Risk Assessment and Health Effects Studies of Indirect Potable Reuse Schemes

Final Report

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This report is a revised and updated version of an original report (CWWT Report 2007/01) that was commissioned and prepared for the Local Government Association of Queensland (LGAQ) in January 2007.

Following a request from the Water Services Association of Australia (WSAA), the LGAQ permitted WSAA to make the report available to its members. CWWT have taken this opportunity to revise small sections of the report in the light of additional information, including the addition of section 5, Treatment Plant Reliability.

WSAA wishes to thank LGAQ for making the report available.

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Executive Summary

Planned potable reuse of municipal wastewater refers to the purposeful augmentation of a potable water supply (surface water or groundwater) with highly treated reclaimed water derived from conventionally treated municipal effluents. In 'indirect' potable reuse schemes, the mix of reclaimed and traditional source waters receives additional treatment prior to distribution to customers.

Municipal wastewaters contain a complex mixture of chemicals and microbiological organisms. As a result, they pose particular challenges for assuring the safety of their use as sources of potable water. These challenges have been addressed by the incorporation of Advanced Water Treatment (AWT) processes that provide a level of treatment that is not normally used in either existing sewage treatment plants currently discharging into Australia's rivers and oceans or drinking-water treatment plants currently operating on water abstracted from Australia's aquifers, rivers or dams.

Planned indirect potable recycling schemes have been implemented and assessed in terms of their human safety in the USA since the 1960s. A number of major case studies are presented in this report including:

- Montebello Forebay Groundwater Recharge Project (California)
- Potomac Estuary Experimental Water Treatment Plant (Washington DC)
- Denver Direct Potable Reuse Demonstration Project (Colorado)
- San Diego Total Resources Recovery Project (California)
- Tampa Water Resource Recovery Project (Florida)
- Singapore Water Reclamation Study "The NEWater Study"

The planned potable water recycling schemes provided different levels of advanced water treatment, ranging from simple filtration and disinfection in the early studies conducted on the Montebello Forebay, through to granular activated carbon (GAC), reverse osmosis (RO) and ozonation used in schemes located in Colorado and Florida. Notwithstanding this, the health-effects studies from each project are extremely encouraging in terms of the potential safety of planned potable water recycling in Australian cities. In spite of comprehensive investigations, no clear deleterious effects have been identified. Furthermore, waters treated in preparation for recycling were routinely shown to be of equal or greater quality than traditional potable water sources. This applies to both microbial and chemical water quality. Risks associated with indirect potable reuse (while never zero) are successively decreased with increasing levels of treatment.

Specific conclusions from this study are:

1. Despite more than forty years experience, no clear deleterious health effects from planned indirect potable recycling schemes have been observed.

2. As judged by potable water standards the microbial and chemical quality of water intended for indirect potable recycling is generally very high even before its release into the natural environment and further drinking-water treatment.

3. Advanced treatment processes such as reverse osmosis and advanced oxidation are highly effective barriers to recently identified chemicals of concern such as the pharmaceutically active steroidal hormones and molecules like NDMA and 1,4-dioxane which can be difficult to remove from water using traditional treatment processes.

4. Unplanned, or incidental, indirect potable water recycling is common in many developed countries including Australia. The manner and extent to which water is unintentionally indirectly used for potable purposes is distinguishable from planned indirect potable recycling schemes primarily by lower levels of treatment involved and less stringent approaches to water quality monitoring and risk management. Therefore, it should be acknowledged that the level of stringency applied to planned indirect potable water recycling schemes is well beyond that which is common international practice and already occurs in water supplies in Sydney, Brisbane and Melbourne.

5. Treated municipal wastewaters are complex sources of potable drinking-water and differ from natural source waters in several major ways. For example, the range of potential contaminants in municipal wastewaters is significantly greater than in well protected environmental waters. Furthermore, concentrations of chemical and microbial contaminants can fluctuate during events which may be difficult to detect by conventional monitoring (e.g. as a result of gastrointestinal illness in the community). Accordingly, there is a need for the application of more comprehensive risk management regimes to protect human health than may normally be applied for traditional water sources.

6. A range of new methods for risk assessment have been introduced worldwide to better and more quantitatively assess microbial and chemical risks associated with drinking-water generally. These are applicable to indirect potable recycling and their application in this context is already underway especially in the USA.

While studies undertaken overseas bode well for the safety of recycled water generally, exactly how effectively these studies can be translated to potential Australian schemes is less clear. Water sources will differ and water treatment processes will differ. Furthermore, environmental barriers (surface water or groundwater environments) may differ significantly from scheme-to-scheme. Therefore, in order to ensure the full protection of public health, a comprehensive health assessment should be undertaken specifically for any planned Australian scheme. Australian health risk assessment guidelines such as those published by the enHealth Council provide guidance on how such risk assessments should be undertaken. More specific guidance is anticipated in Phase 2 of the National Guidelines for Water Recycling which is undergoing development during 2007.

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1 Introduction

Planned potable reuse of municipal wastewater refers to the purposeful augmentation of a potable water supply (surface water or groundwater) with highly treated reclaimed water derived from conventionally treated municipal effluents. In 'indirect' potable reuse schemes, the mix of reclaimed and traditional source waters receives additional treatment prior to distribution to customers.

Indirect potable reuse differs from direct potable reuse where highly treated reclaimed water is introduced 'directly' into the drinking-water system without further treatment. Windhoek in Namibia is the only community that has a direct potable reuse scheme (du Pisani, 2005). The practice has not been adopted by any other community and is not being considered as a solution to water supply problems in Australia or overseas. Notwithstanding this, significant health studies have considered the feasibility of putting treated wastewater directly back into the distribution system without further treatment.

Planned indirect potable reuse differs from the current situation experienced by many communities in Australia where consumers are already exposed to treated wastewater water via existing drinking-water systems. This situation is commonly referred to as 'unplanned' or 'incidental' potable reuse, and occurs where the water source used to supply drinking-water receives wastewater as a result of an upstream discharge. In most situations, there is significant dilution of the treated wastewater with the catchment source water which lowers risk profiles. Examples where incidental reuse occurs in Australia include:

- Lake Burragorang (Warragamba Dam) which services Sydney and receives upstream effluents from Goulburn and Lithgow;
- The Nepean River (Western Sydney), which services the North Richmond Drinking-water Treatment Plant and receives effluents from the Penrith Sewage Treatment Plant;
- Sugarloaf Reservoir which services Melbourne and receives effluent from Olinda Creek Sewage Treatment Plant;
- The Mount Crosby Weir system which services Brisbane and receives effluent from Fernvale, Esk, Lowood, Toogoolawah, Gatton and Laidley; and
- The City of Adelaide draws part of its supplies from the Murray River, to which is discharged treated effluents from towns along the Murray and Darling River systems.

Planned potable water reuse is a relatively recent topic of public discussion in Australia. However, it is not such a recent topic in some other parts of the world. For example, planned indirect potable recycling schemes have been implemented and assessed in terms of human safety in the USA since the 1960s (Frerichs, 1984).

Major population centres with established planned indirect potable reuse schemes include Singapore, Orange County (California) and the Upper Occoquan region in Virginia (USA). Singapore operates four plants at Bedok, Kranji, Seletar and Ulu Panda producing a total of approximately 200 megalitres per day. The majority of the treated water is supplied to industry, including the micro-processor chip manufactures, as high quality process water. Presently, between 1-2 per cent of the water is returned to the island's raw water reservoirs at Kranji, Bedok and Seletar. However, in the future under the Four National Taps Programme, NEWater will supply up to 15 per cent of the islands water supply (Tortajada, 2006). The Upper Occoquan Sewage Authority in Virginia produces close to 200 megalitres of recyclable water per day, which is discharged into the Upper Occoquan reservoir to supply nearly one million people in the area around Washington DC. Orange County in California has operated an indirect potable reuse scheme since 1976. The Orange County scheme is currently undergoing expansion to be recommissioned in 2007 to supply an anticipated 264 megalitres of recyclable water per day.

In the late 1990s, the US National Research Council (NRC) identified a need to more fully assess the viability, health effects, and safety of potable water reuse. To do this, the NRC appointed a committee with expertise in environmental and chemical engineering, microbiology, risk assessment, epidemiology, and toxicity to evaluate these issues. The NRC published the committee's findings in 1998 (National Research Council, 1998). The report's conclusion was that "…planned indirect potable reuse is a viable application of reclaimed water –but only when there is careful, thorough, project-specific assessment that includes contaminant monitoring, health and safety testing, and system reliability evaluation." Much of the information relied upon by the committee to arrive at that conclusion is described in some detail in this current report. Further detail is also provided, particularly from some studies published more recently than the NRC document.

1.1 Purpose of this report

This report is based on an original report prepared by the Centre for Water and Waste Technology (CWWT) for the Local Government Association of Queensland (LGAQ). The intended purposes of the report and the associated services performed by the CWWT were to:

1) Review currently available information pertaining to risk assessment and potential health impacts of indirect potable water recycling schemes;

2) Consider the implications of these findings for the development of indirect potable water recycling in South East Queensland.

The report does not cover all aspects or forms of recycled water. It is limited primarily to planned indirect potable recycling schemes and only introduces and discusses other water recycling schemes in so far as the information is relevant to indirect potable recycling.

Following permission by LGAQ to distribute the report to members of the Water Services Association of Australia, CWWT took the opportunity to update the report in the light of additional information and specifically with the addition of section 5, Treatment Plant Reliability.

The report content is not, and should not be considered, an opinion concerning issues not covered by the scope of this report. This report has been prepared on behalf of and for the exclusive use of the LGAQ, and is subject to and issued in connection with the provisions of the agreement between CWWT and the LGAQ. The CWWT accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon this report by any third party.

2 Identification and management of contaminants in water

Hazardous substances in drinking-water can be classified as one of two general types. These are chemical hazards and pathogenic hazards, which are considered separately below.

2.1 Chemical hazards

Chemical hazards consist of a wide range of naturally occurring and synthetic, organic and inorganic species. They include industrial chemicals, chemicals used in households, chemicals excreted by people and chemicals formed during wastewater and drinking-water treatment processes. The risks posed to human health by chemicals are also variable. Some chemicals may be acutely toxic, meaning that they impart toxic effects in a short period of time subsequent to a single significant dose. Others may be chronic health risks, meaning that long periods of exposure to small doses can have a cumulative effect on human health.

Some key classes of chemicals of concern include heavy metals, synthetic industrial organic chemicals, volatile organics, pesticides or their metabolites, algal toxins, disinfection byproducts, radionuclides, pharmaceuticals, estrogenic and androgenic hormones, and antiseptics. Each of these classes are briefly discussed in the following paragraphs.

Heavy metals may be present in raw wastewaters as a result of industrial discharges to sewers. Some heavy metals such as cadmium, chromium and mercury have been associated with human health concerns.

Depending on the catchment area, and the extent of the trade waste programme to control chemicals at the wastewater source, a very wide range of synthetic industrial chemicals are often measurable in raw sewage that flows into the sewage treatment plant (STP). Examples include plasticisers and heat stabilisers, biocides, epoxy resins, bleaching chemicals and byproducts, solvents, degreasers, dyes, chelating agents, polymers, polyaromatic hydrocarbons, polychlorinated biphenyls and phthalates. Many of these chemicals are known to be toxic to a diverse range of organisms including humans.

Volatile organic compounds (VOCs) are widely used as industrial solvents. Many are constituents of petrochemical products, and a number of halogenated compounds may be formed as byproducts of chlorine disinfection. Some VOCs are suspected to be teratogenic or carcinogenic to humans. Because of their high potential to contaminate traditional potable water sources and supplies, they are tightly regulated in drinking-waters. Many of them are environmentally conservative, so careful control will be particularly important for planned indirect potable reuse schemes.

Pesticides may enter municipal wastewater systems by a variety of means including stormwater influx and illegal direct disposal to sewage systems. Additional routes, of unknown significance, include washing fruit and vegetables prior to household consumption; insect repellents washed from human skin; flea-rinse shampoos for pets; washing clothes and equipment used for applying pesticides. Pesticides have been designed and used to have detrimental effects on a wide range of biological species.

Algal toxins such as microcyctins, nodularins, cylindrospermopsin and saxitoxins are all produced by freshwater cyanobacteria (blue-green algae). Under suitable conditions, cyanobacteria may grow in untreated or partially-treated wastewaters, producing these and other toxins. Numerous algal toxins have been implicated as having serious impacts on human and animal health by the consumption of contaminated water. Many of these toxins are hepatotoxic and some are neurotoxic.

Disinfection byproducts are formed by reactions between disinfection agents and other constituents of water. High initial concentrations of organic components or ammonia may lead to excessive production of disinfection byproducts. The vast majority of the compounds of concern originate from chlorine-based disinfectants. However, some (such as formaldehyde) can be produced by other oxidising disinfectants such as ozone. Some more recent byproducts of concern include bromate and epoxides (from ozone treatment) and nitrosodimethylamine (NDMA). Disinfection byproducts have been the source of much public health concern due to their widespread identification in water produced at drinking-water treatment plants.

Radionuclides may enter sewage by natural run-off or as a result of medical or industrial usage. In most parts of the world, radium is a constituent of bedrock and hence a natural contaminant in groundwater. In some cases, radium is removed from drinking-waters by coagulation and the concentrated sludge is transferred to sewage systems. Radionuclides are carcinogenic and mutagenic substances.

Pharmaceuticals (and their active metabolites) are excreted to sewage by people as well as direct disposal of unused drugs by households. Since pharmaceuticals are designed to instigate biological responses, their inherent biological activity and the diverse range of compounds identified in sewages (and the environment) have been cause for considerable concern during the last decade. Specific concerns have not been raised for most classes of drugs, but issues regarding potent endocrine disrupting compounds, aquatic toxicity and the spread of antibacterial resistance have significant ecological implications.

Natural steroidal hormones such as oestradiol, oestrone and testosterone are also excreted to sewage by people. During the last two decades, natural steroidal hormones have been widely implicated in a range of endocrinological abnormalities in aquatic species impacted by sewage effluents. Impacts have been identified by a number of bio-indicators, most commonly elevated production of the protein vitellogenin which is an essential precursor for egg production in fish.

Antiseptics such as triclosan are commonly used in face washes and anti-gum-disease toothpaste. Following trends from the USA, they are increasingly being used in a wider range of household products including deodorants, antiperspirants, detergents, dishwashing liquids, cosmetics and anti-microbial creams, lotions, and hand soaps. Triclosan has been detected in sewage effluents and impacted surface waters as well as in the bile of wild fish in proximity to sewage treatment plant effluents. Toxic effects of triclosan have been reported for a diverse range of aquatic organisms.

2.2 Pathogens

The main groups of pathogens of concern in recycling of water are parasitic protozoa such as *Cryptosporidium* and *Giardia*, bacterial pathogens such as *Campylobacter* and *Salmonella* spp., viruses such as Norovirus and Hepatitis virus and helminth eggs (parasitic worms). These groups of pathogens are relatively long lived in the natural environment compared with pathogens as a whole. They do not have fixed maximum lifetimes but rather lose viability or infectiousness over time. In practice this means that a proportion of the population will ‘die’ over a given and measurable period. For example if one starts with 100 *Salmonella* per litre on day 0, one might see 10 per litre on day one, 1 per litre on day 2 and 0.1 per litre on day 3. This species would be considered to have a “T_{90}” (time for 90% to die off) of 1 day. These pathogens of concern typically have T_{90}s of several hours to months and even years under optimum conditions in the natural environment (e.g. cool temperatures, little or no sunlight).

Pathogen groups and species differ from one another between, and within, the same genus in several important respects which influence the risk of their infecting people. Important differences include:

- Size : Helminth eggs may be > 0.1 mm and visible to the naked eye where as viruses may be 10,000 smaller in diameter (10 nm) and less than one billionth the volume.
- Reproduction: Viruses cannot reproduce in the natural environment but some bacteria such as *Salmonella* can grow in the environment;
- Abundance: Viruses are excreted by infected individuals in numbers which may be as much as 1,000,000 times greater than the highest rates for protozoa. Helminths tend to be less abundant, and more easily removed from water, than protozoa. Accordingly, if protozoa are controlled, it is generally assumed that Helminths are even more so.
- Infectivity: Following ingestion the probability of being infected by a single *Salmonella* may be as small one chance in a million, whereas for some viruses it may be greater than 1 chance in 10.
- Resistance to inactivation in the environment and environmental conditions: Solar radiation may increase inactivation rates by up to 1000 fold for some organisms.
- Response to removal and inactivation processes used in water treatment plants: Protozoa are relatively well removed by physical sand filters but viruses pass easily through. Bacteria are easily killed by chlorine whereas *Cryptosporidium* are virtually unaffected by normal doses.

The detection of pathogens in water is still notoriously expensive and difficult so faecal bacterial indicators, which are present in wastewater at higher concentrations than pathogens, are commonly assayed for in their place. Common ‘indicators’ are *Escherichia coli* (abbreviated to *E. coli*), Enterococci, *Clostridium perfringens* and total coliforms (*E. coli* like bacteria). These are not pathogens but they have been very important historically in managing pathogens because their presence can be taken to indicate the likely presence and general abundance of pathogenic types. Measurements of indicator concentrations have been used for water quality objective setting in a range of contexts and guidelines.

Conceptually, water-borne pathogens have been recognised as posing a serious threat to human health for over a century since the original development of germ theory and epidemiology in the late 1800s. The separation of untreated sewage from drinking waters and the introduction of filtration and chlorine disinfection into drinking-water supplies has been credited as the single most effect public health intervention that has saved many millions of lives over the last 100 years by preventing the spread of water borne disease. However it is only in the last 10 to 20 years that a sound, detailed and quantitative picture of the range of hazards and risks, and the ecology of pathogens has emerged in the scientific literature.

Much of this change has been due to technological developments. In addition to the nucleic acid technology which has revolutionised microbial taxonomy and made viral detection close to routine, there have been a range of other contributing developments including the:

- Development of methods for extracting microbial cells from water volumes as large as one kilolitre;
- Application of quantitative statistics to the theory of microbial risk assessment (known as Quantitative Microbial Risk Assessment or QMRA); and

- The development of systematic frameworks such as Hazard Analysis and Critical Control Point (HACCP) techniques for identifying and managing risks.

2.3 Water quality management theory and practice

Scientific understanding of risks associated with toxic chemicals and water borne pathogens has developed rapidly during the last few decades. As a result, water management can -in theory- be much more comprehensive and knowledge based than it has been in the past. Complementing this, much more effective water treatment technologies have been developed such as membrane filtration and advanced oxidation techniques.

On the other hand, analytical developments, periodic disease outbreaks, and more systematic systems analysis based on management principles have exposed many gaps in traditional approaches to toxic chemical and pathogen management and generated new demands requiring greater due diligence and improved risk management. For example, as recently as the mid 1990s, the achievement of water without coliform or enterococci indicators in tap water was accepted within the water industry as sufficient for customer protection. The limitations of this paradigm of what constitutes a microbially hazardous situation were spectacularly demonstrated by the 1994 Milwaukee *Cryptosporidium* waterborne outbreak where over 400,000 people were affected and the 1998 incident in Sydney even though the latter did not lead to any clear illness or infection cases ascribable to the *Cryptosporidium* and *Giardia* detected analytically.

In response to these incidents and developments in water management theory there have been significant advances in best practices for the management of microbial and chemical water quality during past decade. The best recognised development in Australia has been the introduction of 'Water Safety Planning'(via the addition of the Framework for the Management of Drinking Water Quality in the 2004 Australian Drinking Water Guidelines) and introduction of risk assessment techniques pioneered in the food industry where similar hazards are encountered. These developments have been widely introduced only in the last 10 years since the publication of the NRC (1998) report and are still being incorporated into water management best practice. Their relevance to potable water reuse is as follows:

1. They are fully consistent with all the recommendations in the NRC (1998) report and indeed work in potable water management generally has addressed many of the NRC recommendations and highlighted knowledge gaps;
2. Excellent guidance now exists for a much more rigorous management regime for potable water supply in Australia and any potable reuse would need to be managed consistently;
3. Best practice in past potable reuse cases may not be best practice now.

Updated guidelines for water and health management reflect these developments and are placing increasing demands on water managers and other decision makers including regulatory agencies.

2.4 Aims of advanced water treatment

Indirect potable reuse projects rely on a suite of Advanced Water Treatment (AWT) techniques and processes that are not widely used in existing sewage treatment plants or drinking-water treatment plants. AWT processes have varied potentials and limitations in the treatment and removal of chemical and microbial contaminants in water. The selection and compilation of the available treatment options will depend on a diverse range of economic, environmental and social constraints and targets.

For indirect potable recycling, water quality targets need to be determined in terms of contaminant concentrations that are deemed to be fully protective of human health. The aim of AWT processes then, must be to reliably produce water with contaminant levels below those known or reasonably suspected to cause adverse human health outcomes.

No potable water supply (from any source) can currently be guaranteed to contain only molecules of H_2O and no other species, regardless of how minute the concentrations of other species may be. The goal of advanced water treatment is not to provide such guarantees, but to achieve water qualities equal to or greater than accepted standards, including standards currently being developed for augmentation of drinking water supplies with recycled water. It is now possible to design advanced water treatment systems capable of ensuring concentrations of any identified contaminants meet any standards that may be articulated. For example, processes such as membrane filtration and activated carbon adsorption are capable of removing organic carbon concentrations to levels sufficiently low that subsequent advanced oxidation processes may be used to efficiently mineralise remaining species. However, in practice, the overall removal of chemicals will be determined by treatment plant design and operating conditions such as membrane system design and advanced oxidation applied doses. The selection and sequence of AWT process that are used in indirect potable reuse schemes is determined by the prevailing regulatory and environmental considerations for each project.

3 Evaluation of risks from chemical contaminants

Estimations of human health risks from exposure to specific chemicals are generally based on extrapolations of the results of toxicological experiments on animals. These extrapolations provide standard human 'dose-response' relationships for the chemicals. When considered along with estimations of human exposure to the chemicals, the risk from that exposure can be quantitatively estimated.

This approach has generally been used by health authorities for the determination of safe levels of specific chemical contaminants in drinking-waters. The approach is considered to be generally very effective for drinking-water derived from relatively pristine sources or sources that have been used for a long time without evidence of harm. However, current drinking-water standards are not intended to ensure the safety of less traditional water sources such as reclaimed water. Furthermore, they should not be assumed to do so since wastewater may introduce new, unknown or unquantified sources of contamination. Even if the operators of a water reuse system could identify all of the organic chemical components in the processed wastewater, there would be scant toxicological data available for most of them and thus little basis for assigning risks. Because of this, and because many compounds in wastewaters are simply unidentifiable, it has been suggested that toxicological testing of reclaimed wastewater may be the only way to ensure the water's chemical safety (National Research Council, 1998). Such testing will generally require at least a pilot-scale advanced water treatment plant to be constructed in order to provide relevant samples for testing.

Screening level risk assessments can be undertaken prior to the construction of any plant in order to assist in the identification of issues that may be relevant for more detailed risk assessment. A comprehensive example of a screening level health risk assessment was recently undertaken for Sydney Water's 'Replacement Flows Project' (Roser *et al.*, 2006). The scheme was concerned primarily with the substitution of environmental flows with highly treated water from three of Western Sydney's sewage treatment plants. The risk assessment did however estimate the health risks arising from the consumption of chemical (and pathogen) loads likely to be emitted by the plant with and without further treatment as two of the possible exposure scenarios. The Screening Health Risk Assessment for this project was undertaken by initial consideration of historical monitoring data of chemical loads in the raw water source (tertiary treated effluent). Consideration of expected removal efficiencies of individual chemicals during advanced treatment processes and environmental residence allowed for estimations of human exposure. Comparison of this anticipated exposure with known dose-response relationships for individual chemicals provided an estimation of health risks associated with each one.

Chemical dose-response considerations form the foundation of most modern drinking-water standards. However, direct chemical measurements are limited in that they will only identify the chemicals that are specifically targeted. This can only ever be a small subset of the all the chemicals that may possibly be present. Numerous decades of water quality monitoring have provided a reasonable (though always improving) understanding of which chemicals are likely to be present in drinking-waters of traditional sources at significant enough concentrations to present an elevated level of risk.

Other important limitations of chemical species monitoring are that the full additive toxicity of a large number of chemicals, each present at very low concentrations may not be identified unless each of the individual species is analysed for and determined to be present at concentrations greater than analytical detection limits. Finally, there is some concern that the toxicity of complex mixtures is poorly understood and in some cases may amount to more (or less) than simply additive impacts from each of the contributing species.

Toxicity testing of whole-effluent mixtures may be undertaken by a variety of biological assays. Assays may generally be distinguished as *in vivo* or *in vitro*. These are Latin terms referring to whether the test is undertaken within a living organism (*in vivo*) or external to it such as testing of cells in a test-tube (*in vitro*). Some *in vivo* and *in vitro* tests that have been used for testing for the presence (or effects) of toxic chemicals in complex water mixtures include the Ames test, sister chromatid exchange assays, the micronucleus test, the 6-thioguanine resistance assay, as well as testing for the induction of adenomas, toxic effects or bioaccumulation.

The Ames test is commonly used to determine whether a chemical is able to cause cell mutations to the bacteria (Salmonella typhimurium) that are used in the test. Such chemicals are classified 'mutagens', the significance of which is the assumption that mutagens may also turn out to be human carcinogens. This assumption is imperfect since there are substances that are known to give a positive Ames test result, yet are not carcinogenic and others which are carcinogenic, but give a negative Ames test result. Nonetheless, the Ames test remains a valuable screening tool due to its ease and low cost.

Sister chromatid exchange assays are an *in vitro* test for cell mutagenicity. Animal cells have most of their DNA packaged into structures called chromosomes. At certain stages of reproduction (replication), chromosomes consist of two identical strands called chromatids, which are joined at what is called a centromere. These two chromatids (from a single chromosome) are referred to as sister chromatids. Sister chromatid exchanges refer to the breakage of both chromatids, followed by an exchange of whole DNA duplexes. This process is efficiently induced by mutagens that form DNA adducts or that interfere with DNA replication. The occurrence of sister chromatid exchanges has been correlated with recombinational repair and the induction of point mutations, gene amplification and cytotoxicity.

The micronucleus test is a similar assay to the sister chromatid exchange assay. Micronuclei are small bodies formed in cells when chromosomes fail to become incorporated into daughter cell nuclei during cell division. Because genetic damage to chromosomes leads to micronucleus formation, the incidence of micronuclei serves as an index of such damage. Detecting micronuclei is much faster and less technically demanding than other forms of chromosomal aberrations and micronuclei arise from two important types of genetic damage. Accordingly, the micronucleus assay has been widely used to screen for chemicals that cause these types of damage.

The 6-thioguanine resistance assay measures mutagenic inactivation of a certain gene (known as HGPRT) in a cell line established from hamster ovaries. Similarly, the mammalian cell transformation assay measures the ability of chemicals to induce changes to a certain strain of cells (called C43H10T1/2 cells) that are injected into immunosuppressed mice.

Lung adenomas (tumours) can be induced *in vivo* by the presence of carcinogenic chemicals and thus the rate of induction in susceptible species can be a useful assay for the relative carcinogenicity of a chemical or mixture of chemicals. The induction of adenomas in the lungs of strain A/J mice is a widely used as a test for carcinogenicity of chemicals.

One particular outbred line of mice has been used extensively for carcinogenesis experiments. These strains are known as SENCAR mice, which is derived from SENsitivity to CARcinogenisis. SENCAR mice are used to test for the presence of carcinogens and/or promoter agents to induce carcinogenesis.

Other live-animal testing may include monitoring for subchronic toxicity (leading to death or other end-point indicators) or fetotoxicity. Fish biomonitoring may also be employed to test for effects of bioaccumulating chemicals as well as a range of toxic endpoints.

3.1 Toxicological testing case studies

Some examples of previous toxicological studies and their findings are summarised in the following sections. Much of this information is derived from the NRC report and supplemented with additional data from its preceding sources as well as later case studies and investigations. Where possible, original source material is cited, however in some cases, the original reports were not available to the current authors and the expert interpretations of the NRC committee have been relied upon.

It should be remembered that the schemes described in this section are variable in terms of their source water and advanced treatment processes. Only a few of the schemes incorporated reverse osmosis membrane treatment and none of them used advanced oxidation treatment at the time of the studies. While the Singapore scheme employs ultraviolet (UV) disinfection, this is not advanced oxidation since no means is included to enhance the formation of hydroxyl radicals. Advanced oxidation using UV with hydrogen peroxide has now emerged at some schemes (notably Orange County and West Basin in California) in response to the identification of two new contaminants, N-nitrosodimethylamine (NDMA) and 1,4-dioxane. UV and hydrogen peroxide has been shown to be highly effective at destroying these compounds (Stefan & Bolton, 1998; Stefan & Bolton, 2002).

3.1.1 Montebello Forebay Groundwater Recharge Project (California)

Potable water supplies have been intentionally replenished with recycled water in Los Angeles County of California since the 1960s. The Montebello Forebay Groundwater Replenishment Project (MFGRP) is located within the Central Groundwater Basin in Los Angeles County, where the Districts' recycled water, blended with imported river water and local storm runoff, have been used for replenishment since 1962. Stormwater was diverted through a series of tee levees constructed in the San Gabriel River. Recycled water was produced at an existing sewage treatment plant to a secondary standard and chloraminated to meet the California Department of Health requirements for groundwater recharge. In 1977 media filtration was added to enhance virus inactivation during final disinfection. Stormwater and recycled water were returned to the groundwater supply through dedicated percolation basins that were operated to maintain a distinct vadose zone (unsaturated zone) between the bottom of the basin and the top of the water table.

A five-year toxicological study was initiated in 1978 to evaluate possible health effects from the MFGRP (Nellor *et al.*, 1984). At the time of the study, recycled water comprised around 16 per cent of the total inflow to the groundwater basin. The toxicological study sought to detect, isolate, characterise, and if possible, trace the origins of any previously unidentified carcinogens in the recycled water sources (three sewage treatment plant effluents) and well waters.

The Ames test and *Salmonella* tester strains (TA98 and TA100) were used to screen for mutagenic organics in 10,000 to 20,000-fold concentrates of reclaimed water prior to groundwater replenishment, stormwater, imported water, and also in chlorinated and unchlorinated groundwaters (Nellor *et al.*, 1984). Some mutagenic activity was detected in 43 of the 56 organic concentrates tested, including at least one from each source. The level of mutagenic activity was (in decreasing order):

Storm runoff > dry weather runoff > reclaimed water > ground water > imported surface water

The majority of the mutagenic activity appeared to be derived from chlorination processes. No relationship was observed between the estimated proportion of reclaimed water in the various wells and strength of mutagenic responses. Attempts were made to identify specific chemical species that may be responsible for the observed mutagenicity in groundwater samples, however these efforts were not conclusively successful.

Based on the results of the Health Effects Study (Nellor *et al.*, 1984) and recommendations of the State of California Scientific Advisory Panel (Robeck, 1987), authorisation was given in 1987 by the Regional Water Quality Control Board to increase the annual quantity of recycled water used for replenishment. The water reclamation requirements for the project were revised again to allow for even greater recharge volumes and up to 50 per cent reclaimed water in any one year providing that the running three year total did not exceed 35 per cent reclaimed water. In 2007, the Los Angeles County Sanitation District continues to divert tertiary quality wastewater and captured stormwater into the groundwater recharge basins in the Montebello Forebay. This water contributes to the groundwater supply in Los Angeles County.

3.1.2 Potomac Estuary Experimental Water Treatment Plant (Washington DC)

In the 1980s, the Potomac Estuary Experimental Water Treatment Plant (EEWTP) was constructed adjacent to a conventional sewage treatment plant on the Potomac Estuary in Washington DC. The US Army Corps of Engineers undertook a research program to determine the feasibility of using the EEWTP to produce potable water as a potential source for the city (Montgomery, 1983).

Based on potential future water use plans, an influent mix of 50 per cent estuary water and 50 per cent nitrified secondary effluent was selected for further treatment at the EEWTP. The blended water underwent treatment by a series of processes that are generally considered to be conventional drinking-water treatment processes (such as flocculation, sedimentation and disinfection) as well as some additional processes including filtration and granular activated carbon adsorption. Advanced water treatment processes that would nowadays be considered for planned potable recycling (such as reverse osmosis or advanced oxidation) were emerging technologies at this time and not included in trials at the EEWTP. Three overall treatment trains were tested and these were compared to current water supplies from three local conventional drinking-water treatment plants.

Two short-term *in vitro* toxicology tests were selected to characterise the produced and conventional waters. These tests were undertaken with concentrated (150-fold) organic extracts used in the Ames *Salmonella* / microsome test, and a mammalian cell transformation test. Results showed low levels of mutagenic activity in the Ames test with the EEWPT-produced water exhibiting less activity than the three conventional drinking-water plants. The cell transformation test showed a small number of positive samples with no difference between the EEWPT water and the conventional drinking-water.

Within the limits of the analytical techniques used and the influent water quality conditions observed it was concluded that the process combinations monitored at the EEWPT were technically feasible for producing a water acceptable for human consumption from a 50 per cent blend of treated effluent (Montgomery, 1983). However, it is important to note that a National Research Council review panel did not support this conclusion on the basis of the limited toxicological tests that were conducted (National Research Council, 1984). This outcome was to have a significant impact in ensuring more thorough assessment of future trials in order to more comprehensively establish safety.

3.1.3 Denver Direct Potable Reuse Demonstration Project (Colorado)

A Potable Water Reuse Demonstration Project was constructed in Denver, Colorado in 1985 (Lauer, 1993). This project's purpose was to examine the feasibility upgrading secondary treated effluent to a potable quality that could be piped *directly* into the drinking-water treatment system. In other words, this project was an assessment of planned direct potable recycling. The influent water for the reuse plant was unchlorinated secondary effluent from the Denver wastewater treatment plant.

During the first three years a number of alternative processes were evaluated in order to select an optimum treatment sequence which was then subject to a two-year animal feeding health-effect study (Lauer *et al.*, 1990). The selected advanced treatment processes included high-pH lime treatment, single- or two-stage recarbonation, pressure filtration, selective ion exchange for ammonia removal, two stage activated carbon adsorption, ozonation, reverse osmosis, air stripping, and chlorine dioxide disinfection (Lauer *et al.*, 1991). Analytical studies compared the water produced by the plant to existing drinking-water standards and to Denver's current potable supply. The recycled water exceeded the quality of Denver drinking-water for all chemical, physical, and microbial parameters tested except for nitrogen, and alternative treatment options were subsequently demonstrated for nitrogen removal (Rogers & Lauer, 1992). Furthermore, the recycled water quality exceeded all state and federal standards for definable constituents.

A comprehensive two year heath effects study was undertaken to investigate chronic toxicity and oncogenicity effects of the reclaimed water using rats (Condie *et al.*, 1994). These tests were conducted using 150-fold and 500-fold reclaimed water concentrates. Denver's current drinking-water was used as a negative control since it is derived from a relatively protected source.

70 male and 70 female Fischer 344 rats were supplied with concentrates of one of three kinds of water. These were drinking-water (DW), reverse osmosis reclaimed water (RO) or ultrafiltration reclaimed water (UF). An additional 70 male and 70 female rats were supplied with distilled water and served as the control group. A further 15 males and 15 females served as the sentinel group.

The parameters evaluated in this study include clinical observations, survival rate, growth, food and water consumption, haematology, clinical chemistry, urinalysis, organ weights, gross autopsy and histopathological examination of all lesions, major tissues and organs.

The incidence and types clinical signs were comparable in all groups of the same sex. There were numerous statistically significant differences between control and treated groups in weekly measurements of body weight, food consumption, and water consumption, but all of these were minor and not consistent with treatment groups throughout the study. Therefore the differences were not considered to be treatment related.

There was a decrease in survival rates in some of the male treatment groups. The toxicological significance of this finding was not known since there was no similar decrease in survival in the female treatment groups. Furthermore, there was no decrease in survival rates in any male or female treatment group in a parallel mouse study.

Clinical pathology, gross pathology, and microscopic pathology conducted at weeks 26 and 65 and at the end of the study (week 104) did not reveal any findings that could be considered to be treatment related. The variety, frequency and severity of spontaneously occurring incidental lesions and neoplasms were within the anticipated range for the age and strain of rat. There was a higher incidence of thyroid 'C' cell adenoma in a group of male rats fed conventional drinking-water concentrates. However, this higher incidence was reported to have been well within the historical range anticipated for this type of neoplasm.

The authors resolved that the administration of concentrates of RO reclaimed water, UF reclaimed water, or Denver's present drinking-water at up to 500 times the concentration of the original water samples to F344 rats over an extended period of the animal's life expectancy did not result in any demonstrable toxicological or carcinogenic effects. On the basis of this study as well as the parallel chronic mouse study and a two-generation reproductive study, it was concluded that the application of AWT process to a secondary treated effluent can produce water that may be safely added to a water supply used as a source of drinking-water for public consumption.

While the focus of this study was on direct potable reuse, it is considered to be of relevance to indirect potable reuse in that the observed safety of the advanced-treated recycled water was determined to be comparable to the traditional raw drinking-water source. This relationship would be unlikely to be affected by subsequent environmental residence or drinking-water treatment.

3.1.4 San Diego Total Resources Recovery Project (California)

The San Diego Total Resources Recovery Project (SDTRRP) was developed with a fairly unique treatment system using channels containing water hyacinths in place of the traditional secondary treatment process. The water hyacinth system was part of the AQUA 2000 scheme with the aim of promoting sustainable wastewater treatment processes. Effluent produced by the water hyacinth plant was comparable with a conventional secondary treatment process. It was further processed in an AWT plant consisting of chemical coagulation and media filtration to produce a tertiary quality effluent that was subsequently demineralised using reverse osmosis and polished using air stripping and carbon adsorption prior to final disinfection with chlorine.

A health effects study was undertaken to compare the SDTRRP effluent with the city's present raw water supply (Thompson *et al.*, 1992; Western Consortium for Public Health, 1992; Olivieri *et al.*, 1996). The study was referred to extensively when the City of San Diego attempted to develop an indirect potable reuse scheme in the late 1990's that would deliver treated wastewater to the San Vicente Reservoir. Water from the reservoir is abstracted and treated prior to distribution to consumers.

The study involved the identification, characterisation and quantification of specific pathogenic organisms and potentially-toxic chemicals. It also included screening for mutagenicity and bioaccumulation of the chemical mixtures present in both water sources. Furthermore, the study included a reliability analysis, using data from the technical performance evaluation of unit processes in the demonstration water reclamation plant (Eisenberg *et al.*, 1998).

Chemical screening and monitoring of SDTRRP effluent and raw drinking-water was carried out over a three year period. The average total organic carbon concentration was 1.37 $mg.l^{-1}$ in the reclaimed water and 9.83 $mg.l^{-1}$ in the raw drinking-water source. A number of inorganic species (boron, calcium, magnesium, manganese, molybdenum, phosphorus, sodium and strontium) were measured in both water sources. Low concentrations of arsenic were identified in raw drinking-water (mean 1.5 $\mu g.l^{-1}$), but not detected in reclaimed water. The only extractable organic compounds measured in either water source were phthalates. In particular, Bis(2-ethylhexyl)-phthalate was identified in reclaimed water ranging from <0.5 μg per litre geometric mean to 7.6 μg per litre arithmetic mean and in raw drinking-water from <0.5 μg per litre geometric mean to 4.2 μg per litre arithmetic mean. Bis(2-ethylhexyl)phthalate is a plasticiser that is commonly found in PVC pipes used in the pilot demonstration plants. Although they were analysed, no polychlorinated biphenyls, pesticides or chlorinated dibenzodioxins/dibenzofurans were identified above detection limits in either water source. Tests were conducted to determine the formation potential of the common disinfection byproducts, trihalomethanes (THM). These tests revealed that the raw drinking-water source had a THM formation potential ten times greater than that of the SDTRRP.

Genetic toxicity and carcinogenicity testing were undertaken in a short-term study using four separate bioassay systems. These were the Ames Assay, Micronucleus Test, 6-Thioguanine Resistance Assay, and Cellular Transformation Assay. The data from these bioassays of organic extracts indicate that the SDTRRP effluent exhibited less genotoxic or mutagenic activity than the low levels observed in the raw drinking-water source.

Fish biomonitoring experiments were undertaken to provide information on chronic exposure to trace contaminants that accumulate in tissue but are not known to be identified by genetic toxicity screening bioassays (de Peyster *et al.*, 1993). Juvenile fathead minnows (*Pimephales promelas*) were exposed to SDTRRP effluent, drinking source water or laboratory-control water in flow-through aquaria. The biomonitoring measurements were survival and growth, swimming performance, and trace amounts of 68 base/neutral/acid extractable organics, 27 pesticides, and 27 inorganic chemicals found in fish tissues after exposure.

Survival of fish in the three water sources during 28-day experiments ranged from 94 to 99 per cent. With longer exposures, survival over the 180-day experiment continued to be 93-99% in the laboratory-control water but fell to 82 per cent in SDTRRP effluent and approximately 50 per cent in the raw drinking-water source. High mortality observed in the raw drinking-water source occurred in the first 5 days after the fish were transferred, and the survival rate in remaining fish over the second 90-day period was still only 65 per cent. This higher mortality could not be explained by chlorination upstream or other wastewater treatment plant records. Mortality in the SDTRRP effluent was gradual, but still occurred mostly within the first 90 days of the 180-day exposure period. During the second 90-day period, the survival rate in the SDTRRP effluent was 96 per cent.

There were no significant differences in weight or standard length attributable to water source after the 28-day exposure. However, after 90 days weight and standard length of SDTRRP and raw drinking-water source fish were statistically different. Fish from the SDTRRP effluent at both 90 and 180 days had significantly lower mean weight and standard length than those from the raw drinking-water source.

In seven comparisons of SDTRRP effluent fish to laboratory control water fish, mean critical swimming speed (CSS) was higher in SDTRRP effluent fish in three trials, lower in three and essentially the same in one. Slightly higher CSS was seen in fish from raw drinking-water compared to laboratory control water in six of the seven comparisons.

The authors of the biomonitoring study postulated that the underlying reasons for better growth, and, probably as a consequence, better swimming performance of fish grown in the raw drinking-water source may be related to ionic composition (de Peyster *et al.*, 1993). They point out that fish are known to thrive better in water containing an abundance of calcium, magnesium and other minerals. SDTRRP effluent did not contain as much of these and other trace elements as the raw drinking-water source because of the use of reverse osmosis process that generally removes more than 95% of monovalent and divalent cations from the feed water. Also, the SDTRRP effluent contained no zooplankton and algae that were common in the raw drinking-water.

The vast majority of the chemicals analysed in fish tissue were below analytical detection limits in samples. SDTRRP effluent and raw drinking-water samples were not readily distinguishable in terms of bioaccumulation of organic chemical contaminants, with the exception of higher pesticide levels in fish from the raw drinking-water. Concentrations of certain inorganic analytes were statistically different between the two sources. Higher lithium in the fish from SDTRRP effluent was reported to be associated with added lithium introduced to the SDTRRP plant during spiking experiments conducted in conjunction with the microbiology component of the health study. However, nickel accumulation in the tissue of fish from SDTRRP effluent was presumed to be a result of original source water (sewage effluent) quality.

Plant reliability was assessed to provide an indication of the ability of the SDTRRP system to consistently achieve the level of treatment that was used for the basis of the health risk assessment (Thompson *et al.*, 1992; Eisenberg *et al.*, 1998). This involved a determination of the reliability of the mechanical systems, characterisation of the treatment process variability, and determination of the probabilities of effluent characteristics to be consistent with specific measured data. A review of summary statistics of the water quality data showed consistent and virtually complete removal of biological indicator organisms, 'conventional' pollutants removal ranging between 87-98 per cent and metal ion removal between 74-91 per cent. These removal ranges were determined to be consistent with other comparable facilities. This statistical analysis and a mechanical reliability was used to indicate that satisfactory contaminant concentrations could be maintained by the treatment plant on a long term basis, with a low probability of exceeding acceptable levels (generally less than 1 in 1000 for individual metals). Results of the mechanical reliability analysis indicated that, over a 30 month period, critical equipment are expected to be operational nearly 100 per cent of the time. Furthermore, the analysis confirmed statistically that observed plant equipment failures do not tend to cause a significant interruption to the operation of the overall plant (Eisenberg *et al.*, 1998).

Chemical spiking studies were conducted at the SDTRRP by dosing the influent waters with a range of chemicals that could potentially enter the treatment plant as a large pulse flow. A summary of the results are provided in Table 1. Regardless of the high concentrations spiked into the system, all chemicals were not detectable in the final effluents of the plant. Accordingly, minimum removals were calculated based on analytical detection limits. Overall, the SDTRRP removed between >99.5 and >99.997 per cent of each of the spiked chemicals (limited only by the analytical sensitivity).

Table 1 Spiked chemical removal efficiency hyacinth ponds and advanced treatment processes at the SDTRRP (Thompson *et al.*, 1992)

	Spike (ug/L)	Hyacinth pond effluent (ug/L)	Removal by pond (%)	Advanced treatment effluent (ug/L)	Removal by advanced treatment (%)	Overall removal by SDTRRP (%)
Chromium	182	74	59.3	<1	>98.6	>99.5
Tetrachloroethylene	900	29	96.8	<0.03	>99.9	>99.997
Tetrachloroethane	224	53	76.3	<0.1	>99.8	>99.996
Trichlorobenzene	813	130	84.0	<0.3	>99.8	>99.996
Tetrachlorobenzene	140	2	98.6	<0.03	>98.5	>99.98
Lindane	70	12	82.9	<0.03	>99.7	>99.96

Finally, a chemical risk assessment was undertaken using the acquired relevant data. The chemical risk estimates in the raw drinking-water source were dominated by arsenic and trihalomethanes (apparently from upstream chlorination and discharge), and in SDTRRP effluents by bis(ethylhexyl)phthalate. Risk calculations, using US EPA upper confidence level estimates, indicate that SDTRRP effluents, if used directly as a potable water supply, would represent an estimated lifetime risk of 3.2×10^{-6} (ie. 3 excess cancers per million people). This compares with 1.2×10^{-4} (120 excess cancers per million people) for the raw drinking-water source. The SDTRRP risk estimate is approximately 40 times less than the estimated risk associated with the raw drinking-water source. Results of the noncarcinogenic risk indicated that, for both water sources, non-carcinogenic chemicals were not determined to result in any significant health risk.

The overall conclusion reached by the Health Advisory Committee was that the health risk associated with the use of the SDTRRP as a raw water supply would be less than or equal to that of the use of the existing raw water supply (Thompson *et al.*, 1992).

3.1.5 Tampa Water Resource Recovery Project (Florida)

A pilot advanced water treatment plant was operated in Tampa, Florida from 1987 to 1989 (CH2M Hill, 1993). This was known at the Tampa Water Resource Recovery Project (TWRRP). Influent to the TWRRP was a sewage treatment plant effluent which had undergone secondary treatment, filtration and denitrification.

The project evaluated the treatment efficacy of four advanced water treatment processes. In each case the feedwater to the AWT process was clarified secondary effluent. The first treatment train consisted of pre-aeration, coagulation at pH 11.4 using lime, clarification, recarbonation, media filtration, and ozone disinfection. Treatment trains two, three and four included one additional process for organics removal. The organics removal process was located downstream of the media filters and upstream of the ozone disinfection. The processes included granular activated carbon (GAC), reverse osmosis (RO) and ultrafiltration (UF).

The TWRRP was originally operated using chlorine as the final disinfectant, but this was replaced with ozone since the results of Ames testing indicated that ozone-disinfected product waters were less mutagenic. For similar reasons, the treatment train using GAC was selected for toxicological testing based on preliminary screening using the Ames assay.

The performance of TWRRP was assessed in comparison Tampa’s current water supply. However, in this case the raw water supply (from the Hillsborough River) was first disinfected with ozone prior to analysis to make it more analogous to the TWRRP product water.

Concentrated extracts of these water sources were used to prepare doses for toxicological testing at up to 1000 times the potential human exposure of a 70 kg person consuming 2 litres of water per day. Eight different toxicological tests were conducted to assess potential genotoxicity (Ames and sister chromatid assays), carcinogenicity (strain A lung adenoma and SENCAR mice initiation-promotion studies), fetotoxicity (teratology in rats and reproductive effects in mice), and subchronic toxicity (90-day gavage studies in mice and rats). The results were reported to be uniformly negative for the TWRRP product water (Hemmer *et al.*, 1994).

3.1.6 Singapore Water Reclamation Study “The NEWater Study”

The Singapore Water Reclamation Study is commonly known and referred to as the “NEWater Study”. Its primary objective was to determine the suitability of using recycled water as a source of raw water to supplement Singapore’s potable water supply.

An Expert Panel was formed in 1999 to oversee the NEWater Study. This Expert Panel was comprised of both local and overseas members with expertise in human health and toxicology, microbiology, engineering, water technology, epidemiology, water quality and environmental chemistry.

A pilot scale (10,000 m^3/day) advanced water treatment plant, known as the NEWater Factory was constructed and commenced operation in 2000. The NEWater Factory received water from the

Bedok Sewage Treatment Works, which produced secondary treated effluent. The technologies employed at the NEWater Factory included microfiltration, reverse osmosis and ultraviolet radiation.

An extensive water quality sampling and monitoring program was devised for approximately 190 physical, chemical and microbiological parameters. Samples were tested from the plant feedwater, individual treatment module effluents, final produced NEWater, as well as untreated and treated traditional drinking-water supplies. Overall, almost 20,000 test results from seven sampling locations, including over 4,500 for NEWater were measured between November 1999-April 2002. The physical, chemical and microbiological data for NEWater were shown to be well within current (2002) US EPA and World Health Organization guidelines for drinking-water quality (NEWater Expert Panel, 2002).

A health effects study was conducted with two components. A mice study was undertaken to assess long-term chronic toxicity and carcinogenicity, while a fish study was undertaken to assess toxic and estrogenic effects. In these studies, NEWater was compared with untreated reservoir water.

A sensitive mouse strain (B6C3F1) was used for the mice study. This strain is widely used for conducting long-term health effects studies of new pharmaceuticals. Groups of mice were fed 150-fold and 500-fold concentrates of NEWater and untreated reservoir water over a period of two years. The testing was undertaken with culls at 3, 12 and 24 months. At the time of publication of the expert review panel findings, the 3 and 12 month results were available and these indicated that exposure to concentrated NEWater did not cause any tissue abnormalities or health effects (NEWater Expert Panel, 2002). The 24-month results were due to be completed in October 2002 and remain unpublished.

Fish studies were undertaken in accordance with a recommendation from the NRC report (National Research Council, 1998). The purpose was to assess long-term chronic toxicity as well as the estrogenic potential (reproductive and developmental). The orange-red strain of the Japanese medaka fish (*Oryzias latipes*) was selected for the study due to the availability of an extensive biological database for this species.

The fish testing was conducted over a 12-month period with two generations of fish. The NEWater tests were initially undertaken during 2001 and both generations showed no evidence of carcinogenic or estrogenic effects from exposure to NEWater. However, the fish study was to be repeated owing to design deficiencies of the aquarium system, fish husbandry issues and weaknesses in the study protocol (NEWater Expert Panel, 2002). The repeated fish study was completed in 2003 and confirmed the findings of no estrogenic or carcinogenic effects (Ong & Seah, 2003).

3.2 Endocrine disrupting chemicals

During the last few decades, reports of hormonally related abnormalities in a wide range of species have accumulated (Matthiessen, 2003). These have included invertebrates (Oehlmann & Schulte-Oehlmann, 2003), fish (Jobling & Tyler, 2003), aquatic mammals (Fossi & Marsili, 2003), reptiles (Guillette & Iguchi, 2003) and birds (Giesy *et al.*, 2003).

Chemical contaminants are believed to be responsible for many of these abnormalities, acting via mechanisms leading to alteration in endocrine function. This phenomenon, known generally as ‘endocrine disruption’, has been identified by the World Health Organisation as an issue of global concern (Damstra *et al.*, 2002). The chemicals implicated have been collectively termed 'endocrine disrupting chemicals' (EDCs), or simply 'endocrine disruptors'.

Potential effects from the environmental exposure of EDCs to humans is suspected by analogy with observations from other species. However, such human health effects are yet to be substantiated. Unlike carcinogenic chemicals, a lack of knowledge regarding how these chemicals may be expected to impact on human health has prevented the establishment of traditional dose-response toxicological data. Accordingly, it is not currently possible to make scientifically valid statements regarding what levels of exposure may be considered to be fully protective of human health. The most prudent approach therefore, is to minimise exposure to these chemicals by any non-traditional exposure routes.

In terms of potency, the most significant of the commonly water-contaminating EDCs have been identified as natural and synthetic steroidal hormones (Körner *et al.*, 2001; Metcalfe *et al.*, 2001). Some steroidal hormones have been observed to cause disruption of the endocrine system of fish at ambient concentrations less than 1 ng/L (Purdom *et al.*, 1994).

Steroidal hormones are a large group of organic compounds with important physiological effects in plants and animals. Many steroidal oestrogens are endogenous human (and animal) hormones responsible for numerous complex physiological actions. They are constantly excreted via urine into sewage. For example, in the normal menstrual cycle 10-100 μg/day of 17β-oestradiol is typically excreted by women depending on the stage of the cycle (Williams & Stancel, 1996). During pregnancy, up to 30 mg/day may be excreted. After menopause, oestrogen excretion typically drops to around 5-10 μg/day. Men also excrete oestrogens at a rate of about 2-25 μg/day. Synthetic oestrogens are employed in contraceptive formulations because of their increased oral potency. The most common of these is ethinylestradiol, although its methyl ester, mestranol is also sometimes used.

Concentrations of natural steroidal estrogens observed in British rivers downstream of sewage treatment plant effluents have been shown to be sufficient to cause endocrine disruption of adult male rainbow trout (Routledge *et al.*, 1998). This 'feminisation' of male fish due to environmental exposure to estrogenic hormones has since been confirmed on numerous occasions (Jobling & Tyler, 2003; Rempel *et al.*, 2006). More recently, exposure to androgens has been implicated in the masculinisation of fish (Ankley *et al.*, 2003; Sone *et al.*, 2005; Gray *et al.*, 2006; Jensen *et al.*, 2006). Furthermore, scientists suspect that anthropogenic estrogens, androgens and progestins may act as reproductive pheromones in fish, thus adversely affecting reproduction (Kolodziej *et al.*, 2003; Kolodziej *et al.*, 2004).

Much attention has focused on the removal and/or discharge of hormonal steroids from municipal sewage treatment plants (Braga *et al.*, 2005; de Mes *et al.*, 2005). Municipal STPs with activated sludge treatment for nitrification and denitrification can appreciably eliminate natural and synthetic estrogens (Andersen *et al.*, 2003). Studies undertaken in South East Queensland demonstrate that estrogenic hormones are typically at concentrations too low to be measured after conventional tertiary sewage treatment (Leusch *et al.*, 2005; Leusch *et al.*, 2006).

Advanced water treatment processes such as reverse osmosis membrane treatment (Schäfer *et al.*, 2003; Drewes *et al.*, 2005; Xu *et al.*, 2005; Drewes *et al.*, 2006) and advanced oxidation (Rosenfeldt & Linden, 2004) are each highly effective for the further removal of any remaining hormonal steroids. Accordingly, these processes represent additional barriers ensuring overall protection from these chemicals.

Studies of reproductive effects in mice at the Tampa Water Resource Recovery Project (Florida) and estrogenic effects to fish at NEWater (Singapore) indicate a lack of endocrine disrupting effects from advanced treated recycled water (Hemmer *et al.*, 1994; Ong & Seah, 2003).

4 Evaluation of risks from pathogens

Risk assessment for pathogenic organisms in water supplies may be undertaken qualitatively using risk 'likelihood times consequence' assessment matrices (Nadebaum *et al.*, 2004). However, qualitative microbial risk assessment alone does not provide sufficient information for the determination of scheme safety. Reasons for this include:

- Exposure pathways can be lengthy and complex making qualitative assessment of risks problematic;
- There is often insufficient data available for setting risk ratings for potable reuse based on expert opinion;
- Brief hazardous events can have very high disease impacts.

There are three basic approaches available for quantifying risks posed by pathogenic organisms:

- Assessment of end point water quality and comparison against accepted standards and guidelines (eg. ANZECC, 2000);
- Epidemiologic surveys of infectious disease rates in the community which are a direct measure aggregated disease (Sloss *et al.*, 1996).
- Quantitative microbial risk assessment (QMRA) and associated techniques (Haas *et al.*, 1999).

4.1 End point testing

In developed countries, all reticulated waters intended for human consumption are routinely analysed for bacterial indicators and water intended for indirect potable reuse would not be expected to be any exception.

As a rule, water intended for potable reuse should be free of faecal indicator organisms in light of the multiplicity and range of treatments applied to it. It is common for recycled water to be treated by chemical disinfection, ultraviolet radiation and/or membrane filtration, all of which are capable of significantly reducing microbial concentrations under optimum conditions.

However, indicator-based 'endpoint' testing alone is insufficient for assessing risks and will probably be more useful for monitoring whether processes are functioning nominally on a given day rather than whether all pathogens are being removed. Recent studies have demonstrated that there is a poor correlation between the results of indicator tests and pathogen measurements in respect to water reuse confirming what has been known in the field of water treatment more generally for some years (Harwood *et al.*, 2005). This work has confirmed the need in respect to recycled water to monitor a wider range of analytes in more diverse ways rather than rely solely on indicator endpoint monitoring.

The main limitations of endpoint testing are as follows:

- Because such testing is expensive the number of measurements collected for a system tend to be in the tens per year at best.
- While the detection limits of 1 microorganism per 10, 100, or 1000 L are technologically impressive, some highly infectious pathogens can still be a concern at lower concentrations.
- Such testing tends to sample water quality under nominal conditions rather than during the more significant (in terms of public health) periods of underperformance or malfunction.

Studies where direct testing for pathogenic organisms has been undertaken in the USA are summarised in Table 2 (National Research Council, 1998). The main limitation of much of this information for the context of South East Queensland is that it has been focused on recycling schemes incorporating groundwater recharge. Such surface water reservoir augmentation projects which exist do not appear to have been subjected to a similar assessment of associated risks as those concerned with groundwater. Nonetheless, all data presented in Table 2 refers to treated reclaimed water <u>prior</u> to recharge of groundwater aquifers.

Table 2 Monitoring data at US potable reuse projects for microbial pathogens of concern (National Research Council, 1998).

Facility	**Barriers to pathogens**[a]	**Test attributes**	**Cultivatable enteric viruses**	***Cryptosporidium***	***Giardia***	**Other microbial pathogens examined**
Denver	Lime, sand filtration, carbon, RO or UF	Concentration measured	<1/1000 litres	<1/100 litres	<1/100 litres	*Shigella, Salmonella, Campylobacter, Entamoeba* tested, none detected.
		Positive samples	0/37	0/4	1/15	
		Percent reduction	n.a.	>97.5%	>99.4%	
Water Factory 21 (1979 study)	Lime, ammonia stripping, carbon, RO, chlorination	<u>*After Lime:*</u>		Not tested	Not tested	Not tested
		Positive samples	28/28			
		Percent reduction	99.87			
		<u>*After Chlorination:*</u>				
		Positive samples	1/142			
Water Factory 21 (1980-1981 study)	Lime, ammonia stripping, carbon, RO, chlorination	Concentration measured	<0.1/100 litres	Not tested	Not reported	Helminths: none found.
		Positive samples	1/21		0/20	
		Percent reduction	>99%		None detected after chlorination and RO	
		<u>*Prechlorination*</u>				
		Concentration measured	0.2/100 litres		<0.05/100 litres	
		Positive samples	1/19		-	
		Percent reduction	99.4%		>86.9% removals	
Potomac study	Lime, intermediate chlorination, dual-media filtration, carbon, chlorination	Concentration measured	1/1700 litres	Not tested	None detected using light microscopy	Not tested
		Positive samples	0/56			
		Percent reduction	>87%			

Facility	Barriers to pathogens[a]	Test attributes	Cultivatable enteric viruses	*Cryptosporidium*	*Giardia*	Other microbial pathogens examined
	or ozonation					
Tampa	Lime, sand filtration, RO or UF or carbon, ozonation or chlorination	*After lime*				
		Concentration measured	0.06/100 litres	0.13/100 litres	<1/200 litres in final effluent	
		Positive samples	4/25	1/16		
		Percent reduction	98.3%	99.6%	>99.97%	
		After chlorination				
		Concentration measured	0.02/100 litres	<1/200 litres[b]		
		Positive samples	1/15	0/6		
		Percent reduction	99.4%	>99.8%		
		After ozone				
		Concentration measured	<0.01/100 litres			
		Positive samples	0/4			
		Percent reduction	>99%			
San Diego	Water hyacinth ponds, dual-media filtration, UV, RO, carbon	Concentration measured	<1/1000 litres	1/1000 litres	<1/1000 litres	1/500 ml (*Salmonella*)
		Positive samples	0/32	2/29[d]	0/29	0/29
		Percent reduction	>99.995%	99.995%	>99.9997%	>99%
Upper Occoquan Sewage Authority	Lime, filtration, carbon, chlorination	Concentration measured	<1/500 litres	0.44/100 litres	6.6/100 litres	
		Positive samples	0/11	1/11	2/11	
		Percent reduction	>99.995%[c]	99.97%	99.986%	

[a]All testing is on final effluent unless otherwise noted. Carbon = carbon adsorption; lime = chemical lime treatment, pH 11.2, recarbonation; RO = reverse osmosis; UF = ultrafiltration; UV=ultraviolet disinfection.
[b]After filtration.
[c]Based on raw sewage counts; all other removals based on counts entering the reclamation facility.
[d]Positives seen during spiking trials.

Endpoint water quality measurement is the traditional means of assessing whether a water supply poses a risk to consumers. Pathogen end point testing may be undertaken routinely or as part of short to medium term studies.

Extensive pathogen end-point testing was undertaken on the San Diego Total Resources Recovery Project (SDTRRP) (Thompson *et al.*, 1992). The pathogenic organisms that were measured included representative bacterial, viral and parasitic species. Data were collected over a thirty month monitoring program from both the SDTRRP effluent and the untreated raw water supply. No *in situ* viruses were detected from either source in samples concentrated from as much as 3800 litres. It was concluded that there was no significant difference in the virus concentrations of the two waters. The study also showed that the reclaimed water had a much higher microbial quality than the raw drinking-water source based on indicator organism data (total and faecal coliform and enterococcus). The microbiology of the SDTRRP effluent, without disinfection, met all microbial criteria for recreational waters and raw drinking-water source requirements. In addition, four virus spiking studies were undertaken using an attenuated vaccine strain of Poliovirus 2. None of the spiked virus was recovered in the final effluents, indicating a removal efficiency of at least eight orders of magnitude (99.999999%).

Endpoint testing was also reported for microbial testing during the NEWater study in Singapore (NEWater Expert Panel, 2002). Results for thermo-tolerant coliforms, total coliforms, heterotrophic plate counts (HPC), *Giardia*, *Cryptosporidium* and *Enterovirus* were assessed against USEPA and WHO standards/guidelines and determined to consistently meet the requirements of both. Four additional microbial parameters were also assessed as potential microbial parameters for future drinking-water standards/guidelines. Out of the 10 microbial water quality parameters, only HPC were consistently detected in NEWater and concentrations were reported to be well within the USEPA Drinking-water Standards. It was noted that NEWater HPC concentration (5.2 CFU/ml) was lower than those observed for Singapore raw drinking-water (3,850 CFU/ml) and treated drinking-water (15.2 CFU/ml).

Table 3 Summary of NEWater (Singapore) microbial results (NEWater Expert Panel, 2002)

Parameter	Units	Mean	Min.	Max.	No. samples	No. detectable	No. not detectable
Faecal coliforms	CFU/100 ml	NC	ND	ND	99	0	99
Total coliforms	CFU/100 ml	NC	ND	ND	99	0	99
HPC	CFU/ml	5.2	1.1	80	97	80	17
Coliphage-somatic*	PFU/100 ml	NC	ND	ND	87	0	87
Coliphage-male specific*	PFU/100 ml	NC	ND	ND	87	0	87
Enterococcus*	CFU/100 ml	NC	ND	0.2	99	1	98
Clostridium perfringens*	CFU/100 ml	NC	ND	ND	91	0	91
Giardia	Cysts/100 L	NC	ND	ND	16	0	16
Cryptosporidium	Oocsyts/100 L	NC	ND	ND	17	0	17
Enterovirus	Present/absent	Absent	-	-	21	0	21

* These parameters are additional to those listed in the USEPA and WHO standards/guidelines.
ND = Not detectable; NC = Not calculated.

4.2 Epidemiology

Epidemiologic data is available for some indirect potable reuse schemes and some important case studies are presented in Section 6 of this report. Importantly, no infectious disease problems have been detected associated with any of these schemes (or other less studies schemes). However, such epidemiologic studies have the following limitations in terms of pathogenic organisms:

- Many epidemiologic studies tend to be relatively insensitive as a means of detecting impact because background levels of gastrointestinal illness from other sources such as food contamination tend to obscure any ‘signal’ from water;
- The studies undertaken in the US relate mainly to aquifer recharge and aquifer characteristics tend to be relatively location specific.

The main benefits of epidemiologic studies is the confirmation that there is no problem, public reassurance, and the (potential) detection of outbreaks or other impacts on exposed populations.

4.3 Quantitative microbial risk assessment (QMRA)

Compared to endpoint testing, a conceptually more sensitive technique for estimating risks is by quantitative microbial risk assessment (QMRA) processes involving the following steps:

1. measurement of pathogen concentrations in the initial wastewater;
2. determination of the effectiveness of each treatment train component for the reduction or inactivation of organisms;
3. use of Monte Carlo simulation techniques to estimate probable concentration ranges of pathogens remaining and their potential for infecting consumers under nominal water reuse conditions;
4. investigation of various additional scenarios to assess the robustness of a treatment system to underperformance or breakdown, and uncertainties in the input assumptions.

Quantitative microbial risk assessment is based on modeling principles detailed by Haas *et al.* (1999), general Water Safety Plan and risk assessment principles described in Fewtrell & Bartram (2001). These techniques have been applied increasingly to full scale water supply systems notably in recent years to twelve full catchment-to-consumer systems via the European Commission MicroRisk Project (Medema *et al.*, 2006).

There are many pathogens whose infection rates might be considered for assessing indirect potable recycling schemes (Haas & Eisenberg, 2001). But a relatively limited number of microbial groups appear to account for the majority of infections (outbreaks), so pathogen risk analyses tend to focus on ‘index pathogens’ representing the major gastrointestinal illness-causing groups (Westrell, 2004). Potential index organisms include:

- *Cryptosporidium* representing parasitic protozoa
- *Campylobacter* representing bacterial pathogens
- Rotavirus representing waterborne viruses.

All three pathogens are known to be present in the sewage of developed countries, and have a low dose-response relationship (i.e. these pathogens are highly infectious).

Application of QMRA to water reuse risk assessment in California indicates that aquifer recharge is generally extremely safe with infection probabilities as low as 10^{-57} being calculated (Asano *et al.*, 1992; Tanaka *et al.*, 1998). The main limitation of such quantitative risk estimates is that they are very dependent on input assumptions. For example a small change in the virus removal coefficient used in the latter model from 0.6 d^{-1} to 0.1.d^{-1} led to the calculated probability of infection increasing from *ca* 10^{-50} to 10^{-7}.

For this reason it is critical to develop realistic exposure scenarios, test a range of scenarios and use the information generated as a decision support tool rather than as precise measure of absolute risk which may be uncritically compared to an acceptable risk bench mark.

Bahri & Brissaud (2004) and Salgot *et al.* (2003) describe how QMRA is being increasingly adopted in Europe for assessment of water reuse schemes including those involving potable recycling. A study undertaken at the University of New South Wales has recently applied these techniques for the assessment of a river flow augmentation project which has many features in common with indirect potable recycling (Roser *et al.*, 2006). The assessments of risk obtained are consistent with those reported elsewhere in the literature.

5 Treatment plant reliability

Quantitative health risk assessments for water recycling schemes tend to focus on the estimation of chemical and pathogen concentrations expected when a scheme is operating under normal performance conditions. However, in order to fully assess risks, it is also essential to understand system effectiveness when there are mechanical breakdowns, loss of treatment integrity, power failures, poor management etc. These issues have been taken very seriously in current indirect potable indirect reuse projects. For example, Soller *et al.* (1999) and Soller *et al.* (1997) present a useful set of data on the performance of compromised membranes which illustrate how variable removal by individual units can be.

The importance of this issue was alluded to in a recent report from the Adelaide Advertiser newspaper (Peddie, 2007):

> *The former SA Water chief scientist, who in 2004 oversaw a review of national drinking water guidelines and who was last week recognised in the Australia Day honours for his contribution to water quality research, says the technology that would make recycled sewage suitable for drinking already exists, but he is not confident we have the back-up systems to ensure it stays safe.*

Prof. Bursill explained that although the technology exists to provide extremely high quality water under normal conditions, the risks to public health are determined by the performance reliability of the system. Accordingly, it is considered that in order to effectively evaluate the risks posed by planned indirect potable water recycling schemes, a comprehensive analysis of system reliability is required.

5.1 A protocol for system reliability analysis

A protocol for the evaluation of water and wastewater treatment plant reliability has been proposed by Eisenberg et al (Eisenberg *et al.*, 2001). This includes a methodical evaluation of mechanical reliability and plant performance (variability). The methodology relies on a range of measurements and observations to characterise treatment facility reliability with respect to:

1. variability of treatment effectiveness under normal operation
2. probability of mechanical failures
3. impacts of observed or projected mechanical failures upon final water quality.

The methodology allows for the use of individual process performance data to make an estimation of overall treatment reliability for the entire facility. This is essential for constituents which may normally be removed to levels that are below levels of detection in the treatment plant effluent.

The evaluation of treatment variability under normal operation may be achieved by summarising observed water quality using basic statistical tools associated with frequency analysis (means, standard deviations, etc). The overall system variability may be characterised by estimating the cumulative probability distributions associated with individual contaminants at key treatment units throughout the facility. These probability distributions allow the estimation of probability that treatment goals would be exceeded. Eisenberg et al recommend the assumption of a lognormal distribution for contaminant variability (Eisenberg *et al.*, 2001). Water quality variability may then be characterised by the construction of lognormal cumulative probability plots, such as the one shown for TOC in Figure 1 (Eisenberg *et al.*, 2001).

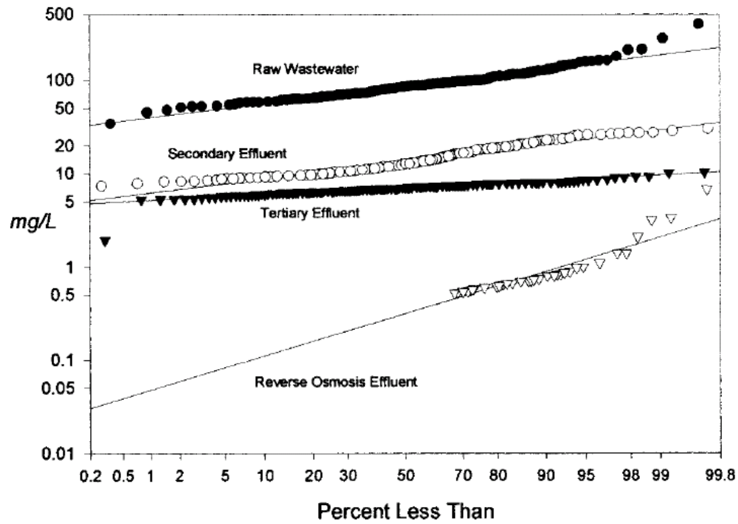


Figure 1 Log normal cumulative probability plot for TOC after various treatment processes (Eisenberg *et al.*, 2001).

As can be observed from Figure 1, TOC levels in raw wastewater from this plant could be expected to range between 30 – 500 mg/L, secondary effluent 7-20 mg/L, and tertiary effluent 2-7 mg/L. 70 per cent of the data for reverse osmosis effluent were reported to be below detectable limits (0.5 mg/L) and 99% were below 1 mg/L. The reverse osmosis data demonstrate the use of this kind of analysis to estimate the distribution of treatment plant performance when a large percentage of data are below detection limits. Such procedure allows for the estimation of summary statistics such as mean and standard deviation for largely unobserved data.

The overall performance distribution of a multiple barrier system may be estimated using consequence frequency assessment methodology analogous to procedures which have become increasingly accepted for quantitative microbial risk assessment (QMRA) (Haas *et al.*, 1999; Haas & Eisenberg, 2001). The concentration of a given contaminant at each stage of treatment is described mathematically as a conditional probability density function. A useful approach is then to employ a Monte Carlo simulation procedure (Burmaster & Anderson, 1994). This requires fitting distributions to the removal of a particular contaminant across each treatment unit, sampling each distribution repeatedly, and computing the final concentration for each set of random samples. By this approach, the plant performance may be represented in a probabilistic manner which explicitly acknowledges both the uncertainty and the variability of the underlying data. An example of the type of cumulative removal that may be forecast is presented in Figure 2.

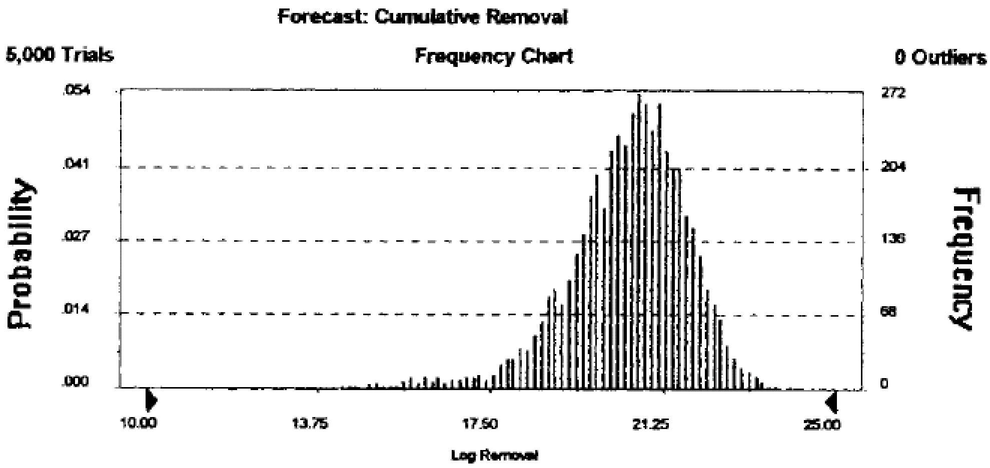


Figure 2 Result of consequence frequency assessment for the removal of a contaminant through an AWT (Eisenberg *et al.*, 2001).

The mechanical reliability of a water treatment system can be assessed by the identification of key pieces of equipment in the plant whose failures may be related to effluent quality. The operational availability and maintainability of all treatment units and key components are then determined.

The mechanical reliability assessment can be undertaken by the use of a Critical Component Analysis methodology developed after methods described in US EPA guidance documents (Shultz & Parr, 1982).

The Critical Component Analysis is carried out by creating a list of all components in the facility and then categorising the components by treatment unit, component and subcomponent. Data is collected for all planned and unplanned maintenance events. This data is aggregated and then used to compute performance statistics for treatment units and for individual components in the treatment system. The performance statistics describe the expected time between failures for treatment units, the overall mean time between failures of components, and the fraction of time that a unit or component was operating, either including or excluding preventative maintenance. An example of the type of data that may be accumulated are presented in Table 4 (Eisenberg *et al.*, 2001).

Table 4 Plant performance statistics for mechanical reliability (Eisenberg *et al.*, 2001).

Treatment unit	Number of maint. Events[1]	Number of unplanned events[2]	ETBF (days)[3]	Operating availability[4]
Headworks	16	13	26	0.9953
Primary	36	28	41	0.9985
Secondary	82	40	9	0.9757
Tertiary	30	27	13	0.9994
UV	1	1	212	0.9991
Reverse Osmosis	55	35	10	0.9990

[1]Number of times repairs were made including scheduled maintenance on components within the given unit.
[2]Number of times repairs were made due to component failure within the unit.
[3]Expected time between failure somewhere in unit process, based on chi-square distribution.
[4]Fraction of the study period that all components in the unit were operating.

The data in Table 4 indicates that there were a number of planned and unplanned maintenance events on each unit process. The expected time between failures within the unit processes varied between 9 and 212 days. The operating availability, defined as the fraction of the study period that all components in the unit were operating for each of the treatment units was greater than 0.97. Eisenberg et al conclude that all treatment units were operational more than 97 per cent of the time and that neither component maintenance nor failure caused a significant interruption in the operation of the overall plant (Eisenberg *et al.*, 2001).

This type of analysis provides a foundation from which an assessment of the inherent reliability of a treatment system may be made. For example, if it can be demonstrated that a treatment facility is operational nearly 100 per cent of the time on a long-term basis, plant performance data (as described above) may be used to evaluate the probability that the effluent will meet a specified set of criteria. Otherwise, it may be necessary to investigate if and/or how component failures impact treatment plant effluent quality.

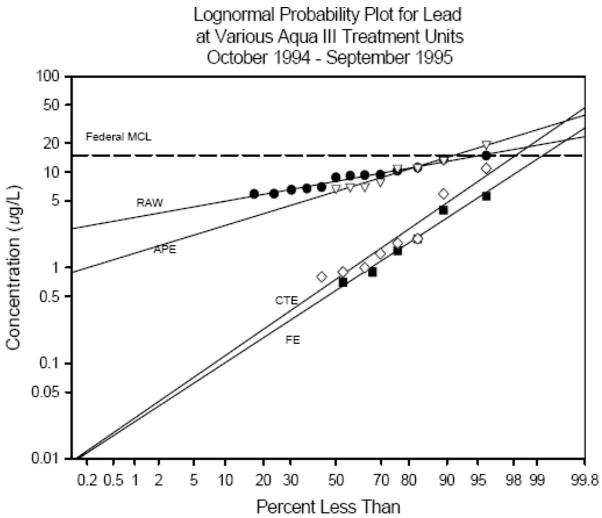
5.2 Case study: San Diego Aqua III

A pilot scale advanced water treatment plant (AWT) was constructed and intensively investigated in the City of San Diego during the 1990s. This scheme, known as the Aqua III AWT, was subjected to a comprehensive suite of health effects studies (Thompson *et al.*, 1992; Western Consortium for

Public Health, 1992; de Peyster *et al.*, 1993; Olivieri *et al.*, 1996). Furthermore, a comprehensive reliability analysis of the plant was undertaken and reported by Eisenberg *et al* (Eisenberg *et al.*, 1998).

The reliability of the Aqua III AWT was evaluated in terms of the facility's ability to produce a consistent water quality (plant performance) and the probability of failure of mechanical components (mechanical availability).

The plant performance was assessed in terms of physical parameters, nitrogen compounds, anions, trace and major metals, organic compounds and bacterial indicators. Parametric time series analysis was conducted to identify and investigate trends and periodicity that may have occurred within the collected data at the specific sampling sites. Lognormal probability plots were created for all constituents with sufficient detected data. For example, the lognormal probability plots for lead and nickel concentrations in raw wastewater (RAW), secondary effluent (APE), tertiary effluent (FE), and AWT effluent (CTE) are shown in Figure 3 below (Eisenberg *et al.*, 1998).



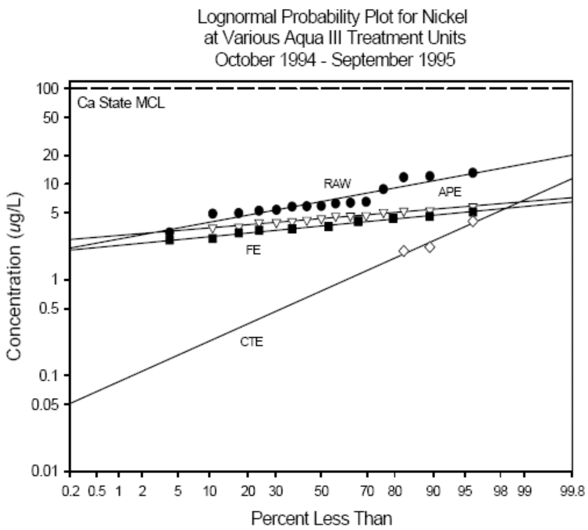


Figure 3 Lognormal probability plots Lead and Nickel at the Aqua III AWT (Eisenberg *et al.*, 1998)

The geometric mean values for both lead and nickel for all unit processes were shown to be well below the corresponding maximum contaminant levels (MCL). Furthermore, the lognormal probability plots demonstrated that the probability that the final plant effluent (CTE) will exceed the MCL was approximately 0.03 for lead and was estimated through extrapolation to be 0.00001 for nickel. The study revealed that the Aqua III AWT produced highly consistent effluent with minimal variation.

The mechanical reliability of the Aqua III AWT was undertaken by determination of the inherent availability (AVI) and the operating availability (AVO). The AVI was used as a measure of the fraction of time that the component or treatment unit could be expected to be operational excluding preventative maintenance downtime. The AVO was used to describe the fraction of the time in which the component or unit was operating.

A statistical analysis was undertaken on the 11 treatment units and the 295 plant components in the Aqua III facility. A summary of the statistical parameters rating mechanical reliability indicated mechanical availability (AVO and AVI) greater than 99 per cent, and that failures within the facility did not affect the overall mechanical reliability of the treatment units.

To investigate the relationship between plant failures and effluent quality, bacteriological indicator organism monitoring results were correlated to plant component failures. The results indicated that there was no observable association between any specific maintenance procedure or plant failure and the occurrence of indicator organisms concentrations above the detection limit.

6 Epidemiologic studies

A study that examines the health statistics of a population in order to try to identify causes of illness is called an epidemiologic study. Significant epidemiologic studies have been conducted for two major international potable water recycling schemes. These are the direct potable water recycling scheme at Windhoek (Namibia) and the indirect potable water recycling scheme in Montebello Forebay, California (USA).

The Windhoek scheme is the only direct potable water recycling scheme in the world (du Pisani, 2005). It is situated within a very different social and public health context compared to Australia. Accordingly, the transferability of public health studies and epidemiologic outcomes to Australia is questionable. For this reason, the various studies conducted in Windhoek are not reviewed here. However, interested readers are directed to publications by Sayed *et al.* (1989); Hattingh & Bourne (1989), Odendaal (1991) and Hrudey & Hrudey (1990) for information that is available.

At least three epidemiologic studies have been conducted to examine health risks associated with the Montebello Forebay Groundwater Replenishment Project. The first studied health outcomes from 1969 to 1980 (Frerichs *et al.*, 1982; Frerichs, 1984). The second examined cancer incidence, mortality and infectious disease outcomes from 1987 to 1991 (Sloss *et al.*, 1996). The third evaluated the incidence of selected adverse birth outcomes between 1982-1993 (Sloss *et al.*, 1999).

6.1 Montebello Forebay Epidemiologic Study 1: 1969-1980

Although water extracted from the recharged system consistently met current drinking-water standards, there was concern that potentially hazardous substances may have been either overlooked or not considered due to low concentrations. To address this concern, an epidemiologic study was under taken over the period 1969-1980 (Frerichs *et al.*, 1982; Frerichs, 1984).

The proportion of recycled water in drinking-water supplies was (and is) variable in different parts of LA. In order to monitor the health of the population potentially exposed to unknown water contaminants, four separate study areas were identified. In two of the areas (the northwest and central control areas) drinking-water did not contain any recycled water. In the third area (low recycled water area) households received less than 5 per cent recycled water. In the fourth area (high recycled water area) households received 5 per cent or more recycled water. During the course of the study (in the mid-1970s), the proportion of recycled water increased to nearly 16 per cent in the high recycled water area and 6 per cent in the low recycled water area. At the time, around 1.2 million people resided with the combined four study areas.

The epidemiological study relied on census health data and a local cancer surveillance program which was established in 1972. In addition, a household survey was conducted in 1981 among approximately 2500 women living in the central control area and the high recycled water area. This survey was added to pick up information about adverse reproductive outcomes such as miscarriages; general indicators of illness such as bed-ridden days; possible confounding effects such as alcohol consumption and cigarette smoking; patterns of water consumption; and general morbidity (illness). The health and disease outcomes included in the monitoring program were as follows:

- Existing Vital and Health Data
    - Mortality (deaths)
        - Death due to all causes
        - Diseases of the heart
        - All cancers (malignant neoplasms)
        - Cancer of the stomach
        - Cancer of the colon
        - Cancer of the rectum
        - Cancer of the bladder
        - Death due to all other causes
    - Morbidity (illnesses)
        - All potential waterborne diseases
        - Hepatitis A
        - Shigellosis
    - Birth Outcomes
        - Low weight birth (less than 2,500 gms)
        - Very low weight birth (less than 1,500 gms)
        - Neonatal deaths
        - Infant deaths
        - Congenital malformations at birth
- Cancer Surveillance System Data
    - Incident Cases
        - Cancer of the stomach
        - Cancer of the colon
        - Cancer of the rectum
        - Cancer of the bladder
- Household Survey of Women
    - Adverse Reproductive or Gynecological Outcomes
        - Infertility
        - Menstrual problems
        - Congenital defects
        - Spontaneous abortions (stillbirth)
    - Functional Impairment
        - Restricted activity days
        - Bed-disability days
        - Hospital-bed days

The relative incidences of these health effects were statistically analysed in the four study areas. The effects of several confounding variables were controlled for where appropriate, including age, sex, race, age of mother and birth weight.

If the consumption of recycled water contributed to excess disease or death, we would expect the relative incidences to be greatest in the high recycled water area, intermediate in the low recycled water area, and similar to the remainder of LA County in the two control areas. Furthermore, we would expect this dose-response relationship to be more amplified in the later years of the study since the concentration of recycled water gradually increased.

Some minor statistical differences were observed between the study areas, including deaths due to all cancers, cases of shigellosis, very low births, and neonatal mortality. However, for none of these factors, were the differences in a direction that would support the hypothesis that increases in concentrations of recycled water contributed to excess disease.

In the household survey, no significant differences were observed between the two groups of women in restricted-activity days, bed-disability days, hospital bed-days, or recent contacts with a health professional. Nor were differences observed in the rate of spontaneous abortions, congenital malformations, menstrual problems, or problems of fertility.

The authors of the study summarised their conclusions as follows (Frerichs *et al.*, 1982):

> "*While we can never ensure the complete safety, it is reasonable to assume that the disease risk attributed to the consumption of reclaimed water has been minimal for persons residing in the high and low recycled water areas in eastern Los Angeles County. This does not mean that there is no risk. Nor does it mean that there will be no risk in the future. Rather, available epidemiologic evidence provides no indication that the reuse of water has had a noticeable harmful effect. If findings in the on-going water characterization study are also negative, the combined investigations should provide strong evidence to both the public and to the responsible governmental officials as to the relative safety of water reuse.*"

6.2 Montebello Forebay Epidemiologic Study 2: 1987-1991

This study was designed to measure the association between reclaimed water and cancer incidence, mortality and incidence of infectious disease (Sloss *et al.*, 1996).

Existing data on cancer incidence, mortality, and infectious disease were reviewed and frequencies of the health outcomes were compared in the reclaimed water and matched control areas. The analysis was based on routinely collected data on cancer incidence (all cancers and cancer of the bladder, colon, esophageus, kidney, liver, pancreas, rectum, and stomach), mortality (deaths due to all causes, heart disease, stroke, all cancer, and the same eight specific cancer sites), and infectious diseases (Giardia, hepatitis A, Salmonella, Shigella, and several less common diseases).

The study areas receiving reclaimed water were assigned to one of five exposure categories based on the percentage of reclaimed water in the drinking-water supply. The maximum percentage of reclaimed water over the 30-year period (1960–1991) ranged between 0 and 31 percent for the 66 water systems in the Montebello Forebay. For most systems, the estimated annual percentage of reclaimed water increased consistently over the 30- year period.

The study concluded that between 1987 and 1991, almost 30 years after groundwater recharge with reclaimed water began, the frequencies of cancer, mortality, and infectious disease were similar in the area of Los Angeles County receiving reclaimed water and a control area not receiving reclaimed water.

Frequencies of these health outcomes were also similar in areas receiving higher and lower percentages of reclaimed water. Regions with less reclaimed water tended to have higher frequencies of adverse health outcomes than regions with more reclaimed water.

A few instances were identified in which frequencies of disease or death were significantly higher in areas receiving reclaimed water than in the control area. These included a significantly higher incidence rate of liver cancer in the area with the highest percentage of reclaimed water. However, the weakness of these associations, the absence of patterns consistent with a dose-response relationship, and the lack of scientific evidence to support a causal relationship between reclaimed water and liver cancer led to the conclusion that these results were most likely explained either by factors unrelated to reclaimed water or by chance occurrence.

The authors concluded that the results of the study did not show any evidence of an association between reclaimed water and higher frequencies of cancer, mortality, or infectious disease.

6.3 Montebello Forebay Epidemiologic Study 3: 1982-1993

This study was designed to evaluate the incidence of selected adverse birth outcomes in a population receiving reclaimed water from the Montebello Forebay area scheme (Sloss *et al.*, 1999). This study was intended to complement the previous study of cancer incidence, mortality, and infectious diseases (Sloss *et al.*, 1996).

Data on adverse birth outcomes among infants born between 1982 and 1993 to women living in the study area was analysed. This period is from 20 to 30 years after groundwater recharge with reclaimed water was initiated in the Montebello Forebay.

A ZIP-code-level cohort study was used to examine the association between residence in an area with reclaimed water and several adverse birth outcomes. Existing birth data was acquired from 1982-1993 birth certificates and death certificates, as well as registry data from the Birth Defects Monitoring Program from 1990-1993.

Each birth was assigned to an exposure group based on the average annual percentage of reclaimed water in water supplied by the systems serving the ZIP-code.

The birth outcomes considered were rates of low birth weight, very low birth weight, preterm birth, infant mortality, and 19 categories of birth defects (all birth defects, excluding syndromes; all chromosomal syndromes; all syndromes other than chromosomal; and 16 specific types of birth defects).

Frequencies of each of the adverse birth outcomes were compared between the area in eastern Los Angeles County with reclaimed water and a matched control area in Los Angeles county with no reclaimed water. Logistic regression methods were used to generate odds ratios in confidence intervals to compare outcome frequencies in the reclaimed water and control groups.

The results obtained in this study indicated that the frequencies of the prenatal development outcomes, infant mortality, and all types of birth defects were similar in the reclaimed water and control groups. Some outcome frequencies were significantly higher and others were significantly lower for the reclaimed water groups compared to the control group. However, the study did not generally support the hypothesis of an association between residence in an area receiving reclaimed water and higher frequencies of these outcomes. If reclaimed water led to an increase in any of these outcomes, the results would be expected to show some evidence of a dose-response relationship in which the outcome frequencies increase with increasingly more reclaimed water. However, the results followed no such pattern.

Overall, the adverse prenatal development outcomes occurred at about the same rate or less frequently in the reclaimed water groups than in the control group. Several of the reclaimed water groups had statistically significantly lower frequencies for the prenatal development outcomes than the overall average. The group with the highest percentage of reclaimed water had significantly lower frequencies for low birth weight and for infant mortality. This finding could be attributable to the inability of the study to control completely for many differences (eg. personal health habits) among the areas. There was no indication of a pattern consistent with a decreasing or increasing dose-response relationship with reclaimed water for any of the outcomes.

The results for birth defects indicate that they occur at about the same frequency in the reclaimed water and control groups. The two groups with lower percentages of reclaimed water tended to have some higher frequencies than the control group, whereas the group with the highest percentage of reclaimed water tended to have frequencies similar to or lower than the control group. The authors concluded that this study did not find an association between reclaimed water and increased rates of birth defects.

The authors of the report point out that the limitations of epidemiologic methods render drawing conclusions about the effects of reclaimed water on adverse birth outcomes difficult. The limitations include the possibility of a biological model other than dose-response (eg. a threshold model). Furthermore, it was not possible to control for potential confounding factors such as cigarette smoking, alcohol consumption or occupational exposure.

Place of residence was used as a surrogate measure for actual reclaimed water exposure during pregnancy. The accuracy of this surrogate relationship was not tested, but is clearly dependant on a number of factors including volume of tap water consumed, time spent away from home, and consumption of bottled water and other beverages. Finally, the high population mobility in Los Angeles made detecting an effect more difficult.

6.4 Residence in the London area and sperm density

In 1994, 'The Lancet' published a letter to the editor titled "Residence in the London area and sperm density" (Ginsburg *et al.*, 1994). The principal author was Dr Jean Ginsburg from the Division of Clinical Pharmacology at the Royal Free Hospital School of Medicine (London). While the letter did not describe a study of the health effects of recycled water, a brief mention is warranted due to the controversy that it has raised.

Ginsburg's letter described a study that her team had undertaken which they claimed to show decreasing sperm densities in London during the period 1984-1989 compared to 1978-1983. They analysed the sperm of the partners of 260 infertile women who were receiving treatment at their clinic. Ginsburg reported that mean sperm density fell from 101 million per ml in the earlier period to 96 million per ml in the later period (Ginsburg *et al.*, 1994). Regardless of the very small sample size, these results appear to be roughly consistent with reports of declining world-wide average sperm counts during the second half of the 20th Century (Carlsen *et al.*, 1992).

To investigate possible environmental influences, Ginsburg's team examined their data with reference to the water supply of where the couples lived. They divided the couples into two general groups based on whether they lived within the Thames Water Area (TWA) or outside the TWA. Of the 260 couples, 77 were excluded from this part of the study since they were from outside the UK, had temporary addresses or lived on the border of the TWA. This left 79 couples who lived within the TWA and 104 couples outside the TWA.

Of the 79 couples from within the TWA, 34 were from the 1978-1983 period and the remaining 45 were from the 1984-1989 period. Of the 104 outside the TWA, 46 were from the 1978-1983 period and the remaining 58 were from the 1984-1989 period.

Comparing sperm data from these groups, Ginsburg observed that average sperm motility appeared constant (55%) for couples outside the TWA between the two periods and decreased for those within (from 57% to 52%). Abnormal sperm morphology increased for those outside the TWA (18% to 32%) and also for those inside the TWA (19% to 30%). Sperm density increased outside the TWA (99 million per ml to 110 million per ml) and decreased inside the TWA (105 million per ml to 76 million per ml). Motile sperm density also increased outside the TWA (56 x 10^4 per ml to 62 x 10^4 per ml), and decreased inside the TWA (62 x 10^4 per ml to 41 x 10^4 per ml).

Ginsburg's letter did not mention recycled water and did not include any analysis of the relative proportions of recycled water consumed by the various cohorts. It is well known that the Thames River is subject to considerable loads of discharged conventionally treated wastewater (ie. unplanned indirect potable recycling). However, details of the water supplies of the couples outside the service area of the TWA are not known. Ginsburg's letter clearly stated "We emphasise that we do not assume that the only environmental factor peculiar to those living within the TWA was their water supply" (Ginsburg *et al.*, 1994).

Representatives of Thames Water responded to Ginsburg's letter in a subsequent issue of The Lancet (White & Dennis, 1994). This response further weakened the suggestion of any relationship between the observed changes in sperm quality and water source:

> "*Water suppliers in the area surrounding our own draw upon the same or similar sources; indeed, in some areas the water supply is identical because the water we treat is also supplied to adjacent companies. Moreover, the water supplies in London are not homogeneous because they come from surface and groundwater sources. Thus by using the Thames Water supply boundary Ginsburg et al did not delineate areas of distinct water quality. The two groups of men were merely those living in or outside urban London.*" (White & Dennis, 1994).

Because of the extremely small sample size and the complete lack of analysis of recycled water consumption, Ginsburg's letter to the editor can not reasonably be considered to be a valid study of the heath effects of drinking recycled water. This is no criticism of Ginsburg or her colleagues, since they have never claimed that their study could be interpreted as such.

7 Recommendations of the NRC report

The major recommendation from the NRC report was that water agencies considering potable reuse fully evaluate the potential public health impacts from the microbial pathogens and chemical contaminants found or likely to be found in treated wastewater through special microbiological, chemical, toxicological, and epidemiological studies, monitoring programs, risk assessments, and system reliability assessments. Some specific recommendations were provided regarding methods for assessing health risks of reclaimed water.

For assessing risks associated with microbiological organisms, the NRC report recommended the consideration of using some of the newer analytical methods, such as biomolecular methods, as well as additional indicator microorganisms, such as *Clostridium perfringens* and the F-specific coliphage virus, to screen drinking-water sources derived from treated wastewaters. It argued that risk estimates should consider the effects pathogens may have on sensitive populations and the potential for secondary spread of infectious diseases in the community. Furthermore, the NRC report recommended further research to be undertaken regarding the removal of pathogens by natural environmental processes and engineered treatment systems.

For chemical risk assessment, the NRC report recommended that where toxicological testing appears to be important for determining health risks, emphasis should be placed on live animal test systems that are capable of expressing a wide variety of toxicological effects. Furthermore, toxicological testing standards for reclaimed water should be supplemented by strict regulation of the recycled water production processes.

The NRC report also provided some specific recommendations regarding reliability and quality assurance issues for reuse systems. The endorsement of indirect potable water reuse as a viable water supply strategy should be considered within the context of these recommendations. The recommendations are as follows:

- Potable water reuse systems should employ multiple, independent barriers to contaminants, and the barriers should be evaluated both individually and together for their effectiveness in removing each contaminant of concern.
- Barriers for microbiological contaminants should be more robust than those for forms of contamination posing less acute dangers.
- Because performance of wastewater treatment processes may vary, such systems should employ quantitative reliability assessments to gauge the probability of contaminant breakthrough among individual unit processes.
- Utilities using surface waters or aquifers as environmental buffers should take care to avoid “short-circuiting”, a process by which treated wastewater influent either fails to fully mix with the ambient water or moves through the system to the drinking-water intake faster than expected.
- Potable reuse operations should have alternative means for disposing of the reclaimed water in the event that it does not meet required standards.
- Every community using reclaimed water as drinking-water should implement well-coordinated public health surveillance systems to document and possibly provide early warning of any adverse health events associated with the ingestion of reclaimed water.
- Finally, operators of water reclamation facilities should receive training regarding the principles of operation of advanced treatment processes, the pathogenic organisms likely to be found in wastewaters, and the relative effectiveness of the various treatment processes in reducing contaminants concentrations.

8 Relevant guidelines in Australia

National Guidelines for Water Recycling are currently under development in Australia. Phase 1 of the Guidelines was published in 2006 by the National Resource Management Ministerial Council and the Environment Protection and Heritage Council (NRMMC & EPHC 2006). Phase 1 does not cover the development or management of potable water recycling schemes, but provides guidance on managing the health and environmental risks associated with the use of recycled water for:

- residential garden watering, car washing, toilet flushing and clothes washing;
- irrigation for urban recreational and open space, and agriculture and horticulture;
- fire protection and fire fighting systems;
- industrial uses, including cooling water; and
- grey-water treated on-site (including in high rise apartments and office blocks) for use for garden watering, car washing, toilet flushing and clothes washing.

Phase 2 of the National Guidelines for Water Recycling will include stormwater reuse, aquifer storage and recovery and indirect potable reuse as methods for recycling reclaimed water. The development of Phase 2 is being undertaken during 2007.

In addition to the completed National Guidelines for Water Recycling, there are numerous additional documents which outline standards and principles that any indirect potable recycling scheme would be required to meet as a minimum. Some important additional documents include:

- A Guide To Hazard Identification and Risk Assessment For Drinking-water Supplies (Cooperative Research Centre for Water Quality and Treatment, 2004) developed in support of the Australian Drinking-water Guidelines' new focus on risk assessment and management (National Water Quality Management Strategy, 2004).
- Health Impact Assessment Guidelines (enHealth Council, 2001);
- Environmental Health Risk Assessment: Guidelines for assessing human health risks from environmental hazards (enHealth Council, 2002);
- Australian Drinking-water Guidelines (National Water Quality Management Strategy, 2004);

The risk assessment and risk management frameworks presented in these documents reflect the ongoing international development of scientific understanding of water quality issues, technology, and institutional change.

Each of the documents is distinct in its content and design. While the Australian Drinking-water Guidelines include a range of notionally tolerable contaminant concentration limits by which potable water can be judged, others introduce other aspects of water management best practice. The CRCWQT document introduces the generic advice on risk assessment for potable water supplies. The enHealth Council documents provide general frameworks for how risk should be assessed in general terms and details on how the technical assessment process might be carried out.

These documents are also notable in that they provide a reference set of criteria for assessing the strengths and limitations of risk studies undertaken for potable water reuse examples in the literature and any future projects in Australia. They describe current best practices in terms of Australian regulations, but which is also which are fully consistent with the recommendations of the

NRC (1998) report. For example, the risk assessment steps in the NRC (1998) report are identical with the following from the enHealth Council (2002) document:

1. Issue Identification;
2. Hazard Identification divided into:
    a. Hazard Assessment involving collection and analysis of relevant risk data; and
    b. Dose-Response Assessment also involving collection and analysis of relevant data;
3. Exposure Assessment involving;
    a. Analysis of hazard locations
    b. Identification of exposed populations
    c. Identification of exposure pathways
    d. Estimation of exposure concentration for pathways
    e. Estimation of contaminant intakes for pathways
4. Risk Characterisation;
    a. Characterisation of potential adverse health;
    b. Summarise risk information
    c. Implementing reality checks on hazard and exposure assessment
5. Uncertainty analysis (identified in the above four assessment steps and arising in the course of assessment as a whole); and
6. Risk Management;
    a. Define options and evaluate health economic social and political aspects of options
    b. Make informed decisions
    c. Take actions to implement decisions
    d. Monitor and evaluate the effectiveness of the action taken.

Other generic processes requiring understanding which are implicit in the above list and more explicit in other guidelines are as follows:

7. The need for agreed, definable and (ideally) quantifiable risk benchmarks such as the 10^{-6} cancer probability;
8. The influence of mediating processes on exposure pathways including environmental processes;
9. The concept of hazardous events;
10. The development of realistic risk exposure scenarios for normal and abnormal (i.e. hazardous event associated) conditions.

These ten generic risk assessment activities provide a check list which stakeholders may use to assess whether risk assessments for planned indirect potable water recycling schemes have been adequately undertaken.

9 Conclusions

Planned indirect potable recycling schemes have been implemented and assessed in terms of their human safety in the USA since the 1960s. A number of major case studies are presented in this report as well as a more recent study from Singapore.

These health-effects studies are extremely encouraging in terms of the potential safety of planned potable water recycling in Australian cities. In spite of comprehensive investigations, no clear deleterious effects have been identified. Furthermore, waters treated in preparation for recycling have routinely been shown to be of equal or greater quality than traditional potable water sources. This applies to both microbial and chemical water quality.

Water treatment processes have improved considerably during the operation of the planned potable water reuse projects presented in this report. Until the late 1980s, planned potable recycling studies were undertaken with secondary or tertiary treated sewage effluents (see case studies on Montello Forebay Groundwater Recharge Project and Potomac Estuary Experimental Water Treatment Plant). After 1985, some studies began to include the use of reverse osmosis membrane treatment. Since 2000, a couple of schemes (notably Orange County and West Basin in California) have begun to add a further barrier to chemicals in the form of advanced oxidation. The protection afforded by this system of multiple barriers must be considered to be significantly greater than that used in any of the studies presented in this report, or the existing level of treatment that exists in "incidental" reuse schemes. In other words, any risks associated with indirect potable reuse (while never zero) are successively decreased with increasing levels of treatment.

Some specific conclusions from this study follow:

1. Despite more than forty years experience, no clear deleterious health effects from planned indirect potable recycling schemes have been observed.

2. As judged by potable water standards the microbial and chemical quality of water intended for indirect potable recycling is generally very high even before its release into the natural environment and further drinking-water treatment.

3. Advanced treatment processes such as reverse osmosis and advanced oxidation are highly effective barriers to recently identified chemicals of concern such as the pharmaceutically active steroidal hormones and molecules like NDMA and 1,4-dioxane which can be difficult to remove from water using traditional treatment processes.

4. Unplanned, or incidental, indirect potable water recycling is common in many developed countries including Australia. The manner and extent to which water is unintentionally indirectly used for potable purposes is distinguishable from planned indirect potable recycling schemes primarily by lower levels of treatment involved and less stringent approaches to water quality monitoring and risk management. Therefore, it should be acknowledged that the level of stringency applied to planned indirect potable water recycling schemes is well beyond that which is common international practice and already occurs in water supplies in Sydney, Brisbane and Melbourne.

5. Treated municipal wastewaters are complex sources of potable drinking-water and differ from natural source waters in several major ways. For example, the range of potential contaminants in municipal wastewaters is significantly greater than in well protected environmental waters. Furthermore, concentrations of chemical and microbial contaminants

can fluctuate during events which may be difficult to detect by conventional monitoring (e.g. as a result of gastrointestinal illness in the community). Accordingly, there is a need for the application of more comprehensive risk management regimes to protect human health than may normally be applied for traditional water sources.

6. A range of new methods for risk assessment have been introduced worldwide to better and more quantitatively assess microbial and chemical risks associated with drinking-water generally. These are applicable to indirect potable recycling and their application in this context is already underway especially in the USA.

While studies undertaken overseas bode well for the safety of recycled water generally, exactly how effectively these studies can be translated to potential Australian schemes is less clear. Water sources will differ and water treatment processes will differ. Furthermore, environmental barriers (surface water or groundwater environments) may differ significantly from scheme-to-scheme. Therefore, in order to ensure the full protection of public health, a comprehensive health assessment should be undertaken specifically for any planned Australian scheme. Australian health risk assessment guidelines such as those published by the enHealth Council provide guidance on how such risk assessments should be undertaken. More specific guidance is anticipated in Phase 2 of the National Guidelines for Water Recycling which is undergoing development during 2007.

As a component of planned potable water recycling risk assessment for major schemes, it is recommended that comprehensive water quality testing be undertaken prior to mixing with potable water supplies. This could be achieved either by the construction of a pilot plant or a full-sized plant with the water initially being used for non-potable purposes. In particular, and in order to address community concerns, the use of biological assays for the determination endocrine disrupting effects and other toxic effects is recommended. Further important components of any assessment include quantitative microbial risk assessment as well as the comprehensive assessment of system reliability.

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