1	4,55	l/kg
	Strawberries (Canned)	17,8	6,8	21	l/kg
	Tomatoes (Canned)	2,44	2	3	l/kg
	Broccoli (Frozen)	25	-	-	l/kg
	Cauliflower (Frozen)	25	-	-	l/kg
	Carrots (Frozen)	8,1	6	26	l/kg
	Corn (Frozen)	4,63	-	-	l/kg
	Green Beans (Frozen)	27	10	15	l/kg
	Peas (Frozen)	30	-	-	l/kg
	Potatoes (Frozen)	25,7	-	-	l/kg
	Other (Frozen)	19	-	-	l/kg
	Other (Canning)	9	-	-	l/kg
	Berry (Canning)	17	6,8	27,65	l/kg

(<u>https://www.greencape.co.za/assets/Uploads/Natsurv-summary.pdf</u> – revised/updated based on the Edition 2 documents)

The sector is thus highly dependent on a constant and reliable supply of water of a suitable quality to ensure that it remains viable, competitive and meets broader business goals of use efficiency, optimisation, waste reduction and sustainability. While supply may be available, poor water quality can impair industrial processes, production, products and increase the carbon footprint of the site. Water quality is thus a key driver that must be sustainably managed within the use scenario that is presented, which highlights the importance of a shift in approach to a framework that supports more informed decision making.

### 3.2 Importance of Water Quality to the Industrial Sector

Water is used by most industrial sites for a range of purposes in addition to that required for domestic purposes. Water is used for steam generation, fabricating, processing, lubrication, washing, diluting, cooling, humidification or transporting a product, amongst others. Water quality requirements differ widely among industries in South Africa because of the number of uses to which water is put by industry. Within any one particular industry, there may be several different unit processes, each requiring a different quality of water. Some processes are highly sensitive to water quality changes, while others may be unaffected. Consequently, in a single industry, water that is ideally suited for one process may be totally unfit for another. Depending on the product being manufactured and the raw water quality of the intake/ source water, different levels of water purity maybe needed. Optimisation of water use in such a case may be achieved by performing water pinch studies.

For example, high purity water for food and beverage manufacturing will differ to water needed for steel and iron production or metal finishing. Even within these segments, water quality will vary between food types – for example dairy to confectionary, and drinks, from soft beverages to alcoholic beverages. Coupled with local regulations and global export standards (health, safety and product), it is therefore a complex mixture of quality requirements. Hence there is a need to further characterise the water uses into subcategories and to specify water quality requirements at a sub-use level (DWAF, 1996), which are dependent largely on the degree of water purity or limited range of specification for the required quality.

The water quality requirements of an industrial water use are determined by considering (DWAF, 1996):

- The specifications of process and/or product;
- The nature of the effects of less than fit water quality on the use;
- Typical water quality problems associated with a particular water use or the role that water quality plays in sustaining the use;
- The water quality constituents which are generally of concern; and
- Any other site- or case-specific characteristics of the water use that may influence its water quality requirements.

The term water quality as used in the context of this project, is to express the suitability of water to sustain various uses or processes. Any particular use will have certain requirements for the physical, chemical or biological characteristics of water. Consequently, water quality can be defined by a range of variables which if present, limit water use. (UNEP/WHO, 1996). Water quality is further influenced by complex interactions between variables. For industrial use the water quality composition and the presence of contaminants in source water can result in a number of problems depending on its suitability for the process or type of use. These problems can range from equipment damage from scaling, fouling, corrosion, abrasion, embrittlement and other forms of damage or premature wear, to interferences with processes such as precipitation, colour changes; foaming, gas production, odours, biological growth and sediments, to impact on product quality such as health hazards, contamination, discolouration,

taste and odour impacts and to difficulties with waste handling such as of salts, suspended solids, metals, silica, amongst others.

The quality of the water used in industrial processes thus if not suitable (fit for use), impacts on the return on investment to the user, either directly through impacts on the costs and quality associated with the use (use and disposal) and indirectly on the cost per unit of goods, services or products. Thus it is a key determinant of water use. Water quality management is also critical for maintaining compliance with increasingly stringent environmental, safety and industry standards.

For the industrial sector, the degree to which water is suitable for use and sustainable is dependent largely on the user and what the user is prepared to do to treat the water to the desired quality. Water quality can affect the cost of treating water before use, sophistication of technology required to treat the water to adequate quality, product quality, operation and maintenance costs and disposal requirements. Its importance therefore cannot be overemphasised.

Water quality guidance as it currently exists addresses the suitability of influent water for an industrial application or operation and is supported by extensive and well researched science. Such guidance presents the generic guidelines on fitness for use. However, in a sector where the water purity range and stringency of specification of the parameters are known, and achieved through available and continually advancing treatment technology, water quality guidance needs to evolve to address site-specific conditions and the risk scenarios presented beyond intake, in order to optimise water use and improve efficiencies, which this project seeks to address through a decision support system.

While a comprehensive set of guidelines for industrial water use in South African does exist (DWAF 1996), and parts of these guidelines include a description of waterborne hazards and the effect of exposure, it does not include an explicit risk-based approach to industrial water use, that considers site specificity. This is not only true for the local context but also internationally where no risk-based analysis for the use of water in industrial applications could be found.
# 4.0 FUNDAMENTALS OF THE RISK-BASED APPROACH

The guidelines are intended to differ in a fundamental way from the existing 1996 guidelines by adopting a risk and site-specific approach that accounts for exposure conditions although still being concentration-based. The term "risk-based water quality guidelines" implies that the regulator and experts have accounted for all the factors that constitute a risk description (Jooste, 2015). It requires the quantification of the risk to yield measurable descriptors of the water quality constituent of concern associated with a fitness for use or water requirement goals.

The intention is that the risk-based guidelines provide the risk assessment to the industrial user who is then able to apply the result to the risk management process (decision making context). It is important also to note that it is seldom possible to make a binary (good/ bad) decision in an environmental assessment. How a constituent presents itself in the uptake or exposure process can have a critical impact on the expected outcome: presence does not necessarily mean availability. At the same time one constituent may be experienced differently by the target/material so it is important to recognise the use scenarios. The risk a certain constituent poses may also be dependent on secondary parameters, e.g. corrosive properties of water containing chlorides is more severe in applications at higher temperatures and that lower temperatures.

Simply put, a risk assessment analyses constitutes what can go wrong, how likely it is to happen, what the potential consequences are, and how acceptable the identified risk is to the user. As part of this process, the resulting determination of risk may be expressed in a quantitative or qualitative fashion. Using available science and user-specific factors, outputs need to be presented in a manner that support management decisions within an industrial water use context.

In adopting a risk-based approach the focus moves from regarding exposure to a water quality constituent concentration as safe due to an expectation of a "no adverse effect" at or below that stated concentration, to an acceptable risk level following exposure. This is a statistical concept defined as the expected likelihood or probability of undesirable effects resulting from a specified exposure.

In the existing guidelines the fundamental approach of a "desired water quality range" for selected water quality constituents is adopted, and given the variability in industrial uses and process, the derived target range is based on an assumed water consumption value and the most sensitive endpoint. Inevitably this leads to a conservative guideline which creates the situation when using surface and groundwater resources that few, if any, fully comply with the guideline limits set. This situation is evident in setting of catchment water quality objectives when the requirements of various users have to weighed up against each other

It should be noted that in principle the process is similar to a source, pathway and receptor analysis typically adopted in which the following general steps are involved in the risk assessment process:

• Hazard Identification (the science): As source assessment involving tasks of:

- Sampling, monitoring, chemical and targeted constituent analysis and assessment of the data gathered.
- Determining whether the water quality constituent has the potential to cause harm and/or potential to cause physical damage and/or potential to reduce the desirability (literature based). At the higher assessment levels (tiers of the decision support system) additional constituent source sampling and analysis provide more site detail and increase the degree of assessment performed. At the higher level this may thus include operational considerations, site specifics and other screening tools.
- Determining whether exposure to a constituent can cause an increase in the incidence of specific adverse effects (e.g. damage, process impairment)

The outputs of this step guide the further steps in terms of the key constituents and adverse effects. Hazardous agents include microbial, chemical, physical and radiological agents (and constituents of emerging concern). Appropriate source assessment allows for a more focussed pathway assessment to be performed, with the corresponding site-specific data inputs (e.g. industry sector and process types) aiding in this regard.

- **Exposure Assessment (site-specificity)**: An assessment, in which what is known about the frequency, timings, magnitude, and levels of contact with the constituent is examined:
  - Exposure assessment considers the exposure pathway (the course a water quality constituent takes on the surface (s) being contacted (receptor). The exposure route is generally further described as intake or uptake. Plausible exposure is assessed and evaluated to determine whether each pathway would be operable for each 'receptor'.
  - In terms of industrial use the receptor may constituent the equipment or the process technology, materials, etc.
  - This makes less use of assumptions (as in the mg/L typical guideline approach at the generic target water quality range) and increased use of actual on-site measured water quality data, with each step thus more accurately performed with higher levels of assessment.
  - Key specifics required in this step include:
    - A more detailed description of the exposed receptor types (thus not simply process or water requirement type, but industrial sector subcategories linked to the processing units, materials and equipment, etc.).
      - This receptor analysis is essential to identifying the key risk factors, and potential acceptable risk level applicable.
    - Pathway assessment (e.g. process, equipment type and material composition).
    - Calculating the exposure concentrations (thresholds based on intake, material and duration)
  - It should be noted that each step makes use of empirical data and observed site data, for example pathway analysis involves chemical analysis, transformations and key point of use exposure values.

- **Risk characterization (risk guidance)**: in which the exposure assessments related to adverse effect produce a quantitative or qualitative risk estimate of the hazard.
  - It is a combination of the probability, or frequency, of occurrence of a defined hazard (water quality constituent (s) and the magnitude of the consequences of the occurrence.
  - It examines how well the data support conclusions about the nature and extent of the risk from exposure to the hazards.
  - In this step information that has been gathered from the exposure assessments are combined to determine if a potential risk exists. Risks may be estimated qualitatively based on scientific judgement for a screening level risk assessment, or in a more detailed risk assessment, quantitatively assessed.
  - The level of risk for each hazard (water quality constituent) can be estimated by identifying the likelihood of occurrence (e.g. certain, possible, rare) and evaluating the severity of consequences if the hazard were to occur (e.g. insignificant, minor, moderate, significant). The aim is to distinguish between these ranges of risks.
  - This is performed typically as a form of index, for example, a Hazard Index (HI = threshold value) where an index value of <1.0 provides acceptable risk.</li>
  - It is important that the index value derived does not provide a value for the probability of harm as the result of exposure, but rather quantifies the absence of effects from exposure.

In the development of the risk-based approach, the DSS should also provide assistance to the user by support information which aims to fundamentally reduce the sources of uncertainty in the assessment. These are typically factors such as:

- Failure to adequately provide source (water quality hazard) characterisation.
- Lack of reference data, for example, where reference data (as is the case for most chemicals) to determine possible adverse outcomes linked to exposure are lacking (scientific evidence).
- Uncertainty regarding exposure assessment. It should be noted that this is again a benefit in many industrial operations systems in which the actual duration and future potential exposure is known or can be easily validated.

## 4.1 The Concept of Risk Management

The estimation of risk (probability of the adverse effect occurring) constitutes the risk assessment process, which would then have to be taken by the user into the risk management phase to assess if the estimated risk is an acceptable one in the context of the situation. The risk assessment supports the risk management process, but the decision making will further also need to be based on industrial process impact, operational aspects, economic issues or other related considerations.

Most activities are associated with hazards. The concept of "zero risk" is rarely achievable in any facet of an industrial process. It logically follows, therefore, that a trade-off is made in conducting any process activity, between the hazard and risks expected versus the benefits. The trade-off is made at a point at which the situation is deemed acceptable. If the risks are too high, the proposed process should be modified until an acceptable result is obtained. This implies that the process of risk management is an iterative one.

## 4.2 The Concept of Acceptable Risk

In the context of industrial water use, and in the development of the risk-based approach, the concept of acceptable risk is seen to relate to the probability of specific adverse/undesired effects manifesting within the industrial processing units based on an input water quality (treated or untreated or re-used), and based on a calculation methodology that accounts for site specific factors to enable 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.

In industrial water use processes the risks versus benefits are primarily assessed on the basis of capital or operational expenditure, however other considerations such as process optimisation, product quality and aesthetics are also important.

## 4.3 Fitness for Use

The concept of fitness for use is well defined and in the context of water quality guidelines, 'is a judgement of how suitable the quality of water is for its intended purpose' (DWAF, 1996). The concept of fitness for use of water in industrial applications differs in some respects from other water user groups.

Most industries are comprised of various water-using processes, often each with its own specific water quality requirements. Some processes are highly sensitive to water quality changes, while others may be unaffected. Consequently, in a single industry, water that is ideally fit for one process may be totally unfit for another. Treatment technology also permits that any quality water can be used for a specific purpose provided it can be treated to the required specifications.

Therefore, in industrial applications, how fit a particular water source is for use depends on the design specifications of the process technology and how much the user is prepared to invest in treating the water to comply with these specifications. Thus while it would seem that the fitness for use concept's relevance and applicability to industrial water uses might be irrelevant, this holds true if one only considers the hazard concentration in the input (source) water. However, the applicability of the risk-based guidelines extends beyond source water input and by the incorporation of the exposure water use scenarios and site specific risk factors within the process, the user is presented with added guidance on the probability of the risks that are likely to occur within the process. This fitness for use concept is thus extended from a hazard basis to a risk basis accounting for the suitability of the water to be assessed and interpreted in terms of specific adverse effects.

The fitness for use assessment thus still forms the core technical requirement of the guidelines. The focus of this endeavour has therefore been to formulate a mathematical approach (modelling) to the

fitness for use analysis as the basis for derivation of the risk-based guidelines. The ability of the user to provide some input to the risk assessment process and contextualising the scenario, supports the proposal of presenting the guidelines as a software product rather than a static document.

For industrial water use the risk-based guidelines would thus serve the purposes,

- in a generic context evaluating the fitness for use of the source water, and
- in a specific context as a screening tool to guide and support decision-making regarding process technology aspects of specific industrial problems (e.g. effects such as scaling, corrosion, fouling, foaming, abrasion).

# 5.0 APPROACH AND METHODOLOGY DEVELOPMENT

For the purposes of the risk-based Water Quality Guidelines: Volume 3 Industrial Use, the guidelines are applicable to any water that is used for industrial purposes, irrespective of its source (municipal supply, borehole, river, etc.), whether or not it has been treated or not. The industrial user water quality guidelines are to provide the risk of specific adverse effects for a range of physical, chemical or microbiological contaminants in water, in relation to industrial use categories that define the similar water use characteristics and whose exposure profile is sufficiently similar.

## 5.1 Definition of Water used for Industrial Purposes

For the purposes of the risk-based guideline development, it was considered necessary to assess how to adequately and appropriately cater for the range and varied uses of water for industrial purposes. The rationalisation process included:

- the 1996 approach of the industrial processes be used,
- use of industry types or industrial technologies applied; or
- categorisation based on stringency of water quality requirements, water quality problems or water use types.

The difficulty in developing water quality guidelines for industrial use is the inherent difference between industries, even between those manufacturing similar products. Following a literature survey, analysis and assessment of the various industries it was considered prudent to define the mainstream risk-based approach to cater for the processing units, equipment and structures within sectors, to enable the guidelines to be as widely and nationally applicable as possible. This aligns to the norms adopted in the 1996 guidelines which included impacts on equipment and structures and interference with processes. The risk-based approach now accounts for site specific scenario and exposure factors.

The incorporation of the product quality norm was considered impractical and too varied and complex to account for in the risk-based guideline assessment as one would need to assess the chemical composition of each product and science-based evidence related to interaction with the water quality hazard. This is a mammoth task that can be considered as virtually impossible and is not easily suited to a national applicable guideline tool. At this point product quality is not included, however one can consider possibly the inclusion of an assessment approach at the Tier 3 level of the DSS at a later stage where the expert user is able to apply the in-depth knowledge and scientific data specific to his/her product to determine the probability of the risk occurring.

It should be noted that the risk-based guidelines is not meant to cater for all possible circumstances and consequences and meet all possible needs, but rather serve the purpose of providing risk-based guidance to the commonly encountered adverse effects related to water used for industrial purposes across a range of use sectors.

## 5.2 Industrial Use Categories

For purposes of the risk-based guideline development, the following manufacturing and processing industrial sectors were reviewed and assessed to identify the generic key risk factors. Although these groupings do not cover all industrial water users in South Africa they do, nevertheless, include the largest manufacturing and processing industrial water users. This is approached at a high level per sector. At this stage some sub-sectors within a sector are also included where data availability and access to industry specific information is easily mined. However it is envisaged that the defined risk-based assessment approach for industrial water use in South Africa, would be easily adapted to include other sectors and specifically sub-sectors through the incorporation of situations specific and scenario specific information into the DSS.

Sectors selected for methodology development:

- Power generation
  - o Coal Processing
  - o Coal Powered
  - o Nuclear
  - Hydro Power
- Iron and steel industry
- Sugar refining
- Brewery and Malt industry
- Textile industry
- Petrochemical industry
- Chemical industries
- Beverage Industry
- Dairy industry
- Laundry industry
- Pulp and paper industry
  - Pulping
  - o Paper

A brief overview of the selected sectors and nature of the processing aspects are defined below. The characterisation of the processing aspects within a sector forms the basis to determining the receptors, exposure routes and associated consequences of the water quality hazard, which forms the key components of risk-based analysis.

**Power generation:** There are four major types of power generating processes utilized in South Africa namely coal-fired, nuclear, hydro-electric and gas turbine power generating processes. Hydroelectric and pumped storage schemes are only used during South Africa's peak periods. Gas-turbine power stations are only used during extreme emergencies due to their very high operating costs. Electricity in South Africa is mainly produced using coal-fired power stations with coal fired processes

having the highest water consumption (Natsurv 16, WRC 2005). In a coal-fired power station, coal is crushed and then burned to heat water to produce steam. The steam turns a turbine, which turns a generator to produce electricity. The main demand for water within a thermoelectric power plant is for condensing steam generation. The main water quality required for steam generation is deionized water. Sources of water include raw water from national water supply infrastructure, borehole extraction or the municipality which are upgraded to deionised water quality.

**Iron and Steel Industry**: The South African industry supplies the full demand of the domestic market's iron ore, and the remaining volumes are beneficiated and exported. Water use within the iron and steel industry vary and is dependent on the availability of water, age and condition of the plant and equipment, process and plant operating and emergency procedures. Most of the water used in the Iron and Steel Industry is used for cooling and to protect equipment. A smaller, but still considerable, amount of water is used as process water to cleanse coke-oven gases, quench coke and slag, descale steel and for boiler feed water (Natsurv 17, WRC 2017). The key processes include production of liquid ore within the blast furnace from using coal, lime and iron ore. The liquid iron ore is converted to steel at the basic oxygen furnace. This is then cast into steel slabs by using continuous casting process. The cast moulds are further processed in the rolling plants.

**Sugar Refining:** The sugar industry combines agriculture and manufacturing to produce raw and refined sugar. The production of white sugar from sugar cane consists of two processes: extraction of raw sugar, and refining. A number of steps are required to produce raw sugar from cane. All of these processes require energy in the form of mechanical energy and/or heat. Although water is required in large volumes for juice extraction, minimal external water is required for the direct recovery of sugar from the cane because cane contains around 70% water, and process water is recycled. However, additional water is usually required for start-up, shut-down and various auxiliary activities in the refinery (Natsurv 6, WRC 2017).

**Beer and Malt:** The malt brewing process involves milling, mashing, separation, boiling, cooling, fermentation with yeast, maturation and pasteurization, and packaging. The major steps of beer production include malting, brewing, fermentation and storage (bottling or barrelling) (Natsurv 1, 2016). Water consumption within the malt and beer industry is dependent on the type of beer produced and the brewery outcomes. The sources of water include raw water and/or borehole water used for plant washing and potable water for actual processes within the brewery. Beer manufacturing is sensitive to water quality in terms of process chemistry, biological conversion, flavour formation, product stability, food and process safety.

**Textile Industry**: The textile industry consists of companies that are involved in the manufacture and processing of textiles through various processes: the production of yarn from natural raw materials (e.g. cotton, wool, mohair) and/or manmade fibres (e.g. viscose, rayon); the production of woven or knitted fabrics from spun yarn; the dyeing and printing of fabrics; and the application of finishing processes (e.g. the production of technical textiles or textiles with industrial applications which include nylon and

propylene, yarns, astro-turf bitumen and other ranges of commercial and residential products). The textile companies vary from those involved in dyeing, finishing and washing, to manufacturers and suppliers of yarns and fibres, knitted fabrics, technical textiles, and home textiles, to name a few. Potable water is required for steaming and cooling during the processes. Potable water is also required for the manufacturing process such as fibre and yarn extrusion, twist, air entanglement, needle punch, tufting, backing.

**Petrochemical Industry**: The South African petrochemical industry comprises both synthetic fuels and conventional oil based refineries. The oil based industry is divided into upstream and downstream activities. The upstream category comprises of the exploration and the production of crude oil. The downstream category refers to the refining, transportation and marketing of the end-user products. The main petroleum products produced are petrol, diesel, jet fuel, illuminating paraffin, fuel oil, bitumen and liquefied petroleum gas. The major liquid fuels used within South Africa is petrol and diesel. Water is a critical feedstock required at a high level of assurance for the oil and gas operations. The industry is heavily reliant on water in almost all their business processes. Water is used for mining purposes, process cooling water, utility cooling water, raw water to produce flocculated water, condensate production, boiler feed water, polished water, fire water and potable water.

**Chemical Industry:** The chemical industry is categorised as the manufacturing and sales industry. The key product and services include scale inhibitors, corrosion inhibitors, coagulants, flocculants, defoamers, paper process chemicals, leather process chemicals, sugar and ethanol process chemicals. Filtered or softened water is required for the manufacturing process. The process steps that consume the most water is the manufacturing process, utilities, cooling and heating as well as steam production. The raw water received requires treatment before use within the processing plant. Sedimentation that removes most of the colloidal particles in the raw water, screening, clarification which removes the suspended solids, filtration, ion exchange and membrane technology. The range of water quality flexibility is dependent of the use and type of chemical produced. The majority of the water received is at potable standards and is satisfactory for most direct uses.

**Beverage**: Water is the main raw material for soft drink manufacture, making up between 87% and 92% in a typical beverage (Shachman, 2004). The quality of the water used must meet stringent standards as it has a serious impact on the taste and appearance of the drink as well as its physical and microbiological stability on the shelves in stores. The type of water treatment processes used depend on the product being produced and the packaging to be used. These include carbonated drinks, fruit drinks and bottled water.

**Dairy:** The dairy industry in South Africa is significant, both from a water intake and effluent discharge point of view. Dairy products include primarily pasteurized milk, milk powder, condensed milk, butter, ice cream and cheese production as well associated milk products. Dairy processes are diverse, depending on the product. The majority of water usage in the dairy industry is associated with the various cleaning processes but steam is also used in various processing steps. Major processing steps

in milk production include reception, pasteurization, standardization, de-aeration, homogenization, cooling and packing.

**Laundry**: There is limited data regarding the water and wastewater practices of laundries in South Africa. A few large commercial laundries are operational in South Africa. Water is the universal solvent for water-soluble dirt particles and chemical detergents. The quality and quantity of water that laundries use is also essential towards the laundering process. The amount of water used is influenced by the type of washing machine, the type of textile being laundered, the type and amount of dirt/stains and the number of cycles for each main stage (e.g. rinsing requires the highest amount of water used, which must also be fresh water).

**Pulp and Paper:** The major producers of paper and pulp in South Africa not only operate nationally but also in the international market. The pulp utilised for the manufacturing of paper is typically derived from either wood, bagasse, or recycled paper. The pulping of wood is a much more extensive process than the use of recycled paper, requiring additional treatment processes, as well as larger quantities of raw materials. Paper manufacturing comprises pulp refining, paper machine feed, coating and finishing.

The industrial sectors comprise the first component of the risk-based approach, defining the basis of the 'scenario', by framing the manufacturing and/or processing context of the situation/site.

#### 5.3 Risk Assessment Process

In defining a water quality risk-based guideline, the decision support outcome is a function of the intrinsic risk of the water quality constituent (the hazard present in the water) and the extrinsic risk presented by the site scenario, *i.e.* industrial process, unit, route of exposure, exposure conditions that is derived through a mathematical modelling approach (calculation methodology) that compromises the risk assessment. A result generated as the output, based on these components is presented as the "risk" (water quality guidance of the probability of the adverse effect).

As outlined in Section 4.0 the elements of the risk assessment process include:

Hazard identification (presence of the hazards), in which a determination is made as to whether a
stressor (the water quality constituent) has the potential to cause physical damage to property, limit
production capacity and/or potential to reduce the desirability (aesthetics). It is the process of
determining whether exposure to a water quality constituents can cause an increase in the
incidence of specific adverse effects (e.g. corrosion, fouling). Hazardous agents include chemical,
physical and microbiological agents.

For industrial use adverse effects are predominately driven by chemical, physical and microbiological water quality hazards. For, the risk-based process once the hazards were identified through engagement with the sector and literature based information on water quality hazards and the major adverse effects of concern, this then required an examination of the available scientific

data for a given chemical (or group of chemicals) and a weight of evidence was developed to characterise the link between the negative effects and the chemical/physical hazardous agent. This has formed the basis of the approach development.

- Hazard Characterisation (presence of receptors and exposure pathways), in which what is known about the frequency, timings, magnitude, and levels of contact with the stressor is examined. Exposure assessment considers the exposure pathway (the course the water quality hazard takes from source water input point through the treatment, manufacturing and processing units being contacted. Plausible pathways were assessed and evaluated to determine the exposure routes that would be operable for each industrial sector or sub-sector. Exposure assessment is the process of estimating the exposure to the water quality hazard under a given exposure scenario (*i.e.* processes associated with an industrial use sector).
- *Risk characterisation,* in which the hazard data and exposure assessments are combined to produce a quantitative risk estimate of the adverse effect. It examines how well the data support conclusions about the nature and extent of the risk from exposure to the hazards.

For the risk characterisation information that has been gathered from the exposure and chemical assessments are combined to determine the probability of the risk (adverse effect) occurring. For the purposes of the DSS the presentation of the risk characterisation has focused on three common and most significant water quality adverse effects, *viz.* corrosion, scaling and fouling relevant to the industrial water user that is well supported by empirical scientific data.

Risks may be estimated qualitatively based on scientific judgement applying a screening level risk assessment (the Tier 1 of the tool), or in a more detailed risk assessment (Tier 2). Establishing risk for a hazard will, by its very nature, consider typical mechanisms of exposure of the industrial processing unit to the water quality composition in question.

The level of risk for each hazard can be estimated by identifying the likelihood of occurrence (e.g. certain, possible, unlikely) and evaluating the severity of consequences if the hazard were to occur (e.g. insignificant, minor, moderate, significant). The aim is to distinguish between these ranges of risks.

The above process as a basis to the methodology is applied in the decision support system. The decision support tool considers the industrial sectors and the scenarios in which they take place. The building blocks comprising the risk approach applied in the development of the industrial user water quality guidelines therefore involves:

- Definition and description of the scenarios/situation (Section 5.4)
  - Description of the scenarios for industrial uses
- Characterisation of the risk assessment components (Sections 5.5 and 5.6)
  - Hazard identification;

- Hazard Characterisation (defining effect concentrations of no effect and the full adverse effect), and
- o Categories of adverse effects (to determine the risk methodology to be applied).
- Risk assessment (evaluation based on the above to determine probability of occurrence of the risk posed) *i.e.* the Decision Support System (Section 5.7)
  - Calculation Methodology formulation

The approach and methodology described here forms the basis of the informatics to the decision support tool.

## 5.4 Description of the Scenarios/Site-specific Situation

Each industrial sector/sub-sector dictates the exposure scenario and on that basis the route of exposure (how is the water being contacted) and the receptor details (the characteristics, the threshold tolerance, exposure relationships, susceptibility of the contact point to the water quality constituent, *i.e.* the hazard) in which the potential risk presents itself.

The potential receptor and exposure site scenarios as it pertains to industrial use relates to:

- the manufacturing and processing units/components of the industry sector,
- the mechanical/civil infrastructure,
- the materials of construction.

The exposure scenarios based on the various sector manufacturing and processing units were defined. This included the definition of the mechanical/civil infrastructure associated with the processing components/steps that are linked to some form of water usage in the major industrial use sectors identified. The approach required defining the materials of construction (MOC) component of the infrastructure as this comprises the ultimate receptor which needs to be characterised to define the risk (the probability of occurrence of the adverse effect) (Figure 4 to Figure 16). The MOC forms the basis of the risk approach definition for industrial water use. While the MOC has been characterised for a number of processing sub-units/components for inclusion into the DSS, the reference database can be easily expanded to include new MOCs and related data as they become available.

The typical materials of construction from the various industries and typical operating parameters are shown in Table 4 and discussed in sub-sections 5.4.1 to 5.4.14.

These exposure scenarios comprise the primary building block to the risk analysis approach adopted for the decision support system, in that it directs the criteria and considerations into the selection of the type of calculation methodologies that should apply to determining the risk, based on the adverse effects that manifests relate to hazard that is presented.



Figure 4: Mechanical/Civil infrastructure and Materials of Construction associated with the Soft Drink Industry



Figure 5: Mechanical/Civil infrastructure and Materials of Construction associated with the Distilled Beverage Industry



Figure 6: Mechanical/Civil infrastructure and Materials of Construction associated with the Hot Beverage Industry



Figure 7: Mechanical/Civil infrastructure and Materials of Construction associated with the Malt/Beer Industry



Figure 8: Mechanical/Civil infrastructure and Materials of Construction associated with the Wine Industry



Figure 9: Mechanical/Civil infrastructure and Materials of Construction associated with the Dairy Industry



Figure 10: Mechanical/Civil infrastructure and Materials of Construction associated with the Sugar Refining Industry



Figure 11: Mechanical/Civil infrastructure and Materials of Construction associated with the Power Generation Industry



Figure 12: Mechanical/Civil infrastructure and Materials of Construction associated with the Pulp and Paper Industry



Figure 13: Mechanical/Civil infrastructure and Materials of Construction associated with the Chemical Industry



Figure 14: Mechanical/Civil infrastructure and Materials of Construction associated with the processing units of the Textile Industry



Figure 15: Mechanical/Civil infrastructure and Materials of Construction associated with the processing units of the Iron and Steel Industry



Figure 16: Mechanical/Civil infrastructure and Materials of Construction associated with the processing units of the Petrochemical industry

# Table 4: Common Materials of construction and their parameters (Sinnot, 2011)

Material of	Parameter																	
	Compo	sition	(%)										Tensile Strength	Ductility	Corrosion Resistant	Sustainability to Solvents	Stress Capability	Typical industry Used in:
	С	Si	Mn	Cr	Ni	Cu	Fe	AI	Mg	Pb	Ti	Мо						
Mild Steel	0.05- 0.25												MEDIUM	MEDIUM	MEDIUM	LOW (Cannot be used with applications with chlorinated solvents)	MEDIUM	Engineering and Chemical Applications
High Silicon Irons		14- 15											LOW	LOW (Brittle)	HIGH	HIGH (Cannot be used in applications that contain hydrofluoric acid)	N/A	Sulphuric Acid Production and other chemical applications
Stainless steel																		
304	0.08	-	2	17.5	8	-						-	GOOD	GOOD	MEDIUM	<b>MEDIUM</b> (Except in high chloride environment)	LOW Stress corrosion cracking can occur at temperatures over 60°C.	Saucepans, Cutlery and flatware, Architectural panelling, Sanitary ware and troughs, Tubing, Brewery, dairy, food and pharmaceutical production equipment, Spring, nuts, bolts and screws
304L	0.03	1	2	17.5	8	-						-	-					
321	0.12	1	2	17.5	9	-						-	<b>GOOD</b> (extremely good at Low temperatures and high altitudes)	GOOD (extremely good at Low temperatures and high altitudes)	MEDIUM	MEDIUM	LOW	Aircraft engines, Expansion joints, Refinery equipment, High temperature chemical process equipment, Food processing equipment and storage
347	0.08	1	2	17.5	9	-						-	MEDIUM	MEDIUM	HIGH	MEDIUM (Better than 304/304L as its much stabilised)	MEDIUM	Boilers, Heat Exchangers, High temperature steam services and high temperature chemical process
316	0.08	1	2	17.5	10	-						2	HIGH	HIGH	HIGH	HIGH	HIGH	Exhaust manifolds, furnace parts, heat exchangers, valve and pumps, chemical processing equipment, tanks, evaporators, pulp, paper and textile processing equipment and for any parts exposed to marine environments
200	0.03		2	17.5	10	-						2				шен		Deiler heffles Furness servers (
ວບອ	0.2	-	-	17.5		-						-		nigh	пібн	пюп		Oven linings, Fire Box sheets, other high temperature containers

Material of	Paramo	Parameter																
Construction	Compo	osition	ı (%)										Tensile Strength	Ductility	Corrosion Resistant	Sustainability to Solvents	Stress Capability	Typical industry Used in:
	С	Si	Mn	Cr	Ni	Cu	Fe	AI	Mg	Pb	Ti	Мо						
310	0.25	-	-	17.5	19	-						-	HIGH	HIGH	HIGH	HIGH	HIGH	Fluidised bed combustors, kilns, radiant tubes, tube hangers for petroleum refining and steam boilers, coal gasifiers internal components, lead pots, thermowells, refractory anchor bolts, burners and combustion chambers, retorts, muffles, annealing covers, aggers, food processing equipment, cryogenic structures
High Alloy Stainless Steel				20	30	-							HIGH	HIGH	HIGHER than stainless steel	HIGHER than stainless steel (good resistance to acids and acid chlorides)	HIGHER than stainless steel	Automotive applications, chemical processing and power generating equipment, Aqueous environment
Nickel					>99	-							HIGH	HIGH	HIGHER than stainless steel	HIGH	HIGHER than stainless steel	Storage cylinders for liquefied gases and for low temperature applications, Heavy forgings, turbine blades, highly stressed screws, bolts, nuts, shafts, gears, propeller shafts and keys. The main use is for equipment handling caustic alkalis at temperature above that which carbon steel could be used, above 70 degrees
Monel (Ni Cu Alloy)					66	33							HIGH	HIGH	HIGHER than stainless steel	HIGH	HIGH	Marine engineering, chemical and hydrocarbon processing equipment, valves, pumps, shafts, fasteners and heat exchangers
Inconel				15	76		7						HIGH	HIGH	MEDIUM	MEDIUM (Not suitable for use in sulphiding environments.	HIGH	Oil and Gas extraction, sea water equipment and chemical plant equipment
Incoloy				25	76								HIGH	HIGH	HIGH	HIGHER than Inconel	HIGH	
Hastelloy's																		
Hastelloy's B					65		6					28	HIGH	HIGH	HIGH	HIGH (outstanding resistance to non- oxidising acids such as HCI or Sulphuric Acid)	HIGH	Chemical processes, petrochemical, Oil and Gas, Pharmaceutical, Geothermal, Sea Water, Water Desalination, Liquefied Natural Gas,

Material of	Parame	ter															
Construction	Compos	sition	(%)									Tensile Strength	Ductility	Corrosion Resistant	Sustainability to Solvents	Stress Capabilit	
	С	Si	Mn	Cr	Ni	Cu	Fe	Al	Mg	Pb	Ti	Мо					
Hastelloy's C				15	54		5					17	HIGH	HIGH	HIGH	HIGH (outstanding resistance to non- oxidising acids such as HCI or Sulphuric Acid)	HIGH
Copper						>99							MEDIUM	HIGH	MEDIUM (Biofouling as well)	HIGH	HIGH
Copper Alloys						70							MEDIUM	HIGH	HIGER than Copper	HIGHER than copper	HIGH
Aluminium								>99					MEDIUM	MEDIUM	MEDIUM	MEDIUM (Attacked by mineral acids and by alkalis but is suitable for concentrated nitric acid)	MEDIUM
Aluminium Alloys							4	95.5	0.5				MEDIUM	MEDIUM	MEDIUM	MEDIUM (Attacked by mineral acids and by alkalis but is suitable for concentrated nitric acid)	MEDIUM
Lead										>99			HIGH	HIGH	HIGH	HIGH (Especially for sulphuric acid uses)	HIGH
Titanium											>99		HIGH	HIGH	HIGH	HIGH (Especially in chloride solutions)	HIGH
Tantalum													HIGH	HIGH	HIGH	HIGH	HIGH

/	Typical industry Used in:
	Biomass, Mining, Utilities, Nuclear and Solar power
	Power transmission lines, Architectural applications, Cooking utensils, Spark plugs, Electrical wiring, cables and bush bars, High conductivity wires, Electrodes, Heat Exchangers, Refrigeration tubing, Plumbing, Water-cooled copper crucibles
	Chemical processes and linings
	Chemical processes, Halide processes, Liquid-phase oxidation processes such as manufacturing terephthalic acid.
	Used where glass or glass lining. Also used in glass-lined equipment for Tantalum plugs. Chemical industry discussed by Fensome and Clark (1984) and Rowe (1994-1999)

Material of	Parame	Parameter															
Construction	Compos	sition	(%)										Tensile Strength	Ductility	Corrosion Resistant	Sustainability to Solvents	Stress Capabilit
	С	Si	Mn	Cr	Ni	Cu	Fe	AI	Mg	Pb	Ti	Мо					
Zirconium													MEDIUM	HIGH	MEDIUM	HIGH	HIGH
Silver													MEDIUM (140MPa)	HIGH	HIGH	HIGH	HIGH
Gold													MEDIUM (120MPa)	HIGH	HIGH	HIGH	HIGH
Platinum													<b>MEDIUM</b> (125-165 Mpa)	HIGH	HIGH	HIGH	HIGH
Plastics		1	1	1	1	1	1	1			1	1	1	1	1	1	1
PVC													LOW	LOW	HIGH	HIGH	LOW
Polyethylene (Low Density)													LOW	LOW	HIGH	HIGH	LOW
Propylene													LOW	LOW	HIGH	HIGH	LOW
PTFE													LOW	LOW	HIGH	HIGH	LOW
GRP													MEDIUM (Less than metals)	LOW	HIGH	HIGH	MEDIUM

y	Typical industry Used in:
	Chemical Industry – used where resistance to hot and boiling acids such as nitric, sulphuric and hydrochloric. Nuclear industry because of their low neutron absorption cross section and resistance to hot water at high pressures
	Silver linings are used for vessels and equipment handling hydrofluoric acid. Food and Pharmaceutical industries where it are vital to avoid contamination of the product
	Thin plating on condenser tubes
	Textile industry – alloy with copper in the manufacturing of the spinnerets used in the synthetic spinning processes
	Chemical Plant construction, Food processing and biochemical plants.

## 5.4.1 Carbon Steel

Uses of carbon steel are most common in engineering material. It is an inexpensive material that is available in a range of standard forms and sizes. It also has a good tensile strength and ductility. Carbon steel is least resistant to corrosion in concentrated sulphuric acid and caustic alkali environments. They are more suited for applications with organic solvents. Carbon steel is used in most industrial boiler and feedwater systems. Carbon steel typically experiences uniform corrosion. This is because carbon steel has a lower corrosion resistance in aggressive environments and hence is corroded uniformly.

## 5.4.2 High Silicon Irons

High silicon irons (14-15% of Silicon) have a high resistance to mineral acids with the exception of hydrofluoric acid. They are particularly suitable for use with sulphuric acid at all concentrations.

### 5.4.3 Stainless steel

Stainless steel is a group of iron-based alloys that contain different concentrations of chromium. The higher chromium content within different grades of stainless steel prevents the susceptibility towards corrosion and other associated risks. To impart corrosion resistance the chromium content must be greater than 12%. A wide range of stainless steels are available, with compositions tailored to give the properties required for specific applications. They can be divided into three broad classes according to their microstructure;

- Ferritic:13-20% chromium, <0.1% carbon and no nickel
- Austenitic: 18-20% chromium, >7% nickel
- Martensitic: 12-14% chromium, 0.2-0.4% carbon and 0-5% nickel

The uniform structure of austenitic stainless steel is the most desired structure for corrosion resistance and its grades are widely used in the chemical industry. The most common grades are 304/304L, 321,347, 316, 309 and 310.

The higher the alloy content of the austenitic grade, the better the corrosion resistance, cracking resistance and other common risks associated with the use of stainless steels. As a rough guide the ranking in order of increasing corrosion resistance is shown below (Table 5) using type 304 as a basis.

Туре	304	304L	321	316	316L	310
Ranking	1	1.1	1.1	1.25	1.3	1.6

 Table 5: Corrosion resistance ranking

Intergranular corrosion, also known as weld decay and stress corrosion cracking, are operational problems associated with the use of stainless steel. Stress corrosion and cracking in stainless steel is caused by chloride rich environments. Generally stainless steels are used for corrosion resistance when oxidizing conditions exist. Stainless steel is a component of boilers such as the superheated elements. Stainless steel has a higher corrosion resistance than carbon steel due to a higher chromium content

as shown in Figure 17. This figure is adapted from (Prasath, Thirugnanan, & Lidhuveniya, 2020), and is based on the uniform atmospheric corrosion resistance. The stainless-steel grade is dependent on the extent of corrosion.



Figure 17: Corrosion Rate of Carbon Steel and Stainless Steel

The following section discusses the most common grades of stainless steel that can be used in the local industries.

### 5.4.3.1 Stainless Steel 304/304L

Stainless steel 304 is an austenitic grade of steel and 304 L is the low carbon version of stainless steel 304. Both grades of steel have dominated the brewery, dairy, food and pharmaceutical industries. It has a relatively high resistance towards corrosion. Pitting and crevice corrosion can occur in environments containing chlorides. Stress corrosion cracking can occur at temperatures over 60°C. Stainless steel 304 has a good resistance towards oxidation for intermittent to continuous service. In instances where corrosion resistance, in water with temperatures within the ranges of 425-860°C, is required, the use of stainless steel 304L is preferred as it has a high resistance towards carbide precipitation. It is inexpensive and is best suited for applications that require low temperature performance. It is also resistant to scaling that may be caused from alkali solution, organic acids and inorganic acids. Although 304/304L is most commonly used in industrial applications. The short coming of this grade is its low mechanical strength (AZO, 2005).

#### 5.4.3.2 Stainless Steel 321

Stainless steel 321 is a titanium settled austenitic stainless steel with a high overall corrosion resistance. It can withstand intergranular corrosion resistance at high temperatures of 427-816°C in chromium carbide precipitation. Whereas unstable alloys such as 304 are subjected to intergranular attack. Stainless steel 321 can be utilised in dilute organic acids at moderate temperatures and in pure phosphoric acid (>99% mw). It opposes polythionic acid stress corrosion in hydrocarbon service. It can

also be used in environments with fluoride-free caustic solutions at moderate temperatures. As versatile and advantageous as the 321 grade is, it still does not perform well in chloride or sulphuric acid applications (Interalloy, 2021).

## 5.4.3.3 Stainless Steel 347

Stainless steel 347 is basis austenitic 18/8 grade 304 with added columbium. The addition of columbium stabilizes the steel and eliminates carbide precipitation which is the main cause of intergranular corrosion. Stainless steel grade 347 is beneficial for its higher creep stress and rupture properties as compared to 304. It can be used in high temperature services such as ASME Boilers and pressure vessels. This grade is typically used in heat exchangers, high temperature stream services as well as high temperature chemical process equipment (Masteel, 2021).

## 5.4.3.4 Stainless Steel 316/316L

Stainless steel grade 316 is a more reliable variation of 304 with the addition of molybdenum and a higher nickel content. This results in an increased corrosion resistance in aggressive environments. The molybdenum makes the steel more resistant to pitting and crevice corrosion in chloride-contaminated media, sea water and acetic acid vapours. The lower rate of general corrosion in mildly corrosive environments gives the steel good atmospheric corrosion resistance in polluted marine atmospheres. At higher temperatures 316 has a higher strength and better creep resistance. This grade of stainless steel has good mechanical properties and fabricability. Stainless steel 316 is used in tanks and storage vessels for corrosive liquids, as well as being widely applied in process equipment in the chemical, food, paper, pharmaceutical, petroleum and mining industries (SKZN, 2021).

### 5.4.3.5 Stainless Steel 309/309S

Alloys 309 and 309S are austenitic chromium-nickel stainless steels that are often used for higher temperature applications. Due to their high chromium and nickel content, Alloys 309 and 309S are highly corrosion resistant, have outstanding resistance to oxidation, and excellent heat resistance while providing good strength at room and elevated temperatures. This grade of stainless steel is exclusively known for is high temperature resistance and resistance to creep deformation in harsh environments. It is used in aircraft and jet engine parts, heat exchangers, heating elements, sulphite liquor handling equipment, Kiln liners, Boiler baffles, Refinery and chemical processing equipment. 309/309S is more corrosion resistant to marine atmospheres than 304. It also has a high resistance towards scaling (PSP, 2021).

### 5.4.3.6 Stainless Steel 310

These grades contain 25% chromium and 20% nickel, making them highly resistant to oxidation and corrosion. Grade 310S is a lower carbon version, less prone to embrittlement and sensitisation in service. The high chromium and medium nickel content make these steels suitable for applications in reducing sulphur atmospheres containing H<sub>2</sub>S. They are widely used in moderately carburising atmospheres, as encountered in petrochemical environments. For more severe carburising

atmospheres other heat resisting alloys should be selected. Grade 310 is not recommended for frequent liquid quenching as it is sensitive to thermal shock. The grade is often used in cryogenic applications, due to its toughness and low magnetic permeability. Typical applications of Grade 310/310S is used in fluidised bed combustors, kilns, radiant tubes, tube hangers for petroleum refining and steam boilers, coal gasifier internal components, lead pots, thermowells, refractory anchor bolts, burners and combustion chambers, retorts, muffles, annealing covers, food processing equipment, cryogenic structures (Materials, 2021).

### 5.4.3.7 High Alloy Stainless steel

Super austenitic, high-nickel stainless steels containing between 29-30% nickel and 20% chromium, have a good resistance towards acids and chlorides. Duplex and super-duplex stainless steels contain high percentages of chromium. They are called duplex because their structure is a mixture of austenitic and ferritic phases. They have a better corrosion resistance than austenitic stainless steel and have a reduced susceptibility to stress corrosion cracking. The super-duplex steels were developed for use in aggressive offshore applications. The principal applications for these steels are for chemical-processing and power-generating equipment involving corrosion service in aqueous or liquid-vapour environments at temperatures normally below 315°C. These alloys are also used for special services at temperatures of up to 650°C (Sinnot, 2011).

#### 5.4.4 Nickel

Nickel has good mechanical properties. The pure metal (>99%) is generally not used in a chemical plant. Its nickel alloys are preferred for most applications. Its main use is for equipment handling for caustic alkalis. Nickel is not subject to corrosion cracking like stainless steel (Sinnot, 2011).

#### 5.4.5 Monel

Monel the classic nickel-copper alloy (ratio of 2:1, two parts of nickel and 1 part of copper). It is commonly used in chemical plants and is more expensive than stainless steel. Monel has good corrosion resistance in dilute mineral acids. It can potentially be used in equipment handling of alkalis, organic acids, salts and sea water (Sinnot, 2011).

#### 5.4.6 Inconel and Incoloy

Inconel is generally used for acid resistance at high temperatures. It maintains its strength at elevated temperatures and is resistant to sulphur free furnace gas. Nickle alloys with a higher chromium content such as Incoloy have a better oxidation resistance at higher temperatures (Sinnot, 2011).

#### 5.4.7 Hastelloy's

Hastelloy's are made from a range of nickel, chromium, molybdenum and iron alloys that were developed for corrosion resistance to strong mineral acids, especially hydrochloric acid. Hastelloy B and C are the most common forms of Hastelloy (Sinnot, 2011).

#### 5.4.8 Aluminium and its alloys

Pure aluminium lacks mechanical strength but has a higher resistance to corrosion than its alloys. The pure metal can be used for cladding on dural plates. The corrosion resistance of aluminium is due to the formation of a thin oxide film. It is most suitable for uses in strong oxidizing conditions. It is not suitable for environments that have mineral acids. Aluminium and its alloys are most commonly used in the textile and food industry (Sinnot, 2011).

#### 5.4.9 Platinum and other Platinum group metals (PGMs)

The platinum group metals are very common with regards to the chemical structure. Platinum, Iridium and osmium are the densest metals. Platinum and palladium are soft and ductile and resistant to oxidation and high temperature corrosion. They have widespread catalytic uses and are often used with the addition of other metals including platinum group metals. Rhodium and Iridium are difficult to work but are valuable alone as well as in alloys. Their chemical compounds have many uses and rhodium is a particularly good catalyst. Ruthenium and Osmium are hard, brittle and difficult to work with. These platinum group metals have a poor oxidation resistance but become valuable when they are added to other metals. PGM's are high in demand and are predominantly used in the electronic equipment and as a catalytic converter (Sinnot, 2011).

#### 5.4.10 Copper

Copper is one of the oldest and most versatile materials that have been used mainly in engineering constructions. It also has a good resistance towards corrosion due to the protective patina that forms on its surfaces. It has a low thermal expansion and is stable and resistant to deterioration from movement. It is relatively light in comparison to lead and other metals. It requires minimal maintenance and has good bio-fouling resistance. It is commonly used to form pipes and tubing for potable water distribution and heating and cooling systems as it is malleable and can easily be soldered. It is recyclable and has relatively low life cycle impacts. It can also be used in boilers and has a high sensitivity to ammonia (Sinnot, 2011).

#### 5.4.11 Brass

Brass is a common material of construction that is made from the combination or alloy of copper and zinc. It is a good conductor of heat and is corrosion resistant. It is typically used in the industry as pipes, tubes, radiators, etc. It has good strength and can be retained even when subjected to high temperatures usually up to 200°C. This material can be used in applications that require high tensile strengths. Brasses can resist corrosion as it does not rust and can resist salt water. When lead is combined with brass it gains a low wear and low friction properties that make them wear resistant (Sinnot, 2011).

#### 5.4.12 Galvanised Steel

Galvanised steel is a steel/iron-based metal with protective zinc coating layer. The zinc layer acts as a corrosion protection layer. Galvanised steel is used in the automotive industry. It is also used as a replacement for plastic pipes in applications where they are not strong enough. Some of the benefits of

galvanised steel is that they have a low initial cost, it has a relatively long-life cycle and can last for about 20-50 years in extremely harsh environments. Its zinc layer acts as a protective buffer between the steel/iron and the moisture or oxygen within the environment (Sinnot, 2011).

## 5.4.13 Plastics

Plastics are predominantly used in the food processing industry and biochemical plants. It is used as a corrosion resistant material and can be divided as being.

- Thermoplastic material soften with increasing temperature, e.g. polyvinyl chloride and polyethylene.
- Thermosetting material materials that have a rigid structure such as epoxy resins.

The biggest uses of plastics are for piping and plastic sheets for lining vessels. Plastics are considered to complement metals as corrosion resistant materials. They have a good resistance to dilute acid and inorganic salt attacks. Plastics absorb metals causing degradation, swelling and softening of the plastic structure. Plastics are also susceptible to solar embrittlement which is the impact of plastics with regards to solar degradation (Sinnot, 2011).

## 5.4.13.1 Poly-Vinyl Chloride (PVC)

PVC is the most common thermoplastic material in the chemical industry. It is resistant to most inorganic acids except for salt solutions, concentrated sulphuric and nitric acid. They are unsuitable when exposed to organic solvents as they are prone to swelling. The maximum operating temperature for PVC is 60°C. The main grade of PVC that is used is CPVC. It has a greater temperature resistance. CPVC also has an excellent chemical resistance and can transport hot fluids. It has been successful in the chemical processing piping systems, pulp and paper processing piping systems, food processing pipe systems and water and sewage treatment piping systems (Sinnot, 2011).

## 5.4.13.2 Polyolefins

Low-density polyethylene is inexpensive, tough and flexible. Its low softening points makes it not suitable for temperatures higher than 60°C. The solvent resistance to polyolefins is similar to that of PVC (Sinnot, 2011).

## 5.4.13.3 Polytetrafluoroethylene (PTFE)

PTFE is commonly referred to as Teflon and Fluon, it is resistant to all chemicals with the exceptions of molten alkalis and fluorine and can be used for temperatures up to 250°C. PTFE is used for gaskets, on valve stems and as coatings which acts as non-stick coating to surfaces such as filter pads. It is also used as vessel linings (Sinnot, 2011).

## 5.4.13.4 Polyvinylidene Difluoride (PVDF)

PVDF is similar to PTFE. It has a good resistance to inorganic acids, alkalis and organic solids. It has a maximum operating temperature at 140°C (Sinnot, 2011).

#### 5.4.13.5 Glass Fibre Reinforced Plastics

Polyester resins, reinforced with glass fibre are the most common thermosetting plastics used in a chemical plant. They are relatively strong and have a resistance to a wide range of chemicals such as dilute mineral acids, inorganic salts and solvents. They are less resistant to alkalis. Reinforced glass fibres are wound on in the form of a continuous filament which results in a high strength material that can be used to make pressure vessels (Sinnot, 2011).

#### 5.4.13.6 Rubber

Rubber is particularly used for linings of tanks and can be used as pipes. It has a good resistance to acids and alkalis but is not suitable for uses that include organic solvents (Sinnot, 2011).

#### 5.4.14 Concrete

Concrete has a good corrosion resistance. It can have a limited pressure range and has the additional risk of corrosion of reinforcement beams/structures and spalding. It can degrade in soft water. It is typically used in a wide range of industries as storage tanks, raw water reactors and versatile equipment handling (Sinnot, 2011).

### 5.5 Hazard Identification (Water Quality Problems)

The physical characteristics of and chemical and microbiological contaminants in water determine its properties and thus its potential to cause undesirable effects to industrial processes, *i.e.* the concentrations/presence of the contaminant or physical property of the water defines the hazard.

The next step of the approach development involved identification of the hazards (the water quality constituents) to be included in the DSS.

This project required that the approach include a suite of representative water quality constituents that addresses the different hazards group types. However, based on the 1996 Vo9lume 3 guidelines and the information gathered through this project tasks through engagement with the sector it is apparent that there are commonly occurring adverse effects, linked to a suite of are key water quality constituents that are not too onerous to include in the methodology as part of the assessment. For industrial water use, the water quality risks are rather defined by the resulting adverse effects than by a specific constituent only.

The key constituents of concern highlighted by the survey conducted of representative industrial sectors undertaken through the step of this project and with the inclusion of constituents included in the 1996 Edition 2, SAWQGs are listed in Table 6. It was found that the water quality constituents of concern identified through this process were highly comparable with almost all of the constituents included in the1996 guideline and are still of relevance today with respect to fitness for use of water. The constituents listed comprise the water quality hazards and were through to the risk assessment and
decision support system development. Chemical, physical and biological water quality hazards were addressed in the risk-based methodology development.

Water Quality Hazards	Characteristic
Alkalinity	Physical
Calcium	Chemical – inorganic
Chloride	Chemical – inorganic
Electrical Conductivity	Physical
Iron	Chemical – inorganic
Magnesium	Chemical – inorganic
Manganese	Chemical – inorganic
Microbiological	Biological
Organics	Organic
Nitrate	Chemical – inorganic
Nitrite	Chemical – inorganic
рН	Physical
Phosphate	Chemical – inorganic
Silica	Physical/Chemical
Sodium	Chemical – inorganic
Suspended Solids	Physical
Sulphate	Chemical – inorganic
Total Dissolved Solids	Physical
Total Hardness	Physical
Total Organic Carbon	Chemical

## Table 6: Water Quality Hazards Identified

Representative constituents linked to the most common adverse effects (water quality problems) have been built into the DSS to present the risk-based methodology.

### 5.6 Adverse Effects (Endpoints)

Industrial water using processes are affected in different ways by interaction with the water (containing the water quality hazard). The DWAF 1996 Industrial Use water quality guidelines used the following norms as yardsticks (end points) for defining the basis of the effects of water quality constituents. Based on the survey undertaken as part of this project the 1996 norms are very much applicable. These included:

- impacts on equipment and structures
- interference with processes
- product quality and
- complexity of waste handling.

Each of the adverse effects resulting from the exposure to the hazard are characterised by an end point which results in negative impact to the industrial use based on the water use being undertaken. Commonly identified effects linked to the norms are listed in Table 7. For the purposes of the risk-based approach development and appropriately scoping what could be achieved through this project given the complexity, and vast differences among the various industrial sectors and sub-sectors, the equipment damage and process problems norms have been accounted for in the DSS tool.

Based on how the tool and methodology has been developed and on the availability of the supporting science and empirical data, the adverse effects may be extended to include other measurable norms that have a wider application, e.g. product problems/quality, impacts on operation and maintenance (lifespan and costs).

Process Type	Equipment Damage	Process Problems	Product Problems	Waste Disposal
Cooling Water	Corrosion Scaling Fouling Blockages	Foaming Sediments Gas production Odours Heat Exchanger impairment		pH Total dissolved salts Chemical oxygen demand Suspended solids
Water for steam generation	Resin film Resin poison Corrosion Scaling	Resin impairment Competition	Inadequate treatment	pH Total dissolved salts
Process Water	Corrosion Scaling Fouling Blockages Embrittlement Discolouration	Precipitates Foaming Colour effects Gas production Interference	Sediment Foam Colour Taste/odour Tarnish	Suspended solids Iron Manganese Total dissolved salts
Product water	Corrosion Scaling Fouling Blockages	Precipitates Foaming Gas production Interference	Sediment Turbidity Foam Colour Taste/odour Coagulation	
Utility water	Corrosion Scaling Fouling Blockages Abrasion		Sediment Turbidity Foam Colour Taste/odour Intestinal irritation Health hazard	pH Total dissolved salts Chemical oxygen demand Suspended solids Iron/Manganese

Table 7: Identified adverse effects associated with various industrial processes (DWAF, 1996)

Process Type	Equipment Damage	Process Problems	Product Problems	Waste Disposal
Wash water	Corrosion Scaling Fouling Blockages Abrasion solutions	Contamination	Contamination Blemishes Sediment Process	pH Total dissolved salts Chemical oxygen demand Suspended solids Iron/Manganese

For industrial use, the adverse effects formed the basis of the risk-based water quality guidelines calculation methodology development.

In order to adequately present the measure of the probability of the risk (e.g. high, medium, or low), the definition and categorisation of adverse effects in terms of an outcome are necessary to present an informative decision support matrix to the user. The 1996 guidelines considered the following as a means to describe the degree of effect:

- Irrecoverable and Recoverable, and
- Reversible and Irreversible

This is largely still applicable in terms of the risk-based approach development, however additional descriptors such as probability and severity have been included in the reporting tool output. It is important that the adverse effect description is categorised in a manner and range such that the user is able to adequately judge the acceptability of the risk.

For purposes of the DSS the three most common adverse effects of significant concern to industrial water use were applied in the development of the risk-based methodology presented in the decision support system, *viz.:* 

- Corrosion
- Scaling
- Fouling.

### 5.7 Hazard Characterization and Risk Quantification

Based on the hazards and adverse effects identified above, the hazard function related to each required characterisation. The hazard characterisation is the process of determining whether exposure to a hazard (water quality constituent) can cause an increase in incidence of specific adverse effects (e.g. corrosion). This forms a fundamental component to the risk assessment quantification as one needs to determine what data would be used to formulate the hazard function for each hazard as related to the end point defined (e.g. corrosion being the end-point).

This is based on the site specific conditions (the relationship between a number of contributing *in-situ* conditions and the input water quality composition) and the exposure assessment (examines what is

known about the materials of construction and the exposure). This forms the basis of the calculation procedures of the fitness for use assessments in order to determine a risk, and how the design of the decision support system is set up. The hazard characterisation also allows the determination of the uncertainties in terms of deriving the guidelines.

The following sub-sections relates to the hazard characterisation and risk assessment calculation methodology for scaling, corrosion and fouling. Both quantitative and qualitative approaches to assessing the likelihood of the risk (adverse effect) occurring are incorporated. The unique adverse effects are highlighted according to the varying materials of construction used by various industries and the associated risk of these adverse effects. Various indices and other quantitative data are used to determine the risk of scaling, corrosion or fouling. These adverse effects were chosen for the assessment based on the quantifiable indices available and the scientific empirical data that exists to support the calculation methodology.

#### 5.7.1 Corrosion

Corrosion is defined as the destruction of a metal by chemical or electrochemical reaction with its environment. Corrosion involves the oxidation of metal atoms to cations, which in turn can react to form oxides, hydroxides, and other species on the metal surface. In these scenarios, the metal cations may not directly be released into the water and could form precipitates or films. If corrosion occurs rapidly enough that the formation of these films is not possible or if the films that form are insufficiently protective, the release of metal cations into the water will occur. At this point, other chemical processes such as precipitation and dissolution of other metal compounds, such as carbonates, silicates, and other scales, then control the quantity and form of metal released into the water.

The extent, rate, and mechanisms of corrosion that occur all depend on numerous factors. Such factors include the pH, temperature, and chemistry of the water such as hardness and chloride content. Water quality analysis is complex and involves the interaction between multiple species and different chemical additions. Each of these factors plays a role in the corrosion mechanism which is also dependent on the material of construction with which the water is in contact.

In industry, corrosion can cause numerous problems. This includes the failure of equipment which has the added cost of replacement and plant downtime. Furthermore, in cooling or heating systems, this can lead to decreased plant efficiency as a loss of heat transfer is observed caused by the accumulation of corrosion products. Corrosion is specific to the water quality and material of construction as discussed below.

#### 5.7.1.1 Factors Affecting Corrosion

#### 5.7.1.1.1 рН

pH is a major contributing factor to metal corrosion and release. The pH can have an effect on multiple factors that range from the rate of dissolution, the solubility and protectiveness of different films and scales, to the appearance and morphology of the corrosion observed. Low pH values (<4) tend to have a higher corrosion rate. At low pH values, acids release hydrogen ions, which oxidize the metals in pipes, accelerating corrosion. At pH values less than 5, rapid corrosion of iron, copper, and lead may occur. At more alkaline pH values greater than 9, corrosion of these metals is typically reduced due to the formation of protective films. However, at higher alkaline pH values, scale formation and the efficiency of certain corrosion inhibitors can be hindered and hence corrosion may increase again.

#### 5.7.1.1.2 Temperature

Temperature does play a significant role in corrosion in water systems. A general rule with regards to the effect of temperature on the corrosion rate is that the corrosion rate will double for every 10°C increase in temperature. Furthermore, an increase in temperature influences both the rate of corrosion and the type or mode of corrosion (e.g. critical pitting temperature). Temperatures over 60°C are not recommended for stainless steel grades 304 or 316 due to the risk of sudden failure from chloride stress corrosion cracking. Furthermore, oxygen degassing occurs at temperatures >60°C, which generates a higher level of corrosion. The effect of temperature is addressed in the indices calculation (See Section 5.7.4) as these calculations are dependent on the water temperature.

#### 5.7.1.1.3 Hardness

Hardness refers to the concentration of dissolved calcium and magnesium in the water. Hard water has a high concentration of calcium and magnesium, which has a tendency to result in scaling. Consequently, this makes this water less corrosive due to the tendency to form protective films in the pipe. However, this is dependent on the alkalinity and pH. Soft water has a lower concentration of calcium and magnesium and thus is often more corrosive than hard water. Typically, water is considered soft if the total hardness is less than 50 mg/L CaCO<sub>3</sub> while values greater than 150 mg/L CaCO<sub>3</sub> are considered hard water. Galvanized piping, like steel and cast-iron piping, tends to experience its best performance in hard water compared to soft water due to scale formation. However, hard water is not always the most beneficial as in cases whereby copper piping is used, pitting corrosion in typically observed and occurs at low temperatures. However, if the hardness in the water is primarily non-carbonate, the chlorate and sulphate ions will tend to keep the calcium in solution and will prevent scale formation. Excessive scale formation is also not preferable as high amounts of scale deposition on the surface will limit the heat transfer efficiency of certain equipment.

Table 8: Hardness Indication

Hardness (mg CaCO <sub>3</sub> /L)	Classification	Risk
0-50	Soft	Unacceptable
50-150	Moderately Hard	Acceptable
150-300	Hard	Ideal
>300	Very Hard	Tolerable

Based on the common materials on construction, the following guidelines are proposed with regards to water hardness –

- Concrete Soft water is found to be detrimental to concrete. This is observed as, when the concrete is in contact with soft water, the calcium hydroxide in the hardened concrete matrix is leached out in order to establish an ion balance. This causes weakening of the concrete matrix and is referred to as a soft water attack. A study done by (Otieno, Alexander, & du Plessis, 2019) showed that a loss of 10 mm depth of concrete could take place over a period varying from less than 1 year to 22 years. This is accompanied by an increase in surface roughness. Moderately hard water is preferred and will lead to a lower corrosion rate as if the water contains more calcium, the likelihood of the leaching is reduced. However, very hard water will cause scale formation on the concrete surface also resulting in increased surface roughness.
- Carbon steel It was found that soft water has a higher corrosion rate than hard water. This is due to scale formation in hard water that deposits on the surface. It was also found that soft water leads to uniform corrosion whereas hard water corrodes unevenly through hard deposits
- (Nallasivam & Perumal, 2016).
- Stainless steel No significant difference between soft and hard water on the rate of corrosion has been found with regards to stainless steel (Munn, 1993). However, this is dependent on the chloride concentration.

As seen above, soft water is more corrosive, and corrosion is further enhanced when the water contains a low pH and low total dissolved salts (TDS). Although scale can be seen as a corrosion control mechanism, scale formation varies and can be porous or soft and irregular. Corrosion can still occur under conditions that are favourable to the formation of scale or even when scale is already present. This is referred to as under deposit corrosion and is discussed in Section 5.7.4.1.3.

### 5.7.1.1.4 Alkalinity

Alkalinity measures the buffering capacity of water and its ability to neutralize acids. Alkalinity is a good indicator of the total dissolved inorganic carbon (bicarbonate and carbonate anions) present. Alkalinity is a measure of how easily the pH of the water can be changed. Hence it is considered to be a mitigating influence with regards to extreme pH levels. Water with a high alkalinity is more likely to be scale-forming even at a relatively low pH. In contrast, low alkalinity waters lack the buffering capacity to deal

with acids, so they can easily become more acidic and corrosive. High alkalinity is preferred as it helps control pH changes which reduces corrosion.

Alkalinity (mg CaCO <sub>3</sub> /I)	Classification	Risk
<12	Very low	Unacceptable
25-41	Low	Tolerable
41-98	Medium	Tolerable
98-148	High	Acceptable
>148	Very high	Ideal

 Table 9: Alkalinity Classification Levels and associated Risk

### 5.7.1.1.5 Chlorides

Chlorides are found to be the most aggressive ion regarding corrosion, specifically in the case of crevice and pitting corrosion. Typically used stainless steel grades with continuous exposure at neutral pH and ambient temperatures, the following chloride levels are proposed per grade as shown in Table 10.

Chloride Level	If Temperature >35°C and pH <7, Limits Decrease To:	Suitable Stainless-Steel Grades
<200 mg/L	50 mg/l	304, 304L
<300 mg/l	100 mg/l	316/316L
<400 mg/l	150 mg/l	Alloy 20
3000 mg/l	2000 mg/l	904L
>3600 mg/L and seawater	3000 mg/l	Duplex Stainless steel
<200 mg/L	50 mg/l	304, 304L

Table 10: Chloride Levels for Stainless Steel at ambient temperature

The maximum level guidelines allow for the presence of crevices (such as bolt heads, flanges or deposits) but assume that the surface has been passivated. In alkaline environments whereby the pH>7, higher chloride levels can be tolerated. Higher temperatures reduce the maximum tolerated chloride level. In general, if the temperature is greater than 35°C or the pH is lower than 7, the maximum chloride level should be lowered. For 304L, an upper limit of 50 mg/L should be adapted and 100 mg/L for 316L (Cutler, 2003). The combined action of environmental conditions (chlorides/elevated temperature) and stress – either applied through a load or residual causes stress corrosion cracking (SCC). Only austenite stainless steel is susceptible to this type of corrosion.

### 5.7.1.1.6 Chloride to Sulphate Mass Ratio

Increasing the chloride to sulphate mass ratio (CSMR) will accelerate corrosion in the presence of materials that contain lead or copper. Edwards & Triantafyllidou, 2007 found that while sulphates tend to inhibit corrosion by forming passive protective film layers and reducing galvanic currents between dissimilar metals, chlorides prevent the formation of such passive layers and stimulate galvanic current. Thus, if the source water contains natural levels of chloride and the treatment process is designed to remove sulphate, this will increase the CSMR and potentially increase the rate and likelihood of corrosion.

The risk of CSMR is evident when pipes contain lead such as galvanized pipes, brass/bronze fittings, faucets or lead solder. If the CSMR >0.5, there is a significant risk of corrosion which may be difficult to control and will result in lead exposure. However, if the CSMR >0.5 coupled with alkalinity <50 mg/L as CaCO<sub>3</sub>, there is a serious risk of corrosion and lead exposure. In such cases, treatment is recommended to remove or reduce the chloride and sulphate concentration.

### 5.7.1.1.7 Sulphate Attack

Sulphate attack is specific to concrete. It is a complex process, which includes physical salt attack due to salt crystallization and chemical sulphate attack by sulphates in the surrounding water. Sulphate attack can lead to expansion, cracking, strength loss, and disintegration of the concrete.

Index	Description	Risk	Treatment Recommendations
>= 10 000 mg/l	Very severe risk of sulphate attack	Unacceptable	Treatment Recommended – Water treatment for sulphate removal
>=1 500-<0 000 mg/l	Severe risk of sulphate attack	Tolerable	Treatment Recommended – Water treatment for sulphate removal
>=150-<500 mg/l	Moderate risk of sulphate attack	Acceptable	Treatment May Be Needed – Water treatment for sulphate removal
<150 mg/l	Low risk sulphate attack	Ideal	No Treatment

Table	11.	Sulphate	Concentrations	and	Risk (	of Sul	nhate	Attack
Table		ouipilate	ooncentrations	and	I VION V	Ji Oui	priate	Allach

#### 5.7.1.2 Corrosion Indices

#### 5.7.1.2.1 Langelier Index

Based on the factors discussed above which includes the pH, temperature, hardness and alkalinity, the Langelier index analysis is a combination of these parameters to determine the extent of corrosion on different materials of construction.

The Langelier Saturation Index (LSI) is an equilibrium model derived from the concept of saturation. It is purely an equilibrium index and deals only with the thermodynamic driving force for calcium carbonate scale formation and growth. The calcium carbonate saturation is useful in determining in a specific water quality is aggressive/corrosive, balanced, or scale-forming (high LSI). The LSI is given by the following formula –

$$LSI = pH - pH_s$$

Whereby pHs is given as follows -

$$pH_s = (9.3 + A + B) - (C + D)$$

Whereby the factors are given by -

$$A = \frac{Log_{10}[TDS] - 1}{10}$$
  

$$B = -13.12 \times Log_{10}(^{\circ}C + 273) + 34.55$$
  

$$C = Log_{10}[Ca^{2+}as \ CaCO_{3}] - 0.4$$
  

$$D = Log_{10}[Alaklainity \ as \ CaCO_{3}]$$

[\_\_\_\_\_

The following conclusions can be derived by the value of the LSI -

- LSI is negative: Risk of corrosion.
- If LSI is positive: Low risk of corrosion
- If LSI is close to zero: Borderline corrosion potential. Water quality or changes in temperature, or evaporation could change the index.

LSI	Description	Risk	Treatment Recommendations
>= -5	Severe Corrosion due to CaCO <sub>3</sub>	Unacceptable	Chemical treatment recommended – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality

LSI	Description	Risk	Treatment Recommendations
>= -2-<-5	Mild Corrosion due to CaCO <sub>3</sub>	Tolerable	Treatment may be needed – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality
>0.5-<-2	Mild Corrosion due to CaCO <sub>3</sub>	Acceptable	Treatment may be needed – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality
>= 0.5	Minimal to no risk of corrosion	Ideal	No treatment required
>= -5	Severe Corrosion due to CaCO <sub>3</sub>	Unacceptable	Chemical treatment recommended – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality

### 5.7.1.2.2 Ryznar Index

The Ryznar index (RI) is considered in conjunction with the LSI index as it affords greater protection against corrosion, than does the more familiar Langelier Index. It boosts the calcium hardness to a point, where scale begins to form, which actually helps protect the equipment, from corrosion. This index aims to quantify the relationship between the calcium carbonate saturation state and scale formation. The index was founded in 1944 (Ryznar, 1944).

The Ryznar index is calculated as follows, the pHs is as calculated above (In Section 5.7.4.1.1).

$$RI = 2 \times pH_s - pH$$

### Table 13: Ryznar Index Rankings

RI	Indication/Description	Risk	Treatment Recommendations
>= 8,5	Severe Corrosion due to lack of CaCO <sub>3</sub> formation	Unacceptable	Chemical treatment recommended – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR

RI	Indication/Description	Risk	Treatment Recommendations
			Consider additional treatment of the water to more suitable feed quality
>=7,8-<8,5	Mild Corrosion due to lack of CaCO <sub>3</sub> formation	Tolerable	Treatment may be needed – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality
>=6,8-<7,8	Mild Corrosion due to lack of CaCO <sub>3</sub> formation	Acceptable	Treatment may be needed – Treatment through addition of corrosion inhibitors OR Consider an alternative material of construction OR Consider additional treatment of the water to more suitable feed quality

### 5.7.1.2.3 Pitting Corrosion

Many alloys, such as stainless steels and Aluminium alloys, are useful only because of passive films, which are thin (nanometre-scale), oxide layers that form naturally on the metal surface and greatly reduce the rate of corrosion of these alloys. However, these passive films are often susceptible to localized breakdown resulting in the accelerated dissolution of the underlying metal (Frankel, 1998). Pitting corrosion is highly dependent on the chloride content, pH, temperature and the presence of an oxidizing agent.

This type of corrosion occurs when the passive film is damaged and becomes exposed. This can occur through chemical attack, mechanical damage, presence of microstructure irregularities such as non-metallic inclusions which is caused by machining. Stainless steel resistance to pitting corrosion is dependent on temperature, pH, aggressive anion concentration and on the alloy's composition. This is particularly important with regards to the chromium and molybdenum percentages in stainless steel. A particular steel's resistance to corrosion pitting can be evaluated as its chromium equivalent or PREN (pitting resistance equivalent) through the following equation:

$$PREN = \%Cr + (3.3 \times \% Mo) + (16 \times \% N)$$

The percentages must be expressed as mass percentages. The greater the PREN value, the better corrosion resistance. A PREN:

- >35 is required for pitting resistance in seawater,
- >40 in the case of hot and stagnating seawater,
- >45 for crevice corrosion resistance.

The PREN value is useful to compare stainless steel grades resistance against pitting. The PREN value cannot be used in isolation to determine whether a particular grade will be suitable for a given application.

The critical pitting temperature is an important parameter that determines the minimum temperature at which alloys start to corrode. Pitting corrosion is accelerated by temperature. According to the ASTM G48 standard, the critical pitting temperatures are shown in Table 14. Critical pitting temperatures determined by different methods should not be compared. The critical pitting temperatures are found to decrease with increasing chloride concentrations.

Grade	Typical PREN Value	Critical Pitting Temperature
304/304L	20	18°C
316/316L	25	20°C
Alloy 20	30	90°C
904L	36	40°C

Table 14: Critical Pitting Temperatures

# 5.7.1.2.4 Larson Skold Index

The Larson-Skold index refers to an empirical scale used to measure the degree of corrosiveness of water relative to mild steel metal surfaces. This index looks at the potential corrosivity of iron and steel. The Larson-Skold index is the ratio of twice the number of moles per litre (mol/L) of sulphate (SO<sub>4</sub><sup>2-</sup>) plus chlorides (Cl<sup>-</sup>), to the moles per litre of alkalinity that is typically in the form of bicarbonate and/or carbonate. The Larson-Skold index scale presents the following outcomes of corrosion tendency –

$$Ratio = \frac{(Sulphate \times 2) + Chloride}{Alkalinity}$$

### Table 15: Larson-Skold Index

Index	Tendency to Corrosion	Risk	Treatment Recommendations
			Treatment recommended – Water
>= 1,2 Severe pitti corrosion			treatment to reduce the sulphate or
	Severe pitting	Unacceptable	chloride concentration
	corrosion		OR
			Consider additional treatment of the water
			to more suitable feed quality

Index	Tendency to Corrosion	Risk	Treatment Recommendations
			Treatment may be needed - Water
			treatment to reduce the sulphate or
	Significant		chloride concentration
>= 1,0-<1,2	pitting corrosion	Tolerable	OR
			Consider additional treatment of the water
			to more suitable feed quality
			Treatment may be needed - Water
			treatment to reduce the sulphate or
>=0.8-<1	Mild pitting		chloride concentration
	corrosion	Acceptable	OR
			Consider additional treatment of the water
			to more suitable feed quality

# 5.7.1.3 Aggressive Index

The aggressive index (AI) relates to the corrosive tendency of water. It is particularly important in pipes that contain cement and asbestos. It is given by the following equation –

$$AI = pH + log (A \times H)$$

Where -

A is the alkalinity in mg/L CaCO<sub>3</sub> and H is the hardness in mg/L CaCO<sub>3</sub>. The relative risk rankings and limits for the aggressive index are shown in Table 16. The aggressive index relates to the corrosion of the concrete reinforced bars and hence would only be applied in specific cases.

AI	Indication/Description	Risk	Treatment Recommendations
>= 12	Nonaggressive – Lack of pitting corrosion of the concrete reinforced bars	Ideal	No Treatment
>=11 to <12	Moderately aggressive – Moderate pitting corrosion of the concrete reinforced bars	Acceptable	Treatment may be needed – Chemical treatment through addition of Antiscalants OR Water treatment for softening
>=10 to <11	Mildly aggressive – Mild pitting corrosion of the concrete reinforced bars	Tolerable	Treatment may be needed – Chemical treatment through addition of Antiscalants OR Water treatment for softening

Table	16:	Aggressive	Index	Rankings
Table	10.	Aggiessive	mack	Rankings

AI	Indication/Description	Risk	Treatment Recommendations
<10	Very aggressive – Severe pitting corrosion of the concrete reinforced bars	Unacceptable	Treatment recommended – Treatment recommended – Chemical treatment through addition of Antiscalants OR Water treatment for softening

### 5.7.1.4 Summary

It can be seen that there are various water properties that have an effect on the corrosivity of the material which it is in contact with. A general summary of each parameter and this effect can be seen in Table 17.

Water Properties	Corrosivity
Hardness	As hardness increases, corrosion decreases.
Alkalinity	Increase in alkalinity causes a decrease in corrosion.
рН	Corrosion depends on its value – Corrosive at low pHs, as pH increases up to 8.5, corrosion decreases.
Temperature	Increase in temperature, corrosion increases
Chloride	Higher chloride concentration increases water corrosivity
Sulphate	Higher sulphate concentration increases water corrosivity
Temperature	Pitting corrosion is accelerated by temperature

Table 17: Water Properties and Effect on Corrosion

# 5.7.2 Corrosion Rate

A study conducted by (Pisigan, 1985) predicted the expected corrosion rate of stainless steel based on an eight-variable empirical mode. The models suggest that increasing chloride, sulphate, alkalinity, and dissolved oxygen levels would accelerate corrosion, whereas increases in calcium, buffer capacity, saturation index, and exposure time would lead to decreasing corrosion rates. This index was used to predict the corrosion rate based on these variables. The calculation of the corrosion rate is shown below –

$$Corrosion Rate = \frac{(Cl^{-1})^{0.509} \times (SO_4^{2-})^{0.025} \times (Alkalinity)^{0.423} \times (DO)^{0.799}}{(Ca)^{0.676} \times \beta^{0.030} \times (10^{SI})^{0.107} \times Day^{0.381}}$$

Where: DO = dissolved oxygen (mg/l as O<sub>2</sub>), Ca = calcium (mg/l as Ca2<sup>+</sup>),  $\beta$  = buffer capacity (mg/l as CaCO<sub>3</sub>), SI = Langelier Saturation Index, Day = days.

# 5.7.3 Mitigation Methods

In instances whereby the risk of corrosion is high, the following mitigation methods can be adopted (other than those stated in the tables above) –

- Chemical corrosion inhibitors.
- Water quality monitoring to identify constituents of concern.
- Regular cleaning and maintenance, and
- Consideration of metal plating or the use of protective coatings.

# 5.7.4 Scaling

The following parameters can be used to determine the extent of scale possible in water systems.

### 5.7.4.1 Scaling Indices

### 5.7.4.1.1 Langelier Saturation Index

The LSI can also be utilised to assess scaling risk. It is an equilibrium model derived from the concept of saturation. It is purely an equilibrium index and deals only with the thermodynamic driving force for calcium carbonate scale formation and growth. The calcium carbonate saturation is useful in determining in a specific water quality is aggressive/corrosive, balanced, or scale-forming (high LSI). Although the index is useful in determining whether the water quality is scale forming or corrosive, it provides no indication as to how much scale or calcium carbonate will actually precipitate in order to bring water to equilibrium. Furthermore, it does not consider film formation by phosphates and silicates The LSI is given by the formula as given in Section 5.7.1.2.1. The model was initially developed in 1936 (Langelier, 1936) as a qualitative test used primarily for potable water rather than cooling water. Furthermore, it was initially used for scaling prediction and has since been adapted to predict corrosion.

The following scale formation risk conclusions can be derived by the value of the LSI -

- LSI is negative: No potential to scale, the water will dissolve CaCO<sub>3</sub>.
- If LSI is positive: Scale can form and CaCO<sub>3</sub> precipitation may occur.
- If LSI is close to zero: Borderline scale potential. Water quality or changes in temperature, or evaporation could change the index.

LSI	Indication/Description	Risk	Treatment Recommendations
0	Balance – No scale	Ideal	No Treatment
0.5 to 2	Mild scale formation	Acceptable	Probably no treatment
3	Moderate Scale Formation	Tolerable	Treatment recommended
4	Severe Scale Formation	Unacceptable	Treatment recommended

### Table 18: LSI Rankings

#### 5.7.4.1.2 Puckorius Scaling Index

The Puckorius Scaling Index (PSI) is based on the buffering capacity of the feed water, and the maximum quantity of precipitate that can form in bringing the water to equilibrium (Puckorius, 1990). Water containing high concentrations of calcium, but low in alkalinity and buffering capacity can have a high calcite saturation level. The high calcium level increases the ion activity product. Such water might have a high tendency to form scale due to the driving force, but scale formed might be of such a small quantity as to be unobservable. The water has the driving force but not the capacity and ability to maintain pH as precipitate matter forms. The PSI index is calculated in a manner similar to the Ryznar stability index. Puckorius uses an equilibrium pH rather than the actual system pH to account for the buffering effects as shown in the equation below –

$$PSI = 2pH_s - pH_{eq}$$

Where -

$$pH_{eq} = 1.465 \times log_{10}[Alkalinity] + 4.54$$

Table 19 shows the Puckorius scaling index and the relevant risk and descriptions. The scale tendency increases as the index decreases and the corrosive nature to carbon steel increases as the index increased. Based on the typical industry uses, the Puckorius Scaling index was not used in the tool. The Ryznar index would provide a more accurate indication of scaling and hence that index was adapted.

Table 19	9: Puckorius	s Scaling Index	

PSI	Indication/Description	Risk
4,5 > PSI	Optimal range	Tolerable/Acceptable
PSI < 4,5	Water has tendency to limescale	Unacceptable

#### 5.7.4.1.3 Under Deposit Corrosion

Under deposit corrosion (UDC) is a form of localized corrosion that develops beneath or around deposits present on a metal surface. These deposits preferentially form at the bottom of pipes under stagnant or intermittent flow conditions (e.g. in dead legs or during plant shutdowns) or in areas where the flow velocity is at a minimum. (Although scale formation is a commonly implemented control method to prevent corrosion, under deposit corrosion may still occur. The main driving force behind UDC is the chemical and physical differences between the covered and uncovered areas, created by the formation of the deposit, which promotes corrosion attack. This includes pH differences, a higher or lower concentration of particular ions or molecules (*i.e.* oxygen or corrosive species) or the presence of microbial cultures underneath the deposits (Obot, 2021). The presence of other contaminants such as microbes, inorganic and organic scales like FeS, FeCO<sub>3</sub>, CaCO<sub>3</sub>, asphaltenes or waxes cause under deposit corrosion which results in pitting corrosion.

Similar limits apply as mentioned in the sections above for the predication of corrosion occur, however this type of corrosion will only occur if the surface has fouling or scaling. Furthermore, corrosion can be enhanced in the case of biological deposits. Certain bacteria release harmful by products which further enhance the rate of corrosion.

Under deposit corrosion occurs through multiple steps which include deposit formation, onset of primary corrosion, oxygen depletion, start of secondary corrosion and acceleration of acidic corrosion. In general, corrosion mechanisms deplete free oxygen. In steel piping systems, the primary corrosion mechanism depletes free oxygen and continues as long as free oxygen and moisture are in contact at the pipe wall. While this is the most common corrosion route, some systems do not include the oxygen depletion step. The secondary corrosion occurs after the galvanic cell is set up. Finally, if the correct ions are present, the pH decreases and the water trapped in the deposit becomes more acidic. The lower pH accelerates the corrosion rate.

### 5.7.4.1.4 Calcium Phosphate Scaling

Calcium phosphate (CaPO<sub>4</sub>) is less soluble in neutral and alkaline conditions and dissolve in acidic conditions. Aluminium and iron phosphates, however, are less soluble at moderately acidic conditions. Thus it is important to remove aluminium and iron in a pre-treatment step as well. Because of the complexity of phosphate chemistry, it is not easy to predict a threshold level of phosphate scaling. The calcium phosphate stability index (SI), however, was proposed by (Kubo, 1979).

The calcium phosphate stability index is determined by the levels of calcium and phosphate present, pH, as well as the temperature. A negative stability index (SI)I signifies a low potential for calcium phosphate scaling and a positive value indicates the potential for calcium phosphate scaling. SI is determined by the following equation –

$$SI = pH_a - pH_c$$

Where pHa is the actual pH of the water and pHc is the critical pH. The critical pH is calculated by -

$$pH_c = \frac{11.755 - \log(CaH) - \log(PO_4) - 2\log(t)}{0.65}$$

Where CaH is the calcium hardness (mg/I CaCO<sub>3</sub>), PO<sub>4</sub> is the phosphate concentration (mg/I) and t is the temperature as °C.

SI	Indication/Description	Risk	Treatment Recommendations
=<0	Balance – Low potential for scale formation	Ideal	No treatment
>0	Potential of Scale Formation	Tolerable	Treatment recommended

#### **Table 20: Calcium Phosphate Stability Index**

### 5.7.4.2 Rules of Thumb

There are many simple rules of thumb and indices used to predict scale formation and, in many cases, to determine the maximum concentration ratio between two parameters for effective operation. The following rules of thumb were adapted from (Ferguson, 2004).

Magnesium silicate is a common scale produced in industry. Magnesium silicate can form in a cooling system via two distinct mechanisms, namely the formation of a stoichiometric MgSiO<sub>3</sub>, and through interaction with precipitating magnesium hydroxide. If the ion product is greater than the specified limit, unacceptable magnesium silicate scaling is expected. However, if the ion product is below the limit, acceptable magnesium silicate scaling is expected. The ion product limit is shown in Table 21.

Table 21. Maynesium Sincale Scaling
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рН	Ion Product Limit [Mg (mg/I)] x [SiO <sub>2</sub> (mg/I)]
>= 7.5	<= 12 000
<7.5-<8.5	>=6000-<12 000
>= 8.5	0 -<6000

Calcium sulphate is also another common scale produced in industry. Gypsum is the expected form of calcium sulphate scale in cooling systems whereas anhydrite is more prevalent at temperatures above those normally encountered in cooling water. The ion product limit is shown in Table 22.

### Table 22: Calcium Sulphate Scaling

Water Treatment	Ion Product Limit [Ca (mg/l)] x [SO4 (mg/l)]
No water treatment with regards to antiscalants	0-<50 000 mg/l
With water treatment with regards to antiscalants	>=50 000-10 000 000 mg/l

### 5.7.4.3 Mitigation Methods

In cases whereby scale formation is high, the following mitigation methods can be adopted -

- Addition of scale inhibitors.
- Pre-treatment methods such as cold lime softening.
- Regular cleaning and maintenance, and
- Long term water quality monitoring to ensure all scale or corrosion causing contaminants are monitored.

#### 5.7.4.4 Silica

Silica deposits are glass-like coatings that can form almost invisible deposits on metal surfaces. The solubility of silica increases with higher temperatures and pH. Consequently, this occurs in opposite operating regimes to CaCO<sub>3</sub> scale formation. Once formed, it is difficult to remove even with aggressive acid cleaners. The solubility of silica in steam increases with an increase in temperature. Thus, the solubility of silica increases as steam is superheated. In boiler water systems, as steam is cooled by expansion through the turbine, silica solubility is reduced and deposits are formed, usually in cases where the steam temperature is below that of the boiler water. To minimize this problem and prevent silica scale from forming, the concentration of silica in the steam must be controlled. The maximum limits of silica in the steam should be 0.02 mg/L (Suez Water Technologies and Solutions, 2021).

Silica content (mg/L)	Indication/Description	Risk	Treatment Recommendations
>0,02	Severe scale forming	Unacceptable	Treatment recommended
<0,02	Limited to no silica scale formation	Acceptable	Treatment may be needed

#### 5.7.5 Fouling

Fouling occurs when insoluble particulates suspended in a water system form deposits on a surface. Fouling mechanisms are dominated by particle-particle interactions that lead to the formation of agglomerates. Fouling is typically experienced in membrane systems through precipitation and deposition of molecules or particulates on the membrane surface or membrane pores. The consequences of membrane fouling are increased membrane separation resistances, reduced productivity, and/or altered membrane selectivity.

Particulate fouling is caused by suspended solids (foulants) such as mud, silt, sand or other particles in the water. Fouling can occur due to inorganic mechanisms such as silt deposition or organic mechanisms such as in the case of microbial sludge deposition. Biofouling occurs when living matter grows on the equipment. In many cases, re-circulating cooling systems are ideal for promoting the life of microorganisms thus promoting biofouling. In cases whereby fouling occurs, under deposit corrosion may be a concern as the deposits create a favourable environment for this type of corrosion. Fouling typically occurs in membranes as well as different types of equipment and in pipelines. Each is discussed separately as they occur differently.

Other types of fouling include corrosion fouling which occurs when corrosion products accumulate and adhere to the surface of the equipment. Biological fouling which occurs when living organisms such as macro-organisms and /or microorganism grow and are deposited onto the walls of the equipment.

These deposited biofilms are of concern as they can accumulate debris that may impede or completely block flow through the equipment.

# 5.7.5.1 Fouling in Equipment and Pipelines

Fouling in equipment and pipelines occurs due to the accumulation and formation of unwanted materials on the surfaces of equipment or pipelines. This type of fouling is of concern in heat transfer equipment as fouling on the fouling of heat transfer surfaces drastically reduces the efficiency. Furthermore, as fouling deposition occurs, the cross sectional area is reduced, which causes an increase in pressure drop across the equipment.

### 5.7.5.1.1 Suspended Solids

Suspended solids (SS) consist of inorganic and organic matter which includes silt, sand, clay, particles or any type of suspended matter. Particulate fouling occurs due to a high suspended solids in the feed which results in deposition of these suspended solids in the process streams due to gravity settling as well as other deposition mechanisms. Limits of the suspended solids concentration in a feed is shown in Table 24.

SS (mg/L)	Indication/Description	Risk	Treatment Recommendations
>= 30	High chance of fouling	Unacceptable	Treatment recommended – Upfront filtration pre-treatment
>=15-<30	Moderate fouling	Tolerable	Treatment may be needed – Upfront filtration pre-treatment OR Chemical treatment by addition of dispersants
>=5-<15	Mild fouling	Acceptable	Treatment may be needed – Upfront filtration pre-treatment OR Chemical treatment by addition of dispersants
0-<5	No fouling predicted	Ideal	No Treatment

### Table 24: Suspended Solids Risk

# 5.7.5.2 Fouling in Membrane Systems

Membrane fouling occurs when a foulant is deposited on a membrane surface which causes a blockage of the membrane pores. This occurs in membrane bioreactors, reverse osmosis, forward osmosis, membrane distillation, ultrafiltration, microfiltration, or nanofiltration systems. Fouling in membrane systems decreases the performance of the membrane. The risk of scaling and corrosion of membrane systems is dependent on the LSI index. This is because the LSI index does not favour CaCO<sub>3</sub> precipitation. Any scale formation is not advisable in membrane systems as this can block the membrane pores.

### 5.7.5.2.1 Particle Size

The fouling tendency is dependent on the size of the particles requiring removal and the type of membrane technology. The fouling tendency of membranes is dependent on the size of the particles requiring removal and the type of membrane technology. In general, the fouling layer is formed by particles having a dimension up to 10 times the pore size. Table 25 shows the typical membrane operation and pore sizes. If the particle size is less than the pore size, it will pass through and generally not cause fouling.

Particle Size	Indication/Description	Treatment Recommendations	
>1000 µm	Pre-treatment required	If Particle size > Lower limit, Treatment Recommended – Consider use of microfiltration	
0,1 to 1 µm	Microfiltration	If Particle size > Lower limit, Treatment Recommended. This technology is recommended for suspended solids and larg colloids	
0,1 to 0,001 μm Ultrafiltration		If Particle size > Lower limit, Treatment Recommended. This technology is recommended for removal of proteins and large organics	
0,001 µm Nanofiltration		If Particle size > Lower limit, Treatment Recommended. This technology is recommended for organics and dissolved solids	
<0,001 µm Reverse Osmosis		If Particle size > Lower limit, Treatment Recommended. This technology is recommended for dissolved salts and organics	

### Table 25: Fouling Particle Size Guideline

### 5.7.5.2.2 Silt Density Index

Silt is composed by suspended particulates of all types that accumulate on the membrane surface. The silt density index (SDI) is a method for estimating the rate at which colloidal and particle fouling will occur in water purification systems, especially using Reverse Osmosis systems (RO) or Nanofiltration membranes systems. The SDI is purely a measurement of the fouling potential since each suspended particulate matter differs in size and shape. The test is dependent on the site-specific details and should

be performed according to the standard test method (ASTM D4189, 2014). Table 26 below shows the fouling potential based on the SDI in RO systems.

SDI	Indication/Description	Risk	Treatment Recommendations
<1	Several years without colloidal fouling	Ideal	Treatment not Recommended
>= 1-<3	Several months between cleaning	Acceptable	Treatment Recommended – Regular cleaning required
>= 3-<5	Particular fouling likely a problem, frequent cleaning	Tolerable	Treatment Recommended – Regular cleaning required
>5	Unacceptable, additional pre-treatment is needed	Unacceptable	Treatment Required – Additional upfront pre-treatment required

### Table 26: Fouling SDI Risk

# 5.7.5.3 Mitigation Methods

The following mitigation methods can be adopted to reduce the risk of fouling -

- Increase the velocity through the specified equipment if possible. Turbulent flow is desired as it
  will keep the particles in the fluid in suspension. In this way, particles are unable to settle and
  collect on the surface resulting in fouling. Furthermore, turbulent flow improves the heat transfer.
  However, this flow must be maintained below a level where erosion of the equipment may become
  a problem.
- Continuous water quality monitoring to ensure that large particles do not enter the system.
- In the case of biofouling Chlorination is typically used as it is known to kill bacteria and algae.
   However, caution must be applied as chlorine largely contributes to corrosion. Thus, shock chlorination is typically implemented whereby large doses of chlorine are added over brief periods throughout a time period. Alternatively, limit biofilm production through the use of microbicides, biodispersants, or by limiting nutrients. Biofilms can cause significant deposit and corrosion problems.
- Continuous cleaning and maintenance of equipment to remove any deposition of contaminants on the surface.

### 5.7.6 Materials of Construction

Based on the factors discussed above, a summary of the various indices per each material of construction is shown in Table 27. In the case of cooling water, the Puckorius index is used as opposed to the Ryznar index as it accounts for the buffering capacity of the water.

Material of Construction	Adverse Effect	Risk Quantification Calculation	
	Corrosion	Ryznar index Aggressive Index	
Concrete	Scaling – Calcium Carbonate and silica	Ryznar index Silica concentration	
	Sulphate attack	Sulphate concentration	
	Fouling	Suspended solids	
	Corrosion	Ryznar index Temperature Chloride concentration Fluoride concentration PREN Value	
Stainless Steel	Scaling – Calcium Carbonate and silica	Ryznar index Silica concentration in Steam Magnesium and Silica concentration Calcium and sulphate concentration	
	Fouling	Suspended solids	
	Corrosion	Larson Skold Index Ryner Index Pisigan and Shingley corrosion rate	
Carbon steel	Scaling – Calcium Carbonate and silica	Ryznar index Silica concentration in Steam Magnesium and Silica concentration Calcium and sulphate concentration	
	Fouling	Suspended solids	
	Corrosion	Ryznar index Larson index Chloride to sulphate mass ratio PREN value	
Alloys (With lead)	Scaling – Calcium Carbonate and silica	Ryznar index Silica concentration in Steam Magnesium and Silica concentration Calcium and sulphate concentration	
	Fouling	Suspended solids	
Plastic	Scaling	Ryznar index	
	Fouling	Suspended solids	
Equipment and piping	Fouling	Suspended solids	
	Scaling	Langelier saturation index	
Membranes	Fouling	Suspended solids Silt density index Particle size	

Table 27: Material of Construction Summary

### 5.7.7 Risk Quantification

The core of the proposed approach requires accounting for the end point adverse effects posed by the water quality constituents and the manner and extent to which they express themselves, and further within site specific scenarios.

The probability of occurrence of the risk is derived through a modelling approach in the DSS comprising the risk assessment. The risk that is obtained as an output, provides guidance about the probability and significance of the risk from exposure to the water quality constituent. Risk is assessed based on the computation of the following components:

- The exposure scenario industrial sector:
  - Selection processing unit/sub-unit, material of construction;
- The assessment conditions (site specific components):
  - The water quality composition (concentrations)
  - o In-situ conditions
  - The receptors characteristics material specific inputs.

The following screens are illustrative of the modelling (calculations) that are addressed through the DSS tool based on a water quality composition input and the calculation methodologies described in the previous sections. The modelling accounts for the relationships defined between the receptor characteristics (materials of construction) and the quantitative of qualitative linkages to the specific risk calculation related to the adverse effect of interest.

	INPUTS
	7.59
µS/cm at 25⁰C	4460
mg/L	457
mg/L CaCO₃	129
mg/L CaCO₃	0.099
mg/L	4479
mg/l	82.5
°C	25
mg/L	9.63
mg/l	0.69
mg/L	3260
mg/L	509
	1
mg/L	5
Days	365
	μS/cm at 25°C mg/L mg/L CaCO <sub>3</sub> mg/L CaCO <sub>3</sub> mg/L mg/l °C mg/L mg/L mg/L mg/L mg/L mg/L Days

### Input Water Quality Example:

# Langelier Saturation Index Calculation:

LANGELIEF	R SATURATION INDEX, LSI					
It indicates t	he tendency for limescale form	nation and growth.				
In order to c	alculate the LSI, The input par	ameters required ar	e the alkalini	ty, hardness, TDS, actual pH, and temperature of the water.		
Data (insert	t data manually on sheet LSI	, IS, RSI, PSI, Lal, A	NK, TH):			
	EC	uSlom at 25%	1160	1		
	EC	µ3/011 at 25 C	4400			
	TDS	mg/L	4479			
	Temperature (T)	°C	25.0			
	рН		7.59			
	Ca <sup>+2</sup>	mg CaCO <sub>3</sub> /L	1139.65			
	Alk	mg CaCO₃/L	129.00			
Calculated	values:					
	Δ	f (TDS)	0.27	]		
	В	f (TDS)	2.08			
	c	f (Ca)	2.66			
	D	f (Alk)	2.11			
	<b>.</b>			1		
	pHs <sub>LSI</sub>	(9.3+A+B)-(C+D)	6.88			
	Langelier Saturation Index	x pH - pHsat <sub>LSI</sub>	0.71			
It is defined	l as:					
LSI= pH - pH	Hsat					
Calculation	method:					
$p_{\text{sat}} = (9,3 + 1)$	(C + D)					
B = -13 120	ng[T(°C)+273 2]+34 55					
$C = \log[Ca(r)]$	$m_{1} = \frac{1}{2} - \frac{1}{2$					
$D = \log A K(r)$	mg CaCO <sub>2</sub> /I)					
2 1097 111(1	D - log Air(ing CaCO <sub>3</sub> ))					
Source: W. F.	Langelier, The analytical control of anti-	-corrosion water treatmen	t, Journal of the	American Water Works Association, V28 #10,		

# Ryznar Index:

Ryznar Sa	aturation Index				
Ryznar Sa	turation Index gives of	nly an indication abo	ut the aggressiveness	of the water	
Data					
Data:					
	pН			7.59	
	EC		µS/cm a 25⁰C	4460	
	Calcium		mg Ca <sup>+2</sup> /L	457	
	Calcium		mg CaCO₃/L	1139.65	
	TDS			4479	
	Temperature (T)		°C	25	
Calculate	d values:				
	٨	f (TDS)	0.27		
	В	f (T)	2.08		
	C	f (Ca)	2.66		
	D	f (Alk)	2.11		
	r				
	pHs <sub>LSI</sub>	(9.3+A+B)-(C+D)	6.88		
	RSI	2pHsat <sub>LSI</sub> -pH	6.17		
It is she fire					
it is define	ed as:				
RSI = 2(pl	Hsat) <sub>LSI</sub> - pH where				
nH - th	a actual nH of water				
pHsat) <sub>LSI</sub> =	= saturation pH				
	Calculation meth	iod:			
	pH <sub>sat</sub> = (9,3 + A +	B) - ( C + D )			
	A = 1/10(log[TDS	]-1)			
	B = -13,12log[T(°	C)+273]+34,55			
	C = log[Ca(mgCa	CO <sub>3</sub> /I)]-0,4			
	D= log AlK(mg Ca	aCO <sub>3</sub> /I)			
Source: J. W. Ryznar: A new index for determining amount of scale formed in water. Journal of the American Water Works Association, V/36 #2, pp. 472-486, 1049					
Jourge. J.		action in the amount of soa	ale formed in water, oournart	si ale i anchean water works	10000iai0ii, 100 π2, pp +12-400, 1040.
L					

### Larson Index:

Larson Index (Lal)							
Larson Ind	on Index (LaI) is based upon evaluation of in-situ corrosion of carbon steel						
Data:							
	chloride sulphate bicarbonate	mg/L mg/L mg/L	9.63 3260 128.80				
	carbonate	mg/L	0.20				
Calculated	l values:						
	Cí SO $_4^{2^2}$ HCO $_3^{-2^2}$ CO $_3^{2^2}$ Larson (Lal)	meq/L meq/L meq/L meq/L	0.3 67.87 2.11 0.01 <b>32.2</b>				
It is define	ed as:						
Lal = ([CI] + $[SO_4^2])/([HCO_3] + [CO_3^2])$							
NOTES:							
concentration as meq/L.							
Source: T.E., LARSON & R.V., SKOLD, Laboratory Studies Relating Mineral Quality of Water to Corrosion of Steel and Cast Iron (1958) Illinois State Water Survey, Champaign, IL pp. 43-46: ill. ISWS C-71							

### Puckorius Index:

#### Puckorius Index (PSI)

Puckorius Index (Practical Scaling Index) uses the equilibrium pH instead of the actual pH of the water to determinate the aggressiveness of the water or the tendency for limescale formation. In this case it's important the buffering capacity of the water.

Data:					
	рН			7.59	
	EC		µS/cm at 25⁰C	4460	
	Calcium Calcium		mg Ca <sup>+2</sup> /L mg CaCO₃/L	457 1139.65	
	TDS			4479	
	Temperature (T)		٥C	25	
Calculated v	alues:				
	A B C	f (TDS) f (T) f (Ca)	0.27 2.08 2.66		
	D	t (ALK)	#NAME?		
	pHs <sub>LSI</sub>	(9.3+A+B)-(C+D)	6.88		
	Alk		129.00		
	pH <sub>EQ(Puckorius)</sub>	1,465 x Log [Alk] + 4,54	7.63		
	PSI	2(pHsat) <sub>LSI</sub> - pH <sub>EQ(Puckorius)</sub>	6.13		
It is defined	as:				
PSI = 2(pHsa where, pH <sub>EQ</sub> = 1,465	at) <sub>LSI</sub> - pHeq <sub>(Puckorius)</sub> 5 x Log [Alk] + 4,54				
Source: R. Puck 1991, P. R. Puck treatment costs,	korius and J. M. Brooke, A ne korius and G. R. Loretitsch, C Paper IWC-47, International \	w practical index for calcium carb ooling water scale and scaling inc Nater Conference, Pittsburgh, PA	oonate scale prediction in o lices: what they mean - ho , 1999.	cooling systems, Corrosion, pp 280-284, A w to use them effectively - how they can cu	.pril

### Pisigan and Singley Index

Parameters on which index depends: pH, Alkalinity, Ca hardness, chlorides, EC, sulphate, Disolved Oxygen, TDS, Temperature, Days of exposure					
рН		7.59			
P Alkalinity	mg/I as CaCO3	0.099			
Total Alkalinity	mg/l as CaCO3	129			
Ca Hardness	mg/I as CaCO3	22.80439			
Total Hardness	mg/I as CaCO3	3229.4			
Chlorides	mg/I as Cl	9.63			
Conductivity	microS/cm	4460			
Sulphate	mg/I as SO4	3260			
Dissolved O2	mg/l	5			
T.D.S.	mg/l	4479			
Temperature	deg C	25			
Days Exposure	Days	365			
Corrosion Rate		mmpy 1.993			

## 6.0 THE DECISION SUPPORT SYSTEM

The DSS has been designed to account for the risks for industrial use associated with utilizing water of a given composition under site-specific and generic circumstances. The risk assessment and calculation methodology defined in the previous sections of this report have informed the informatics for structure and functionality design of DSS tool and the resulting graphical user interface. As 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). Thus 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. It serves as a predictive tool designed to assess the likelihood of the adverse effect and severity and present potential consequences of a water quality related to a specific industrial use context.

The prototype DSS available as a functional tool, is presented as a standalone deliverable to be experienced in conjunction with this summary final report (Volumes 1 and 2).

#### 6.1 Risk Assessment Modelling

The DSS tool has been designed at three levels specified to cater for a range of target audiences (novice, intermediate and expert user) based on the availability of the measured water quality data and site specific detail. Transition between Tiers 1 and Tier 2 is the primary focus of the tool, with Tier 3 representing a higher degree of user defined input and updates to the risk methodology. The transition to Tier 3 aligns with the objective of determining an acceptable risk level as new data captured, for example, specific material of construction detail, chemistry or exposure conditions, could lead to a significant change in the risk posed under the specific site-conditions applicable.

These tiers are 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.

The DSS has been designed to present:

- Generic risk-based water quality requirements for industrial related water quality problems; and
- Site specific assessment of the fitness for use of input water quality and the operational conditions.

The tool is designed to cater for the exposure scenarios of the particular industrial water use situation (the risk-based functionality of the DSS). By assessing the specific aspects built into the modelling approach of the tool such as processing unit and material of construction, water quality data inputs of

the sample composition and exposure conditions, a potential risk is calculated. At this point the riskbased guidance has focused on the risk probability of the occurrence of corrosion, scaling and fouling as the major water quality problems to industrial water use.

Fitness for use of the water quality is determined by defining the material of construction of the mechanical/civil infrastructure of the industrial process in question, which is then assessed on the basis of the input water quality composition that is entered. Using the built-in reference data and the calculation algorithms coded in the DSS for corrosion, scaling and fouling, the probability of risk of the water quality problem is presented based on the assessment of the water quality relative to the material of construction. This predictive quantitative output is presented as indices or ranges linked to the scientific literature based reference data and associated calculations. The tool reports on the significance of the adverse effect and if it is feasible to take remedial/mitigation action or not. The results are output as a PDF report which incorporates mitigation measures in instances where a risk has been noted.

The components and data flow relating to the modelling aspects in the DSS tool, at the 3 tiers is provided below.

#### 6.1.1 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-based assessment of water quality composition entered and material of construction, the user will apply additional protocols to assess detail site data such as water pressure, density, material thickness, etc. The Tier 3 functionality is still to be developed further with the protocols and modules to be applied.

#### 6.1.2 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. The exposure scenario is defined by the material of construction and exposure conditions.

The calculations are run in the model to generate the fitness for use report of quantitative outputs (calculated indices and ranges for scaling, fouling and corrosion related to the water quality hazards of relevance). 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.

#### 6.1.3 Tier 1

Tier 1 requires very little input from the user and presents the water quality requirements for industrial water use with an account of associated risk to the material construction of the

processing/manufacturing infrastructure in reference to the water quality problem of concern. It can be considered somewhat 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 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 material of construction of the processing/manufacturing infrastructure if this is known.

#### 6.2 Development Platform

The project design specification required the adoption of open-source software for the Decision Support System (DSS). Python was selected to develop the DSS since it is an open-source, cross-platform programming language well-suited for developing desktop applications. It has a valuable collection of frameworks, such as PyQt5, a graphical interface designer for quickly creating user-friendly interfaces. The database is built on the JSON framework, an open-source document database that operates on Linux, Windows, and several Unix platforms.

## 7.0 CONCLUSION

The objective of this project, to develop a risk-based philosophy and site-specific methodology for assessing water quality requirements and fitness for use of water for industrial use has been achieved within the scope of the SAWQGs series. A risk-based approach and quantification methodology for the risk assessment and a prototype decision support system that demonstrates the main decision contexts for industrial water use has been presented here.

The fundamentals of the approach and the various components that comprise the risk assessment for industrial water use have been determined. The major adverse effects of concern to industrial water use and associated calculation methodologies were presented based on the availability of the supporting science and empirical data that could be sourced. The outcome of these components has been used to develop a hierarchical decision tree that has guided the software development of a prototype model that can be tailored to the needs of the industrial end-user.

It must be noted that the risk prediction methodologies utilised in the tool development are based on rules of thumb that predict scaling, fouling and corrosion. These rules are purely used to highlight the risk of these adverse effects occurring and these calculation methodologies cannot serve as a standalone technical assessment of the water quality and range of adverse effects associated with that water quality. Furthermore, the inputs are purely based on the incoming water into the process unit. In cases such as a boiler or evaporator, the water becomes concentrated due to the water loss. Hence, there is a change in water quality through the various water cycles. This tool does not account for this variation and is based on the input water quality to the various process units.

The following must be noted as limitations of the tool -

- All indices calculated in the tool as based on their own assumptions. The original references of the calculation must be consulted in order to determine the specific limitation of each equation
- The tool does not consider specific process operating conditions such as velocity, pressure or presence of other contaminants.
- With regards to fouling, biological fouling has not been considered. Furthermore, the effect of the suspended solids particle densities and liquid viscosity has not been accounted for, *i.e.* the variables stated in Stokes Law.

The risk-based methodology and DSS may be built upon by further research and development work to consider other risk factors to the assessment as well other water quality adverse effects. The limitation is generically applicable literature based scientific data to support the risk analysis. This could possibly be addressed through more in depth detailed data mining and to carry out research to collect the necessary data.

As the intention of the Industrial Water Use Water Quality Guidelines (Volume 3) is focused on the assessing risk associated with the use of 'freshwater' sources, as with the rest of the South African water quality guideline series, the scope of the DSS tool functionality has been defined to meet that purpose. The fitness for use assessment still forms the core technical requirement of the guidelines. However, in the design of the tool any input water quality composition (treated, not treated, from any source) maybe assessed to determine fitness for purpose relative to the industrial infrastructure. The ability for a user to input a user-defined water quality guidelines are presented, for South Africa and internationally as well. This adds significant value in terms of applicability and relevance of the revised water quality guidelines.

Through the assessment of a range of input parameters as opposed to a single pollutant's risk in isolation, and consideration of interactivity between these parameters a holistic assessment approach is achieved that is a unique value added approach for this type of guideline

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