

Dual-pipe reticulation for non-potable water: a survey of public health risks and their mitigation

Paul Jeffrey^a, Kristell Le Corre-Pidou^a, Peter Kuin^b, Sheryll de Valk^b and Gerard van Houwelingen^b

^aCranfield Water Science Institute, Cranfield University, Cranfield, Bedfordshire, UK; ^bRoyal HaskoningDHV, Amersfoort, The Netherlands

ABSTRACT

Dual pipe reticulation schemes which supply non-potable water for domestic purposes can reduce potable water demand and make a contribution to achieving a supply-demand balance. Such schemes are not without their risks and this contribution outlines the public health risks associated with dual pipe distribution infrastructure. The first survey of its kind, the paper draws together material from a variety of published sources to present evidence from a wide range of jurisdictions to illustrate the risks, and assembles a suite of risk mitigation actions which can be used to improve the safety of such schemes. We find that three types of risk dominate the reported incidents and are particularly challenging to manage; cross-connections due to faulty installation or post-commissioning householder DIY projects, cross-contamination as a result of factors other than a cross-connection, and the deliberate or inadvertent misuse of a non-potable supply.

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Introduction

As is well documented, many countries around the globe are experiencing increasing pressure on their freshwater supplies resulting from, amongst other phenomena, population growth, urbanisation, changes in land use, and climate change (WMO 2024). In this context, water recycling to supply water for functions such as toilet flushing and landscape/garden irrigation, is increasingly being considered as a means of securing an alternative source of water that will also help alleviate the pressure on natural water levels in rivers, streams, and aquifers (EEA 2024). The potential for non-potable supplies to displace potable supplies will depend on many factors, including the profile of domestic water use across micro-components (e.g. drinking, toilet flushing, food preparation, etc.). Taking toilet flushing in isolation, credible data sources from Europe suggest that between 16% and 51% of total household water demand could be saved through the provision of a non-potable supply (EA 2008). The actual performance of installed systems is equally variable depending on the types of potable water use displaced by a non-potable supply. A recent survey of multiple operational schemes in San Francisco reporting that savings ranged between 18% and 50% of total supply (SFPUC 2018).

Governments and environmental regulators are encouraging housing developers to achieve water

neutrality by building new properties fitted with low water using devices like showers and washing machines and use rainwater or grey water for toilet flushing and watering plants (Ofwat 2022). Where a sub-potable supply is involved, a secondary (dual pipe) system is often required within a building or in its vicinity to facilitate distribution in a safe manner. Such systems are installed in residential properties, commercial and industrial premises to convey water via two separate distribution networks. This allows for the use of an alternative water supply for end-uses not necessarily requiring water of potable quality (e.g. toilet flushing, irrigation, etc.), thereby reducing freshwater demand.

The use of dual pipe systems for non-potable reuse was first reported in the USA, with early examples dating as far back as the 1920s in the Grand Canyon Village, Arizona (Okun 1997). In the late 1970's, the first major urban dual pipe system was commissioned in St Petersburg, Florida (Anderson 2003). By 2015, this scheme was connected to 11,172 properties, over 90% of which were residential (Alsharif, Rivera, and van Beynen 2021). Even during these early days of dual pipe schemes the additional risk control measures needed to safely provide a non-potable supply inside residential buildings were being expressed (see Grigg et al. 2013). Dual pipe systems for non-potable reuse have also been trialled and/or implemented in several other countries around the globe such as Japan,

Germany, Denmark, the UK, and the Netherlands. For example, by 2006, Tokyo counted 20 water reclamation schemes around the city resulting in circa 5.8 million m³ of water recycled per day used for toilet flushing and other urban uses (Takeuchi and Tanaka 2020).

It has been in Australia however that dual-pipe schemes have, in one sense, come of age with relatively rapid growth in their implementation and an attendant growth in regulation. The maturation of the sector in Australia started with the New South Wales Guidelines for Urban and Residential Use of Reclaimed Water (NSW 1993) which covered requirements for the use of dual reticulation systems and permissible uses as well as management and monitoring strategies. Comprehensive guidance on managing the risks of different forms of water reuse was made available in 2006 and 2009 as the Australian Guidelines for Water Recycling as part of the National Water Quality Management Strategy (NRMMC 2006; 2009a). A recent comprehensive review of water reuse and recycling in Australia by Radcliffe and Page (2020) provides insight into a wide range of dual pipe schemes in Australia. Their assessment exposes many of the challenges faced by scheme designers and operators. It also notes the difficulties faced by regulators in shaping legal instruments, standards, and guidance to ensure safe operation of the systems.

Dedicated water recycling infrastructures require careful design and management. The primary risks requiring control are inappropriate use of the delivered non-potable water and contamination of drinking water supplies resulting from cross-connections between potable water and recycled water networks. Useful diagrammatic representations of such systems can be found in BSI (2010; 2011). By 'cross-connection' we mean pipework which allows – for whatever reason – non-potable water to enter the potable water supply. Indeed, cross-contamination between potable water supply systems and other source of water, as well as backflows are widely acknowledged to constitute a health risk for consumers (WHO 2014). Whilst most water quality incidents have their root causes at the front end of supply systems (e.g. treatment works, storage reservoirs), increased use of dual pipe supply systems in residential and commercial buildings constitute an additional source of risk. Cross-contamination events have been reported in a number of countries. For instance, in the Netherlands in December 2001, 200 people contracted gastroenteritis from norovirus infection as a result of a non-potable supply system in a new housing estate being cross-connected with the drinking water supply. The resultant action from the Dutch Government was to ban all large-scale dual pipe water

supply schemes for households, based upon concerns of possible misuse of the water and the unacceptable risk that it poses to public health (Fernandes et al. 2007).

The contribution below outlines the public health risks associated with dual pipe systems, presents evidence from a wide range of jurisdictions to illustrate those risks, and assembles a suite of risk mitigation actions which can be used to improve the safety of such schemes. Its value is in drawing together a disparate and fragmented evidence base to provide a unified picture of the risks associated with dual-pipe schemes and the effective management of those hazards. We concentrate on risks to human health which result from the reticulation infrastructure whilst noting that other risk vectors are relevant (e.g. inappropriate or ineffective water treatment or water quality standards). Our findings are thereby limited to an improved understanding of the processes and behaviours by which residents may be exposed to non-potable quality water. The study covers dual pipe systems which are fed by collected/treated rainwater, stormwater, greywater, wastewater, or a combination of these.

There is an expansive literature on many aspects of water reuse (e.g. treatment, resource optimisation, public acceptance, water quality) including useful overviews of why reuse schemes fail to deliver their intended outcomes (West et al. 2016). However, academic work concerned with understanding and managing the risks from a distribution infrastructure perspective is less common. This is surprising given that, as demonstrated below, there is a noteworthy catalogue of public health incidents whose root cause is associated with the distribution network itself. Those authors who have engaged with the problem have provided useful overviews of specific schemes (e.g. Landers and McLeod 2008) or located the risks within a wider context (Nadebaum et al. 2004). The findings of comparable studies which have considered cross-connections and backflow incidents in drinking water distribution systems (e.g. Viñas et al. 2022) also provide useful parallels.

The terminology used to describe the form and function of dual pipe water supply systems as well as the quality of the water flowing through them is inconsistent, often within single jurisdictions. A short list of relevant signifiers would include; recovered, recycled, reused, reclaimed, sub-potable, non-potable, non-drinking, unwholesome, dual pipe, third pipe, second pipe, purple pipe. For our purposes we use the term 'dual pipe' to describe the systems of interest and understand it as the physical infrastructure through which a second water supply, of a poorer quality to that provided through the drinking water mains, is delivered for

specific uses. Potential applications for the second supply include both indoor (e.g. toilet flushing, laundry) and outdoor (garden irrigation, vehicle washing) functions. We use 'dual pipe' in this broad sense unless referring to a specific case or context, or where referencing/quoting from secondary sources.

Approach

The data presented here were gathered as part of a wider study of dual pipe systems conducted in the UK (DWI 2024). Data collection involved identifying (i) reports of public health incidents associated with dual-pipe schemes and (ii) standards, regulations, and guidance which offer advice on the mitigation of risks from dual-pipe schemes. We deployed a soft form of document analysis when it came to extracting relevant material. The raw content of pertinent documents is the unit of analysis here rather than any interpretation involving themes or topics. The skill set required is simply to be able to identify pertinent information and to separate it from that which is not (Corbin and Strauss 2008).

Information on both public health incidents and risk mitigation measures were recovered from documents relating to water management in Australia, USA, UK, Belgium, and the Netherlands. The authoring team were aware of, and knew how to access, much of this material beforehand with internet searches being used to expand the range of candidate texts. The types of texts collected included legislation, standards, academic papers, policy documents, sector reports, and web pages. We paid particular attention during data acquisition to issues of credibility and authenticity (Bowen 2009). These concerns were addressed in two ways; (i) for the material on public health incidents we sought secondary sources as a way of triangulating the details and (ii) for the mitigation actions we traced the provenance of the accessed documents to ensure that we were using the most recent versions and charted the many cross-references between official documents. The vast majority of the accessed documents were in English with a small number in Dutch or French.

Our document search strategy did not privilege the legal standing of collected documents. So, for example, material on risk mitigation actions was extracted from both hard (e.g. statutory) and soft (e.g. standards/advisory) regulatory frameworks. The determining factor for inclusion of a document was the authority of authorship. Sources from federal or regional governments, professional or trade institutions, standards bodies, etc. were exclusively used. The relationship between these different forms of regulation is worth noting here. For example, governments often use standards when putting

together legislation or guidance documents. Standards are used to establish the technical detail, allowing the legislation to concentrate on the big picture and principles. Compliance with a standard will therefore often demonstrate compliance with the relevant legislation, although there are usually ways of being compliant with legislation without using a standard.

Risks associated with dual pipe water recycling systems

Public health risks associated with water recycling are primarily linked to waterborne diseases resulting from exposure to pathogenic micro-organisms (e.g. bacteria, viruses) (Asano, Burton and Leverenz 2007, NRMCC 2006). For schemes involving dual pipe reticulation systems in urban environments (e.g. residential areas, commercial buildings), exposure routes include; (i) ingestion resulting from cross-connections between potable and non-potable water distribution networks, (ii) inhalation/ingestion of aerosols emitted during toilet flushing, garden irrigation or other uses of the water that may generate aerosols, and (iii) use of supplied water for a purpose it is not intended for.

Human health risks resulting from exposure to chemical substances (e.g. metals, personal care products, surfactants, pharmaceutical residues and other emerging contaminants) from water recycling are typically considered lower than the health risks resulting from microbiological contaminants, which can cause serious illnesses after a single exposure (NRC 2012). This is due to their presence in low concentrations in treated recycled water, in the ng/L range (Toze 2006). This is especially true for recycling applications where ingestion risks are limited and likely to be incidental. In the specific case of recycling for toilet flushing, risks of exposure to chemicals are considered low due to low concentrations and relatively short exposure times compared with other uses (e.g. garden irrigation) (WRc 2015). The U.S. Environmental Protection Agency (USEPA) guidelines for water recycling also indicates that public exposure to trace chemical constituents in recycled water for irrigation or other types of use is negligible (USEPA 2012).

For systems where sources such as greywater are used, the high variability of its physico-chemical and microbiological properties resulting from household activities can impact its overall characteristics, reduce its treatability. Such variability can impact its suitability for specific end uses such as irrigation (Kadewa et al. 2020). Rainwater may additionally present risk of exposure to heavy metals such as zinc and lead leaching from harvesting structures (e.g. roofs) due to their acidic character (WHO 2017). Antimony, a component used in solar

panels, can also pose a health risk where panels are present on roof surfaces (DWI 2018). The disposal of liquids with high concentrations of chemical pollutants (e.g. paints, solvents, etc.) via kitchen or bathroom sinks can compromise the efficacy of greywater treatment processes and result in pollutant breakthrough into delivered water. Pollutants in rainwater and stormwater runoff such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) have been investigated in terms of their potential impact on human health through recycling systems and the development of robust risk assessment models to derive a hierarchy of hazard control (Ma et al. 2019).

Significant variation in demand (e.g. triggered by low occupancy) can also adversely impact the quality of water in a dual pipe system. For example, low demand can leave water stagnant in storage tanks leading to regrowth of microbial contaminants. Suppliers of treatment equipment also need to be aware of the potential for contaminant build up in closed loop greywater schemes where the same water using appliance is both the supply of raw greywater and is being supplied with treated greywater. However, these risks can be controlled through careful design and maintenance of the collection, treatment, and delivery infrastructure.

Pipework, fixtures and fittings need to be matched to the quality of water which is being delivered through them as such water may contain contaminants at concentrations which interfere with their usual and safe operation. The risk here is elevated where water has (amongst other characteristics) higher levels of solids, dissolved salts or sulphates, heightened salinity, high or low pH, raised temperature, and raised levels of calcium and iron. Experimental studies have explored the impact of these parameters in the context of managing scaling, corrosion, colour, turbidity and microbial growth in recycled stormwater distribution networks (Gonzalez et al. 2016). Greywater sources, particularly those with personal care products in them, can be a particular concern in this context as they are more mineralized and have higher conductance than potable waters. Pipework and fittings will therefore require more frequent maintenance.

Research conducted on behalf of the Water Research Foundation (WRF), Water Environment Research Foundation (WERF), and the USEPA (Grigg et al. 2013), highlighted that whilst pipe age is not the only determinant of its condition, the likelihood of physical, hydraulic or water quality failure is positively correlated with it. Distribution of recycled water through pipework made of ferrous materials presents more opportunities for internal and external corrosion, when compared to wholesome water, because recycled water is more

mineralized with higher conductance and chloride content and lower pH. The report also suggests that because secondary supply water lines are often the last pipe installed, there is an increased opportunity for stray current electrolysis or coating damage. Characterising the threat as like plaque building up in arteries, the authors argue that dual systems will normally encounter more severe operating conditions than potable systems and are therefore more prone to premature aging and sudden failures unless properly maintained and inspected. Overall, although requirements may vary from one country to another and depend on the type of recycling application targeted, water quality standards typically cover a set of pathogen indicators and key physico-chemical parameters.

Evidence of public health incidents

In the following we discuss those incidents identified through the document analysis which evidence public health risks resulting from the installation and use of dual-pipe schemes (Table 1). Incidents were included where publicly accessible information was available in either English or Dutch on the nature, causes of, impact of, and response to the event. Consequently, the list does not contain all reported incidents. We select a subset of the events listed in Table 1 (where the citations for each event can be found) for detailed discussion so as to provide representative samples of the causes of risk exposure and incident responses. The incidents have not necessarily resulted in scheme users becoming unwell but they have, in all cases, exposed them to risk.

Accounts of building occupiers utilising unwholesome water for unsuitable purposes are a particularly problematic aspect of the risks associated with dual pipe installations, as evidence is sparse and much of the available commentary is either based on anecdote or founded on hearsay. This is perhaps unsurprising given that systematic behaviour observation would be required to generate more credible evidence. One of the few reported incidents was from an early study of the Rouse Hill scheme in Australia where testimony from residents' interviews suggested that nearly 16% of pool owners were using recycled water in swimming pools against the advice of the scheme operator (O'Toole et al. 2012, De Rooy and Engelbrecht 2003).

Several studies have demonstrated the presence of infectious organisms or high numbers of faecal indicator bacteria in both greywater and rainwater (WRc 2015). However, we were unable to find any unambiguous evidence (in terms of the root cause) of illness resulting from the use of recycled water where the water quality

Table 1. Public health incidents associated with dual-pipe supplies.

Scheme	Description	Incident	Response/corrective measures	Reported in
Rouse Hill residential development, Sydney, Australia.	Residential scheme using treated municipal wastewater for toilet flushing /external taps (irrigation, etc.)	<ul style="list-style-type: none"> 50 cross-connections identified by builders and plumbers during the construction phase (i.e. before recycled water brought on stream). Subsequently, at least four incidents attributable to plumbing errors have been documented, including one that affected 82 houses. According to Hambly et al. (2012) comparable events also took place at the Sydney Olympic Park and at Pimpama-Coomera (see below) In March 2007, recycled water was supplied inadvertently for 19 days to a kitchen at Melbourne Water's Eastern Treatment Plant, which was reported to have led to a number of staff illnesses 	<ul style="list-style-type: none"> Recycled water conveyed via purple pipes. Different diameter of pipes for house services from the main to the meter (25 mm for recycled water/20 mm for drinking water) Separate meters: Recycled water meter is purple, drinking water meter is green Backflow prevention devices fitted to the drinking water lines but NOT the recycled water. Surface water fittings distinguished by different labels on surface boxes. External tap equipped with a removable handle All internal plumbing in accordance with the relevant standard and codes 	Radcliffe and Page (2020), NRMCC (2006) Law (1996) Hambly et al. (2012)
Leidsche Rijn, Utrecht, the Netherlands	Surface water for laundry, toilet flushing, garden tap	<ul style="list-style-type: none"> During maintenance work, the non-wholesome supply was connected to the wholesome one for cleaning purposes. Following maintenance, the cross-connection was not removed, and the systems were re-started, resulting in a higher relative pressure in the non-wholesome water network, allowing unwholesome water to circulate in the drinking water network. A total of 921 households were affected resulting in an outbreak of gastroenteritis related diarrhoea. Affected community exhibited a 54.1% higher incidence than that found in a non-exposed cohort of 1529 households from an adjacent area. Early in 2002, an incident occurred at one household due to an accidental miss-match of the dual pipe system. 	<ul style="list-style-type: none"> Based on this experience in Leidsche Rijn, the VROM (i.e. Housing, Spatial Planning and the Environment Inspectorate) concluded that an independent inspection of each individual house connection afterwards (i.e. after its construction) must be considered necessary to prevent cross-connections in the future. This independent retrospective check of the individual house connections would also ensure that any errors, as with the first incident, are identified in good time (i.e. prior to commissioning). Following the incidents at the end of 2001 and the beginning of 2002, it was decided to discontinue the supply of unwholesome water. 	Oosterholt (2003) Fernandes et al. (2007)
Noordwest (Wageningen), the Netherlands	Mix of groundwater (70%) + surface water via bank filtration (30%)	<ul style="list-style-type: none"> Following the Leidsche Rijn incident, and subsequent inspections imposed by the VROM inspectorate, two incorrect connections were found at two households at the Noordwest site. 	<ul style="list-style-type: none"> Enquiry concluded that despite the different colour coding used for the materials transporting drinking and recycled water, human error still posed a risk. 	Oosterholt (2003), Oosterholt et al. (2003).
Meerhoven (Eindhoven), the Netherlands	Surface water	<ul style="list-style-type: none"> Multiple cross-connections were identified. Some of these were caused by the tenants who, for example, connected a faucet or fountain to the unwholesome water supply pipe 	<ul style="list-style-type: none"> The supply of unwholesome water was stopped 	Oosterholt (2003), Oosterholt et al. (2003)
Upton Eco-Housing Development, UK	Residential scheme using rainwater harvesting for toilet Flushing and garden Irrigation	<ul style="list-style-type: none"> In 2010, complaints of a sewage odour from tap water were reported. Samples taken from one of the houses contained >100/100 mL E. coli and coliforms. Cross-connections between a rainwater harvesting system and the potable water supply were identified in 26 houses. 	<ul style="list-style-type: none"> Boil water notices and an explanatory letter were issued to all affected properties, along with bottled water Water company staff instructed to check for both rainwater and greywater recycling systems during all investigations at customer properties. Company has also briefed relevant staff on the circumstance of the event and familiarised them with relevant standards and regulations. 	DWI (2010)

(Continued)

Table 1. (Continued).

Scheme	Description	Incident	Response/corrective measures	Reported in
Pimpama, Coomera, Queensland, Australia	Residential scheme using treated municipal wastewater for toilet flushing, external taps, and irrigation	<ul style="list-style-type: none"> • A major cross-connection affecting 630 houses was identified in 2009 after residents reported bad taste and odour from kitchen and bathroom taps. • Both the potable and recycled water services were restored after 11 hours following identification of the issue. • Reports of gastroenteritis were recorded. 	<ul style="list-style-type: none"> • Researchers involved in the reporting of the events indicated that methods to detect cross-connections between recycled and potable water systems should be a priority research area for water utilities. 	Grigg et al. (2013)
Mawson Lakes, Adelaide, Australia	Residential scheme using treated municipal wastewater for toilet flushing, external taps, and irrigation.	<ul style="list-style-type: none"> • A single cross-connection between recycled and potable distribution networks resulting in a couple drinking and bathing in recycled water for eight years (2010–2018). • Cross-connection made at time of construction. 	<ul style="list-style-type: none"> • Auditing procedures modified. • Health Board indicated that although not considered suitable for drinking, the recycled water is highly treated and of low risk to residents. 	ABC (2022) Radcliffe et al. (2017)
Mt Ridley College, Craigieburn, Australia	Recycled wastewater used for toilet flushing	<ul style="list-style-type: none"> • Cross-connection identified during routine maintenance. • Bottled water supplied to the school which remained open 	<ul style="list-style-type: none"> • Commissioning of R&D including an anti-ingestant trial and a smart water cross-connection detection system (Richards et al. 2016). 	Yarra Valley Water (2015)
City of Cape Coral FL, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • (2008): Four cases of cross-connections 	Unknown	Grigg et al. (2013)
Cary Public, NC, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • (2007): At least four cross-connections discovered at residences in 2007. No associated illnesses were reported. 	<ul style="list-style-type: none"> • In reclaimed water service areas, water is now sampled at the outside hose bib to the house at the time of the plumbing final inspection as well as when a reclaimed water service is requested. 	Grigg et al. (2013)
Dunedin FL, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • One cross-connection incident due to a plumbing mistake on a residential renovation project. This occurred at the onset of the reclaimed water project and there were no resulting illnesses 	Unknown	Grigg et al. (2013)
Marin Municipal Water District, CA, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • One cross-connection identified during construction of a subdivision consisting of several single-family homes. No illnesses resulted from the cross-connection. 	Unknown	Grigg et al. (2013)
Oviedo, FL, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • Reports that the city sometimes encounters a DIY resident who has contaminated their own system. 	<ul style="list-style-type: none"> • Pro-active inspection programme providing backflow prevention guidelines. 	Grigg et al. (2013)
Pinellas, FL, USA	Polished municipal wastewater for toilet flushing	<ul style="list-style-type: none"> • (2006): Two illegal cross-connections identified. 	<ul style="list-style-type: none"> • New connections to the recycled water system inspected when connected and cross-connection tests performed. • Existing residential reclaimed water customers are inspected as needed • Wells and irrigation systems connected to the potable water system must be disconnected when a site to be connected to the reclaimed water system. 	Grigg et al. (2013)

had been demonstrated to be fit for the intended use. An important caveat here is that illnesses resulting from water ingestion are often difficult to distinguish from those resulting from food ingestion and may therefore not be reported accurately.

The largest study of potential health impacts from dual pipe installations (which are used as intended) was conducted in Australia in 2009 using almost 36,000 patient records from the Rouse Hill development and a control group. The study covered a two year period

and looked for differences in how frequently patients presented to their GP with acute gastroenteritis, acute skin complaints or acute respiratory conditions. These illnesses are plausibly related to exposure to pathogenic microorganisms, chemicals, or bacterial endotoxins in recycled water. No significant difference in presentation rates for the three conditions were found between residents living in houses connected to the Rouse Hill Recycled Water Scheme, compared to residents from surrounding suburbs connected to the conventional water supply (Sinclair et al. 2010). Other epidemiological studies conducted in Australia (O'Toole et al. 2012) and Israel (Busgang et al. 2015) also reported no or little correlation between the use/detection of pathogens in source greywater or delivered water and reported gastro-intestinal illness in households. Whilst no targeted study of the impact of rainwater harvesting or water recycling on immunocompromised populations have been carried out, several studies have drawn attention to the risks, particularly where there is little or no treatment involved in a scheme (Jongman and Korsten 2016).

In comparison to the lack of public health incidents where dual pipe systems are properly connected and the water used as intended, there have been several incidents caused through either cross-connections or accidental/intentional misuse of dual pipe system supplies. For example, whilst at Rouse Hill multiple cross-connections were identified between the potable and non-potable systems before recycled water was fed into the system, other cross-connection incidents, unfortunately, have resulted in human illness as explored next.

A particularly significant incident occurred in the Netherlands in the early 2000s. Between 2000 and 2002, five neighbourhood scale demonstration pilot projects were launched for the large-scale delivery of recycled water via separate pipeline networks. An accompanying study to the pilots analysed a number of scheme features including water quality and the effects of use on the environment and the customers. This study identified a number of cross-connections between the dual pipe systems which resulted in contamination of the drinking water affecting more than 921 households and leading to an outbreak of gastroenteritis (Fernandes et al. 2007). To clean the recycled network before use, this was connected to the live drinking water network. Upon completion of this maintenance work, the connection was not removed and remained in place when the recycled network was started. This resulted in higher pressure in the recycled water network than the potable network, causing recycled water to backflow into the drinking water network. Affected consumers were not aware that they were receiving recycled water at potable end-use points

and therefore unknowingly drank non-potable water (Fernandes et al. 2007, Oosterholt 2003, Oosterholt et al. 2003).

At the time, the Netherlands had developed dual reticulation systems for water recycling of partially treated alternative water sources (e.g. surface water, groundwater) at a number of sites across the country. Some limited controls were in place for aspects such as colour coding of pipework but other important standards, including for delivered water quality, were more lax. The pilot study incident and others brought about a hiatus in approvals of such schemes in the Netherlands with the Dutch Minister of Housing, Spatial Planning and the Environment banning the further operation and development of large-scale recycling schemes due to the risks to public health except in the case of rainwater harvesting for toilet flushing (VROM 2003). A subsequent monitoring report (Kiwa 2003) serves as a basis for the current regulations in the Netherlands on the use of recycled water supply and use.

In Australia, cross-connection events have been reported at multiple sites, including the Sydney Olympic Park (New South Wales), Mt Ridley College (Craigieburn, Victoria), Mawson Lakes (Adelaide, South Australia), and Pimpama-Coomera (Queensland, Australia), despite Australia having probably the most comprehensive range of regulatory tools, standards and codes in place to prevent them. For instance, measures include the use of colour coding for material in contact with the recycled water, the use of different diameters for pipes conveying recycled water (25 mm for recycled water/20 mm for drinking water), training schemes for system installers, backflow prevention devices fitted to the drinking water lines and the use of removable handles on external taps. Notwithstanding these controls, which have gradually reduced the incidences of cross-connections during installation, post-installation cross-connections continue to be a problem due to householders' DIY projects.

Despite the number of cross-connections discovered in Australian schemes, the public health impact has been low, principally due to the advanced treatment of supplies to a good water quality. The following two examples stand out in this context, where despite cross-connections, no human health issues were reported. Firstly, an incident in 2015 at St. Peters College, Cranbourne East, Melbourne involved a Class A recycled water supply being connected to a drinking water fountain for over a year before discovery. Secondly, one of the multiple cross-connections discovered at the Mawson Lakes development post construction was not identified for eight years (ABC, 2022).

Table 2. Effectiveness of common risk mitigation measures.

Risk mitigation measure	Specimen sources	Cross-connections	Cross-contamination	Improper use of non-potable water
Scheme design, installation and commissioning				
Protect drinking water systems with approved air-gap	USEPA (2003); ABCB (2019)			
Protect drinking water systems with approved back-flow prevention devices	USEPA (2003); MPMSAA (2008)			
Integrate the design and operation of dual pipe systems into a whole-system multi-barrier approach to risk management	NSWG (2015)			
Implement a service pressure differential between potable and non-potable supplies.	GSA (2017)			
Locate non-potable infrastructure (predominately pipework) in a consistent spatial relationship to potable equipment.	GSA (2017)			
Provide an engineering certification of compliance in accordance with all relevant standards, codes and guidelines as well as treatment validation testing.	MPMSAA (2008)			
Do not install permanent cross-connections between the recycled water and drinking water systems (e.g. for top up purposes) within the network downstream of storages.	HMSO (1999)			
Develop quality control and inspection processes to ensure that properties' drinking water service pipes and meters are only connected to the drinking water main in the street	BSI (2010); BSI (2011)			
Install, activate, and commission potable water supply systems prior to activating and commissioning the non-drinking water service.	GSA-OTR (2020)			
Implement an appropriate scheduled maintenance program for the non-potable supply network to cover property connections.	BSI (2010); BSI (2011)			
Flush recycled water systems following recharge events.	Victoria Government (2005)			
Manage burst mains and flushing events in accordance with procedures laid down for potable systems.	Victoria Government (2005)			
Require that only licensed and dual pipe accredited plumbers install dual pipe systems (including work on meters, check valves, and backflow prevention).	BSI (2021)			
Only use approved materials with the appropriate markings.	AWWA (2015); Victoria Government (2005)			
Separate recycled water and drinking water infrastructure by a minimum prescribed distance	SOEPA (2015); GSA (2017)			
Complete pipe work plans should be maintained and updated to provide a permanent record of the location and depth of recycled water pipes.	Private Water Supplies (England) Regulations (2016)			
Ensure recycled water fittings are not interchangeable with drinking water fittings (by using, for example, different sized threads).	GSA-OTR (2020); Victoria Government (2005)			
Drinking water and non-drinking water meters to be located in separate housings.	GSA-OTR (2020)			
Where multiple residences or businesses are supplied by a central system, commissioning should include a cross-connection audit for every unit.	Victoria Government (2005)			
An overflow and manual diversion to the main sewerage system to be provided from any type of greywater or rainwater treatment unit.	Queensland Government (2019)			
Require written authorisation for any interconnection between a drinking water supply and a non-potable water supply.	SOEPA (2015)			
Provide an audit and education program for identification of household cross-connections	Victoria Government (2005); NSWG (2015)			
Scheme operation				
Require designation of an entity which will provide ongoing maintenance of the system and keep records of such.	NSWG (2015)			
Ensure that tools used for sewer repairs are not used to repair the recycled water main.	Victoria Government (2005)			
Require that only licensed and dual pipe accredited plumbers maintain dual pipe systems. This should include any work on meters, check valves, and backflow prevention.	SCWRCB (2018); USEPA (2012)			
Maintain a chlorine residual in the non-potable supply.	Victoria Government (2005); USEPA (2012)			
Provide a cross-connection self-test kit for residents.	Victoria Government (2005)			
Conduct regular auditing of contractors.	Victoria Government (2005)			
Audit dual-pipe installations regularly	GSA-OTR (2020); USEPA (2012)			
Consider use of anti-ingestants or other markers such as colourings				

(Continued)

Table 2. (Continued).

Risk mitigation measure	Specimen sources	Cross-connections	Cross-contamination	Improper use of non-potable water
Adapt regulations around water fittings inspections to include dual pipe supplies	USEPA (2012); NRMCC (2009a)			
Signage				
Implement a national colour coding system for non-potable equipment. Colour coded pipework and equipment to be coloured on delivery to site.	USEPA (2012); NRMCC (2009a)			
Locate warning signs on all recycled water access points no further than 150 mm from the tap (this should include toilet cisterns). These signs should include the words 'Do Not Drink'.	BSI (2021); USEPA (2012); GSA-OTR (2020)			
All signage (whether using icons, colours or words) should be designed for accessibility by all.	Victoria Government (2005); SCWRCB (2018)			
Ensure that outdoor recycled water taps are suitably marked (coloured), have a removable handle, are accompanied by appropriate signage, and are located at least 300 mm from any drinking water tap	NRMCC (2009b)			
Awareness Raising				
Provide water mains and plumbing contractors with training on dual pipe supplies and an appropriate accreditation scheme	USEPA (2012)			
Provide a central repository of dual-pipe incident and response reports	Victoria Government (2005)			
Implement ongoing awareness raising.	NRMCC (2009b); USEPA (2012)			

Very Effective Somewhat Effective Not Effective.

Similar instances of cross-connections have been identified in the USA. In their comprehensive review of dual water systems, Grigg et al. (2013) report the occurrence of such events in various cities. Some of the reported cross-connections occurred during the construction phase, with others being the result of plumbers' or householder errors during post-commissioning work. Notably, of the 37 case studies cited, just under one third (11) reported the discovery of cross-connections either pre or post commissioning. All were considered minor events with no associated illnesses being reported. As the report suggests, this is not to say that dual pipe systems in the USA do not present risks, but that they are generally well-managed and that stringent regulation acts as an effective control measure to prevent public health incidents.

In the UK, the Drinking Water Inspectorate (DWI) published an event assessment report of a cross-connection event that occurred in 2010 in Northampton. The report was published to provide a point of learning for the water industry on the risks associated with cross-connections. The incident took place at the Upton Eco-Housing residential development where 142 new houses (108 private properties and 34 housing association properties) were installed with rainwater harvesting systems for toilet flushing and outdoor use. These systems were cross-connected with the mains water supply. The cross-connection was discovered after complaints of sewage odour in tap water were reported. Water samples taken from one of the houses contained *Escherichia coli* and coliforms at numbers

greater than 100 per 100 mL. Additional water fittings inspections have been conducted to reduce risk but there remain challenges around adoption (responsibility for maintenance, etc.) and with the handover of system information to new owners or new tenants. Over 30 properties have proved difficult to inspect, despite repeated efforts to contact the consumer.

Our final example comes from Australia where, following a cross-connection event in Aurora, Australia an audit was performed by Yarra Valley Water. A qualitative risk assessment, forming part of the audit and performed following the methods described in the Australian Guidelines for Water Recycling, identified areas for improvements to prevent risk associated with water recycling schemes. One opportunity for improvement was a reduction of the three-year period between the first inspection of an installation and a second inspection to one year. The audit found that cross-connections typically occurred within the first year of operation as a result of work completed by plumbers with limited knowledge of the system installed, and of configuration and plumbing requirements for existing or newly installed systems. The report commented that third parties constituted the highest risk to public health (presented by the operation of dual reticulation system). This was because of improper installation of recycled water plumbing (cross-connection risk), the erroneous approval of improper plumbing installations during site inspections, and modifications to the plumbing by customers without consulting Yarra Valley Water (Telford Environmental Consulting Services 2016).

Risk mitigation options

Table 2 provides a listing of risk mitigation measures for dual pipe supplies, classified under four headings; Scheme Design, Installation, and Commissioning, (ii) Scheme Operation, (iii) Signage, and (iv) Awareness Raising. Many mitigation interventions are mentioned in multiple documents and across multiple jurisdictions. We therefore provide one or two specimen sources for each measure; some of which are in the form of guidelines and others in the form of regulations or standards. The table also indicates the relative efficacy of each measure with respect to the three major risk factors for dual pipe systems as indicated in **Table 1**; cross-connections, cross-contamination (not related to a cross-connection), and improper use of a non-potable supply. 'Very effective' measures are those that, if followed, effectively eradicate or significantly minimise the identified risk (e.g. the use of backflow prevention devices significantly reduces the risk of cross-contamination); and 'Somewhat effective' measures are those that have the potential to reduce the level of the identified risk (e.g. effective signage can reduce the risk of improper use). **Table 2** is not intended to be a comprehensive listing of what measures could be implemented but is rather a directory of measures which are recommended in the texts we reviewed through this study. Although they have been sourced from a small number of countries, they comprise actions imposed or recommended by more than one country which operates/regulates for dual pipe systems. An appropriate balance of measures will be dependent on existing regulatory requirements and context

Comparing the data in **Tables 1 and 2** highlights a critical feature of dual pipe system risk management. The causes of many of the reported public health incidents occurred in jurisdictions where the dangers of cross-connections and cross-contamination were well understood and provided for through regulation or technical guidance, and yet mistakes still occurred. The oft stated root cause in incident reporting is simply human error, highlighting the need for everyone from designers, contractors, and inspectors to building owners and water users to be more aware of how dual pipe schemes work, how risks are controlled, and what the implications of failing to control such risks are. The provision of non-potable water through a dual pipe scheme is both uncommon and unusual in societies where a potable supply has been the sole water service delivered through in-building pipework, valves, taps, etc. for decades and in some cases well over a hundred years. Post-commissioning householder DIY projects and the deliberate or inadvertent misuse of a non-potable

supply are also often cited as causes of public health incidents. Both are potentially harmful to health and will have impact immediately, making mitigation actions such as auditing and inspections largely ineffective. In addition to warning of the risks inherent in both behaviours, some service providers have recently made the use of non-potable water for inappropriate purposes a cause for breach of contract, thereby removing liability for consequential loss and damage (see for example [Unity Water 2023](#)).

Conclusions

The listing presented in **Table 1** is populated by schemes implemented in countries with mature water and sanitation sectors and tight public health protection measures. Each scheme would have been subject to close professional attention during design, construction and operational phases. The reported incidents have therefore occurred in spite of a swathe of reasoned and agreed risk management measures being in place. The frequency of incidents also shows little sign of petering out over time.

Of further concern must be the possibility that the number of actual cross-connections/misuse of non-potable water incidents is higher than the ones reported in those sources accessed as part of this study. For example, cross-connections discovered prior to building occupation (e.g. during interim building inspections) are unlikely to find their way into published reports or academic papers. This will also be the case for incidents of inappropriate use which, for whatever reason, do not cause illness (or at least are not reported to the medical authorities). The volume of this hidden set of incidents can of course only be speculated on but the discrepancy between recorded and non-recorded events has been highlighted previously ([Lee et al. 2003](#)).

Where we might have more confidence is in proposing the reasons why cross-connections and appropriate use appear to be recalcitrant aspects of safe dual-pipe system use. Two features of the historical development of water service provision help to explain this. Firstly, domestic water supplies traditionally conform to a one-in-one-out model with only potable water being delivered to, and only wastewater being conveyed away from, the interior of the property. Secondly, and related to the above, there is an expectation that all water delivered to properties is of drinkable quality. This has been the case for over 100 years in some countries and hence both property owners and plumbing professionals are unaccustomed to a second supply and perhaps struggle to relate its configuration and risks to the customary layout.

Two forms of intervention, each noted in various guises in Table 2, can help to counteract these risks. Firstly, where dual pipe systems are not covered by commercial operational and maintenance contracts (which minimises the temptation to interfere with the infrastructure) then there is an effective transfer of risk and responsibility to the building owner/occupier. Controlling who can legally work on water systems (e.g. only approved plumbers) would provide an additional layer of surety here. Secondly, the majority of regulations and standards we encountered during this study focus very strongly on the design and installation phases of dual pipe systems. This is (partially) understandable given the context within and time at which they were developed. As the sector matures however more attention should be given to the operational phase of dual pipe schemes with overarching guidance on non-potable supplies and improved integration of standards and guidance with relevant regulation.

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Data availability statement

The data that support the findings of this study are available in open access sources. Data sharing is not applicable to this article as no new data were created or analysed.

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Dual-pipe reticulation for non-potable water: a survey of public health risks and their mitigation

Jeffrey, Paul; Le Corre-Pidou, Kristell; Kuin, Peter; de Valk, Sheryll; van Houwelingen, Gerard

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