Review of ACT Government Proposal for use of Water Purification Plant to Augment Drinking Water Supply

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The Australian Capital Territory (ACT) Government through the ACTEW Corporation as a part of the Water Security Program proposes the construction of a Water Purification Plant (WPP) to augment recycled wastewater into the drinking water supply. The proposal will see the construction of a WPP utilising Microfiltration (MF) and Reverse Osmosis (RO) treatment of feed water from the Lower Molonglo Water Quality Control Centre (LMWQCC). The advanced treated effluent would then be piped to created wetlands before flowing into the enlarged Cotter Reservoir for abstraction through the Mt Stromlo Water Treatment Plant (WTP) for integration into the Canberra drinking water supply. The key concern for the use of reclaimed water is the possible significant impact on the natural ecosystem and the health of the consumer population. The objective of this study is to achieve comparison of the proposed treatment process to established worldwide standards for conventional water quality and then subsequently for the lesser known microcontaminants. More specifically the effect of nutrient loading on the Cotter Reservoir in the form of Nitrogen and Phosphorus leading to eutrophication has been modelled using MATLAB computer software. The main focus of this modelling is to determine the impact of increased frequency of nutrient loading expected from the WPP effluent compared to less frequent natural runoff nutrient loads. From this, considering equivalent annual nutrient loads, a constant inflow will produce lower maximum algal concentrations than episodic inflows. It is seen that a constant inflow of nutrient leads to a lower maximum algal concentration compared to an equivalent load caused by larger less frequent loading events. The plan to incorporate this water into the reservoir may lead to the combined action of heightened ambient concentrations of algal matter from the WPP effluent with smaller natural loading events causing eutrophication.

Keywords: ACTEW, Water Security Program, Reverse Osmosis, Micro Filtration, Cotter Reservoir, reclaimed water, nutrient loading, eutrophication

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Abbreviations

ACTEW = ACTEW Corporation Ltd
AWTP = Advanced Water Treatment Plants
BAC = Biologically Activated Carbon
CSTR = Continuously Stirred Tank Reactor
Ecowise = Ecowise Environmental Ltd
LMWQCC = Lower Molonglo Water Quality Control Centre
MF = Micro Filtration
nSEC = Non-Steroidal Estrogenic Compounds
PhAC = Pharmacologically Active Compounds
RO = Reverse Osmosis
UV = Ultraviolet Radiation
WPP = Water Purification Plant
WTP = Water Treatment Plant
WWTP = Waste Water Treatment Plant

Nomenclature

a = Concentration of algal matter [mgChla/m³]
a_{pa},a_{na} = Ratio of nutrient to chlorophyll a in algae [mg mgChla⁻¹]
k_{d} = First order decay rate [day⁻¹]
k_{g} = Growth rate [day⁻¹]
k_{g,20} = Growth rate at T=20°C [day⁻¹]
k_{g,max} = Maximum growth rate [day⁻¹]
k_{d=20} = Decay Rate at T=20°C [day⁻¹]
k_{sp},k_{np} = Half Saturation Constant for Phosphorus, Nitrogen limitation [mg Pm⁻³,mg Nm⁻³]
n = Concentration of Nitrogen [mgN/m³]
N = Nitrogen
n_{in},P_{in} = Nutrient inflow concentrations [mg m⁻³]
p = Concentration of Phosphorus [mgP/m³]
P = Phosphorus
p, n = Phosphorus, Nitrogen Concentration [mg Pm⁻³,mg Nm⁻³]
Q = Flow rate [m³ day⁻¹]
T = Temperature [°C]
V = Volume [m³]
φ_{L} = Light limitation term
φ_{N} = Nutrient limitation term
φ_{p}, φ_{a} = Limitation term for Phosphorus, Nitrogen [Dimensionless]
I. Introduction

The ACT Government through the ACTEW Corporation has proposed the construction of a Water Purification Plant (WPP) utilising microfiltration (MF) and reverse osmosis (RO) to produce water of a quality suitable to be reintegrated back into the ACT water supply. Initially the proposal only refers to a demonstration centre to be established as a trial of the suitability of the water purification treatment train and water would not be reused for human consumption. Assuming that this trial is successful, the proposal is to treat water from the Lower Molonglo Water Quality Control Centre (LMWQCC) and reintegrate the purified water back into the drinking supply through the proposed enlarged Cotter Reservoir.

The aims and objectives of this study are detailed in the Management Documentation attached as Appendix A. Specifically this study will identify the key risks from previous studies conducted for similar treatment facilities internationally as well as other water reuse schemes within Australia. After identifying these key risks for water quality comparison between the current standard of the LMWQCC, proposed WPP output, water quality of Cotter Reservoir and Australian Drinking Water Guidelines then the key concerns for the feasibility of the project as a whole may be identified.

The main objectives are focused around comparison of proposed treatment process to known worldwide standards for conventional water quality and then subsequently for the lesser know microcontaminants such as pharmaceuticals. More specifically the effect of nutrient loading as produced from the waste water treatment process and also from natural runoff following rainfall will be compared utilising computer modelling to predict the impact on the Cotter Reservoir. The main focus of this study will be to determine the possible impact of constant nutrient loading from artificial means against less frequent episodic events.

II. Outline of ACT Water Reuse Scheme

A. Existing Water Treatment

The ACT Government owned ACTEW Corporation administers the running of the Water Security Program and handles all water and wastewater schemes for the ACT. The two shareholders of the ACTEW Corporation are the Chief Minister and Deputy Chief Minister of the ACT ensuring a political outlook on all decisions.

The LMWQCC is an existing treatment facility in the ACT region of Holt where sewage and waste is collected from the ACT catchment area, tertiary treated and then released into the Molonglo River. The Molonglo River then flows into the Murrumbidgee River and subsequently through Lake Burrinjuck and towards a known water abstraction point at the town of Jugiong. The Jugiong water supply system is the main water supply for the Shire of Young with water being supplied to over 8000 people. This already existing reuse cycle within the ACT and NSW shows that indirectly the tertiary treated effluent from the LMWQCC is being reused for drinking water following further natural treatment through detention time within the river system. Between 2001 and 2004 water quality parameters were monitored at the Jugiong extraction point and compared to the Australian Drinking Water Guidelines (ADWG) and it was found 2% of samples showed evidence of Escherichia Coli indicating faecal contamination. The detection of coliforms may indicate that recycled effluent from the LMWQCC is having a recorded impact at the abstraction point although there may be other sources of E. Coli such as farm animals or wildlife. It is also of importance to note that no recorded health impacts are known to have resulted from the drinking water supply system in Young.

Water treatment processes can be classified dependant on the level of treatment provided and the impurities that are removed. Tertiary and advanced treatments refer to similar treatment processes however are reserved for waste water and drinking water respectively. The treatment processes are outlined in Box 1.

<table>
<thead>
<tr>
<th><strong>Primary Treatment</strong></th>
<th>- Primary treatment involves the removal of floating solids and suspended solids, both fine and coarse from raw sewage.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Secondary Treatment</strong></td>
<td>- Secondary Treatment involves biological processes and results in decanted effluents and separated sludge containing microbial mass together with pollutants</td>
</tr>
<tr>
<td><strong>Tertiary Treatment</strong></td>
<td>- The tertiary process removes pollutants not adequately removed by secondary treatment, particularly Nitrogen and Phosphorus, accomplished by means of sand filters, micro straining or other methods.</td>
</tr>
<tr>
<td><strong>Advanced Treatment</strong></td>
<td>- Refer to treatment processes providing the same treatment standard as tertiary however refer to drinking water treatment as opposed to wastewater treatment.</td>
</tr>
</tbody>
</table>

Box 1 Glossary of Water Treatment Terms
The LMWQCC utilises physical and biological treatment processes in order to provide tertiary treatment to effluent. Figure 1 outlines the eight stage treatment process of the LMWQCC with sewage inflow in the top right and release to the Molonglo River in the bottom right. The proposal for the WPP would see the feed water drawn from the LMWQCC at the clarifiers in step 4. This water would then be passed through additional denitrification tanks which are currently under construction at LMWQCC before flowing through the MF and then into the RO unit.

B. ACT Water Security Project

The proposed Water Purification Plant forms the main part of the Water Security Project for the ACT and will be a three stage water treatment train. The plant will draw its source water partially treated from the LMWQCC and continue with advanced water treatment utilising micro filtration and reverse osmosis (to form a dual membrane process) at the Molonglo site with the water then pumped to a series of created wetlands near the Cotter Reservoir. The created wetlands will allow for further natural treatment through UV Sterilization, filtration through sand beds and nutrient consumption from plants which will create a further buffer between the treatment process and the consumer population. These wetlands will also create a temperature buffer before the water enters the Cotter Reservoir allowing for temperature adjustment. There will also be the consumption of any remaining nutrient through the algal growth process as outlined within Section VII which may disrupt the natural balance of the ecosystem within Cotter Reservoir. The detention time within the Cotter Reservoir will allow for further testing to be conducted and allow for the presence of contaminants to be detected before abstraction to the Mt Stromlo WTP. At the Mt. Stromlo WTP further testing and treatment will occur before the recently commissioned addition of UV disinfection is used as the final barrier between the treated water and the consumer population. The ACT Water Cycle including the proposed Water Security Project is displayed as Appendix B with a simplified network showing the WPP system as Figure 2.
Currently the proposal which has been approved by ACT Government is for the construction of a single train treatment centre to be constructed alongside the LMWQCC to be utilised as a testing and education centre for future works. The proposed display centre will utilise water extracted from the LMWQCC and will initially release treated effluent back into the Molonglo River creating no extra initial impact on the ecosystem. If this water can be safely guaranteed to perform to drinking water requirements then the above described process may be approved and we will see integration of recycled water into the ACT drinking water supply. Work has also begun on another three key proposals forming the remainder of the ACTEW Water Security Project as follows;\textsuperscript{6}

- Enlarged Cotter Dam,
- Murrumbidgee to Googong Project, and
- Tantangara Transfer Project.

III. Water Purification Plant

A. Treatment Process Overview

The treatment process was originally considered for two main treatment methods, 1.Dual membrane filtration with UV Disinfection or 2.Ozonation with Biologically Activated Carbon (BAC).\textsuperscript{7} Common to both options was the addition of de-nitrifying filters which would be constructed as a part of the LMWQCC in order to lower the nitrate loading on the membrane filtration system as well as to ensure that nutrient targets are met for release into the Cotter Reservoir. Dual membrane filtration provides a higher treatment performance with regards to removal of pathogens when compared to option 2 involving Ozone and BAC. Because of this it is seen to be the more suitable option for reclaimed water treatment for human consumption. The removal of salt through the Dual Membrane option is also preferable as an increase in the release effluent would increase the salinity of the Cotter Reservoir and in turn slowly increase the salinity of the Canberra drinking supply network until a limiting concentration was reached as the water is constantly recycled. This concept of a chemical residual occurring within the water cycle due to the repeated recycling of water provides significant risk in the form of microcontaminants such as pharmaceutical products which will be discussed later within this report.

Dual membrane systems involve microfiltration or ultra filtration before reverse osmosis to generate a higher level of advanced water treatment in preparation for potable use. The microfiltration removes particles including bacteria, colloids and suspended solids from the influent and reduces the overall loading on the Reverse Osmosis filter membrane. This decreases the requirement for cleaning of the membrane and allows for longer running times due to less fouling. Reverse Osmosis would then be utilised to remove further impurities down to a smaller particle diameter than that achievable with microfiltration alone. The Reverse Osmosis treatment process also removes dissolved salts from the solution which produces potential environmental impact as these salts require disposal as well as the effluent lacking natural salinity. In this case when compared to the Cotter Reservoir the effluent should be of comparable salinity\textsuperscript{8} and will therefore not create stratification issues. Because of this temperature will remain the main control of stratification.

B. Feasibility Study Options

1. Treatment Flow Rate

The initial plan is for the purchase and installation of an 8ML/day pilot plant in order to generate experimental data for the proposed treatment train with Canberra sewage as feed water. If this proves successful then the two main options being considered for the treatment plant are either a 25 ML/day or a 75 ML/day treatment capacity option.\textsuperscript{9}

2. Created Wetlands

Wetlands refer to a body of water which is permanently saturated without enough clear depth of water to be a dam or lake. Wetlands are especially useful for water recycling treatment processes because their shallow depth allows for greater exposure to natural disinfection through UV from the sun. Wetlands if populated with flora also utilise nutrients from the water for growth leading to further reductions in nutrient concentrations following advanced treatment options. The treatment option of dual membrane filtration may be sufficient to reduce the nutrient concentration to prevent nuisance algal blooms which are possibly harmful for native fauna within the reservoir.\textsuperscript{10} Because of this the design wetlands proposed by ACTEW have been sized only for temperature balancing to avoid stratification due to temperature gradient. Benefits may still be evident for nutrient loading on the reservoir as polishing will still occur creating a buffer preventing large inflow variations.
3. Nutrients

The RO option will reject above 90% of Phosphorus bringing the effluent concentrations well below target values. Nitrate concentrations are usually reduced by 80-85% which will not quite meet the required standards. This further required reduction will be achieved by de-nitrifying filters to be constructed at LMWQCC as well as nutrient polishing within the constructed wetlands. The impact of nutrient loading at the specified target values of the Cotter Reservoir is covered in more detail later in this report.

IV. Existing Water Reuse

A. Water Purification Plants (International)

The WPP process of water recycling and the subsequent augmentation into the drinking supply has an inherently high risk due to the level of exposure to the population. Based on the plan to reinforce Cotter Reservoir with reclaimed water the key risk can be identified as illness suffered by consumers following exposure to chemicals or pathogens in the output of the treatment process. In order to decrease this risk existing international examples should be considered as a benchmark for proposed systems. Some key international examples of treatment plants along with any relevant managing documentation or organisations are discussed in more detail as follows.

1. Singapore.

Singapore utilises a WPP under the management of the Public Utilities Board and the project title of NEWater. NEWater was identified as an essential alternative for water supply by the Singapore government which sees the introduction of desalinated water and recycled water by the year 2012. The initiative is crucial in order to cope with the combined effect of an increased demand with lessened supply due to the end of the water trade agreement with Malaysia. The NEWater WPP has been set up as a trial scheme to conduct real time testing on quality output as well as increase public awareness through tours and open displays, similar in nature to the ACT proposal.

The NEWater plant uses a multi stage process in order to produce clean filter output of drinking quality water. The initial stage uses microfiltration to remove impurities and additives from the water. The water then goes through the reverse osmosis process to remove bacteria, pharmaceuticals and viruses. The final stage includes UV Sterilisation producing a water quality higher than local tap water. This model can be seen as the closest comparison in design to the proposed model for the ACT. The Public Utilities Board utilises the World Health Organisation (WHO) Guidelines as well as its own higher standard internal product water quality.

2. United States.

Within the United States of America (USA) the governing body for the monitoring of water reuse quality control is The US Environmental Protection Agency (EPA). There are varied levels of water reuse programs currently in use in the USA however only four states have regulations or guidelines for indirect potable reuse. Information with regards to monitoring programs from US facilities have been utilised by ACTEW in order to establish the ACT program. Some key water reuse programs in the US and their associated treatment processes are shown below.

- Gwinnett County Department of Public Utilities, Lawrenceville, GA, USA.
  - Secondary treated wastewater is passed through a microfiltration system followed by granular activated carbon absorption and ozonation before release into natural waterways. These waterways are used as drinking water supply sources.
- Clayton County Water Authority, Morrow, GA, USA.
  - Secondary treated wastewater from an extended aeration plant is discharged to land for landfiltration. This water is discharged to a reservoir which is the source water for a WTP.
- West Basin Municipal Water District, Fountain Valley, CA, USA.
  - WPP discharges water to groundwater (to combat seawater intrusion) and commerce and industry non-potable applications. The plant is capable of producing separate outputs of water quality depending on the expected use. Treatment processes include, microfiltration, RO (single and dual pass) and advanced oxidation using UV/hydrogen peroxide.
- Upper Occoquan Sewage Authority, Centreville, VA, USA.
  - The plant discharges into a river system which is the source for a WTP. Treatment includes; lime precipitation softening, two stage recarbonation, granular media filtration, granular activated carbon, chlorination and dechlorination.

- Orange County Water District, Fountain Valley, CA, USA.
  - Used a system under the project name of Water Factory 21 discharging water to the groundwater system and some other irrigation uses. The plant was reconstructed to utilise microfiltration, reverse osmosis and advanced oxidation using ultraviolet and hydrogen peroxide.

3. Africa

Namibia is currently the only African country that utilises recycled water with the direct potable treatment plant at Windhoek established in 1968 and the Gorangab Reclamation Plant which began operation in 2002. The Windhoek plant discharges treated water to a reservoir which is the source for a WTP. The treatment process includes ozonation, dissolved air flotation, sand filtration, biologically active carbon, ultrafiltration and chlorination.

Within all three countries no documented evidence exists showing detrimental health effects on the human consumer population. It is essential to consider the experience gained by these countries utilising this technology as a benchmark for suitable treatment processes however it is important to note that the performance of these systems may vary greatly dependant on location. Variation in input water quality and therefore the associated load on the treatment process can influence the performance of the system and therefore affect the quality of the treated product. It is essential that real time testing with the proposed pilot plant is comprehensive in establishing the baseline treatment quality for the specific ACT treatment requirements.

B. Domestic Water Recycling

Currently water recycling within Australia, at least directly, is limited to only non potable reuse options. As previously mentioned within Australia and in particular the Murrumbidgee River system, waste water is indirectly recycled back into the drinking water supply through release back into the natural water cycle. The water reuse schemes that currently exist may lead to some indirect ingestion based upon pumping back into water courses however no direct planned water recycling is used as a potable source. Schemes which exist within Australia are based primarily upon commercial/industrial reuse with a recent push towards dual reticulation programs for new domestic developments.

1. Sydney - Rouse Hill.

The Rouse Hill dual reticulation scheme has been established to lower the overall demand placed upon Sydney’s drinking water supplies. Dual reticulation refers to the establishment of dual water supplies, one of drinking quality water for domestic use and the other of recycled waste water primarily for outdoor use. Recycled waste water in the Rouse Hill project is supplied via separate pipe systems and houses are fitted with a separate ‘purple’ meter to monitor household use. The water is produced to a suitable standard for human use however taps are colour coded and marked to identify the water as unfit for human consumption.

This concept is becoming increasingly attractive to water conservationists especially as an option to be installed in new developments. The main step required from a government point of view would be to establish an Australian Standard with regards to dual reticulation and empower local government to enforce new subdivisions to establish dual reticulation infrastructure.\(^1^6\)

2. NSW - Port Macquarie

The Port Macquarie-Hastings Council has developed a program which will utilise dual reticulation to both existing urban areas and the proposal for recycled water schemes to be included in all new developments. The existing Port Macquarie Sewage Treatment Plant produced tertiary treated effluent which has now been improved to include Advanced Treatment processes. This new treatment includes ultra-filtration, RO and UV disinfection creating a treatment quality similar in nature to the ACT proposal. The intended use of this reclaimed water remains non-potable and is being supplied through a new dual reticulation network similar to that described above for the Sydney recycling system.\(^1^7\)
3. South East Queensland

The Western Corridor Recycled Water Project (WCRWP) is the Queensland Government initiative to reclaim water from municipal effluent. The intended use remains primarily for industrial and agricultural applications as an effort to lower demand on drinking quality water. It has been mentioned in previous proposals for the recharge of source water to occur dependant on risk management with regards to drinking water quality however the public voted no to the concept at referendum. The project will include micro/ultra filtration, reverse osmosis and additional processes. Plans exist to construct three new AWTPs to reclaim water from an existing six WWTPs. The project will also require the construction of approximately 200km of pipes to distribute the treated product.

Currently construction of dual membrane treatment plants are underway with the published use being for irrigation and supply to power station cooling systems however it has been discussed that if the drought continues, with public approval the water may be used to reinforce Wivenhoe Dam, a main drinking water supply.

V. Water Quality Parameters

The monitoring of certain parameters can be used to create safeguards for the quality of reclaimed water output. Monitoring may be simplified based on the principle that it is more effective to test for a narrow range of key characteristics as frequently as possible rather than a lengthy analysis less often. Hazard concentrations will be decreased based on the combination of treatments provided and the effectiveness of pathogen reduction will be influenced by design factors such as:

- Pore sizes of membranes,
- Detention times in reservoirs and wetlands, and
- Disinfectant doses and detention times.

By considering the different water quality parameters the review can focus on which aspects are of specific concern for the water recycling and reuse for human consumption. These parameters are split into the following fields, Microbial Indicators, Physical and Chemical Characteristics and Microcontaminants. It is also essential to cover the relevant testing programs and as such this is also covered in a following section.

A. Microbial Indicators

Micro-organisms are conventionally used as indicators of the presence of faecal contamination. With the increasing quality of advanced water treatment, the presence of faecal contamination in treated effluent is becoming less common however is of specific concern to this project. The feed water for the treatment plant will have elevated concentrations of faecal contamination and as such is of specific concern. As previously mentioned the presence of faecal contamination has been detected at the drinking water abstraction point in the Shire of Young downstream from the LMWQCC which demonstrates the possibility of faecal contamination surviving through the treatment process.

Two groups of coliforms exist, total and faecal, both of which are used as indicators. The faecal coliform group, a subgroup of the total coliforms can be used as a specific indicator of faecal contamination and further details of their indicator traits are discussed in Appendix C. It is recommended testing for Escherichia Coli (E. Coli) be utilized as it exists as the most common coliform within faeces at over 90%. A presence of E. Coli indicates recent faecal contamination as it does not generally multiply in the drinking water system. The ADWG does not allow for the presence of E. Coli to be detected in any samples from sources used for drinking water.

B. Physical and Chemical Characteristics

Health and environmental risks are associated with the use of reclaimed water and the effects cannot simply be measured at the output of the plant. Factors affecting the final output of the water quality received by the consumer are influenced by a variation in the quality of both raw sewage inflow to the LMWQCC and the feed water for the RO membranes. The reclaimed water can then have environmental impacts on the Cotter Reservoir with the sustainability of natural species and their ecosystem caused by a decrease in the water quality.
Cotter Reservoir itself has issues with regards to water quality predominantly caused by the 2003 Canberra Bushfires. Following the fires increased erosion under heavy rainfall led to a large amount of sediment being deposited in the reservoir decreasing the overall capacity and increasing turbidity and contamination. Of particular concern is the threat of toxic algal blooms in the form of Cyanophyta (blue-green algae) due to nutrient loading on the reservoir. A partial destratification program has been implemented within the reservoir in an attempt to create mixing to a depth of 12m to manage water quality. This aims to increase dissolved oxygen levels in the upper layer without disturbing the heavy metals in the bottom sediment specifically iron and manganese.

It is essential that water quality is such that it remains suitable for both environmental discharge and supply to the Canberra water system. The key environmental issues as identified by the ACTEW Corporation are included in Box 2. The following sections discuss in more detail the specific water quality parameters which are predicted to be of concern to the ecosystem and the consumer population within this proposal.

<table>
<thead>
<tr>
<th>In selecting the Water Purification Plant design necessary to achieve water suitable for both environmental discharge and supply to the Canberra water supply system it was necessary to consider the impacts of different processes on water quality as outlined below:</th>
</tr>
</thead>
<tbody>
<tr>
<td>consideration of nutrient loading on the Cotter Reservoir and to nuisance algal blooms;</td>
</tr>
<tr>
<td>consideration of physical changes in water quality due to changes in salinity, temperature or nitrates which can impact adversely on the aquatic ecosystem; and</td>
</tr>
<tr>
<td>consideration of salinity changes in any discharges to the Murrumbidgee River and the water supply system;</td>
</tr>
</tbody>
</table>

**Box 2 Environmental Considerations from ACTEW**

1. **Nutrients**

Target nutrient levels have been established by ACTEW based upon the Australian and New Zealand Guidelines for Fresh and Marine Water (ANZECC and ARMCANZ 2000). Nutrients of particular concern for the growth of plant matter are specifically Nitrogen and Phosphorus. Although these nutrients are largely removed within the treatment the remaining residual may have an effect on the environmental balance. The nutrient targets for Cotter reservoir from the WPP are discussed within the Nutrient Loading Modelling section.

Assessment of the conditions of the Cotter reservoir and the required nutrient levels is required to determine the level of denitrification that is to occur as a part of the waste water treatment process. The nutrient polishing wetlands proposed will also aim to decrease this effect however control of the plant output will remain the main priority. Comparison of the nutrient levels for Total Nitrogen and Phosphorus for water before and after LMWQCC treatment and the required WPP output to minimise environmental impact is required. The release of these nutrients leads to the development of the N/P Ratio within the effluent and the growth of plant matter is generally controlled by this ratio or specifically by the limiting nutrient, this is further discussed within Section VII.

2. **Temperature**

The temperature of the inflow into the Cotter Reservoir can produce a temperature gradient especially in the winter months where the reservoir temperature will be much lower than the WPP output. A temperature difference of as high as 8°C is expected to be produced which may lead to disruption of the eco-system and native habitat of aquatic fauna through stratification. Stratification is naturally produced within the Reservoir and the inflow from the WPP through the Wetlands may disrupt this with unknown results. A range of reservoir temperatures considering winter, average and summer temperatures is considered within the computer modelling section.

C. **Microcontaminants**

Organic Microcontaminants such as Pharmaceuticals, Hormones and Personal Care Products that can be introduced to effluent through domestic waste, hospitals and some industrial applications are of serious concern to the safety of both the human consumer and the environment. The proposed treatment system has produced good results overseas at removal of organic microcontaminants however some specific predicted concerns are discussed in Section VI. The monitoring of these parameters within the test samples remains of high importance.
in order to maintain public health and protect aquatic flora and fauna including endangered fish species existing in the Cotter Reservoir.

D. Testing Parameters

The ADWG 2004 provides a summary of guideline values which have been established for Microbial Quality (Table 10.9) and Physical and Chemical Characteristics (Table 10.10) which are included at Appendix D. Comparison of these established standards against both current treatment quality and ACTEW product guidelines is discussed in Section VI.

A key requirement is not just performance monitoring of the treatment process but also the establishment of a suitable monitoring program to predict and avoid ecological/health impacts. Two main monitoring programs have been identified by ACTEW being the Baseline Monitoring Program (BMP) and the ongoing Sampling and Monitoring Program (SAMP). In addition with a commonly used Validation Monitoring phase the following outlines this project’s role in the risk management structure.

1. Baseline Monitoring Program

The key objective of the ACTEW program is to obtain baseline information across the existing sewerage collection system and treatment plant effluent.28 Data collected from raw sewage, LMWQCC treated effluent and Cotter Reservoir water quality have been used in the study. The gathering of baseline information for both the source of recycled water and the receiving environment is essential to determine characteristics for both areas.29 The water quality analysis within Section VI summarises the data existing for the current system and quantifies the existing gap between LMWQCC effluent and the ADWG.

2. Validation Monitoring

Validation monitoring is used to determine whether treatment processes are capable of adequately controlling water quality and exposure levels to meet target criteria.30 Within this study the modelling of the environmental interaction within the reservoir between algal growth and nutrient inflow within Section VII aims to validate the current target values published for nutrient output for the WPP. Once the pilot plant is commissioned and data is established for the treatment process utilising actual case feed water the further refinement of these target values will be made possible.

3. Ongoing Sampling and Monitoring Program

For an established system, further data collection points would be required to establish a safe control system for monitoring output to the consumer. A variety of sampling practices should be established in order to monitor sudden fluctuations as well as diurnal and seasonal variations. The establishment of operational monitoring ensuring that the system processes remain under control as well as verification monitoring to confirm compliance with the water quality management plan is essential.31

Once the WPP is established then real-time data may be used to further validate results found from this study. Analysis of the WPP feasibility will be focused on the water quality comparison of Microbial, Chemical, Physical and Micro Contaminants as well as the computerized modelling of algal growth from nutrient loading within Cotter Reservoir.

VI. Water Quality Analysis

A. Microbial, Chemical and Physical Parameters

In order to evaluate the feasibility of the proposed WPP project a complete understanding of the quantified gap between the current water quality produced from the LMWQCC and the requirements outlined within the ADWG must be established. This can then be utilised to determine the required treatment threshold that must be achieved by the WPP and checked for feasibility against expected performance data.

The water provided from the water purification plant can be shown to be able to be controlled to a suitable level and may even provide a higher water quality than other current sources such as the Murrumbidgee. The data shown in Table 1 shows the comparison between the 90th percentile values of treated LMWQCC effluent and the requirements for drinking water within the ADWG.
Table 1 Water Quality Parameters for LMWQCC and ADWG

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Unit</th>
<th>LMWQCC 90th %ile</th>
<th>ADWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Coli</td>
<td>CFU. p. 100mL</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-log[H+]</td>
<td>7.9</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Suspended Solids</td>
<td>mg/L</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>μg/L</td>
<td>320</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>μg/L</td>
<td>11</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>μg/L</td>
<td>7.7</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>μg/L</td>
<td>0.39</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

This data is then graphically represented in Figure 3 which is shown against an arbitrary scale to show the performance current standard of effluent against the ADWG requirements. An exceedance of the allowable Iron concentration exists as well as in Suspended Solids. The proposed dual membrane treatment will remove both of these impurities from the water however their elevated presence will increase fouling and decrease efficiency of the membranes. The presence of E. Coli has already been mentioned as an effect of dealing with recycled waste water however this faecal contamination should also be removed by the RO treatment. Not represented on this chart are the microcontaminants which are covered in the next section due to a lack of available data and the nutrient concentrations as they are considered separately within the computer modelling. The tertiary treatment provided by the LMWQCC will greatly aid the WPP efficiency as the level of treatment brings the feed water quality relatively close to the required standard for drinking water. It can be seen that the slight exceedance of conventional water quality parameters should be easily handled by the Dual Membrane technology and therefore the focus of this feasibility project will be on microcontaminants and nutrient load.

B. Microcontaminants

The required quality of drinking water must be ensured in order to avoid health impacts within the consumer population. Reservoirs and catchment areas are often contaminated with pesticides and other chemicals mainly from agricultural runoff after rain however the concept of reusing waste water for human consumption sees the possibility of the introduction of other non conventional chemicals. Industrial and domestic waste creates the possible presence of Pharmaceutically Active Compounds (PhAC), non Steroidal Estrogenic Compounds (nSEC) and other Personal Care Products (PCP) in the water supply which may have unexpected effects on the ecosystem and consumers.
As well as by-products released within industrial waste many pharmaceuticals administered to humans are partially excreted which leads directly into the waste water system. A pilot study released on oestrogen in wastewater described the impact of endocrine disrupting chemicals (EDCs) on aquatic fauna causing feminization and masculinisation. The conclusion of the study was that steroidal oestrogen removal was not well predicted for the WWTPs and research was currently being undertaken into advanced treatment technology. It has been demonstrated that advanced treatment of reclaimed wastewater by membrane filtration followed by reverse osmosis is the most efficient combination of filtration against microcontaminants at this stage. These studies included Reverse Osmosis treatment plants similar to the proposed WPP providing a suitable comparison of treated water quality.

Studies of MF efficiency at removal of trace elements have shown that MF does not have a major impact on the concentration of PhAC within the water. Within this scheme the MF will act primarily to lower the amount of organic matter from reaching the RO unit as the influent will not have undergone biological treatment. RO was seen to be the best treatment for removal of both PhAC and nSEC and leads to a build up of chemicals on the membrane which is disposed of in the brine or backwash water. Of significant note is that when considering viable alternatives for brine reuse or disposal the concentration of PhAC and nSEC must be considered in order to mitigate risk. RO provided an improved removal of PhAC and nSEC when compared to other treatment alternatives of ozonation and BAC.

The treatment threshold for the removal of microcontaminants with the use of RO is generally published as lowering the concentration of all target contaminants to below detection. The fact that systems using this treatment process record instances of contaminant in the treated water reservoirs indicates either a build up of background concentration reaching detection levels or contamination from another source. The contamination recorded may be from unmonitored waste disposal or runoff and may not be caused by residual passing through the treatment process however the effects on a human consumer population are unknown as is the possible retention time of certain contaminants within the system. The presence of these contaminants may exist for quite some time and eventually build up to form a harmful concentration to either the native fauna or the consumer population. These studies are not conclusive as to an identified risk to the consumer population however do highlight the importance of microcontaminants being included in future testing programs for the WPP.

### C. Nutrient Loading

The Cotter Reservoir is fed from a catchment of area of 482 square kilometres including the Bendoras and Corin Dams. The majority of the Catchment (88%) lies within the Namadgi National Park with the land use dominated by native forest and some plantations of *Pinus Radiata*. The Canberra area climate is identified as temperate with cold wet winters and hot dry summers. The average long term rainfall is recorded as 980mm however this has seen a common decreasing trend over the last decade.

It is known that for long term planning of impact on reservoirs, annual average nutrient loads provide a sufficiently good measure. It is also found that land use within a catchment area can be used as a summary of many environmental characteristics that influence nutrient export and can therefore be used as a predictor for nutrient loading on a reservoir. The nutrient export rates are well established for North American conditions however are commonly much higher than Australian measured values. Summary average annual nutrient export data for South-East Australia, West Australia and North-East Australia exist. The South-East Australian data exists predominantly for the Murray-Darling Basin of which the Cotter Catchment is a part of within the Upper Murrumbidgee Catchment and as such the South-East Australian data as shown in Table 2 has been used for this study.

<table>
<thead>
<tr>
<th>Broad land use type</th>
<th>Total phosphorus</th>
<th>Total nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Typical</td>
</tr>
<tr>
<td>Urban</td>
<td>0.4-3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Improved pasture</td>
<td>0.1-0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Improved pasture</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Cropping</td>
<td>2.7-143</td>
<td>71</td>
</tr>
<tr>
<td>Market gardens</td>
<td>0.05-0.1</td>
<td>0.06</td>
</tr>
</tbody>
</table>


Table 2 South East Australian average annual nutrient export data
Prior to the 2003 Canberra Bushfires the Cotter Catchment was pristine National Park and as such the water quality within the reservoirs was of very high quality. Due to the heavy amounts of deforestation from the fires an increased amount of erosion and runoff has been caused leading to increased loading within the reservoirs of silts, sediments and subsequently nutrient. For this study the elevated nutrient loadings will not be considered assuming that the catchment will recover suitably by the time the WPP is in operation.

The natural loading on the Cotter Reservoir due to nutrient export from the catchment area has been considered to be Forest. From this average annual nutrient export data values are taken from Table 2 as;

- Total Phosphorus – 0.06 (kg/ha/yr)
- Total Nitrogen – 1.1 (kg/ha/yr)

The Lower Cotter Catchment area is 192.3 km² which is equivalent to 19230 hectares (ha) and the calculated values for the Average Annual Nutrient Load is shown in Table 3. The calculated Annual Nutrient Load expected to be produced by the WPP based on target values produced for the technical feasibility study are shown in Table 4.

### Table 3 Average Annual Nutrient Load from Catchment Runoff

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Area of Catchment (ha)</th>
<th>Average annual nutrient export data (kg/ha/yr)</th>
<th>Average Annual Nutrient Load (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>19230</td>
<td>0.06</td>
<td>1150</td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td>1.1</td>
<td>21150</td>
</tr>
</tbody>
</table>

### Table 4 Average Annual Nutrient Load from WPP

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Flow rate (ML/day)</th>
<th>Inflow Concentration (mg/L)</th>
<th>Annual Nutrient Load (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>25</td>
<td>0.1</td>
<td>910</td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td>0.7</td>
<td>6390</td>
</tr>
</tbody>
</table>

Graphically as presented in Figure 4 it can be seen that the expected nutrient loading on the Cotter Reservoir will be caused mainly by the nutrient export from the catchment. The loading for Nitrogen is substantially larger from catchment runoff than the predicted WPP load. For phosphorus however these annual average loads are much closer which is of higher importance as Phosphorus limiting conditions are predicted to exist within the reservoir. It is of importance to note that the introduction of the WPP effluent may effectively double the current Phosphorus load on the reservoir. If phosphorus limiting conditions do exist then it is to be considered if the steady inflow of nutrient from the WPP may cause elevated concentrations of plant matter and increase the chance of algal blooms.

**Figure 4 Comparison of Nutrient Loading Between WPP and Catchment Runoff**
VII. Nutrient Loading Modelling

Modelling of nutrient interaction and algal growth specifically focused on Cyanophyta (blue-green algae) was conducted in order to predict the impact of the proposed WPP effluent quality on the Cotter Reservoir. The Cotter Reservoir currently exists with a capacity of approximately 4GL and with the Water Security Program and the proposed construction of a new dam wall downstream of the existing wall will see an increase to a total holding capacity of 78GL. It is essential that the model selected can appropriately represent the control space of the Cotter Reservoir and also simulate the contaminant loads from both continuous inputs such as the WPP and episodic cycles such from natural events.

A Continuously Stirred Tank Reactor (CSTR) was chosen for the model as literature based modelling from Chapra already exists and provides an appropriate benchmark for created models in MATLAB to be verified against. A CSTR refers to a reactor in which the liquid is completely mixed and no stratification occurs which is initially unrealistic to be applied to a reservoir and is usually reserved for smaller scale reactors. The WPP will output continuous concentrations of nutrients and other possible contaminants into the reservoir which will create possible issues when compared to the episodic cycles of natural nutrient loading from runoff after rainfall events.

![CSTR Model for Nutrient Modelling](image)

**Figure 5 CSTR Model for Nutrient Modelling**

The model selected for this simulation was a CSTR with volume of 4GL to represent a well mixed stratified layer of volume equivalent to the size of the existing reservoir above further stratified layers making up the remainder of the new reservoir. An outline of the CSTR model utilised in this study is shown in Figure 5 with the reaction between nutrient (Nitrogen and Phosphorus) and algae concentrations as well as the relevant sources (WPP effluent) and sinks (Canberra Reticulation demand, sediment uptake, etc) of the reactions predicted within the Cotter reservoir.

Temperature gradients within the reservoir lead to thermal stratification and break the reservoir into layers as identified by Figure 6. The model has been developed to represent the Epilimnion (Upper Layer) as a CSTR and neglects mixing between layers. Realistically the system would be more accurately modelled to consider some mixing between the layers and consider a CSTR for each layer of the lake and have some flow between the separate reactors. Assuming the Epilimnion to be a standalone CSTR will simplify the hydraulic model and allow for greater focus on the biochemical modelling.

![Thermal Stratification of a Reservoir in Summer](image)

**Figure 6 Thermal Stratification of a Reservoir in Summer**
Differential equations to determine the growth (+)/decay (-) rate for Nitrogen (n), Phosphorus (p) and Algal (a) concentration are presented in their general form as Eq. 1,2,3. The development of these functions and associated terms are explained in the following sections. Once these functions are established then they can be evaluated utilising a finite time step approach within MATLAB to model a,p and n against time (days).

\[
\frac{da}{dt} = f_1(n, p, a, T) + S_m - S_{out} \quad (1)
\]

\[
\frac{dp}{dt} = f_2(p, a, T) + S_m - S_{out} \quad (2)
\]

\[
\frac{dn}{dt} = f_3(n, a, T) + S_m - S_{out} \quad (3)
\]

A. Algal Concentration Modelling

The algal growth rate within this model has been predominantly drawn from theory deduced by Chapra (1997) within “Surface Water-Quality Modelling” and has been adapted to be suitable for use within a MATLAB model created specifically for this project. The main factors identified which contribute to algal growth rate include nutrient concentration, light conditions and temperature with each of these explained in the following sections. Algal growth on a limiting nutrient can be modelled on a mass balance system for a CSTR and is deduced as shown in Eq. 4.

\[
\frac{da}{dt} = k_{g,max} \phi_N \phi_L a - k_d a - \frac{Q}{V} a \quad (4)
\]

Where:
- \(a\) = Concentration of Algae [mgChla m\(^{-3}\)]
- \(k_{g,max}\) = Maximum growth rate [day\(^{-1}\)]
- \(\phi_N\) = Nutrient limitation term
- \(\phi_L\) = Light limitation term
- \(k_d\) = First order decay rate [day\(^{-1}\)]
- \(Q\) = Flow rate through the system [m\(^3\)day\(^{-1}\)]
- \(V\) = Volume of the system [m\(^3\)]

In order to appropriately model the algal growth the terms listed above for Eq. 4 must be quantified. The development of each of these terms is covered in the following sections.

1. Nutrient Limitation (\(\phi_N\))

Algal growth rates are often controlled by nutrient limitation either being that of Nitrogen or Phosphorus. Under high nutrient concentrations algal growth will continue until one nutrient effectively ‘runs out’ becoming the limiting nutrient. The controlling factor with the growth of plant matter results from the ‘Liebig’s law of the minimum’ which states that growth will be controlled by the required nutrient which is of shortest supply. From Chapra’s ‘limitation terms’ for both Nitrogen and Phosphorus have been developed and considered to determine the limiting nutrient. Limitation terms including the Half Saturation constants as shown in Table 5 are expressed as Eq. 5 & 6 with the combined Nutrient Limitation term using Liebig’s Law of Minimum expressed as Eq. 7.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Literature (k_s)</th>
<th>Selected (k_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus</td>
<td>1-5 mg Pm(^{-3})</td>
<td>3 mg Pm(^{-3})</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>5-20 mg Nm(^{-3})</td>
<td>12.5 mg Nm(^{-3})</td>
</tr>
</tbody>
</table>

Table 5 Half-saturation constants for nutrient limitation of phytoplankton growth
\[
\phi_p = \frac{p}{k_{sp} + p}
\]

(5)

\[
\phi_n = \frac{n}{k_{sn} + n}
\]

(6)

\[
\phi_N = \min\{\phi_p, \phi_n\}
\]

(7)

Where,

- \( p, n \) = Phosphorus, Nitrogen Concentration [mg \( P_m^3, mg \ P_m^3 \)]
- \( k_{sp}, k_{sp} \) = Half Saturation Constant for Phosphorus, Nitrogen limitation [mg \( P_m^3, mg \ P_m^3 \)] (Table 5)
- \( \phi_p, \phi_n \) = Limitation term for Phosphorus, Nitrogen [Dimensionless]
- \( \phi_N \) = Limitation term for limiting nutrient [Dimensionless]

2. **Temperature (k\(_{g,T}\))**

Sensitivity for algal growth due to temperature is also incorporated into the model however as studies have shown that growth rate is not directly linear with increasing temperature the model requires specific attention. It has been shown that for different algae types different sensitivities to temperature change have been recorded. The focus for this study will be on blue green algae (Cyanophyta) which can be seen to exhibit a general increase in growth rate for increasing temperature above 0°C. Chapra\(^49\) shows that a growth rate based on the ‘theta model’ demonstrates a relatively good fit to the experimental results for blue-green algae. This leads the temperature dependant growth rate as shown in Eq. 8.

\[
k_{g,T} = k_{g,20} \theta^{T-20}
\]

(8)

Where:

- \( \theta \) = 1.066 based on studies by Eppley (1972) from Chapra.
- \( k_g \) = Growth rate [day\(^{-1}\)]
- \( k_{g,20} \) = Growth rate at \( T=20°C \) [day\(^{-1}\)]
- \( T \) = Temperature [°C]

The literature shows that the development of \( k_{g,max} \) allows the introduction of limits in the form of a limited nutrient source to control the growth rate of plant matter.\(^50\) Evaluation of the \( k_{g,max} \) term using the Hanes method as described in Chapra is shown in Appendix E which demonstrates the resulting relationship between \( k_{g,max} \) as equivalent to \( k_{g,T} \) and therefore dependant on temperature.

3. **Light Limitation \((\phi_L)\)**

Algal growth rate is also controlled by the light conditions within the aquatic region. For Australian, and other Southern Hemisphere lakes where skeletal soils surrounding reservoirs coupled with unreliable rainfall leads to significant soil erosion creating in some cases highly turbid and coloured water bodies.\(^51\) This colour and turbidity limits the depth of penetration of natural light and can control algal growth within the system. Considering that southern hemisphere lakes have been found to have relatively high levels of colouration and turbidity\(^52\) the inclusion of a light limitation factor would produce a lower algal growth rate. To create a more conservative model the algal growth rate has been overestimated leading to more stringent requirements for effluent quality. To achieve this, the value for \( \phi_L \) has been assumed to be unity (1) and will therefore not limit the algal growth rate.
4. Growth Rate ($k_g$)

Combining the effects of nutrient limitation, light dependence and temperature a complete growth-rate model of phytoplankton growth has been developed. The modified equation including temperature and nutrients and considering light as unity (1) is shown in compact form as Eq. 9 and expanded as Eq. 10.

$$k_g = k_{g,\text{max}} \phi_N$$

(9)

$$k_g = k_{g,20} 1.066^{T-20} \min\left\{ \frac{p}{k_{sp} + p} \cdot \frac{n}{k_{sn} + n} \right\}$$

(10)

5. Decay Rate ($k_d$)

Equations must then be determined for $k_d$ which will now be referred to as the decay factor. The decay factor usually comprises two main non predatory losses, respiration and excretion. The decay rate from Chapra\textsuperscript{53} is stated including grazing of zooplankton however for this model predatory losses will not be included and therefore $k_d$ is simplified as equivalent to $k_{ra}$ as shown in Eq. 11.

$$k_d = k_{ra} + k_{gc} = k_{ra}$$

(11)

The decay function is generally expressed in terms of reliance upon temperature and can therefore be modelled in a similar nature to the growth rate dependant on temperature. From Chapra\textsuperscript{54} the decay rate can be expressed as shown in Eq. 12.

$$k_d = k_{ra,T} = k_{ra,20} \theta^{T-20}$$

(12)

Where:

- $\theta_{ra}$ = 1.08 from Chapra
- $k_d$ = Decay rate [day\textsuperscript{-1}]
- $k_{ra,20}$ = 0.025 Decay Rate at T=20°C [day\textsuperscript{-1}]
- $T$ = Temperature [°C]

B. Nutrient Concentration Modelling

Nutrient rate equations are derived from Chapra\textsuperscript{55} for an individual nutrient and the modified equations to represent concentration change for Phosphorus and Nitrogen are shown as Eq. 13 and 14.

$$\frac{dp}{dt} = -a_{pa} k_{g,\text{max}} \phi_p a + a_{pa} k_a a + \frac{Q}{V} (p_{in} - p)$$

(13)

$$\frac{dn}{dt} = -a_{na} k_{g,\text{max}} \phi_n a + a_{na} k_a a + \frac{Q}{V} (n_{in} - n)$$

(14)

Where:

- a,p,n = Concentration of algae [mg Chla m\textsuperscript{-3}] and nutrient [mg m\textsuperscript{-3}]
- $k_g, k_d$ = Growth and Decay rates for algae [day\textsuperscript{-1}]
- $a_{pa}, a_{na}$ = Ratio of nutrient to chlorophyll a in algae [mg mgChla\textsuperscript{-1}]
- $n_{in}, p_{in}$ = Nutrient inflow concentrations [mg m\textsuperscript{-3}]

The main focus of the study was to determine the sensitivity of the reservoir as a reactor for eutrophication from variations in nutrient inflows and natural parameters. The sink factor is controlled by the concentration of the nutrient within the reservoir at the time instant and the flow through the system maintaining a constant volume. The nutrient inflow terms have been taken from performance target values for the WPP effluent.
C. Combined Concentration Model

The Matlab code specifically created for this project Nutrient_Modelling.m attached as Appendix F models the concentrations of Plant Matter (a), Nitrogen (n) and Phosphorus (p) and the resulting interaction between the three for a specified duration. The required inputs dependant on the reservoir conditions include the ambient concentration of plants and nutrient, growth and decay rates for algae, ratio of nutrient to chlorophyll in algae, flow rates, inflow of nutrient and temperature of Reservoir.

\[ a, p, n = \text{Ambient concentration of plants/nutrient [mg m}^{-3}\text{]} \]

\[ k_g, k_d = \text{Growth and Decay rates for algae [day}^{-1}\text{]} \]

\[ a_p, a_n = \text{Ratio of nutrient to chlorophyll} \]

\[ Q = \text{Flow through Reservoir [m}^3\text{day}^{-1}] \]

\[ V = \text{Volume of Reservoir [m}^3\text{]} \]

\[ T = \text{Temperature of Reservoir [°C]} \]

Given a daily rate of nutrient loading, where 1 (daily) through to 5 (one day in 5) the code evaluates an array of nutrient concentrations and flows in order to spread the total equivalent water flow and nutrient load across the selected frequency. This array of nutrient and flow inputs is then evaluated using a time step method of differential equation solving to create an array of concentrations. Incremental constituent changes \( da, dp, dn \) are evaluated for each finite time step, evaluated at a specified interval of 0.001 days which relates to a time scale of minutes where all growth and decay rates are operating on a scale of days. Each change in concentration is then progressively added to the previous concentration within a loop in order to create a final array of concentrations of plant matter, Nitrogen and Phosphorus which has been graphically presented for easy comparison. An output file summarizing the key input parameters and concentrations has also been produced and included within each plot for comparison.

D. Input Parameters

Untreated sewage is discharged in some areas directly into rivers or coastal areas however more commonly as secondary treated reducing the organic matter and microbial contaminants but only marginally reducing the phosphorus before discharge. Currently the main contributor to phosphorus loading within reservoirs occurs from runoff from episodic rainfall events however the WPP will provide a constant inflow of low concentration nutrient producing unknown effects. The natural cycle of nutrient loading generally occurs when rainfall causes runoff and a sudden surge in nutrient rich loading. Once the growth of plant matter begins the concentration of nutrient falls away and as such the growth reaches a maximum value before eventually decaying away again to return to a healthy system. With the proposed constant inflow of nutrient loaded water the algal growth model may not see this nutrient limitation occur and the prediction of maximum algal concentrations becomes more dependent on growth/decay rates, reservoir conditions and variance of the nutrient inflow (through quality control at WPP).

1. WPP Effluent

The flow rate utilised for the study was drawn from project feasibility studies conducted by ACTEW and is predicted at 25 ML per day. The pilot plant to be utilised for real time testing and data collection will have a flow rate of 8 ML per day and the final plant a proposed 75 ML per day however the most likely initial integrated flow into the reservoir will be at 25 ML per day. For modelling within this project the flow rate has been established as equivalent to 25 ML/day.

From the ACTEW design documents for the WPP the design guidelines for total Nitrogen and Phosphorus are as shown in Table 6.

<table>
<thead>
<tr>
<th>Nutrient Targets for water discharge to Cotter Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Effluent from LMWQCC (Target)</td>
</tr>
<tr>
<td>Water quality Cotter Reservoir (Target)</td>
</tr>
<tr>
<td>Total additional removal required</td>
</tr>
</tbody>
</table>

Table 6 Design Nutrient Concentration in WPP Effluent
These concentrations have been used to calculate values for total nutrient loading over a set duration of modeling and then this total load has been spread across the required loading frequency. For instance for constant loading (rate=1) the concentration is at n=700,p=100 for all steps however for loading every second day (rate=2) the concentration is at 0.0 for the first day and at double the rate n=1400,p=200 for the second day providing the same total nutrient load only at a different frequency.

2. Reservoir Parameters

The input parameters required to establish the ambient conditions within the Reservoir have been drawn predominantly from literature values established for Lake Burroinjuck for data collected across a 20 year period between 1979 and 1997. The study concluded final values which have been utilised in this model specifically the mean and standard deviation for values for Phosphorus, Nitrogen, plant matter and temperature. The Burroinjuck values were chosen as the reservoir already receives LMWQCC effluent as previously described and the ambient conditions are expected to be more representative of the new Cotter conditions after integration of recycled water. Values for the ratios of Nutrient to Chlorophyll in algae are also shown with the Burroinjuck values in Table 7.

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Recorded Value</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Orthophosphate</td>
<td>p</td>
<td>7.6</td>
<td>mg/m³</td>
<td>Mean</td>
</tr>
<tr>
<td>a</td>
<td>Nitrate</td>
<td>n</td>
<td>488</td>
<td>mg/m³</td>
<td>Mean</td>
</tr>
<tr>
<td>a</td>
<td>Chlorophyll</td>
<td>(a)</td>
<td>10.18</td>
<td>mg/m³</td>
<td>Mean</td>
</tr>
<tr>
<td>a</td>
<td>Temperature</td>
<td>(T)</td>
<td>18.11±5.57</td>
<td>°C</td>
<td>Mean ± Std Dev</td>
</tr>
<tr>
<td>b</td>
<td>Nitrogen:Chlorophyll</td>
<td>(\alpha_{\text{na}})</td>
<td>10</td>
<td>-</td>
<td>Ratio</td>
</tr>
<tr>
<td>b</td>
<td>Phosphorus:Chlorophyll</td>
<td>(\alpha_{\text{p\ell}})</td>
<td>1</td>
<td>-</td>
<td>Ratio</td>
</tr>
</tbody>
</table>

Table 7 Summary of Reservoir Values from (a) Walter\(^6\) and (b) Lung\(^6\)

VIII. Nutrient Modelling Analysis

A. Model Verification

The MATLAB produced model required verification against the literature models produced by Chapra in order to test the rate of reaction of nutrient/algal concentrations. The designed code uses a slightly varied method to calculate the concentrations using finite time step and as such the values can be expected to give slightly different results. The input parameters for the literature model are not also specified for Volume and Flow Rate of the system which is required for the MATLAB model and as such these have been approximated. The literature relationship between Algae and Phosphorus is shown on the left and the MATLAB produced code on the right of Figure 7. As is seen the MATLAB model performed suitably similar to the expected relationship with the rate of reaction for the growth of algae to consume the Phosphorus within the system as a period of approximately 3 days. The accuracy of the model to predict this relationship within the time scale of days is appropriate for the accuracy required to develop the model further for comparison of nutrient inflows and temperature dependency.

Figure 7 Verification of MATLAB Model against Chapra
B. Considering Nutrient Inflow

In the above model (model verification) the growth of algae is solely based upon the amount of nutrient provided from a single source at the beginning of the timeframe. The WPP effluent as previously discussed will provide a constant supply of nutrient to the reservoir which was determined within the code as the $n_{in}$, $p_{in}$ terms which will act as sources of nutrient for algal growth within the reservoir. Subsequently the model was changed to include all input parameters as previously discussed and to establish the baseline model for the Cotter Reservoir. Modelling Series A was conducted and is included in Appendix G which aims to establish the baseline model and show the initial difference between starting concentration of nutrient and a steady inflow from the WPP. Both models are conducted for a duration of 10 days and have the same values for flow and volume for the life of the model. The only variation between the two is that Model A1 has higher initial concentrations of nutrient which are calculated as the ambient concentrations plus the nutrient flux ($Q/V*N$) for one day of loading as starting concentrations. Model A2 uses ambient values as starting concentrations and then progressively adds the same nutrient flux across a period of one day creating the same nutrient load.

The models both exhibit similar behaviour and for accurate comparison the data file output for both must be compared. The two values of interest are the maximum algal concentration which is calculated as the maximum of the algal concentration array across the duration of the model and the final concentration which refers to the final value calculated for algal concentration at time=duration. Both models show the same final concentration which leads to the conclusion that the long term effect is very similar however there is a slight difference in the maximum value showing that the slightly increased initial concentrations do indeed lead to a higher spike in temporary algal concentrations. There is also a noticeable difference in the rate of reaction with Model A1 the initial concentration of nutrient showing a faster rate of reaction demonstrating that the sudden release of nutrient leads to a faster production rate of plant matter.

As can be seen in Figure 8 Phosphorus exists as the limiting nutrient as the growth curve of Algae is directly proportional to the decay curve of Phosphorus. This is seen for both Models A1 and A2 which agrees with literature discussions that the usual occurrence within Southern Hemisphere reservoirs is Phosphorus limiting conditions on eutrophication. It is clear from these initial conclusions that further analysis is required to determine the long term effect of prolonged nutrient loading from the WPP and which causes greater impact on the reservoir between constant or episodic loading patterns.

![Figure 8 Algae/Nutrient Concentration produced in MATLAB](image)

The above model considered nutrient inflow over a short period in order to check the capability of the MATLAB created code to arrange arrays for $a$, $p$ and $n$ inflows to appropriately model their interaction over a set duration. Considering the WPP effluent the nutrient inflow will be continuous and as such arrays for inflow must be continued for the entire duration. Using the stated input variables and modifying the inflow arrays to be calculated across the entire duration the plot of $a$, $p$ and $n$ concentrations with respect to time is shown as Figure 9. The duration has been extended to 2000 days to allow the algal growth rate to approach zero. The horizontal axis for this plot and all subsequent models has been changed to a log-x scale in order to appropriately display these relationships across the entire domain. Seen in this simulation as opposed to the previous initial nutrient load scenarios is the continued growth of algal matter due to the steady supply of nutrient and the growth rate is limited on a much slower time frame.
C. Reservoir Parameter Sensitivity Analysis

1. Temperature

Before further analysis of the alternative loading patterns the sensitivity of the analysis must be determined in order to identify the required testing range. The growth and decay terms discussed in earlier sections showed a dependence on temperature and as such the sensitivity of concentrations of plant matter within the reservoir was tested against three temperatures. The lower bound of 12.54°C, the mean of 18.11°C and the upper bound of 23.68°C were all tested as modelling reference B1, B2 and B3 and the results are shown in Appendix H. All three models were conducted across the same duration of 2000 days and from comparison of the maximum and final concentrations of algae it can be seen that all three temperatures produce the same final concentrations within the reservoir.

The rate of reaction can be visually analysed to see that an increased rate of reaction is produced from an increase in reservoir water temperature. For subsequent modelling the upper bound of the temperature range was selected of 23.68°C in order to achieve the faster growth rate and decrease required array size within the model by decreasing the overall duration required to see long term effects.

2. CSTR Volume

The assumption was made for the development of the MATLAB model that the control volume for the CSTR of the Epilimnion of the enlarged Cotter Reservoir would be assumed at 4 GL equal to the current capacity of the reservoir. This assumption was simply based on the assumption that the enlarged reservoir should be able to guarantee a well mixed layer either naturally or through the currently existing partial destratification program to ensure a layer of 4 GL in volume. In order to check the sensitivity of this assumption a range of volumes were used all with constant nutrient inflow to determine the impact of the Volume of the Epilimnion. Volumes of 4, 8 and 16 GL were conducted all with constant nutrient inflow equivalent to target values for the WPP and the results are summarised in Table 8 and as Models B4-B6 respectively within Appendix I.
### Table 8 Modelling of volume change

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model B4</th>
<th>Model B5</th>
<th>Model B6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>4 GL</td>
<td>8 GL</td>
<td>16 GL</td>
</tr>
<tr>
<td>$a_{2000}$</td>
<td>69.98 mg a m$^{-3}$</td>
<td>69.88 mg a m$^{-3}$</td>
<td>67.69 mg a m$^{-3}$</td>
</tr>
</tbody>
</table>

A summary of the final concentrations of plant matter are shown as $a_{2000}$ in Table 8. It can be seen that the rate of reaction decreases with an increase in CSTR volume however the maximum concentration still approaches similar values. It can be seen that CSTR volume has an inverse effect when compared to temperature on the rate of reaction for algal growth within the reservoir as an increase in CSTR volume leads to a decrease in growth rate. Of note is that if mixing is achieved through a greater volume of the reservoir then the effect of nutrient loading on eutrophication may be able to be decreased. As all volume sizes tend towards similar algal concentrations the initial assumption of a volume of CSTR of 4 GL was maintained in order to achieve the faster growth rate and decrease the overall duration of the model required to see long term effects.

3. **Half Saturation Constants**

Half saturation constants were taken from literature values provided by Chapra and were assumed to be mean values within the specified range as shown in Table 5. The most accurate method would be to conduct appropriate experiments to determine the actual values for the Cotter Reservoir conditions however in order to establish the effect of the selection of half saturation constants for Nitrogen and Phosphorus, comparison was conducted for the lower bound, mean and upper bound values. The variations covered in models B7-B10 are shown in Table 9 with final algal concentrations as $a_{2000}$ and the resulting output files as Appendix J.

### Table 9 Modelling of Half Saturation Constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model B7</th>
<th>Model B8</th>
<th>Model B9</th>
<th>Model B10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{sp}$</td>
<td>1 mg Pm$^{-3}$</td>
<td>1 mg Pm$^{-3}$</td>
<td>5 mg Pm$^{-3}$</td>
<td>5 mg Pm$^{-3}$</td>
</tr>
<tr>
<td>$k_{sn}$</td>
<td>5 mg Nm$^{-3}$</td>
<td>20 mg Nm$^{-3}$</td>
<td>5 mg Nm$^{-3}$</td>
<td>20 mg Nm$^{-3}$</td>
</tr>
<tr>
<td>$a_{2000}$</td>
<td>69.99 mg a m$^{-3}$</td>
<td>69.97 mg a m$^{-3}$</td>
<td>69.99 mg a m$^{-3}$</td>
<td>69.97 mg a m$^{-3}$</td>
</tr>
</tbody>
</table>

The results shown in Models B7-B10 show changes in the rate of reaction for the consumption of nutrient however in all cases still tend to show Phosphorus limiting conditions in line with the expected performance for a Southern Hemisphere reservoir. The selection of mean values of $k_{sn}=12.5$ mg N m$^{-3}$ and $k_{sp}=3$ mg P m$^{-3}$ should provide an appropriate relationship to model the algal growth within the reservoir and allow for further comparison.

4. **Nutrient Loading**

The nutrient loading concentrations utilised within the model are based on performance target values for the WPP. Variations are expected within the performance of the plant and also some nutrient polishing is expected through the buffer created by the wetlands. A further decrease in the nutrient levels should appropriately lead to a final decreased algal concentration however the effect of a slight drop in performance of the treatment process has been checked against the modelling process. Model B11 is created using an increase in nutrient inflow concentrations of 10% for comparison against the initial case of B3 with the target values as nutrient inflows. Results for comparison are presented in Appendix K.

Table 10 shows a summary of the input parameters and final concentrations in Models B3 and B11 and a direct relationship between changes in concentration of nutrient inflow and final concentrations of plant matter with a 10% increase in inflow leading to a 10% increase in plant matter at 2000 days. For further modelling the targets values will be used as nutrient inflows however it is of specific note that a drop in treatment performance in the WPP nutrient outputs will lead to a direct increase in the plant matter within the Cotter Reservoir.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n$_{in}$</th>
<th>p$_{in}$</th>
<th>$a_{2000}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model B3</td>
<td>700 mg N m$^{-3}$</td>
<td>100 mg P m$^{-3}$</td>
<td>70 mg Chla m$^{-1}$</td>
</tr>
<tr>
<td>Model B11</td>
<td>770 mg N m$^{-3}$</td>
<td>110 mg P m$^{-3}$</td>
<td>77 mg Chla m$^{-1}$</td>
</tr>
</tbody>
</table>

### Table 10 Nutrient Loading Sensitivity
D. Frequency of Nutrient Inflow

The argument still remains as to the effect of the constant inflow of nutrient against the episodic less frequent loading on the reservoir. In order to model this effect in a similar nature to the comparison conducted for Modelling Series A, Series C will consider constant inflow as expected from the WPP and also a frequency of loading every 2, 3, 4 and 5 days. It is essential that the model provides the equivalent flux of nutrient for all frequencies of nutrient loading and as such further loops were utilised within the code to allow the user to set a daily rate which then calculated the array of inflow concentrations of Nitrogen and Phosphorus as well as the flow to produce the same overall nutrient loading on the Reservoir. The results for Series C are shown in Appendix L with plots and output data files for frequencies of 1, 2, 3, 4 and 5 days.

All five variations were conducted for a set duration of 2000 days and the output files compared for maximum algal concentration reached by this time. The results were then plotted as shown in Figure 10 from initial conditions of time=0, a=10.18 to the final conditions for time=2000 and a=max(a). It can be seen that an increase in maximum concentration occurs from a decrease in the frequency of loading, i.e. an increase in the days between loading events. This shows that the maximum concentration of plant matter produced within the reservoir would in fact increase with less frequent inflows assuming that the overall total nutrient load and flow through the system was the same for both cases. This also shows that the sudden load experienced within reservoirs from runoff would produce an overall higher concentration of plant matter than would be seen from the same amount of nutrient being slowly released from the artificial system.
IX. Uncertainty Analysis

The sensitivity analysis conducted for the CSTR provides an insight into the effect that variation of input parameters has on the maximum algal concentration reached within the system. This comparison style of analysis however limits the combination of input variations computed due to the laborious nature of input and comparison. The comparisons represented within this study aim to justify the assumptions made in order to establish the initial conditions for the simulation and allow for general analysis to be conducted for set input variations.

The conclusions drawn from the frequency of nutrient loading simulations show that for equivalent concentrations of nutrient and flows through the reservoir a higher frequency (constant flow) results in lower maximum algal concentrations compared to less frequent loading of higher concentrations. These simulations using singular input values do not however take into account the simulation ‘noise’ or inherent variations due to the natural distribution of input parameters and as such the overall accuracy of the attained values may be in question.

A more detailed and accurate approach would be to utilise a computer based simulation to use either gathered or created distributions of input parameters to plot the created noise of the output data. Monte Carlo Methods are useful for modelling systems which have a high degree of uncertainty in the inputs. The methods use random numbers to simulate statistical fluctuations in order to numerically generate probability distributions. It is a method most commonly used in a system with many degrees of freedom and thus is suitable for the kinetics equations represented within the CSTR for algal growth on a limiting nutrient.

The Monte Carlo Method can be used to compare the results of analytical theories starting with the same model which is the capacity that it would be utilised in this instance. Where the current simulation is using an input of singular mean values, a Monte Carlo Simulation would use a randomly created statistical distribution as an input array. The current simulation produces a single line plot from explicit calculated concentrations whereas a Monte Carlo Simulation would produce a distribution of values and show the relevant noise associated with trends which should follow a similar pattern to those calculated from the mean values.

Figure 11 is a demonstration of the description of ‘noise’ created by the plotting of created distributions of input parameters and then subsequently fitted with a trend line. The current simulations represent the mean values as input parameters and the sensitivity analysis has attempted to establish the approximate variations in maximum algal concentration by simulating the upper and lower bound for inputs. This could be made more accurate utilising the Monte Carlo Methods to run uncertainty analysis and establish the variation between upper and lower bounds of maximum algal concentration variation and check the justification of trends established for varied frequency of nutrient loading.

![Figure 11 Random function showing noise (red) with LOBF (blue) 1](image-url)
X. Conclusions and Recommendations

A. Conclusions

The information provided within this report outlines some key issues with regards to the ACTEW proposal to the ACT Government for the development of the Water Purification Plant to recycle water from LMWQCC to the Cotter Reservoir. Main issues are concerned with the monitoring of key parameters to ensure that the water supplied to the reservoir is of the required standard in accordance with Australian Drinking Water Guidelines and to not further diminish the natural habitat within the Cotter Reservoir.

The discussion to compare a constant inflow of nutrient as predicted to occur from the WPP at low concentrations against the episodic type loading that naturally occurs from runoff can be seen to favour substantially the constant inflow option to produce smaller overall concentrations of plant matter. The proposed WPP through the use of Dual Membrane Filtration and the created wetlands will minimise the nutrient load being imposed upon the Cotter Reservoir and should be able to create a total annual loading lower than that occurring naturally through runoff. The main risk however that occurs with nutrient loading will be the possible effect of the combined action of heightened ambient concentrations of algal matter from the WPP effluent with smaller natural loading events from runoff.

The proposed system uses a multi barrier risk mitigation approach by treatment being provided at the LMWQCC, the constructed WPP, the created wetlands, Cotter Reservoir and finally the Mt Stromlo WTP. The literature available for the Dual Membrane Filtration proposed for the WPP shows that the treatment train is capable of removing contaminants to a suitable standard for use directly as drinking water. The system as a whole should be entirely capable of providing adequate treatment to protect the consumer population from the contaminants present within the feed waste water however adequate attention to monitoring programs must ensure that the treatment efficiency is maintained at all times.

The presence of microcontaminants such as PhAC and nSECs create a very much unknown risk to the concept of waste water recycling for drinking water supply. The literature that has been reviewed demonstrates that the chosen treatment train is the most appropriate at removing microcontaminants from the polluted feed water in most recorded instances dropping levels below detection for all target contaminants. However, studies also exist which demonstrate that microcontaminants have been discovered in the storage reservoirs downstream from WPP which raises serious concern with regards to the safety of the consumer population. Intensive real time testing of the specific equipment to be utilised in the ACT system with actual feed water is required to determine the achievable treatment threshold rather than purely basing the performance on reviews from other sites.

Construction of the Water Purification Plant in order to recycle Canberra waste water to secure future water supplies is a viable option however extensive performance testing is required to substantiate previously documented performance.

B. Recommendations for Future Works

The ACTEW Corporation is planning to place an 8ML/day pilot plant to conduct real time testing of the Dual Membrane performance with LMWQCC treated effluent as feed water. Using data from this system the modelling conducted within this project could be analysed to determine the sensitivity between prediction values and experimental data.

The CSTR model currently used could be improved through the inclusion of the Light Limitation and Zooplankton Grazing Terms from Chapra would be advised. Also, the alteration of Nutrient_Modelling.m to optimize Cotter Reservoir as a system of CSTRs to represent each stratified layer with interlinking boundary conditions would also increase the accuracy of the model by appropriately considering both stratification and vertical mixing.

The use of Finite Element Analysis or a commercially available modelling software to consider localized maxima in algal concentrations would also provide an alternative approach to validate the broad spectrum results found with this model.
Appendices (Separate Document)

Appendix A – Management Documentation
Appendix B – ACT/NSW Water Reuse Diagram
Appendix C – Microbial Indicator Information
Appendix D – Summary of Guideline Values from ADWG
Appendix E – Hanes Estimation of $k_{g,max}$
Appendix F – Nutrient_Modelling.m
Appendix G – Modelling A Outputs
Appendix H – Modelling B outputs
Appendix I – Modelling B4 – B6
Appendix J – Modelling B7 – B10
Appendix K – Modelling B3 and B11
Appendix L – Modelling C Outputs

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