

Microbial Risk Assessment Tool to Aid in the Selection of Sustainable Urban Water Systems

N.J. Ashbolt*, S.R. Petterson*, D.J. Roser*, T. Westrell**, J. Ottoson**, C. Schönning** and T.A. Stenström**

*Centre for Water & Waste Technology, School of Civil & Environmental Engineering, University of New South Wales, Sydney NSW 2052, Australia

**Swedish Institute for Infectious Disease Control, Solna, SE-171 82 Sweden

Abstract Traditionally, the hygienic impact of urban water systems has been assessed by the occurrence of thermotolerant coliforms/*E. coli* at points of exposure or treatment. When some form of treatment is used, pathogens may be present in the absence of these faecal indicators. Quantitative microbial risk assessment (QMRA) is now the preferred approach to assess pathogen risks at points of exposure, based on estimation of pathogen exposure and human dose-response models. The development of a system's life-time approach to applying QMRA is described here (the MRA tool), where different urban water system options can be compared on the basis of infections per month (to account for outbreak potential), the variation/uncertainty in this infection risk (system robustness) and identification of the critical pathogen(s) and pathway(s) of infection (to aid risk management). Overall the MRA tool provides hygiene information appropriate for integration into a systems analysis that may include environmental, social, technical and economic aspects to better assess the sustainability of urban water systems over their intended life-times.

Keywords pathogens, systems analysis, disease, microbial risk assessment

Introduction

Internationally and within Australia, it is becoming less acceptable to discharge wastewaters to receiving waters, if not due to eutrophication or pathogen problems, simply due to water scarcity (Rathjen *et al.*, 2003). Indeed, based on current sources and likely demands, there is no Australian capital city that can be said to be water secure by 2025. Internationally, there is an urgent need to examine alternative urban water strategies (Bartram *et al.*, 2005). Tools to assess potential human health risks that can be integrated with ecological footprints, triple bottom line reporting and other 'scorecard' approaches to assessing sustainability are wanted. Reliance on faecal indicator bacteria is simply inadequate to cover the range of treatment-resistant pathogens potentially released from modern urban water systems (Ashbolt *et al.*, 2001).

Interestingly, pathogen risks appear to be largely ignored in so-called water-sensitive urban designs of ecological sanitation (EcoSan) alternatives, such as described by Michell *et al.* (2003) and van der Vleuten-Balkema *et al.* (2004) respectively, although the need for their inclusion has been noted (Milburn *et al.*, 2002). This is surprising given the interest for EcoSan options in developing regions and that some 3.1% of global deaths (1.7 million) or 3.7% of disability adjusted life years (DALYs) (54.2 million) are attributable to pathogens via unsafe water, sanitation and hygiene (99.8% of deaths associated with this risk factor are in developing countries, and 90% are associated with deaths of children) (WHO, 2003a).

In contrast, international guidelines for waters (WHO, 2003b; WHO, 2004) and current revisions of various Australian guidelines (NH&MRC and ARMCANZ, 2001; NHMRC, 2004) strongly advocate an assessment of the performance of barriers to pathogens from sources through the water supply system to recipients. This approach is now the preferred way to manage all water risks, and the water industry places pathogens as the highest priority hazard. Nonetheless, suitable tools are not yet generally available to support agencies in

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

assessing pathogen risks along with environmental, social and technical aspects in the context of a systems analysis for sustainability assessment.

This paper describes the development of a microbial risk assessment (MRA) tool, that allows integration with environmental, economic, socio-cultural and technical function in association with the Swedish Sustainable Urban Water Project (MISTRA, http://www.urbanwater.org/default_eng.htm), and builds on what has been previously published by the consortium (Malmqvist *et al.*, 2000). In taking a systems approach the MRA tool attempts to account for system failures and intrinsic variability of unit operations over their intended life-times, and in theory can be applied to a broad range of urban water systems.

Materials and Methods

The MRA tool is based on information collected from various small communities within Sweden (Gebers, Vibyåsen & Hammarby Sjöstad in Stockholm, and Vasastan in Gothenburg). MRA data for Hammarby Sjöstad are presented here to illustrate two urban water system structures; a) conventional 'centralised system', and b) blackwater-yellow water (urine) 'source-separation system', based on the life-cycle pathogen flux analysis for index pathogens described by Fane and Ashbolt (2000).

System Structures

The drinking water supply system for Hammarby Sjöstad is proposed to be the same for both the 'Centralised' and 'Source-separation' cases, so there was no relative difference in pathogen risks between the two cases for drinking water exposures. Therefore, attention was paid to the wastewaters, where for the centralised case, wastewater was conveyed by sewer to one large activated sludge plant (with screening, grit chamber, pre-aeration, pre-sedimentation with coagulant, activated-sludge with nitrification-denitrification, and coagulation-sand filtration) with no disinfection of effluent and sludge processed by pasteurization, anaerobic thermophilic digestion, and the KREPRO (Kemwater, Helsingborg, Sweden) nutrient recovery process for soil application of biosolids. A flow diagram of the 'Source-separation' system is provided in Figure 1, with the main difference being that urine was separated by urine-diversion toilets, stored (for disinfection) and used as a fertilizer for crop production.

Data sources

Epidemiologic and literature data along with direct measurements in the Swedish systems were utilised to estimate viral, bacterial, and parasitic protozoan pathogen ranges in source materials (faeces, urine and sewage). Pathogen removal by the key system units (described above) were modelled by reference pathogen numbers (rotavirus/adenovirus, *Campylobacter*, *Cryptosporidium* and *Giardia*). Reference pathogen numbers in source faeces/urine/sewage were described as probability density functions (PDFs) (Table 1) and their dilution/removal/inactivation described as the pathogens 'flowed' through each system structure. Overall, helminth risks were considered low, but were included from estimates in sewage (with *Ascaris lumbricoides* as reference).

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

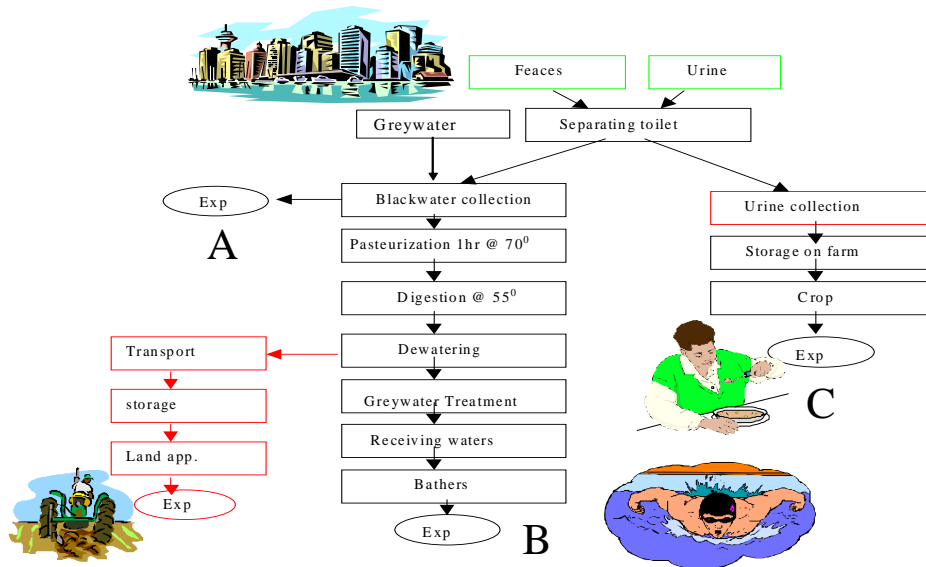


Figure 1 ‘Source-separation’ case for Hammarby Sjöstad. (Drinking water provisions same as for centralised case.) Possible exposure points of concern identified: A - workers fixing plumbing & sewage overflow; B - recreational water users in receiving water; and C - consumers of crops grown with urine fertiliser.

Table 1 Epidemiologic data used to estimate pathogen probability density functions (PDFs) in sewage (modified from Höglund *et al.*, 2002b)

Parameter	Enteric virus (Rotavirus)	Bacterium (<i>C. jejuni</i>)	Protozoan (<i>C. parvum</i>)	Protozoan (<i>G. lamblia</i>)
Yearly incidence of infection (%)	0.95 ^a	15.6 ^b	0.31 ^b	0.84 ^b
Disease rate if infected (%)	75 ^c	23	39	50
Log ₁₀ Excretion time (days)	N*(1.0,0.30) ^d	N(1.18, 0.325) ^e	N(1.48,0.173) ^f	N(1.18,0.325) ^e
Log ₁₀ (Excretion density) (no/g faeces)	N (10, 1) ^d	N (8, 1) ^e	N (7, 1) ^g	N (7, 1) ^h
Estimated # in sewage**				
Mean (per L)	1.53×10 ⁷	3.38×10 ⁶	1.27×10 ⁴	2.13×10 ⁴
50 th percentile (per L)	8.97×10 ⁵	1.87×10 ⁵	8.97×10 ²	1.24×10 ³
95 th percentile (per L)	4.55×10 ⁷	1.03×10 ⁷	4.13×10 ⁴	6.29×10 ⁴

*Normal distribution defined by parameters (mean, standard deviation)

**Assuming 150 g faeces/person.day and 135 litres per capita.day water released to sewer.

^a Wheeler *et al.* (1999), ^b Mead *et al.* (1999), ^c Only for children and the aged (assumed to be 15% of population), ^d Gerba *et al.* (1996), ^e Faechem *et al.* (1983), ^f Stehr-Green *et al.* (1987), ^g Girdwood and Smith (1999), ^h Jakubowski *et al.* (1991)

Concern that our ‘epidemiologic’ approach (Table 1) may over estimate pathogens in faeces/sewage was examined with sewage datasets from Australia (taking into account minor differences in reported disease prevalence’s). Overall there was good agreement (within an order of magnitude) for the reference pathogens, but higher variability exhibited by the epidemiologic approach than assayed (from data collected over one year) (Figure 2). Virus numbers in sewage, however, were estimated to be some two order of magnitude higher than numbers cultured (infective) in sewage, which may reflect reality (virus recovery was not reported, but could be 10-40%). Furthermore, non-culturable viruses such as Norovirus, have been reported by non-culture (i.e. PCR methods) at levels similar to those reported in Table 1

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

(Lodder *et al.*, 1999). Therefore both virus estimations were used in the MRA tool to give an estimation of their overall impact to infection risks.

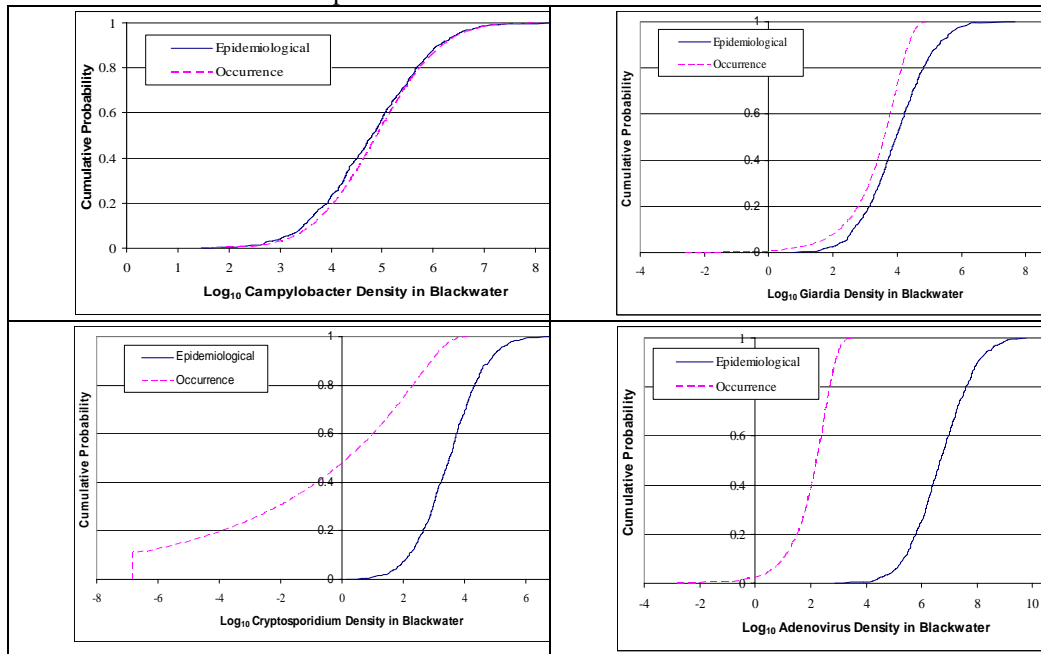


Figure 2 Example output from MRA tool illustrating spread in the pathogen PDF's when estimating numbers in sewage from epidemiologic (dashed line) (see Table 1) or occurrence (solid line) datasets

MRA tool structure

The MRA tool is still under development, but is designed to allow user selection of system components, which defines the specific datasets for pathogen system performance (removal/inactivation) and reliability, coded in the software package Analytica[®] (Version 3, Lumina Decision Systems Inc., Los Gatos, California). Each unit operation in the system structure has pre-described variability and pathogen performance data (e.g. for sand filter, chlorination, distribution etc., called a Hygiene Modifying Process [HMP]) (Figure 2), and users confirm likely points of exposures (e.g. in home, recreation water site, drinking water etc.). Dose-response models for the reference pathogens were used as described by Haas *et al.* (1999) using relevant exponential and beta-Poisson models, with the maximum risk curve ($r = 1$ in the exponential model) (Teunis and Havelaar, 2000) applied for the helminth *Ascaris lumbricoides*, should it be considered important (e.g. for sludge application).

Analytica[®] provides influence diagrams which are hierarchical, providing the user with an intuitive means to see increasing detail, as illustrated in Figure 3. Estimated infections for the life-time of a system structure were compared on a monthly basis by running Monte Carlo simulations of pathogen numbers through each system thousands of times, so as to capture acute effects which may lead to outbreaks. System robustness was estimated based on the range in variability/uncertainty of annual infections, which also helps to identify critical pathogens and pathways of infection, and therefore where to target management actions. Hence, relative comparisons between systems are the prime output of the model, although disease risks are also expressed in a qualitative manner based on the conditional probability of infection (Table 2), to enable integration with the outputs from other sustainability assessments.

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

In our previous quantitative microbial risk assessments of Swedish urban water system (Höglund *et al.*, 2002b; Ottoson and Stenström, 2003; Westrell *et al.*, 2003; Westrell *et al.*, 2004), a large range of sites of potential exposure to pathogens were investigated. The MRA tool makes use of this knowledge and limits potential exposure sites to only those considered more likely and important (although user changeable). For example, sites A-C in Figure 1 and not at the point of biosolids application, given the previous pasteurisation and thermophilic digestion of the sludge.

Table 2 Risk rankings based on estimated disease rates for each system (from (Westrell *et al.*, 2004)

Item	Definition
Catastrophic	Major increase in diarrhoeal disease >25% or >5% increase in more severe disease or large community outbreak (100 cases) or death
Major	Increase in more severe diseases (0.1-5%) or large increase in diarrhoeal disease (5-<25%)
Moderate	Increase in diarrhoeal disease (1-<5%)
Minor	Slight increase in diarrhoeal diseases (0.1-<1%)
Insignificant	No increase in disease incidence (<0.1%)

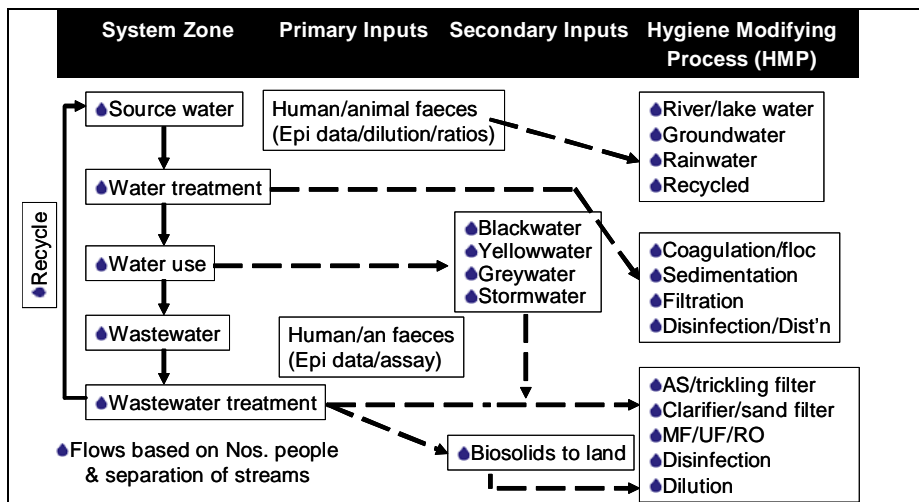


Figure 2 General schematic of the MRA tool for human health assessment

Results and Discussion

The pathogen group of highest concern varied by point of exposure, but based on overall risk, enteric viruses generally dictated the outcome in both the centralised and source-separated alternatives at Hammarby Sjöstad (and in other system structures studied to date [Höglund *et al.*, 2002b; Ottoson and Stenström, 2003; Westrell *et al.*, 2003; Westrell *et al.*, 2004]). The highest likelihoods of infection resulted from obvious risks, such as exposures to raw sewage during mains breaks/leaks in the centralised case or unblocking urine-diversion pipes in the other; yet few individuals would be exposed during such scenarios. Overall community risks were ranked 'minor' for both systems, but the 'source-separate system' yielded the lower risks, due to less impact from recreation swimming.

The MRA tool also provides valuable information for risk management. Rankings of infection risk potential by exposure sites enables the identification of control points for pathogen management, within the Hazard Analysis Critical Control Points (HACCP) risk management approach being adopted by WHO and other water guideline setting agencies.

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

The ranking of microbial risks per system also provides the input values for integration with the other measures of sustainability. Given the potential significance of viral infections, control of aerosols becomes an important aspect to workers near raw wastewater streams. Another important control of viruses is sufficient storage of urine before crop application (from one month for cereals to six months for vegetables) at temperatures of about 20°C (Höglund *et al.*, 2002a). Disinfection of wastewater discharged to receiving waters would also have improve the performance of the ‘centralised system’.

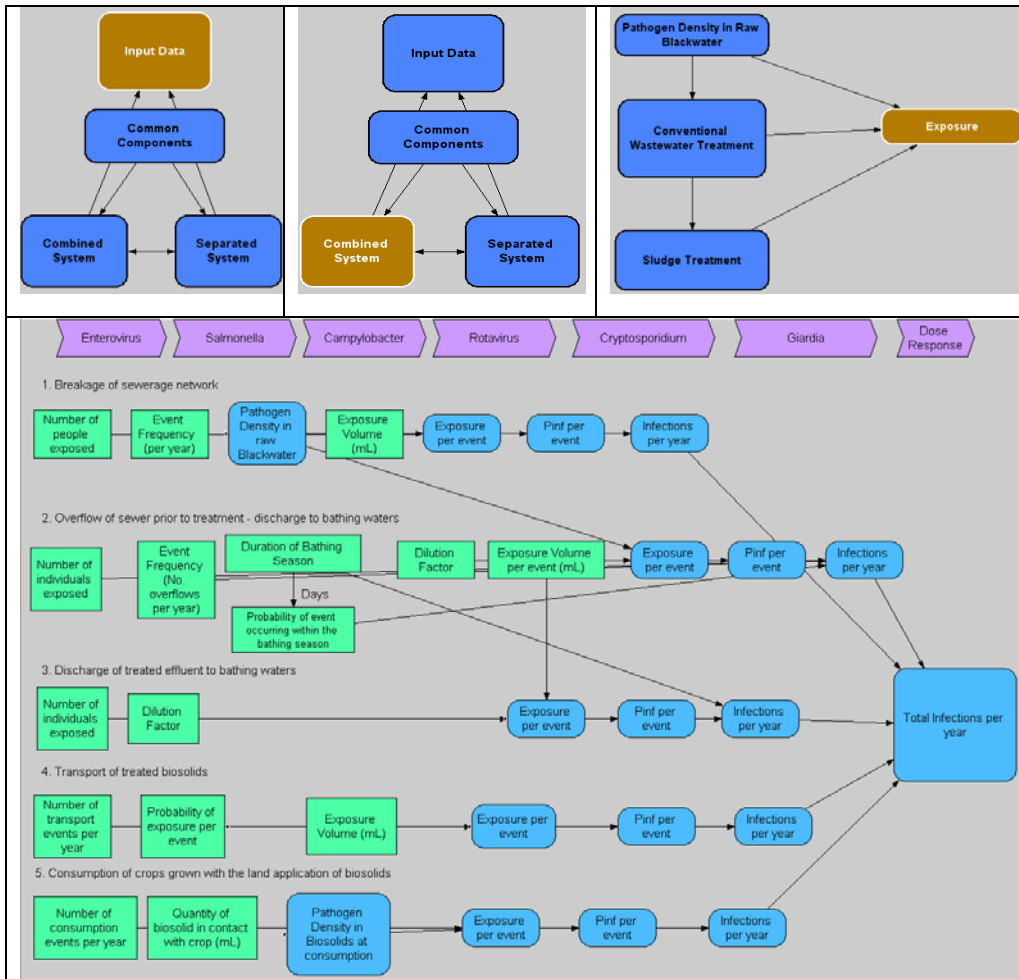


Figure 3 Example influence diagrams within the MRA Tool: all the *Input Data* (top left) within this influence diagram is illustrated in Figure 4; *Combined System* highlighted (top centre) and when the user double clicks it the figure on the top right is revealed; and similarly within the *Exposure* influence diagram, information (bottom diagram) for the five exposure points and range of reference pathogens assessed in the ‘combined system’ to estimate annual infections.

As a tool to aid in selecting treatment options, alternative systems can be compared based on relative levels of infection risk, acknowledging the uncertainties in each. Hence, existing and hypothetical systems can be compared, and when integrated with other assessments (environmental, economic, social and technological) can provide management information (e.g. ‘scorecard’ for each option). During a multi-criteria decision aided (MCDA) process (van Moeffaert, 2003), the MRA tool output can further inform the various stakeholders

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

involved. In such multi-criteria processes, qualitative rankings are all that are generally needed.

One of the advantages of using Analytica[®] is that there is a freely available version of the software to run constructed models, such as the MRA tool. It is envisaged that free versions of the tool will be made available in the medium term, but beta testing of specific systems is currently available through discussion with the authors.

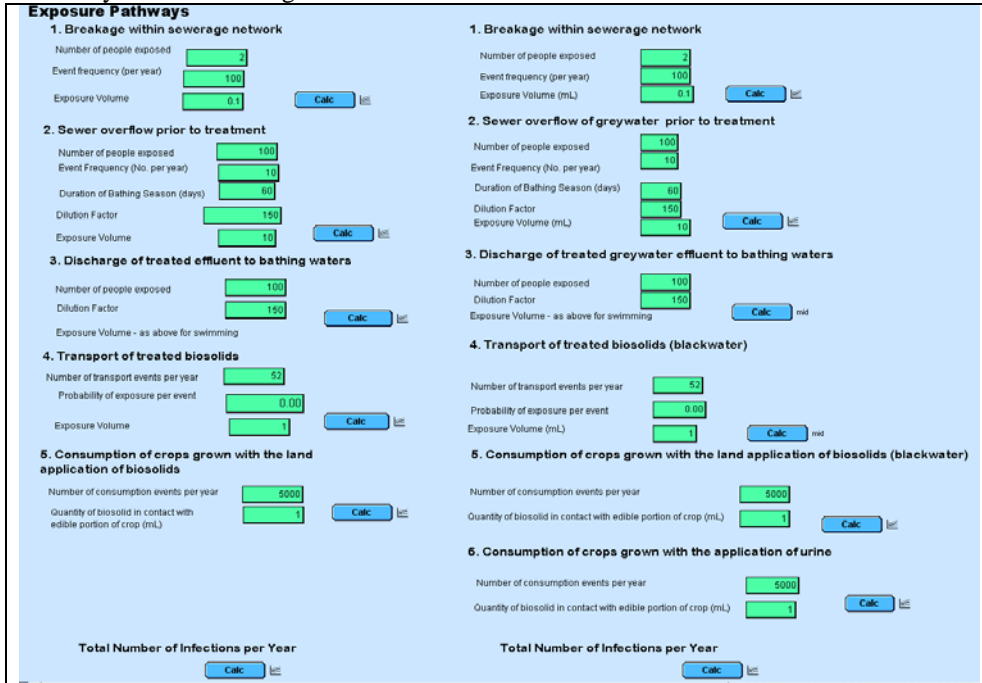


Figure 4 Example influence diagram within the *Input Data* (influence diagram illustrated top left, Figure 3) used to assess the ‘Combined System’ (left) and separated (right). Each input has default values which can be user-changed and the effect shown (within the ‘Calc’ boxes)

Acknowledgements

The authors wish to thank the various members of the Urban Water Programme who have contributed to discussions in the development of the MRA tool, and in particular Erik Kärrman, Daniel Hellström, Håkan Jönsson and Per-Arne Malmqvist; as well as initial work undertaken with Simon Fane. This work was financially supported by the Swedish Foundation for Strategic Environmental Research (MISTRA) and carried out within the Swedish research programme “Sustainable Urban Water Management” (Malmqvist, 1999).

References

- Ashbolt, N. J., Grabow, W. O. K. and Snozzi, M. (2001). *In* "Water Quality: Guidelines, Standards and Health. Risk assessment and management for water-related infectious disease, Chapter 13" (L. Fewtrell and J. Bartram, eds), pp. 289-315. IWA Publishing, London.
- Bartram, J., Lewis, K., Lenton, R. and Wright, A. (2005). *Lancet* **365**, 810-2.
- Faechem, R. G., Bradley, D. J., Garelick, H. and Mara, D. D. (1983). "Sanitation and Disease - Health Aspects of Excreta and Wastewater Management". John Wiley & Sons, Chichester.

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

- Fane, S. and Ashbolt, N. J. (2000). In "Water Recycling Australia" (P. J. Dillon, ed.), pp. 11-16. CSIRO Land and Water, Australian Water Association, Adelaide.
- Gerba, C. P., Rose, J. B., Haas, C. N. and Crabtree, K. D. (1996). *Water Research* **30**, 2929-2940.
- Girdwood, R. W. A. and Smith, H. V. (1999). In "Encyclopaedia of Food Microbiology" (R. Robinson, C. Batt and P. Pattel, eds), pp. 487-497. Academic Press, London and New York.
- Haas, C. N., Rose, J. B. and Gerba, C. P. (1999). "Quantitative Microbial Risk Assessment". John Wiley & Sons, Inc, New York.
- Höglund, C., Ashbolt, N. J., Stenström, T. A. and Svensson, L. (2002a). *Advances in Environmental Research* **6**, 265-275.
- Höglund, C., Stenström, T. A. and Ashbolt, N. (2002b). *Waste Management and Research* **20**, 150-161.
- Jakubowski, W., Sykora, J. L., Sorber, C. A., Casson, L. W. and Gavaghan, P. D. (1991). *Water Science and Technology* **24**, 173-178.
- Lodder, W. J., Vinj, J., van de Heide, R., de Roda Husman, A. M., Leenen, E. J. T. M. and Koopmans, M. P. G. (1999). *Applied and Environmental Microbiology* **65**, 5624-5627.
- Malmqvist, P.-A. (1999). *Vatten* **55**, 7-17.
- Malmqvist, P.-A., Ashbolt, N. J., Fane, S., Hellström, D., Jeppsson, U. and Söderberg, H. (2000). In "Second International Conference on Decision Making in Urban and Civil Engineering" (J.-C. Mangin and M. Miramond, eds), vol. 1, pp. 1-13. CUST Clermond-Ferrand, LIP6 Paris and Universit, de Valenciennes, Lyon, France.
- Mead, P. S., Slutsker, L., Dietz, V., McCaig, L. F., Bresee, J. S., Shapiro, C., Griffin, P. M. and Tauxe, R. V. (1999). *Emerging Infectious Diseases* **5**, 607-625.
- Milburn, A., Matsui, S. and Malmqvist, P. A. (2002). *Water Science and Technology* **45**, 195-198.
- Mitchell, G., Gray, S., Shipton, B., Woolley, R., Erbacher, J., Egerton, G. and McKnoulty, J. (2003). *Water Science and Technology* **47**, 1-9.
- NH&MRC and ARMCANZ. (2001). pp. <http://www.health.gov.au/nhmrc/advice/waterbkd.htm>. National Health and Medical Research Council, Canberra.
- NHMRC. (2004). "Australian Drinking Water Guidelines (ADWG)". National Health and Medical Research Council, Canberra.
- Ottoson, T. A. and Stenström, T. A. (2003). *Water Research* **37**, 645-655.
- Rathjen, D., Cullen, P., Ashbolt, N., Cunliffe, D., Langford, J., Listowski, A., McKay, J., Priestley, T. and Radcliffe, J. (2003). "Recycling Water for Our Cities. Report to Prime Minister's Science, Engineering and Innovation Council (PMSEIC), 28th November 2003". Federal Government of Australia, Canberra.
- Stehr-Green, J. K., McCaig, L., Remsen, H. M., Rains, C. S., Fox, M. and Juranek, D. D. (1987). *American Journal of Tropical Medicine & Hygiene* **36**, 338-342.
- Teunis, P. F. M. and Havelaar, A. (2000). *Risk Analysis* **20**, 511-518.
- van der Vleuten-Balkema, A. J., Otterpohl, R. and Preisig, H. A. (2004). In "Proc. 4th World Water Congress, 19-24 of September 2004, Marrakech", pp. CD-ROM. International Water Association, London.
- van Moeffaert, D. (2003). "MultiCriteria Decision Aid in Sustainable Urban Water Management. MSc. thesis. TRITA-KET-IM 2002:26". Dept. of Chemical Engineering and Technology, Royal Institute of Technology, ISSN 1402-7615, Stockholm.
- Westrell, T., Bergstedt, O., Stenström, T. A. and Ashbolt, N. J. (2003). *International Journal of Environmental Health Research* **13**, 181-197.
- Westrell, T., Schönning, C., Stenström, T. A. and Ashbolt, N. J. (2004). *Water Science and Technology* **50**, 23-30.
- Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London

- Wheeler, J. G., Sethi, D., Cowden, J. M., Wall, P. G., Rodrigues, L. C., Topkins, D. S., Hudson, M. J. and Roderick, P. J. (1999). *British Medical Journal* **318**, 1046-1050.
- WHO. (2003a). In "The World Health Report 2002". World Health Organization, Geneva.
- WHO. (2003b). "Guidelines for Safe Recreational Water Environments. Vol. 1: Coastal and Fresh Waters". World Health Organization, Geneva.
- WHO. (2004). "Guidelines for Drinking-water Quality Third Edition. Volume 1". World Health Organization, Geneva.

Ashbolt NJ, Petterson SR, Roser DR, Westrell T, Ottoson J, Stenström TA (2006). Microbial risk assessment tool to aid in the selection of sustainable urban water systems. In 2nd IWA Leading-Edge on Sustainability in Water-Limited Environments. (Eds MB Beck and A Speers). IWA Publishing, London