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Water reuse and health risks — real vs. perceived

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Abstract

An increasing drive for water efficiency is leading to a corresponding growing interest in a variety of water recycling initiatives to assist in water efficiency efforts. While available knowledge and technologies exist to provide suitable fit-for-purpose recycled water, concern exists relating to water quality issues, particularly microbial pathogens and chemicals-of-concern. At times these concerns result in the requirement for overtreatment of recycled water, which can lead to potentially valuable water reuse projects becoming too costly and inefficient to be viable. The risks from both microbial pathogens and chemicals-of-concern can vary depending on the type of recycled water, the type of pathogen or chemical present and their numbers or concentration, the water treatment employed and the resulting use of the recycled water. Pathogens and chemicals-of-concern can vary in their ability to resist treatment and their survival in receiving environments. In addition, the risks associated with these contaminants depend on their ability to cause illness in susceptible members of the community. The presence of pathogens and chemicals-of-concern in recycled waters, the effectiveness of treatment methods to remove them and their persistence in the environment were examined.

Keywords: Water quality; Pathogens; Chemicals-of-concern; Risks; Treatment

1. Introduction

The recycling of water is gaining acceptance, at least among regulatory agencies and water authorities, as an important part of the total water cycle. Recycled water can be used for a wide range of applications, most commonly for non-potable purposes. Uses can include irrigation, e.g., agricultural, horticultural and green spaces; environmental purposes; and domestic non-potable uses such as third-pipe systems. These uses are often employed to reduce the pressures on other existing water sources or to provide a water source where a suitable one does not already exist.

Recycled water needs to be treated prior to use with the degree of treatment required depending

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on the intended use, the degree of potential human or animal contact and the original source of the water. Treatment is undertaken predominantly to remove contaminants that could cause an increased health risk or environmental impact. Contaminants that cause the greatest health concerns are microbial pathogens and chemicals-of-concern. The level of treatment required depends on the level of risk, either real or perceived, from the potential presence of chemical and microbial contaminants. As the degree of treatment used can have an impact on the practicality and economic viability of a water reuse project, it is imperative to optimise the treatment processes for the intended use (i.e., "fit-for-purpose" use). To achieve this treatment optimisation, one issue needed is to be able to distinguish between real and perceived risks associated with the reuse of a wastewater.

This paper will explore where the health risks from microbial pathogens and trace organics are real and where the risks are more of a perceived risk. If a distinction can be made between real and perceived risk, then issues such as appropriate treatment levels and appropriate operation regimes for a water reuse scheme could be better instituted, improving the economic, social and operational success of such projects.

2. Types of recycled waters

The most common wastewater considered for recycling is treated sewage effluent [1–5]. Sewage effluent has the advantage that it is a constant year-round source of water available for recycling but has the disadvantage that, due to the high level of faecal and urban contamination, the water normally requires significant treatment before it is considered suitable for use. Other waters used for recycling include storm water run-off [1,6], domestic greywater [2], and industrial wastewater [1,7]. These water types can vary in their contamination risk, which primarily depends on their origin and opportunity for faecal and chemical contamination.

The level of treatment required for each water type prior to recycling depends on the opportunity for — and degree of contamination from— faecal material, domestic and industrial chemicals and nutrients, both organic and inorganic. The general rule is that the greater the chance of faecal contamination of the water, the greater the health risk and thus, the greater potential for treatment requirement. In most instances it could be considered that sewage effluent is the most contaminated of recyclable waters, while storm water and some industrial wastewaters, due to the small chance for faecal contamination, are the least contaminated.

3. Microbial pathogens

The most common human microbial pathogens found in water are enteric in origin. Enteric pathogens enter the environment in the faeces of infected hosts and can enter water either directly through defecation into water, contamination with sewage effluent or from run-off from soil and other land surfaces [8]. The types of enteric pathogens that can be found in water include viruses, bacteria, protozoa and helminths. The risk of water-borne infection from any of these pathogens can rely on a range of factors including pathogen numbers and dispersion in water, the infective dose required and the susceptibility of an exposed population, the chance of faecal contamination of the water and amount of treatment undertaken before potential exposure to the water [9].

3.1. Viruses

Enteric viruses are the smallest of the pathogens found in water. They are all obligate intercellular parasites that are only able to replicate by forcing a host cell to produce multiple copies of the virus [10]. Most human enteric viruses have a narrow host range, meaning that only human faecal contamination of water need be considered as a risk for viral infection of humans [9]. Enteric viruses are highly infectious and commonly require the ingestion of only a few viral particles to cause infection. These infectious doses (ID_{50}) can be as few as 10 viral particles or less [11]. In addition, it would be expected that these viruses would have a greater potential to cause infection in susceptible sections of the population such as the elderly, very young and the immuno-compromised.

3.2. Bacteria

Bacteria are the most common and numerous of the microbial pathogens found in recycled waters [12]. There are a wide range of bacterial pathogens and opportunistic pathogens which can be detected in wastewaters. Many of the bacterial pathogens are enteric in origin; however, bacterial pathogens which cause non-enteric illnesses (e.g., *Legionella* spp., *Mycobacterium* spp., and *Leptospira*) have also been detected in wastewaters [13–15]. Enteric pathogenic bacteria can often infect both humans and animals, e.g., *Salmonella* [9], and thus animals can form another contamination source for recycled water as well as being at risk from contact with poorly treated recycled water. The majority of pathogenic enteric bacteria require ingestion of a high dose of cells to be ingested to cause infection(usually $>10^6$ cells), although *Shigella dysenteriae* and *Campylobacter jejuni* have been observed to only require the ingestion of as few as 100 cells to cause infection in susceptible hosts [16].

3.3. Protozoa

Enteric protozoan pathogens are unicellular eucaryotes which are obligate parasites. Outside of an infected host they persist as dormant stages known as cysts or oocysts. There are several protozoan pathogens that have been isolated from wastewater and recycled water sources [17]. The most common detected are *Entamoeba histolytica, Giardia intestinalis* and *Cryptosporidium parvum* [10]. Infection from all three of these protozoan pathogens can occur after consumption of food or water contaminated with the (oo)cysts or through person to person contact [18]. The main reservoir for *C. parvum* and *G. intestinalis* is man, but several domestic and wild animals have been shown to be potential reservoirs for these parasites (e.g., cattle can become infected with *C parvum* and then cause infection in humans due to contact with infected bovine faeces) [8,9]. Like the enteric viruses, all human protozoan pathogens are significantly more infectious than most enteric bacterial pathogens. *Cryptosporidium*, *Giardia*, and *Entamoeba* have all been observed to have the potential to cause infection with less than 10 (oo)cysts [19,20].

3.4. Helminths

Helminths (nematodes and tape worms) are common intestinal parasites which can be transmitted by the faecal–oral route [10]. Helminth parasites that are a significant health risk in reclaimed waters include the round worm (*Ascaris lumbricoides*) [21], the hook worm (*Ancylostoma duodenale* or *Necator americanus*), and the whip worm (*Trichuris trichiura*) [22]. These helminths have a simple life-cycle with no intermediate hosts and are capable of causing infection via the faecal-oral route [10].

The World Health Organization lists intestinal nematodes as the greatest health risk involving agriculture and aquaculture uses of untreated excreta and wastewater [23]. Infection levels are particularly endemic where human faecal matter is used as a fertiliser for growing vegetables [22].

4. Chemicals-of-concern

Most of the recent concern and comments

regarding trace organic contaminants revolve around pharmaceutically active compounds (PhAC) and endocrine disrupting compounds (EDC). PhACs and EDCs originate either from industrial or domestic sources and thus can be detected in a wide range of recycled waters. These chemicals tend to be present at very low concentrations in treated recycled water (usually in the range of ng/L) as well as require the ingestion of large doses over long time periods to produce any clinical effect [24]. Due to the paucity of information on environmental persistence and potential concentrations in recycled water, however, it is an area that currently remains a concern for health regulators and the public.

4.1. Endocrine disrupting chemicals

EDCs are compounds outside of an organism which can have an impact on the structure and function of an organism's endocrine system causing effects on the organism or its progeny [25]. There are a large number of compounds that are known or suspected endocrine disruptors. Known EDCs that can be found in wastewaters and the environment include the estradiol compounds commonly found in the contraceptive pill, phytoestrogens, pesticides, industrial chemicals such as Bisphenol A and Nonyl Phenol, and heavy metals [26]. Untreated sewage effluent can be a source of all these compounds and can contain higher concentrations than most other recycled water sources. This has created concern that these known and suspected EDCs may create health risks from potential contact of community members with recycled waters.

The risk from the different known EDCs varies depending on the estrogenic potency of each organism. For example, the principal human estrogen 17β estradiol has an estrogen equivalent (EEQ) of 1 while Nonyl Phenol has an EEQ of 3×10^{-6} and DDT has an EEQ of 1×10^{-6} [27]. Thus, a person would have to consume 1,000,000 parts of DDT to get the equivalent estrogenic response as 1 part of 17β estradiol [27]. In addition, the concentrations of these chemicals in wastewater are very low compared to the concentration in other sources. The concentration of 17β estradiol in raw sewage has been found to be as little as 19 ng/L [27] where as the modern oral contraceptive pill contains between 20 and 35 μg of estrogen [28]. Thus, it has been estimated that the estimated daily dose for females from the contraceptive pill is 16,675 EEQ, while the equivalent daily EEQ dose from environmental organochlorides is 0.0000025 [29].

4.2. Pharmaceutically active compounds

PhACs are an emerging area of concern for wastewater treatment and potential water reuse schemes. The majority of PhACs detected in water discussed here are pharmaceutical drugs used for a variety of therapeutic purposes for both humans and animals. Examples include analgesics, caffeine, antiepileptics, cholesterol-

Table 1
Concentration of pharmaceutical drugs per dose and concentration in sewage effluent

Name	Drug type	Conc. (mg per tablet)[a]	Conc. in sewage effluent (μg l^{-1})
Ibuprofen	Analgesic	400, 600, 800	0.37[b]
Gemfibrozil	Lipid regulator	600	0.40[b]
Amoxicillin	Antibiotic	250, 500	>100[d]
Ciprofloxacin	Antibiotic	100, 250, 500	0.68[c]
Carbamazepine	Antiepileptic	100, 200, 400	2.1[b]

[a][35]; [b][36]; [c][37]; [d][38].

reducing drugs, antibiotics and antidepressants. These drugs and other chemicals can enter the environment from a range of sources, but one of the most common routes is through treated and untreated sewage effluent. PhACs can be readily detected in wastewaters such as sewage [30,31]; however, some of these compounds have also been reported to be removed by wastewater treatment [31] or via environmental processes [32–34].

Like EDCs, the concentrations of PhACs found in treated wastewaters and in environmental waters are significantly lower than the concentration found in medication used for therapeutic purposes (see Table 1 for examples). Thus, the exact health risk of these compounds in reclaimed water (particularly where minimal human or animal contact occurs) remains to be determined, but based on the evidence given in Table 1 could be considered to be minimal.

5. Issues associated with microbial and chemical contaminants in water reuse

5.1. Number or concentration and distribution in raw and treated wastewater

The risk from a pathogens or organic chemicals in reused water is also dependant on the number or concentration in a volume of the water. Microbial pathogens can vary significantly in number in both raw and treated wastewater depending on the source, pathogen type and treatment effectiveness [40]. Also, as microbial pathogens are discrete particles that are present in low numbers in large volumes, they tend to be randomly distributed in water [9]. This can cause difficulties in the detection and enumeration of microbial pathogens in water and a corresponding difficulty in predicting and managing the risk. In combination with gaps in the knowledge of pathogen behaviour in the environment and treatment effectiveness, this has led to the potential to overestimate the actual risk from pathogens in waters such as recycled water.

In comparison, organic chemicals are more evenly distributed in water. This means that ingestion of an organic chemical in a volume of recycled water is more likely and easy to predict than microbial pathogens. Also, as long as their concentration in water is above technical detection limits, the detection of chemicals-of-concern tends to be more straightforward than for the randomly distributed pathogens.

5.2. Exposure and dose response

The relative health risk from the contaminants depends on the type of contaminant examined. Microbial pathogens, particularly viruses and protozoa, can cause rapid infection if ingested by people in contact with recycled water in which the pathogen is present [9]. While laboratory measurements of infectious doses can vary between different types of pathogens (e.g., <10 viral particles ingested can cause disease while *Vibrio cholerae* may require the ingestion of more than 10^5 cells to infect a healthy individual) [9], the reality is that an infection can be caused by only a single pathogen cell/particle/cyst if that pathogen unit can pass intact through the alimentary canal into the intestines of a host [9].

In contrast, toxic chemicals tend to have an effect only after constant, long-term exposure over a period of months or years. For EDCs and PhACs, this would require the ingestion of large amounts of water over a long period of time before a significant health impact was observed. Even if this very large exposure did occur, it has been concluded that the actual concentration of compounds consumed would have minimal, if any, impact on a person or their offspring [24].

5.3. Treatment efficiencies

It is a commonly held opinion that microbial pathogens can be removed by treatment processes. Different treatment systems, however, are

Table 2
Examples of maximum and minimum Log reduction via different treatment processes

Treatment	Faecal coliforms	Enteric viruses	Phage	*C. parvum*	*Giardia*	Helminths
Secondary	2.5	5	1.6–6.6			
Ponds			0.11–0.39	1	1.6	1.7–3
Chlorination	3		0.1–2.5	0.1		
O3	2–3	3.5–6	2–6			
UV	2–3.5		4–6			
Membrane filtration	7		>6	6–7	6	

more or less effective on the removal of different pathogens. Examples of the efficiency of different treatment systems on viruses, bacteria, protozoa and helminths can be seen in Table 2. Tertiary treatment of recycled water is a common treatment level where close contact with the water is considered a possibility. It has been shown, however, that pathogens can still be detected in tertiary treated recycled water [17,41] and that some pathogens are resistant to disinfection processes (e.g., *Cryptosporidium* is resistant to chlorination [42] and adenovirus is resistant to UV radiation [43]). Thus, the potential presence of microbial pathogens in recycled water, even at very low numbers, must be considered a real risk and the water must be used with due regard to this risk. Treatment levels lower than tertiary treatment are less effective on the removal of protozoa and viruses and thus should only be directly used when there is limited chance of human contact.

The most effective treatment methodology is dual-membrane filtration, which can remove greater than 6 log of pathogens and is often used were there is a high likelihood of human contact (e.g., within domestic housing or for potable uses). Dual-membrane treatment and other similar tertiary treatment systems are expensive to operate, and thus treatment levels still need to be designed to fit the intended use. For example, it would not make economic sense to treat recycled water using dual-membrane filtration if the water is to be used for the irrigation of fodder crops. Conversely, water that is recycled for use within an urban household for non-potable uses would need to be highly treated for health reasons, but it could be expected to get an economic return for this water.

Another potential treatment barrier that has been considered to have potential use with recycled water is the influence of environmental processes on pathogen decay. Environmental processes are known to be able to remove microbial pathogens from water [44] and could have potential for use as part of the treatment and barrier system employed for recycled water use. Much more understanding is needed, however, about the mode of action and efficiency of these natural removal processes before they can be reliably used as an effective treatment barrier [44].

The removal of EDCs and PhACs has been demonstrated for a number of these chemicals by wastewater treatment methods [27,31,32,36,38] and environmental processes [37,45]. For example, it has been demonstrated that the tertiary treatment of wastewater (sand filtration, ozonation and UV disinfection) can reduce EDCs to below detection limits [46]. However, the current large number of known EDCs and PhACs that can be in wastewater, as well as the possible existence of other potential and as yet unknown chemicals-of-concern, makes it difficult to predict the removal of all of these chemicals under all treatment methods or environmental conditions.

5.4. Environmental stability of contaminants

Microbial pathogens vary in their stability in the environment, and this fact needs to be taken into account when determining the risk from different pathogens in recycled water. For example, helminth eggs have been observed to remain infectious in contaminated moist shady soil for up to 10 years [8,21]. Other pathogens can be expected to survive much less than helminth eggs if introduced to an environment in recycled water, with viruses and protozoan (oo)cysts generally being more environmentally resistant than enteric bacteria [40].

There are a range of processes that can have a significant influence on the persistence of microbial pathogens when introduced to an environment [15,43,48]. These factors, which include sunlight, temperature, oxygen, organic carbon concentration and indigenous microorganisms, can be very efficient in reducing the survival of pathogens [43,47,48]. The understanding of the influence of these environmental factors have on pathogen survival is still incomplete however, and when combined with the complexity of the environments receiving recycled water, it is still difficult to predict accurately the stability of various pathogens in different environments [44]. Thus, the potential presence of pathogens still needs to be treated as a real and significant risk, and the influence of environmental factors in reducing their persistence cannot currently be relied on [44]. Until a better understanding is obtained, treatment requirements will remain greater than perhaps necessary if environmental systems are able to be trusted as part of the treatment barrier system for recycled water.

Even less is currently known about the environmental fate and behaviour of EDCs and PhACs, and subsequently on how environmental processes can be used further to reduce the risk to humans and the environment from these compounds. Some of the well known EDCs such as estrogen and Bisphenol A have been shown to adsorb strongly to river sediments and other organic rich soils [39]. One study found that five common EDCs degraded both in marine sediment and marine water [49]. Another study also showed that Bisphenol A rapidly degraded in aquatic environments [50]. Little else is known, however, on the persistence of many of the known and suspected EDCs or PhACs, and significantly more research is required for a valid risk assessment to be made.

6. Assessment of the risk associated with pathogens and chemicals-of-concern

The use of recycled water carries health risks, with the risks escalating with an increasing potential for faecal contamination. The health risks judged by regulatory and health authorities to be the major concern are microbial pathogens and chemicals-of-concern. Reducing the risk from microbial pathogens and chemicals-of-concern is achieved by placing barriers between the recycled water and members of the community. The type and number of barriers used can vary depending on the quality and source of recycled water and the intended use. Barriers can include restricted irrigation and drying times, preventing access to areas where the water is being used and processing of goods that have been irrigated with recycled water.

The most common and effective barrier used is treatment and disinfection of the recycled water before use. The magnitude of treatment and disinfection used normally depends on the source of the recycled water, the potential for faecal contamination, and potential for exposure to community members. Treatment has been widely assumed to be effective for removing contaminants, in particular microbial pathogens; however, recent evidence has suggested that many of the treatment methods may not completely remove microbial pathogens [17,41]. Therefore, they remain a real health risk associated with recycled water regardless of the treatment used.

Another potential barrier that could be of significant use for water reuse schemes in controlling the risk from microbial pathogens is the effectiveness of environmental processes to inactive pathogens. While research undertaken to date and anecdotal evidence suggest that environmental processes can be a valuable treatment barrier, much more information is needed on the effectiveness of environmental processes as a barrier against the persistence of microbial pathogens [44]. In addition, risk assessment and management, still developing as scientific knowledge improves, will make a significant impact on our ability to determine the actual risk from microbial pathogens. Currently risk assessment must make a number of assumptions based on inferior information or gaps in scientific knowledge. Increased research to cover these gaps will significantly improve risk assessment and management.

In contrast, this paper has shown that due to the very low concentrations of chemicals-of-concern in recycled water and the very small effective potential doses possible, even with heavy contact with recycled water, it can be concluded that the potential human health impact from EDCs is minimal. Also, the significant difference between the concentration of these chemicals in medications and solutions used by the community on a daily basis and the much lower concentrations in effluents means that there are extremely few health risks, even if there were exposure of the community to large volumes of recycled water [24]. Where there could be a risk for the use of recycled water because of the presence of these chemicals-of-concern is the impact these chemicals may have on natural environments such as rivers and lakes [51,52]. Thus, for ecological reasons (as opposed to health concerns), recycled water may need to be treated to a level that can significantly decrease any risk to the environment. As this is an area which has had very little research until recently, improvements in detection capability have occurred, but more research is still required to determine the effectiveness of treatment to remove chemicals-of-concern, assess the stability of these chemicals under a wide range of aquatic and terrestrial environments, and determine the actual risk of endocrine disruption and other cellular impact from these chemicals on organisms living in environments exposed to the use of recycled water [53].

7. Conclusions

This paper has established that the major health risks associated with recycled water are microbial pathogens. The information obtained was not able to demonstrate that changes could currently be recommended for the use of more appropriate treatment and management options (e.g., in some cases a relaxation of treatment requirements) as there remains uncertainty on the reliability of barriers such as natural environmental processes for reducing pathogen survival. For water reuse to become a valuable part of a total water cycle in both urban and rural communities, economically viable treatment processes, sensible regulations and improved health risk assessment and management are needed.

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