

# ozwater'09

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The Australian Water Association is an independent, not-for-profit association for water professionals, with an overarching mission to promote the sustainable management of water. AWA is Australia's peak water industry association, being the largest and most broadly based.

It represents and connects individuals and organisations working around the nation, integrating ideas and knowledge among people involved in regulation, consultancy, research, management and operations, drinking water, wastewater and stormwater disciplines.

AWA is represented in sectors including engineering, utilities, science and research, and manufacturing and has over 4,000 individual and 650 corporate members, nationally.

For latest updates, detailed program information and online registration visit: [www.ozwater09.com.au](http://www.ozwater09.com.au)

## Chairman's Welcome



Welcome to Ozwater 2009, the AWA's 23rd national conference and exhibition since the inaugural convention held in 1964.

Ozwater and AWA are synonymous with quality water conferences and exhibitions. In these days of water's enormous profile in all sectors of government and the wider community, there are many forums for discussion.

Ozwater is the pinnacle for balanced and informed presentations and debate, along with networking with more than 1000 national and international delegates.

Ozwater 2009's theme "From Challenges to Solutions" acknowledges the emerging and current solutions for the many challenges facing the water industry such as climate change, water shortages and skills shortages. These solutions are essential to ensure sustainability, not only for water but for the whole planet.

Australia is at the forefront in many aspects of water management; water resource management, water conservation, asset management and institutional arrangements are just a few examples. A further consideration is the interdependence of rural and urban user needs and the careful balance required between them. However, we are not alone in the challenges and it is important to ensure that the latest international trends and learnings are presented.

Consequently some 12 eminent speakers encompassing experiences, challenges and solutions from within Australia, Europe, Asia, the Indian sub-continent and the Americas are presenting under the themes of:

- Integrated Water Management
- Water and Wastewater Systems and Processes
- Policy and Strategy
- Emerging and Innovative Technologies and Research

The keynotes are supported by some 200 platform papers and a multitude of poster papers chosen from over 500 abstracts.

Choosing the papers was a challenge for the Program Committee and the band of paper reviewers; the outcome has been assurance of quality across the many subjects of importance to the water industry.

AWA's national partner, the Water Services Association of Australia, and international partner, the International Water Association, have their specialist themes integrated to ensure a balanced program.

Ozwater 2009 also presents the largest exhibition of water technologies, processes, equipment, materials and intellectual property ever assembled in Australia. The wide range of major multi-faceted companies, along with specialist suppliers of goods and services, ensures the opportunity to view and touch and to discuss particular needs with exhibitor's experts in one location.

Talking location, Melbourne's convention and exhibition complex is unique in providing an opportunity to get some fresh air while moving between the venues, something we should all take advantage of.

The famous Ozwater networking opportunities will be here – the welcome reception, the gala dinner, the exhibition drinks and the breaks throughout the day mean that you will be able to catch up with old acquaintances and make new ones.

Specialist workshops on Sunday and technical tours on Thursday provide opportunities for that little bit extra that the main conference and exhibition cannot cover. And accompanying persons have not been forgotten – a program has been organised to enable you to meet other accompanying persons and have the opportunity to experience some of the inimitable features of Melbourne and its surrounds.

Ozwater 2009 has all the ingredients to continue the internationally-acclaimed conference and exhibition established by previous Ozwaters. The only other ingredient is you – the delegates. I invite you to come along and contribute to the solutions required to the many challenges facing the Australian and international water industries.



**Allen Gale**  
Chairman,  
Ozwater 2009 Committee

## Invitation from AWA's Chief Executive



Water is not just 'Flavour of the Month' it seems; when it comes to topical issues, water is 'Flavour of the Decade'. This is a double edged sword for those in the water industry. It is wonderful to be recognised, to be busy and to have lots of interest in our endeavours. The flip side however is that we all find it very hard to make the time to attend conferences.

But it is exactly because of the criticality of water and the demands placed on us as water professionals that we need to make time. The depth and strategic significance of the challenges that confront us – in Australia and around the world – demand innovative thinking and new approaches and technologies. Whether we are water professionals or we just have an abiding interest in water matters, it is important to take time to reflect; to share our experiences and learn from others; and to celebrate the achievements of our peers. This is the essence of Ozwater.

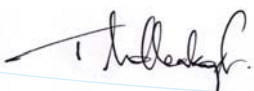
For over forty years now the Australian Water Association has brought together the best and brightest to explore and challenge. Ozwater is without doubt the biggest and best event on Australia's national water calendar. It offers:

- Leading national and international keynotes and invited speakers
- A comprehensive and substantive program of papers, peer reviewed to deliver outstanding quality and relevance
- An extensive exhibition
- Further support through parallel meetings, events and workshops

What makes Ozwater unique is its value proposition; it is run by and for the benefit of water professionals. Behind the scenes there has been a mountain of work done by Allen Gale (the Conference Chairman) and the Committee. Every one of these people is a volunteer who has committed their time and talent to delivering this event. It has been time well spent, as can be seen by the quality of the program and associated activities.

Occasionally one hears the complaint that Ozwater has too much on offer; that delegates cannot attend all the presentations that they would wish to. AWA makes no apology for the extensive coverage of topics and the breadth of the program on offer. What it means is that, whoever is the delegate, their investment in Ozwater will be amply rewarded.

I look forward to welcoming you to Melbourne for what will be an outstanding event.



**Tom Mollenkopf**  
Chief Executive  
Australian Water Association

### From Challenges to Solutions

Ozwater is an event like no other, organised by the industry for the industry where the issues that drive the industry are discussed and future directions decided. Ozwater '09 will take place at the Melbourne Convention and Exhibition Centre, 16-18 March 2009 and will address the wide ranging issues that face the water industry today. These include major national water reforms, climate change and its impacts, technological advances and the challenges of human resources to name a few.

The theme for Ozwater '09 is 'From Challenges to Solutions' where the conference will address some of the important issues that impact on our industry. The Ozwater '09 Conference will feature inspirational international and national keynote speakers, numerous invited speakers, scientific and technical papers, case studies, workshops and poster sessions. This will be a water industry opportunity like no other to network and engage with industry leaders and experts from all over Australia.

As well as an international-standard three day conference, a major component of the event will be an extensive Ozwater '09 Trade Exhibition that will showcase the best of what the industry has to offer. Leading organisations from around the world will participate, exhibiting their products, services and innovations. In addition to the Ozwater '09 delegates, it is anticipated that thousands of trade visitors will attend the free exhibition. An exciting new floor plan layout will ensure maximum interaction between exhibitors, delegates and trade visitors.

There will be extensive multi-level networking and social activities that will offer the opportunity to engage leaders and industry experts on an individual basis and discuss and share issues important to you. No other water industry event in Australia receives the support or promotion as does Ozwater.



# CHLORINE OR CHLORAMINE FOR DRINKING WATER DISINFECTION? A CASE STUDY OF A NEW DECISION FRAMEWORK

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## ABSTRACT

Chlorine and chloramine are the two most widely used disinfectants in drinking water distribution systems. A new framework is proposed, within which the choice between their use is based on the ability of each to achieve specified performance goals within the system of interest. While prediction of chlorine performance can be made with available state-of-the-art chlorine decay modelling, the same cannot yet be achieved for chloramine performance. This approach is demonstrated in a case study where performance of the current chloramination of a distribution system was compared with the modelled performance of chlorination. As work progresses on understanding the development of chloramine-decaying microorganisms, it is anticipated that choice will be based on the performance of each option, as simulated by EPANET and MSX-based network models, such as H2ONET.

## INTRODUCTION

Chlorine and chloramine are the two most widely used disinfectants in drinking water distribution systems. Although chlorine provides more effective microbial control, chloramine is longer lasting at effective concentrations. However, chlorine reacts with dissolved organic matter to generate well-recognised undesirable by-products, while chloramination is a more complex process and chloramine can be degraded rapidly by nitrifying organisms, after which it is often difficult to re-establish a satisfactory residual through the system. A robust framework accounting for all these conflicting factors is needed to assist in deciding which disinfectant is most appropriate for a particular distribution system.

## DECISION FRAMEWORK

The suitability of any given disinfectant can be assessed on the basis of long-term system monitoring data, usually over several years. Alternatively, prediction (modelling) of disinfectant performance can be attempted, without implementing that type of disinfection in the real system. As the ability to assess the performance without the need for trial in the real system offers significant benefits, this paper focuses on such an approach.

The essential elements of the proposed decision framework are shown in Figure 9. The first is the set of goals defined for disinfection, which will usually include a minimum residual level at system extremities to prevent bacterial regrowth and a maximum residual to meet disinfection by-product requirements, and for aesthetic reasons. The second element is the "combined" model, comprising a hydraulic model of the system and a decay model of the disinfectant of interest, with which profiles of disinfectant residual can be generated along any path through a distribution system. The third element comprises the set of scenarios that need to be modelled to determine the more appropriate disinfectant, the location of dosing points and their corresponding setpoints. The final element concerns assessment of loss of chloramine due to nitrifying micro-organisms.

## **Hydraulic system model**

There are many software packages within which detailed dynamic hydraulic models of distribution systems can be built (e.g. EPANET, H2ONET). However, these packages do not usually include an adequate model of chlorine or chloramine decay. For purposes of planning disinfection in systems in which most of the water age accumulates in reservoirs rather than pipes, it is more important to have an accurate decay model than a detailed dynamic model of flows. A steady-state model will generally be sufficient.

## **Chlorine decay in bulk water**

An accurate method to predict the decay of chlorine in a (bulk) drinking water, over a wide range of initial doses and temperatures, has been developed and tested in various Australian distribution systems within the research program of the CRC for Water Quality and Treatment (Fisher et al. 2007). It also accurately describes the impact of rechlorination.

In this method, total decay of chlorine is considered as two components – the decay occurring in the water itself and that due to reaction with the pipe walls and biofilm/sediment deposited or attached to them. This enables accurate prediction of decay (and consequently the residual) without having to try it out in the system itself. It also separates the impact of water-related changes on residual (e.g. treatment) from infrastructure-related changes (e.g.

pipe cleaning or flow/volume changes), so that realistic comparisons of management options can be made.

The model usually adopted by distribution system modellers is that of simple exponential decay. This model has only one coefficient, but it cannot describe the decay that occurs over the range of initial concentrations that may be used in one type of water in different seasons, unless different values of the rate coefficient are used to describe each different combination of initial concentration and temperature that is of interest. It also does not predict any reduction in decay rate if the water is rechlorinated to the same initial concentration – which is the real situation.

To overcome these deficiencies, the “parallel reaction” model was developed within the research program of the Australian Cooperative Research Centre for Water Quality and Treatment (CRCWQT). This model (Kastl et al. 1997 and 1999) represents the decay of chlorine as two simultaneous reactions between chlorine and fast and slow reacting compounds, which are major components of the dissolved organic matter still remaining in the water after treatment. It contains five parameters, which need to be evaluated only once for the model to describe chlorine decay in a particular water, over the whole range of initial chlorine concentrations, temperatures and successive rechlorinations.

The parameters are evaluated from a set of simple laboratory decay tests commencing with at least three different initial chlorine concentrations and carried out at two different (constant) temperatures. Free chlorine concentration is monitored until it is entirely depleted (or up to two weeks).

The chlorine model assumes two reactions of chlorine with compounds present in water:



where Cl is chlorine

F is fast reacting compounds

S is slowly reacting compounds

$\alpha$  is a coefficient of trihalomethane (THM) production

All reactions are assumed to have the same activation energy and the reaction rate constant is described by the Arrhenius equation:

$$k = k_0 * e^{\frac{-E}{R*T}} \quad (1)$$

where k,  $k_0$  are respectively reaction rate constants at temperature T and temperature  $\rightarrow \infty$

E is activation energy

R is the universal gas constant

T is absolute temperature

## Chlorine decay due to wall reaction

In addition to its reaction with organic water in the bulk water, chlorine is substantially decayed by reaction with pipe walls and biofilms/sediments deposited on or adhering to them. This component of decay was characterised simply, using a model with a single parameter (the “equivalent diameter”  $d_e$ ) derived in the CRCWQT research program.

Kastl and Fisher (1997) used the concept of equivalent diameter to link wall reaction with the bulk reaction in the following way:

$$r_T = r_B * \left(1 + \frac{d_e}{d_p}\right) \quad (2)$$

where  $r_T$  and  $r_B$  are total and bulk reaction rates respectively [mg/L/h]

$d_e$  is the “equivalent diameter”, the wall decay rate parameter [m]

$d_p$  is inner pipe diameter [m]

The accelerated loss of chlorine due to reaction with the pipe walls, and any biofilm/sediment attached or deposited on them, can then be characterised by the “equivalent diameter”, which can be derived from the difference between the measured chlorine profile along a distribution system and that predicted to occur in the bulk water alone.

Together, these techniques allow the profile of chlorine (and regulated by-products) along a distribution system to be accurately characterised with a single set of parameters.

## Chloramine decay

In a chloraminated system, decay occurs by both chemical and microbiological mechanisms. In addition to the reaction of organic matter with chloramine (analogous to that with chlorine), chemical decay includes the acid-hydrolysed auto-decomposition of chloramine, both of which are complex to model (Duirk et al. 2005). Despite the complexity of its chemistry, the decay of chloramine in a given distribution system is usually much better characterised as first-order (exponential) than is chlorine decay in the same bulk water. Its use will usually be adequate within the proposed framework.

The ability of an existing or planned disinfection system to meet the goals specified, assuming that chloramine decays in bulk water only by chemical means, can then be assessed within the same framework proposed for chlorine, as shown in Figure 9.

Much greater uncertainty in the rate of chloramine decay in real systems arises from the potential for nitrifying microorganisms to use chloramine either directly or indirectly as a food source. Although this microbial cause of decay has long been recognised in chloraminated systems, the microbial growth required has often been considered to originate in

pipe biofilms, rather than in bulk water, as indicated by the effectiveness of pipe flushing (Kirmeyer et al. 2004). It is therefore not currently possible to characterise the wall reaction as a simple acceleration of the bulk decay rate, as it has been for chlorine decay. Others (e.g. Wolfe et al. 1988) have shown that such growth can also occur in the bulk water in reservoirs with sufficient retention time, which requires further characterisation before adequate prediction of the resulting chloramine decay is possible.

However, a simple method ( $F_m$ ) to measure the chemical and microbial components of total chloramine decay is available (Sathasivan et al. 2005). Application of this method to samples from various locations in an existing chloraminated system (particularly reservoirs) in winter can determine the minimum chemical decay rate occurring throughout the system; i.e. whether there are additional chemical sources of decay in the system. This is similar to estimating the wall reaction with chlorine. Applying the method in summer firstly confirms whether the chemical decay component is consistent with the winter measurements (after allowing for the temperature effect). Secondly, it provides an estimate of the (variable) acceleration of chloramine decay due to microbial agents, particularly nitrifying microorganisms.

With this information, profiles of total chloramine decay can be generated along a distribution system pathway for different scenarios of dosing locations and setpoints, until the most satisfactory arrangement is found for achieving the goals set. This arrangement can then be compared with one based on the profiles obtained for chlorine, to provide an objective basis on which to decide whether to chlorinate or chloraminate a particular distribution system.

## CASE STUDY

### **Rous Water delivery system**

Rous Water is a regional water utility based in Lismore, NSW, which serves four large constituent Councils. It has used chloramination for many years in a distribution system that supplies widely dispersed townships. In a relatively warm climate, rechloramination is needed at some points and the residual can drop quickly without warning due to microbial nitrification. Flushing is often not effective in recovering a satisfactory residual. Generally, switching to chlorination is required for a short period, which is both time-consuming and challenging to manage.

In recent years, the level of treatment prior to distribution has been substantially upgraded. Its use was established long before the Water Treatment Plants (WTPs) were upgraded with ozone and GAC. Ammonia is dosed into water after the GAC filters, followed by chlorine. Due to long residence time in

the system, approximately 3.5 mg/L is the target for the initial dose at Nightcap WTP with a residual of 3.0mg/L leaving the plant. At Emigrant Creek WTP the target residual is 2.4mg/L. Concentration of chloramine diminishes as water travels through the system and addition of chloramine is often needed to sustain the residual concentration. It was suspected that decay of chloramine is due to nitrification processes. Long residence time (more than 10 days in summer) and elevated temperature ( $>20^{\circ}\text{C}$ ), over extended periods of time, are conditions which typically favour chloramine decay due to nitrification. There was also clear evidence of nitrification based on occasional loss of ammonia and increase of nitrite.

The improvements in treatment at the WTPs have had little impact on the nitrification problem. Conversion to chlorination is carried out for short periods in summer/autumn, in several critical parts of the system. After preliminary discussion with WorleyParsons representatives, Rous Water commissioned a study to determine whether chlorination would be a more appropriate means of maintaining a residual throughout the system, particularly in summer, or whether chloramination practice could be substantially improved.

### **Rous Water system model**

With residence time in the system measured in days rather than hours, a steady-state hydraulic model of the pathway of longest residence time was an appropriate basis on which to assess the likely success of chlorination, provided a realistic model of chlorine decay kinetics is adopted. This was provided by the parallel reaction model and the wall decay model (described above).

The steady-state hydraulic model of the pathway from Nightcap WTP to the Fischer Street (Richmond Valley) reservoir was developed in collaboration with the Rous Water system operators. Average flows along this pathway during a rainy summer period (i.e. high temperature, low demand) were extracted from a H2ONET run and transferred to an AQUASIM (Reichert 1994) pipes-and-reservoirs model (shown in Figure 10). Fully mixed reactors represented the five reservoirs along the pathway and advective reactors represented the pipes connecting them, so that chlorine could decay according to the parallel reaction kinetics in both reservoirs and pipes. Water diversions off the pathway were made at the start or end of each pipe, depending on which was more realistic. This ensured the average residence time in each reservoir and pipe was realistic – an essential requirement for residual modelling.

Water Age is assumed zero at the entry to the Clear Water Service Reservoir of Nightcap WTP. As water flows through the system, it ages and simultaneously is replaced by new water. With time, Water Age stabilises as shown in Figure 1 City View Drive Reservoir has a Water Age of approximately

100h, the pipe to Langs Hill Reservoir 200 h, Langs Hill Reservoir 280h, Broadwater Reservoir 308h and Richmond Valley Reservoir 344h. These are long residence times, but according to chlorine decay experiments, it should be feasible to sustain disinfectant residual using a (modelled) chlorine dose of less than 2 mg/L.

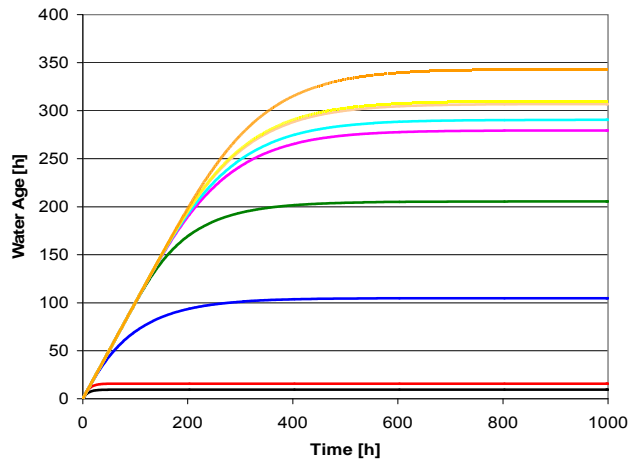


Figure 1: Simulation of Water Age in Rous Water model system

### Chlorine decay model (bulk water)

To assess the suitability of chlorine as a disinfectant in the Rous Water system, a set of decay tests was performed. Test samples were taken from Nightcap WTP after the GAC filter and prior to the chloramination process. The samples were dosed to achieve different initial chlorine concentrations and monitored over time at one of two closely controlled temperatures. The “parallel reaction” model was fitted to the data using AQUASIM software (Reichert 1994) and was then used to predict chlorine residuals throughout a steady-state representation of the Rous Water drinking water distribution system.

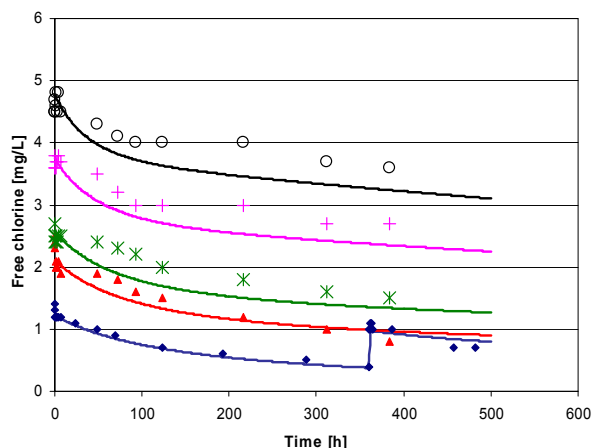


Figure 2: Chlorine decay experiments (markers) and model (lines) at 20°C

The experimental and modelled chlorine profiles are compared in Figure 2 and Figure 3. The fitting procedure for the chlorine decay model was deliberately biased towards the decay test results at lower initial chlorine doses (<3 mg/L), because the chlorine doses needed in Rous Water distribution system are not expected to be higher than 2 mg/L. This model (parameter values listed in Table 1) was considered suitable for simulating the behaviour of chlorine in the Rous Water system.

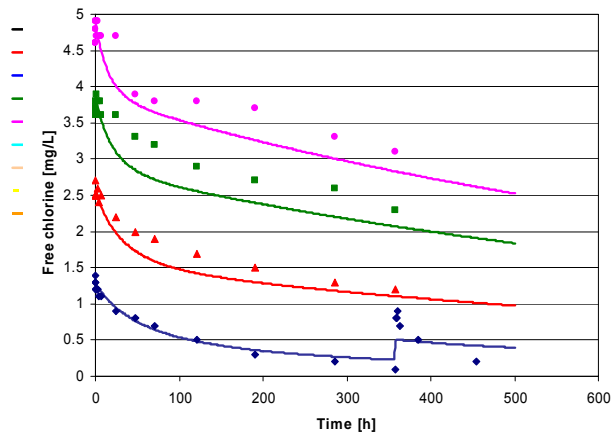


Figure 3 Chlorine decay experiments (markers) and model (lines) at 25°C

The E/R value or 15000 K in Table 1 indicates relatively strong dependence of the reaction rate on temperature, increasing 2.4 times between 20°C and 25°C. There would be an even more dramatic increase in chlorine decay, as the water temperature approaches 30°C.

Table 1 Parameters of the chlorine decay model

Parameter	Value	Units
F0	1	mg/L
k <sub>20F</sub>	0.006	(mg/L*h) <sup>-1</sup>
S0	8	mg/L
k <sub>20S</sub>	5e-005	(mg/L*h) <sup>-1</sup>
E/R	15000	K

NC102  
 NC103  
 NC104  
 NC104  
 NC106  
 NC106

Profiles for chlorine residual through the system were generated using the methods developed in the CRC for Water Quality and Treatment research program. It was shown that chlorine residual could be adequately maintained along the path of greatest residence time and that by-products would be kept well below regulated limits. The highest THM concentration generated (49ug/L) was from dosing 5mg/L at 25°C – well below the 100ug/L MCL of the USEPA and far below the 250ug/L limit in the Australian Drinking Water Guidelines. This was in contrast to the episodes of loss of chloramine residual predicted to continue occurring from the measured levels of microbial acceleration of chloramine decay.



Results for chlorine residual along the pathway selected in Rous Water system are shown in Figure 4. It should be emphasised that these are residuals that would occur along the pathway if chlorine reacted only with organic matter dissolved in the bulk water; i.e. there was no wall reaction. With an initial dose of 1.5 mg/L and without any contribution of wall reaction, chlorine would reach the end of the system with concentration of approximately 0.4 mg/L.

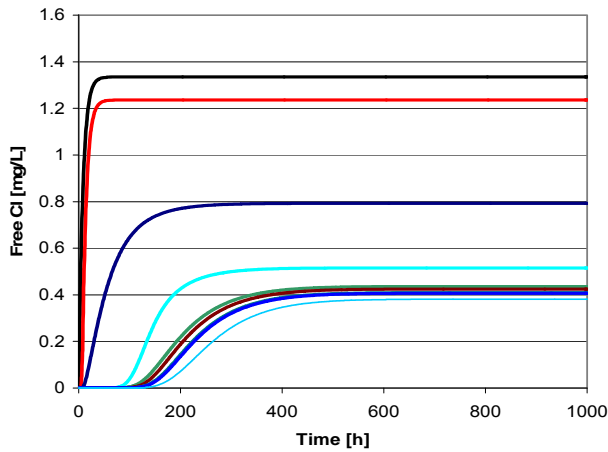


Figure 4: Chlorine concentration in Rous Water simulated distribution system (initial dose 1.5mg/L, 25°C, bulk decay only;  $d_e=0m$ )

### Chlorine decay model (wall effect)

Ideally, “equivalent diameter” ( $d_e$ ) in a pipe is estimated from the difference between the decay predicted by the parallel reaction model (i.e. in bulk water alone) and the decay measured in the system itself. In the current study, this approach is not feasible, as the Rous Water system is currently chloraminated. However, the findings regarding wall decay rates from the CRCWQT program, involving a range of Australian distribution systems, water types and climates (Fisher et al. 2007), can be used instead (Figure 5). In large mains (>500mm diameter), the reaction with cement-lined pipe walls was generally negligible. In smaller pipes (down to 150mm diameter), rates of up to eight times the bulk decay were measured. There was little effect seen in simulations of these systems using higher rates because the chlorine concentrations were so low in the smaller-diameter pipes.

For the Rous Water study, a hyperbolic curve was fitted to the CRCWQT data, as shown in Figure 5, so that the wall reaction rate was calculated as a function of the chlorine concentration in each pipe in the steady-state simulations. The equation of the curve was:

$$d_e = \frac{0.3}{0.15 + c_{Cl}} \quad (3)$$

where  $c_{Cl}$  is chlorine concentration [mg/L]

From Figure 5 it can be seen that  $d_e$  can reach 2m as chlorine approaches 0mg/L and, at 1mg/L of chlorine, it is 0.26m. With an intended range of chlorine of 0.3-1.5 mg/L, the maximum value of  $d_e$  is 0.67m for 0.3mg/L of Cl. This boosts the total decay rate to 5.6 times the bulk rate in the 145 mm diameter pipe at the end of the system. The impact of  $d_e$  also depends on the time that water is exposed to the pipe surface. If the residence time in reservoirs is much larger than residence time in pipes, then impact of biofilm may not be noticeable.

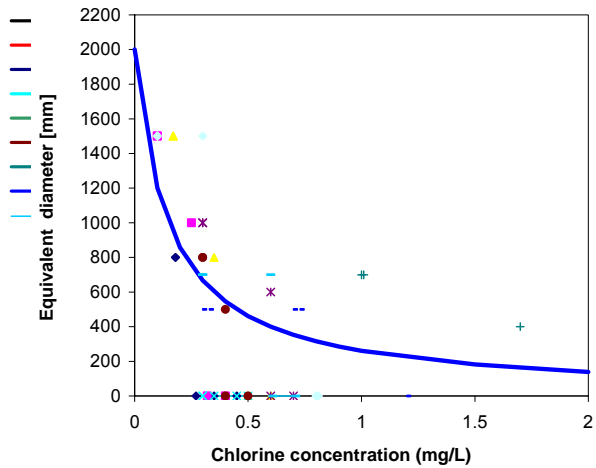


Figure 5: Wall reaction parameter ( $d_e$ ) as a function of chlorine concentration in the pipe

Projection of the above chlorine decay model into the simplified Rous Water distribution system is shown in Figure 6. There is about 0.4 mg/L drop in chlorine concentration across City View Drive Reservoir and another 0.4 mg/L is lost in pipe from City View Drive Reservoir to Lang’s Hills Reservoir. These results are only marginally lower than simulations without wall reaction, as most of the travel time is in reservoirs with low surface area. Additionally, fast reacting compounds are already consumed so acceleration at the wall is not too noticeable.

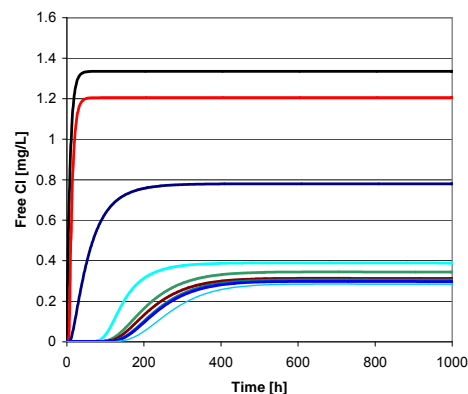


Figure 6: Chlorine concentration in Rous Water simulated distribution system (initial dose 1.5mg/L, 25°C, including biofilm contribution)

There is already provision to boost chlorine in the pipe to Lang's Hills Reservoir at Woodburn, if 0.3mg/L residual in RV reservoir is considered to be too low. Figure 7 shows that adding 0.5mg/L free chlorine at Woodburn would boost the level to 0.7mg/L in Richmond Valley Reservoir.

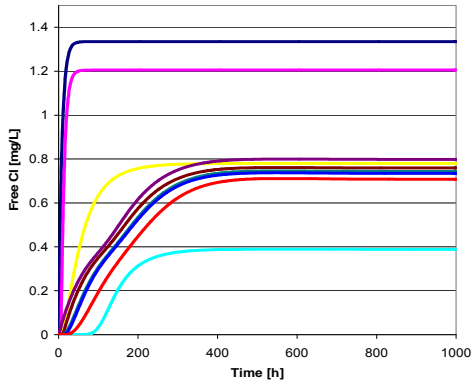


Figure 7: Chlorine concentration in Rous Water simulated distribution system (initial dose 1.5mg/L, 25°C, including biofilm contribution & rechlorination before Langs Hills at 0.5 mg/L)

### Chemical decay of chloramine

Currently, water in the Rous Water distribution system is chloraminated after treatment. Ammonia is dosed after GAC, followed by chlorine. The target dose is 3-3.5 mg/L as total chlorine and the Cl: NH<sub>3</sub>-N mass ratio is targeted to be 4. Chloramine in water is chemically relatively stable with the first order decay constant less than 0.002 h<sup>-1</sup>. In the absence of nitrification, this would still result in a residual of 1.5mg/L at the maximum water age of 360h, so that it was not considered necessary to model profiles in the simplified system. However, it was also shown that some reduction in decay rate is possible simply by switching the order of dosing.

Samples taken immediately after the addition of chlorine at Nightcap WTP had decay rates approximately triple those of samples taken immediately after the GAC and chlorinated, then dosed with ammonia after 15 min, in the laboratory. This may be explained by either chemical reaction of chloramine with reducible compounds in water which were not pre-oxidised by dosing chlorine first or by biologically assisted decay due to the fact that chloramine is a weaker disinfectant than chlorine and therefore ammonia – chlorine enables a higher degree of microbiological survival than chlorine–ammonia. Therefore dosing chlorine first should not only improve chloramine stability but also improve the disinfection efficiency.

### Microbial decay of chloramine

Samples of water containing chloramine were also taken from the Rous Water distribution system and the rate of residual decay was monitored in the laboratory (at 20-25°C). The first order decay constant was fitted to all decay data. The results of these tests are shown in Figure 8. It should be noted that these are indicative of the decay rates in autumn when the nitrification problem is worst. Even though the samples were collected in winter when bacterial growth and populations are likely to be at a minimum, there is clearly an increasing microbial population available to degrade chloramine along the system.

Total decay constants are low down to City View Drive Reservoir. After that, they rapidly increase, with only temporary moderation at the Langs Hills Inlet, probably due to re-dosing of chloramine at Woodburn. Samples further into the system have unacceptably high decay constants. Chemical decay rates were also determined (F<sub>m</sub> method), but the overriding importance of nitrification is clear without considering them further.

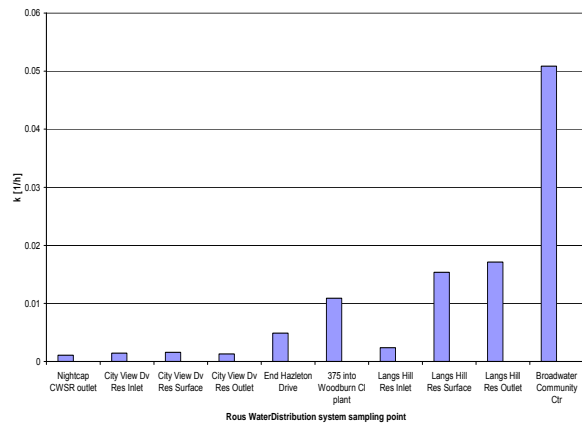


Figure 8: First order chloramine decay constants of samples from Rous Water system

It was concluded that, to prevent acceleration of chloramine decay, chlorine has to be dosed before any major increase in decay constant or loss of ammonia; that is, before the end of Hazleton Drive. Otherwise, stability of chloramine has to be extended, which may require the relocation of the Woodburn booster plant. Changing the dosing sequence (to chlorine then ammonia) may extend the stability of ammonia past the Woodburn booster plant enough to avoid the need to relocate that plant.

Similar testing and analysis would need to be carried out along all other pathways through the delivery system, before chloramination could be considered to meet the disinfection goals specified. After that, a design for each of the satisfactory chloraminated and chlorinated systems can be

costed and the final choice made on the basis of cost and aesthetics.

## DISCUSSION

In this case study, measured data were available on decay of chloramine in the system and desk top predictions could be made about decay of chlorine in the distribution system. In the situation where a distribution system is currently chlorinated, and conversion to chloramination is contemplated, the approach taken in the case study is not currently feasible.

The current state of art allows accurate measurement of microbially assisted chlormaine decay in existing sytems, but does not enable prediction of chloriamine decay without data from the system of interest. A well-designed monitoring program using the  $F_m$  method is needed to adequately characterise development of chloramine-decaying micro-organisms.

## CONCLUSION

A framework is now available, within which the results of chlorination can be predicted just on the basis of tests on treated water entering the distribution system. DSMtool (Fisher et al. 2007) is currently the only network model which has the appropriate chlorine decay model pre-programmed. Recent extension of EPANET/ MSX (multi species extension quality model), enables network models based on EPANET (such as H2ONET) to model chlorine decay realistically. When a chloramine decay model including microbial decay becomes availble, a chloraminated system will also be modelable without the need for measured data from the existing system. This is still under development.

Currently, microbial acceleration can only be characterised by laboratory decay tests ( $F_m$  method) on samples from chloraminated systems. The acceleration from the period of maximum microbial activity (late summer) can be used as a worst case in the framework. This was feasible in the case study, as the Rous Water system is currently chloraminated.

The case study began by defining explicit goals for disinfectant residual at system extremities, and maximum by-product formation. Chlorine decay in (treated) bulk water samples was adequately characterised over a wide range of initial doses and temperatures by a single set of five parameters. The resulting bulk chlorine decay model and a simple wall effect model were embedded in a steady-state hydraulic model of the sub-system having greatest water age. A single rechlorination was shown to easily satisfy both residual and by-product goals.

Microbial acceleration of chloramine decay was measured at various locations in the same part of the Rous Water delivery system. It was shown to increase dramatically between certain locations, even in winter, confirming that it would generally be very difficult to control in summer.

Chlorination was therefore considered to be the more appropriate choice of disinfectant for this system, subject to confirmation that taste and odour were acceptable at the concentration which would reach consumers immediately downstream of the WTPs.

## ACKNOWLEDGMENT

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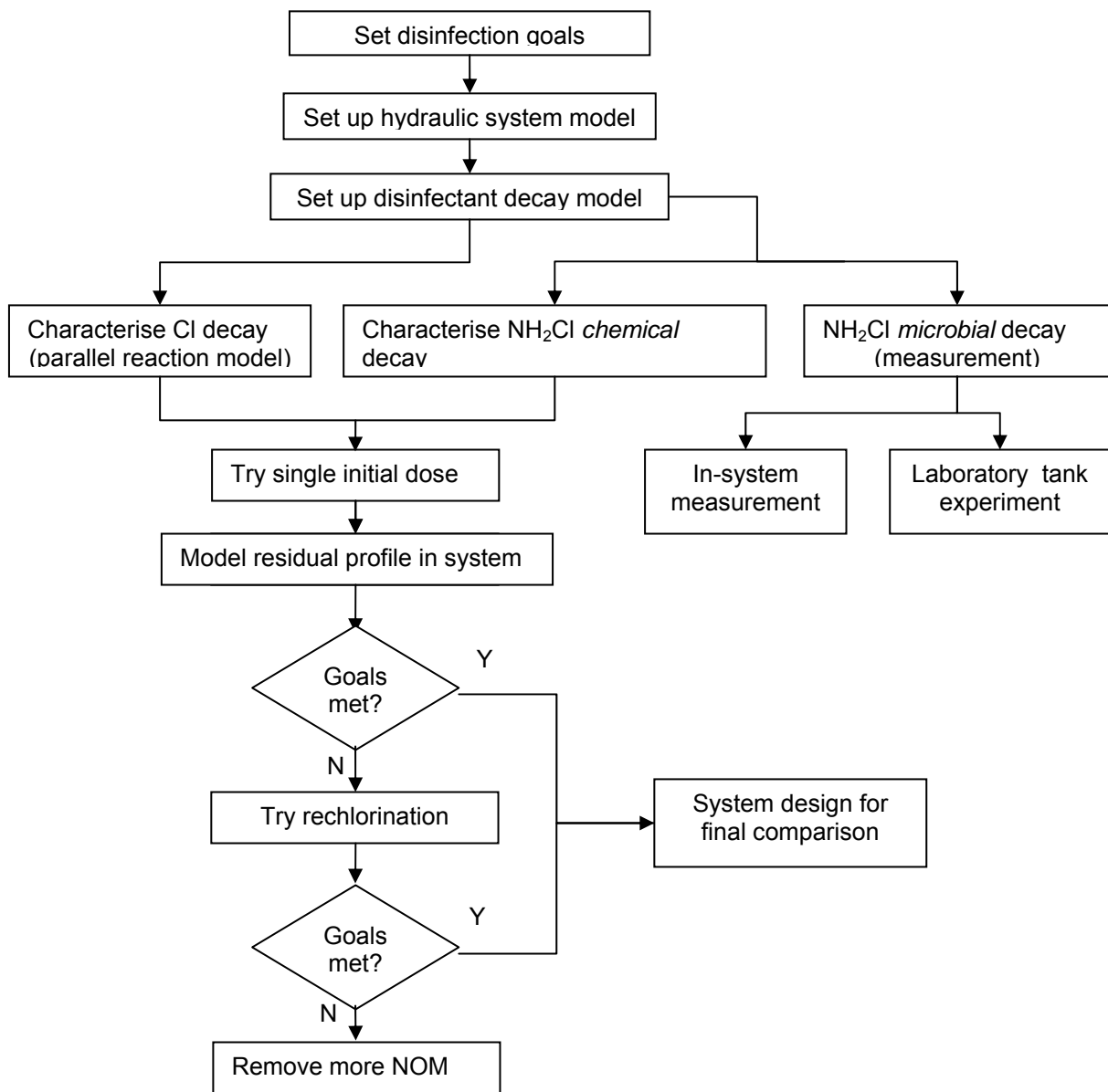


Figure 9: Decision framework for choice of disinfectant

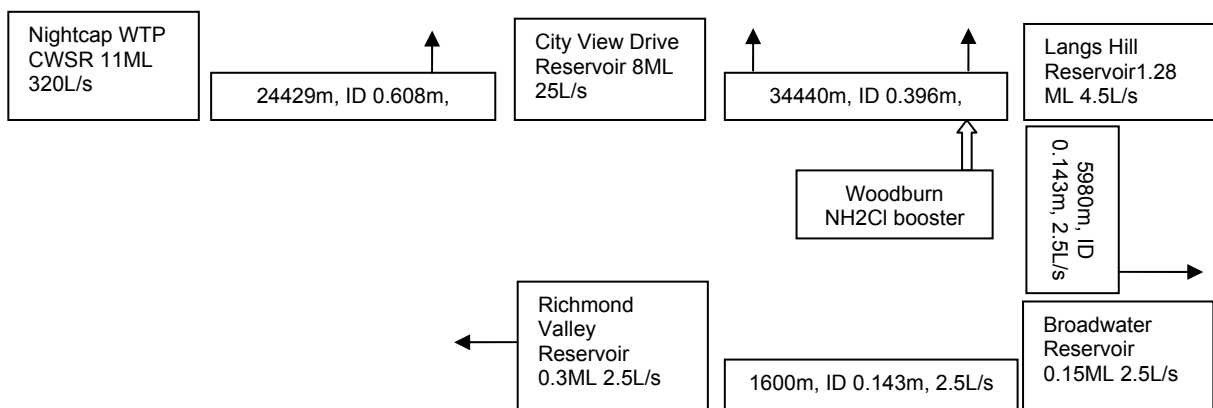


Figure 10: Schematic of RW simplified Distribution System  
(Reservoirs: average active volume, flowrate; Pipes: length, diameter, flowrate)