Chapter 4

Rainwater Tanks, Water Quality and Public Health Issues

> “Before a permanent water supply was introduced …household wells … and tanks, located above or beneath the ground were essentials of life as far as residents were concerned” Armstrong [1967].

> “The generation of today does not count their blessings. We have a plentiful supply of fresh water conducted through pipes into our homes at a nominal cost to the consumer, and its only necessary to open a tap and water will flow out as long as it’s desired. Our homes are protected from fire, hot and cold baths can be obtained in a few minutes, the sanitary conveniences are … free from the objectionable conditions existing in …. the early days. Yet if a slight discoloration appears in the water, or the supply is shut off while repairs or alterations are being made to water mains, complaints are at once made that clothes are being spoilt in the wash tub, or the residents are famished for a drink of water. At drought periods in the early days people were very satisfied to obtain water of almost any quality to tide them over until rain came to replenish the tanks” George Lamont (retired as the Water Supply Superintendent of the Hunter District Water Supply and Sewerage Board in 1936).

4.0 Introduction

In Chapter 2 it was shown that the quality of water in rainwater tanks could be improved by separating the first flush from entry to the tanks. The quality of roof runoff was significantly improved by storage in damaged underground rainwater tanks (stormwater, leaves and soils readily entered the tanks via holes in walls and lids) and further improved when passed through a storage hot water service. Indeed the quality of roof water stored in the damaged rainwater tanks and used in hot water services was always compliant with the health-based requirements of the Australian Drinking Water Guidelines. Water quality in a rainwater tank was also found to vary considerably from the water surface to the point of supply near the base of the tank. Water quality at the point of supply in a rainwater tank was significantly better than at the water surface.

In Chapter 3 the quality of roof runoff stored in a “real” above ground rainwater tank was found to improve and to further improve when passed through an instantaneous hot water system. Although there were some minor exceedences for pH and Zinc the quality of roof water stored in the rainwater tank and used in hot water services was always compliant with the health-based recommendations of the Australian Drinking Water Guidelines. The water quality in the “real” rainwater tank at Maryville was significantly better than the water quality in the damaged rainwater tanks at Figtree Place. The Figtree Place and Maryville experiments suggest that the processes of flocculation, settlement and the action of biofilms appear to improve water quality in the rainwater tanks. The hot water systems at Figtree Place and Maryville appeared to effectively reduce bacterial numbers in the rainwater via a “pasteurisation” process to produce water of a quality compliant with the Australian Drinking Water Guidelines. Roof runoff captured in rainwater tanks was therefore of acceptable quality for toilet, hot water and outdoor uses.

The results from the Figtree Place and Maryville experiments show that the capture of roof runoff in rainwater tanks for toilet, hot water and outdoor uses could significantly reduce the consumption of mains water and the discharge of roof runoff to the street drainage system. The peak daily and instantaneous mains water demand and the peak roof water discharges were also reduced. The widespread introduction of rainwater tanks to supply toilet, hot water and indoor uses has the potential to defer the need to build new dams, reduce the requirement for water supply and stormwater pipes, and reduce impacts on the environment.

The impact of the use of rainwater tanks on urban water cycle infrastructure is dependent on the water uses from the tanks. When the tank is used to supply constant indoor uses (such as toilet and hot water uses) the water levels are consistently drawn down in the tank allowing rainwater to refill the tank more often resulting in reductions in mains water use and stormwater discharges. Paradoxically the use of rainwater tanks to supply outdoor uses alone will rarely produce substantial reductions in mains water use or stormwater discharges. The mismatch between seasonal rainfall and household outdoor water demand results in poor utilisation of rainwater resulting in long periods when the tank is either full or empty.

The use of rainwater for non-drinking indoor purposes can result in significant benefits to the community. Unfortunately authorities often discourage to use of rainwater for indoor uses because they commonly believe that the quality of rainwater is unacceptable. This belief is apparently based on the perceived poor quality of roof runoff and the use of the Australian Drinking Water Standard [NHMRC 1996] to determine the quality of water required for all indoor uses. There is no standard for non-drinking water uses.

In this Chapter other studies are examined that discuss the water quality and health implications of using rainwater stored in tanks. The results of these studies are contrasted with the results from the Figtree Place and Maryville experiments to develop an understanding of potential health risks and acceptable rainwater uses. To further understand the health implications of rainwater use the human gastrointestinal system, water borne diseases and illnesses that can result from microbial, chemical, metal or physical contamination are examined. Pathways for transfer of pathogens or contaminants to users of rainwater are examined.

Guidance provided by the Australian Drinking Water Guidelines is examined for pathogens and contaminants that may be present in a rainwater scheme. The relevance of microbial indicator organisms for prediction of pathogens in rainwater supplies is discussed. The rainwater treatment chain from first flush device, settlement and biofilms in the rainwater tank to pasteurisation in the hot water system also discussed. Finally acceptable rainwater uses and appropriate treatment chains are proposed.

4.1 Quality of Water from Rainwater Tanks: A Literature Review

Pacey and Cullis [1986] explained that the use of rainwater stored in tanks for household uses was an ancient practice. Ionides [1966] argued that the revival of the use of rainwater tanks was inevitable because of increasing demand on water supplies created by population growth and greater opportunities to collect rainwater of acceptable quality due to the use of modern materials for roofs and in the construction of tanks.

The development of water supplies in the Newcastle region of New South Wales in Australia is well documented. Armstrong [1967] explained that the main source of water in the early settlement of Newcastle during the 1800s was roof runoff collected in above and below ground tanks. Square sheet iron tanks with a capacity of 400 gallons were used to

store water above ground. The black iron tanks corroded very quickly causing sediment to accumulate at the bottom of the tanks. Underground tanks constructed using bricks and rendered cement with a capacity of about 3,000 gallons were also used.
The underground rainwater tanks posed a considerable health hazard because they were often poorly constructed allowing sewage from adjacent cesspits, stormwater from roads and seepage from the cemeteries on higher ground to enter the tanks [Lloyd et al., 1992, Armstrong 1967]. Outbreaks of Typhoid were common. Although it was often suggested roof runoff captured in tanks was contaminated by coal dust and disease, water supply from above ground tanks caused relatively few health problems [Lloyd et al., 1992].

About 3 million Australians currently use rainwater from tanks for drinking [ABS 1994] in urban and rural regions with no reported epidemics or wide spread adverse health effects. Fuller et al. [1981], Mobbs et al. [1998] and Cunliffe [1998] found that the quality of rainwater was often adequate for potable uses provided that the rainwater tank and roof catchment were subject to adequate maintenance. In Chapters 2 and 3 it was found that rainwater collected from roofs in an inner city industrial area and stored in tanks was of acceptable quality for hot water, toilet and outdoor uses. Rainwater used in hot water systems (temperature settings: 50ºC to 65ºC) was found to be compliant with Australian Drinking Water Guidelines. Although roof runoff and the surface of stored water was sometimes found to be contaminated, the quality of water at the point of supply in rainwater tanks was significantly improved. The Namoi Valley Public Health Unit [G. Bell, personal communication, 1999] and The Newcastle Public Health Unit [J. James, personal communication, 1999] also reported that the quality of rainwater collected from roofs improved in rainwater tanks.

The microbial quality of drinking water is measured by the presence or absence of coliform or fecal coliform bacteria as indicators of fecal contamination and the possible presence of pathogens [NHMRC 1996]. Studies have shown that the presence of coliforms and fecal coliforms is common in rainwater tanks [Edwards, 1994; Fuller et al., 1981; Thurman, 1995; Gee, 1993; Simmons et al., 2001 and Gardner et al., 2001]. Cunliffe [1998] reports that the significance of these results is unknown given that limited testing by Fuller et al. [1981] and Thurman [1995] failed to detect pathogens such as *Salmonella, Shigella, Cryptosporidium* and *Giardia* in rainwater tanks. Simmons et al. [2001] failed to find *Campylobacter* in roofwater in Auckland, NZ; therefore the they could not support the assumption that birds contributed to faecal contamination of roof surfaces. They also did not detect *Legionella Spp.*

However some studies suggest that drinking rainwater collected from roof surfaces is a potential source of human illness. Simmons et al. [2001] found that the rainwater supplies in Auckland NZ sometimes exceeded drinking water guidelines for lead and microbial indicator organisms. Importantly the presence of potential pathogens *Salmonella Spp.* and *Cryptosporidium* were detected in one and two samples respectively. No illness was reported. The presence of *Aeromonas Spp.* was found in 20% of samples. Residents reporting gastrointestinal systems in households were more likely to have *Aeromonas Spp.* in their rainwater supply than those who did not experience gastrointestinal symptoms. It was also found that houses with roofs that partially consist of lead or galvanised iron were more likely to have lead contamination in their rainwater supply [Simmons et al., 2001].

Brodribb et al. [1995] reported that an elderly immunocompromised woman was subject to reccurring *Campylobacter Fetus* infections. *Campylobacter Fetus* was found in the rainwater tank the woman used for drinking water supply. Koenraad et al. [1997] and Whelan et al. [1983] explain that many birds carry and excrete *Campylobacter.* Cunliffe [1998] suggest that maintenance of roof and gutter system will reduce the likelihood of the presence of *Campylobacter* in rainwater supplies.

Taylor et al. [1999] attributed an outbreak of *Salmonella* to the presence of green tree frogs in a poorly maintained rainwater tank on a building site in Rockhampton in Queensland. Mice were also found in abundance on the building site. The rainwater tanks did not have mesh screens on all inlet and outlets allowing the frogs and mice access to the stored water. It was also suggested that mice excreta deposited on roof surfaces could also contribute *Salmonella* to the stored rainwater. Samples with high counts for Total Coliforms (>80 CFU/100 ml) and *E. Coli* (16 to >48 CFU/100 ml) coincided with the presence of *Salmonella* [Taylor et al., 1999]. The detection of Total Coliforms and *E. Coli* may indicate the presence of *Salmonella* in rainwater stored in tanks. However high counts of Total Coliforms and *E. Coli* were also detected in the absence of *Salmonella* [Taylor et al., 1999].

Reptiles [Freidman et al., 1998 and Minette, 1984] and frogs [Bartlett et al., 1977] are reported to be a source of *Salmonella*. Cunliffe [1998] states that the probable source of indicator bacteria detected in rainwater tanks is excreta from small animals, reptiles and birds. The transfer of pathogens via these sources is considered to be less hazardous than that of human feces because human feces are more likely to contain pathogens [Cunliffe, 1998]. Contamination of rainwater stored in tanks can be minimised by sealing all inlet and outlet points with mesh to eliminate access by vermin to the tank, keeping roof gutters clear of debris and installation of a first flush device to separate the first part of roof runoff [Cunliffe, 1998; Gee, 1993 and Duncan and Wight, 1991].

Gee [1993] reported exceedance of drinking water guidelines for microbial indicator organisms and pH in water from 12 poorly maintained rainwater tanks in the Sydney region although rainwater was sampled from the water surface rather than the point of supply. Water from all of the rainwater tanks complied from the chemical parameters of the Australian Drinking Water Guidelines (except pH). Samples taken from the sludge zone in two rainwater tanks revealed lead levels of 0.6 mg/L and 0.29 mg/L although the corresponding lead concentrations were <0.01 mg/L and 0.02 mg/L at the water surface [Gee, 1993]. A similar result was found at the Figtree Place experiment (Chapter 2). It is believed that the majority of chemical contamination does not remain in stored rainwater rather it settles to the bottom of rainwater tanks.

Gee [1993] also summarised the results from a small number of rainwater tanks reported by the NSW Division of Analytical Laboratories as being polluted. Sources of lead contamination in rainwater are reported to be roofs coated with lead based paint, lead flashing on roofs, a very old corroded galvanised iron tank and close proximity to a lead smelter. In Port Pirie in South Australia emissions from a lead smelter have caused high concentrations of lead in roof runoff collected in rainwater tanks rendering the rainwater unsafe for consumption by small children and pregnant women [Van Der Wal, 2000].

Duncan and Wight [1991] report the findings of four studies of water quality in rainwater tanks in Perth in Western Australia, South Australia and Latrobe Valley, Mortlake Shire and Melbourne in Victoria. The average compliance from rainwater tanks (sample size unknown) with the Australian Drinking Water Guidelines for Total Coliforms and *E. Coli* was 43% and 73% respectively. The sample complied with the physical and chemical parameters in the drinking water guidelines with the exception of pH, Lead and Zinc that showed compliances of 82%, 99% and 63% respectively.

Uba and Aghogho [2000] sampled roof runoff from Zinc, Aluminium, Asbestos and thatch roofs in Nigeria. They found that the Zinc roof provided the best quality runoff. Yaziz et al. [1989] sampled roof runoff from a galvanised iron roof and a tile roof catchment in Malaysia. The galvanised iron roof provided better quality runoff than the tile roof although higher zinc concentrations were found in the runoff from the galvanised roof. Clarke [1987], Jenkins and Pearson [1978] and Yaziz et al. [1989] found that the quality of roof runoff improved with increases in accumulative rain depth since the beginning of the rain event. This result was also found in Chapter 2 indicating that separating the first flush of roof runoff from entry to a rainwater tank will improve tank water quality.

The quality of rainwater stored in tanks can be degraded by poor maintenance of the rainwater tank and in some cases this has resulted in the transmittal of pathogens from human, animal or birds via fecal contamination of stored water to humans causing disease. However the risk of becoming ill from drinking rainwater appears to be small with over 3 million Australians drinking rainwater collected from roofs and stored in tanks. Indeed rainwater from tanks and roof catchments that are subject to appropriate maintenance is often adequate for potable uses. The installation of a first flush device should further improve the quality of rainwater stored in tanks.

4.2 Health Issues

The provision of good quality drinking water is important for the protection of human health. The human digestive system has physical processes and contains microorganisms that provide some protection against water borne diseases. However there are many diseases and illnesses that can result from the consumption of contaminated drinking water and some illnesses can result from contact with contaminated water.

In this section the human digestive system is examined, as well as diseases and illnesses that can develop by drinking contaminated water and the use of indicator organisms for pathogens. An understanding of the health issues that can result from drinking or human contact with contaminated water is important in the determination of acceptable uses of rainwater.

4.2.1 The Human Digestive System

Food (carbohydrates, proteins and fats), water, inorganic salts, minerals and vitamins are required by humans for sustenance, growth and survival. The food we eat consists of molecules, which are too complex for use in the human body. The process of digestion involves mechanical and chemical simplification of molecules to an order useful to the body.

The digestive system is shown in Figure 4.1. After entry to the digestive system via the mouth, food and water passes through the esophagus to the stomach. It is then propelled through the large and small intestines, eventually leaving the system via the anus and the urethra.

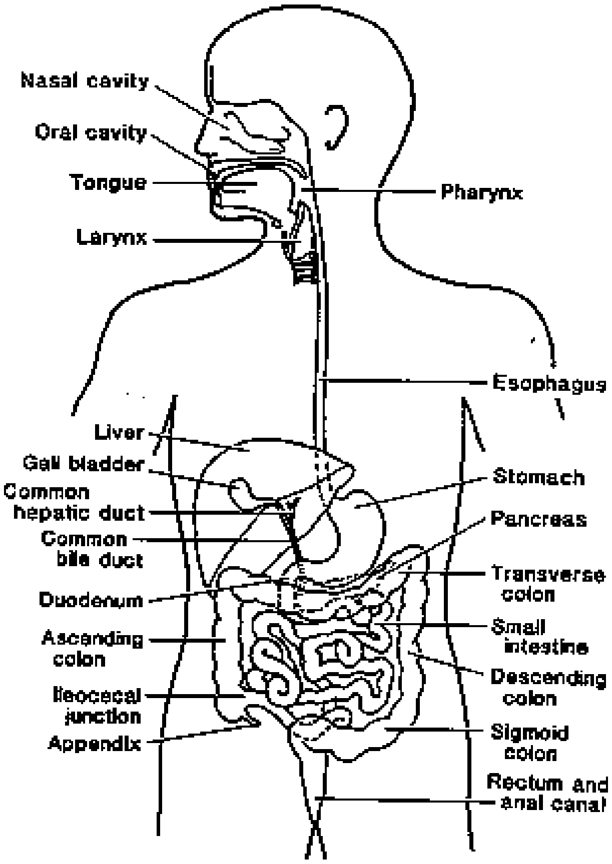

Figure 4.1: Digestive system from the mouth to the anus [Shaffer, 1991].

Epithelial cells that line the stomach and small intestine, salivary glands, pancreas and the liver provide enzymes that facilitate chemical digestion. When food and water is reduced to a sufficiently simple state, the resultant digested and dissolved nutrients are absorbed across the mucosal lining of epithelial cells (Figure 4.2) in the small intestine into the bloodstream.

The inner surface of the digestive system is lined with a mucosa (Figure 4.2), a mucus membrane composed of epithelial cells. Some of the epithelial cells secrete gastric juices while others are involved in absorption. Gastric juices consist of hydrochloric acid, a protein digesting enzyme pepsinogen and an intrinsic factor important for vitamin B_{12} absorption.

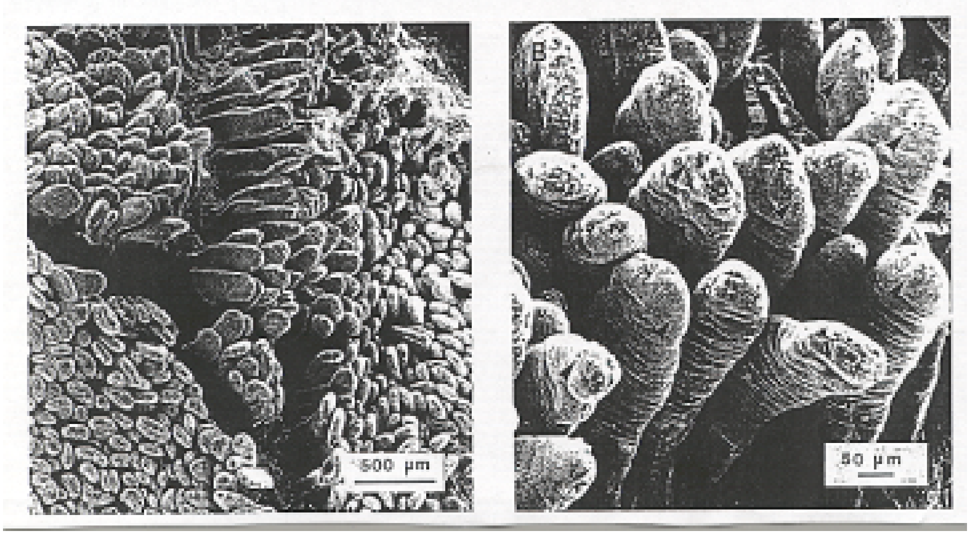

Figure 4.2: Scanning electron micrographs of the small intestine mucosa [Shaffer 1991]

4.2.1.1 Microorganisms in the Digestive System

The digestive system selectively excludes microorganisms and eliminates waste and toxic material from entry into the body. Gastric acid containing hydrochloric acid secreted from epithelial cells in the stomach wall reduces entry of microorganisms ingested from the environment (including food or water) to the small intestine. The acid represents an effective barrier against entry of unwanted potential pathogens which may enter via ingested food. When high numbers of pathogenic organisms are ingested, however, then it is more likely that some may survive and penetrate the acid barrier where they may cause disease or impair digestion and absorption in the small intestine.

The epithelial cells and mechanical function of the small intestine also serve to clear indigestible food residues from the small intestine. Despite the physical “acid barrier”, the small and large intestine harbour an estimated 400 species of anaerobic and aerobic bacteria which provide important roles in digestion and preventing infection by potential pathogens. The human digestive tract is colonised by microorganisms from the moment of birth and includes anaerobes such as *Bacteroides*, *Bifidobacterium*, *Lactobacillus* and aerobes such as *E. coli* and *Klebsiella*.

4.2.1.2 Bacteria in the Gastrointestinal Tract

Most authors agree that human digestive system is colonised by microorganisms soon after birth. Microbial populations are obtained firstly from the mother and then from the surrounding environment (including food and water). The bacterial populations in the gastrointestinal tract then form a complex ecosystem that can include more than 400 different species (Moore and Holderman, 1974). Mevissen-Verhage et al. (1987) isolated 550 strains of *Bifidiobacterium spp.* and 220 strains *Bacteroides spp.* from infant gastrointestinal tracts.

Microflora in the oropharynx and the stomach are similar because most microorganisms are derived from the oral cavity and throat. Some of the first microorganisms to colonise the infant intestine after birth are *E. coli* and *Streptococcus* followed soon after by lactobacilli, bifidobacteria and clostridia [Cooperstock and Zedd, 1983]. Adult humans have higher concentrations of lactobacilli and clostridia, and lower concentrations of bifidiobacteria. Normally low numbers of bacteria, mostly lactobacilli and streptococci are found in the stomach. The magnitude (CFU/g) of viable intestinal and fecal microorganism populations in adult humans as determined from Smith and Crabb [1961] is shown in Table 4.1.

Table 4.1: Viable fecal microflora in the human intestine (CFU/g)

E. coli	***Clostridium perfringens***	***Streptococci***	***Bacteroides***	***Lactobacilli***
10^6-10^9	0 -10^6	10^4-10^9	10^8-10^{10}	10^7-10^{10}

Lidbeck and Nord [1991] found that multiplication of bacteria was dependant on the acidity of the stomach and small intestine motility prevents overgrowth of microorganisms. They recovered Lactobacilli (10^3 – 10^7 CFU/g), Streptococci, Enterococci, Bifidiobacteria and *E. coli* (10^7 – 10^8 CFU/g) from the small intestine. Table 4.2 shows the range of bacterial counts (CFU/g) from the oral cavity, small intestine and the colon of adult humans.

Table 4.2: Viable fecal microflora throughout the gastrointestinal tract (CFU/g)

Location	***E. coli***	***Lactobacilli***
Oral cavity		10^3-10^4
Small intestine	10^7-10^8	10^3-10^7
Colon	10^8-10^{12}	10^4-10^8

Bacteroides, Bifidiobacterium, Lactobacillus and *Clostridium spp.* are able to reduce bile acids in the gastrointestinal tract. In particular, lactobacilli have been shown to grow on media containing bile and colonise mucosal surfaces of the gastrointestinal tract by binding to epithelial cells therefore accounting for their ability to survive in the stomach. Bifidiobacteria (other than B. dentium) and lactobacilli are non-pathogenic bacteria common to the gastrointestinal tract [Charteris et al., 1998 and Goldin et al., 1992]. Clostridia are also normally found in the gastrointestinal tract [Lee et al., 1991]. Predominant Bacteroides species found in the gastrointestinal tract are B. vulgatus and B. fragilis [Duerden, 1980]. Bacteria common to a human host are described as indigenous microflora. The presence of indigenous microflora has benefits to the human host including competitive exclusion of exogenous and pathogenic microorganisms (pathogens), and the breakdown of complex foods in the gastrointestinal tract [Charteris et al., 1997].

4.2.2 Waterborne Diseases and Illness Caused by Contaminated Drinking Water

Although the human digestive system consists of physical and mechanical systems, and indigenous microflora that provide some protection against pathogens and other harmful agents the potential for contraction of disease or illness by drinking contaminated water is always present.

The principal risk to human health from drinking water is the presence of pathogens in the water [Mitchell, 1974; NHMRC, 1996; Spellman, 1997 and Prescott et al., 1999]. The most common source of pathogens in drinking water supplies is recent contamination by human and animal excreta. Pathogens of concern in drinking water include bacteria, viruses and protozoa that can cause gastroenteritis, diarrhoea, dysentery, hepatitis, cholera or typhoid fever [NHMRC, 1996].

While the majority of water borne diseases are caused by pathogens that originate in the gastrointestinal tracts of humans or animals there are microbes existing in the environment that can, in some cases, cause disease in humans [Mitchell, 1974; NHMRC, 1996; Spellman, 1997 and Prescott et al., 1999]. These microbes include the bacteria *Aeromonas, Klebsiella* and *Legionella Spp*. and protozoa such as *Cryposporidium parvum* and *Giardia lamblia*.

Human illness can also be caused by contamination of drinking water with inorganic (such as Lead, Arsenic and Cadmium) or organic chemicals (including Trihalomethanes, 2,4-D and Endrin). This Section will discuss common diseases and illnesses that can be caused by contamination of drinking water with pathogens, environmental microbes, organic chemicals and inorganic chemicals, and bacterial indicator organisms of fecal contamination.

4.2.2.1 Bacteria

Gastroenteritis or inflammation of the stomach and intestinal lining can result from ingestion of food or water contaminated by bacteria [Prescott et al., 1999]. Bacteria that are ingested can grow within the digestive system and then invade host tissues or secrete exotoxins. Alternatively, bacteria can secrete exotoxins into water that is then ingested. These exotoxins, known as enterotoxins, disrupt the function of the intestinal mucosa epithelial cells causing nausea, vomiting and diarrhoea. Common gastrointestinal infections and associated bacteria are discussed below.

Cholera is acquired when food or water contaminated by the bacteria *Vibrio. cholerae* is ingested [Prescott et al., 1999; USFDA, 1999; NHMRC, 1996 and Mitchell, 1974]. It is passed from carriers or patients to new hosts via human fecal materials contaminating food or water. The bacteria adhere to mucosa in the small intestine and secrete the toxin choleragen. An enzyme from choleragen enters intestinal epithelial cells activating the enzyme adenylate cyclase by adding ADP-ribosyl [Prescott et al., 1999]. Hypersecretion of water and chloride ions, and inhibited absorption of sodium ions result causing massive losses of fluid and electrolytes [Prescott et al., 1999 and USFDA, 1999]. Mitchell [1974] explains that the incidence of Cholera is very rare in developed countries as a result of sewerage treatment and chlorination of drinking water supplies. The bacteria Vibrio cholerae is not viable in adverse conditions and rarely survives more than seven days in natural waters. The USFDA [1999] explain that a high dose of *Vibrio cholerae* (about one million organisms) must be ingested to cause illness.

The bacteria *Campylobacter jejuni* (or *fetus*) is found in the intestines of chickens, turkeys and cattle, and in surface waters, and can cause gastroenteritis when ingested in food or water [Prescott et al., 1999; USFDA, 1999; NHMRC, 1996 and Mitchell, 1974]. Campylobacter can be transmitted to humans via fecal contamination of water. *Campylobacter jejuni* invades the epithelial cells of the small intestine, similar to cholera, resulting in hypersecretion of water and chloride ions, and inhibited absorption of sodium ions [Prescott et al., 1999]. The USFDA [1999] state that food contaminated with *Campylobacter jejuni* is the leading cause of bacterial diarrheal illness in America because its infective dose is small (ingestion of 400 – 500 bacteria may cause illness). *Campylobacter jejuni* is described as fragile and sensitive to environmental stresses including heating, acidity and disinfection.

Salmonellosis is commonly caused by ingestion of food or water contaminated with human or animal excreta containing the bacteria *Salmonella Spp.* [Prescott et al., 1999; USFDA, 1999; NHMRC, 1996 and Mitchell, 1974]. The bacteria multiply within the digestive system and invade the mucosa where they produce enterotoxins and cytotoxins that destroy epithelial cells in the small intestine [Prescott et al., 1999]. An acute version of Salmonellosis caused by *S. typhi* can result in Typhoid fever. The USFDA [1999] explain that *salmonella* has a very low infective dose of about 15 – 20 organisms in humans.

Shigellosis is caused by the bacteria *S. sonnei* or *S. flexneri* resulting in inflammation of the digestive system [Prescott et al., 1999; USFDA, 1999; NHMRC, 1996 and Mitchell, 1974]. Shigella rarely occurs in animals. The bacteria can be transmitted via human fecal contamination of food or water to the digestive system [USFDA, 1999 and NHMRC, 1996]. They are facultative intracellular parasites that multiply within the epithelial cells in the colon. After inducing the epithelial cells to phagocytose them and disrupting the phagosome membrane the bacteria reproduce in the cytoplasmic matrix and invade the adjacent epithelial cells [Prescott et al., 1999]. The USFDA [1999] explain that *Shigella Spp.* are highly infectious agents. Ingestion of as little as 10 organisms can result in infection.

Gastroenteritis can be caused by ingestion of food or water contaminated with human fecal material containing the bacteria *E. coli* by several mechanisms [Prescott et al., 1999, USFDA, 1999 and NHMRC, 1996]. However it is noted that *E. coli* is an important natural component of the human gastro-intestional tract and only a small number of virulent strains of *E. coli* can cause illness. Enterotoxigenic *E. coli* produces two distinct enterotoxins. One of the enterotoxins binds to glycoprotein receptors that are coupled to guanylate cyclase on the surface of intestinal epithelial cells [Prescott et al., 1999]. This produces cyclic guanosine monophosphate leading to secretion of electrolytes and water into the small intestine resulting in diarrhea. The second enterotoxin is heat labile binding to specific gangliosides on epithelial cells activating membrane bound adenylate cyclase leading to increased production of cyclic adenosine monophosphate (similar to cholera) and hypersecretion of electrolytes and water into the small intestine [Prescott et al., 1999]. Enteropathogenic *E. coli* is transmitted to humans via fecal contamination of food and water. Once ingested Enteropathogenic *E. coli* attaches to the intestinal epithelial cells causing destruction of the microvilli [Prescott et al., 1999; USFDA, 1999 and NHMRC, 1996]. This destruction is known as effacing lesions and results in diarrhea. Enteroinvasive *E. coli* penetrates and multiplies within intestinal epithelial cells causing diarrhea [Prescott 1999]. They also produce cytotoxin and enterotoxin that disrupts the operation of the intestinal epithelial cells and microvilli. The USFDA [1999] explain that Enteropathogenic *E. coli* are highly infectious for infants with very few documented cases of infections in adults.

Enterohemorrhagic *E. coli* carries the determinants for Shinga-like toxins and for attaching-effacing lesions [Prescott et al., 1999, USFDA, 1999 and NHMRC, 1996]. The attaching-effacing lesions cause abdominal pain, cramps and bloody diarrhea. The Shinga-like toxins kill vascular endothelial cells causing hemolytic uremic syndrome and thrombotic thrombocytopenic purpura [Prescott et al., 1999].

Typhoid fever is caused by virulent serovers of *S. typhi* and is transmitted by ingestion of food or water contaminated by feces from infected humans or animals [Prescott et al., 1999; USFDA, 1999 and NHMRC, 1996]. The small intestine is colonised by the bacteria, which then penetrate the epithelial cells and spread to lymphoid tissue, blood, liver and gall bladder causing fever, headache, abdominal pain, anorexia and malaise [Prescott et al., 1999].

Legionella Spp. is commonly found in natural and man-made aquatic environments [Prescott et al., 1999; USFDA, 1999 and NHMRC, 1996]. The bacteria reproduce in warm stagnant water at temperatures between 25°C and 42°C and occupy the surface micro-layer of water (the air-water interface). Legionellosis is an infection caused by the bacteria *Legionella* pneumonia that has two forms [USFDA, 1999 and Prescott, 1999]. Legionnaires disease is a severe infection that includes pneumonia. Pontiac fever is a milder infection that is similar to influenza and does not include pneumonia. Inhalation of aerosols of water contaminated with *Legionella Spp.* is reported to be a primary mode of entry of the organisms to the human respiratory tract [USFDA, 1999]. Outbreaks of Legionellosis are reported to stem from exposure to contaminated aerosols originating from cooling towers, respiratory therapy equipment and room-air humidifiers. It is also assumed that it is possible to contract Legionella from aerosols originating from showers and faucets although there is no evidence of this mode of transmission [USFDA, 1999].

There are two species of the genus *Yersinia* that can, on rare occasions, cause gastroenteritis namely *Yersinia enterocolitica* and *Yersinia pseudotuberculosis* [USFDA, 1999 and Prescott et al., 1999]. Ingestion of food or water contaminated by animal or human excreta containing *Yersinia Spp.* can cause diarrhoea and vomiting.

4.2.2.2 Protozoa

Cryptosporidium parvum is a protozoan that infects mammals that can cause diarrhoea, coughing and fever in humans [USFDA, 1999; Prescott et al., 1999 and NHMRC, 1996]. Ingestion of water contaminated by animal or human excreta containing *Cryptosporidium Spp.* can cause Cryptosporidiosis [USFDA, 1999]. The most significant source of Cryptosporidium contamination of water is stormwater runoff from pastures and human feces [NHMRC, 1999]. *Cryptosporidium Spp.* is resistant to chemical disinfectants but is susceptible to drying and sunlight [USFDA, 1999].

Giardia lamblia is a protozoan that can infect humans and animals reducing absorption of nutrients and causing diarrhoea in humans [USFDA, 1999; Prescott et al., 1999 and NHMRC, 1996]. Ingestion of water contaminated by human or animal excreta containing *Giardia lamblia* can result in Giardiasis [USFDA, 1999]. The protozoa are most likely to survive in cool and moist conditions [NHMRC, 1996].

4.2.2.3 Toxic Algae

Cyanobacteria inhabit all natural waters achieving high growth in high temperatures, long sunny days and when the water contains a high level of plant nutrients [NHMRC, 1996]. In small numbers Cyanobacteria are of no concern although under ideal conditions excessive numbers of Cyanobacteria can form blooms that produce odours, taints and toxins in water. Ingestion or inhalation of water supporting Cyanobacteria blooms can cause damage to liver or nerve cells and contact with water supporting Cyanobacteria blooms can cause dermatitis [NHMRC, 1999]. The Cyanobacteria produce two major types of intracellular toxins namely hepatotoxins that can damage liver cells and neurotoxins that damage nerve cells [Prescott et al., 1999 and NHMRC, 1996].

4.2.2.4 Organic Chemicals

Organic chemicals can include disinfection by-products such as Trihalomethanes (THMs), naturally occurring organic compounds and pesticides including Lindane, 2,4-D and Heptachlors. A summary of a selection of organic contaminants, health effects derived from ingestion and maximum guideline concentrations (MGC) in drinking water [NHMRC, 1999] is shown in Table 4.3.

Table 4.3: Maximum guideline concentrations of a selection of organic chemicals

Contaminant	Principal health effects	MGC (mg/L)
Lindane	Nervous system, kidney effects	0.02
Aldrin and Dieldrin	Nervous system, kidney effects	0.0003
2,4-D	Nervous system, kidney effects	0.03
Heptachlor	Nervous system, kidney effects	0.0003
Trihalomethanes	Cancer risk, birth defects	0.25

The ingestion of pesticides or agricultural chemicals in drinking water can result in accumulation of those chemicals in fatty tissues of the human body ultimately causing nervous system and kidney disorders [NHMRC, 1996]. Pesticides and agricultural chemicals from aerial spraying or direct application to crops can contaminate water supplies directly or as a component of stormwater runoff.

The potential harmful effects of chlorinated disinfection by-products (Trihalomethanes) are also a concern [NHMRC, 1999]. Bove [2000] reports links between chlorinated disinfection products in drinking water and birth defects such as neural, oral cleft, cardiac and small limb defects. Morris and Naumova [2000] describe increased risks of colon, rectal and bladder cancer in the presence of chlorinated disinfection products in drinking water.

4.2.2.5 Inorganic Chemicals

Inorganic chemicals in drinking water supplies can occur as dissolved solids attached to suspended organic materials such as clay particles [NHMRC, 1999]. The sources of inorganic chemicals in drinking water can originate from corrosion and leaching of pipes and fittings, catchment land use activities, leaching from mineral deposits and air pollution. A summary of a selection of inorganic contaminants, health effects derived from ingestion and maximum guideline concentrations (MGC) in drinking water [NHMRC, 1999] is shown in Table 4.4.

Table 4.4: Maximum guideline concentrations of a selection of inorganic chemicals

Contaminant	**Principal health effects**	**MGC (Mg/L)**
Arsenic	Dermal and nervous system toxicity effects	0.007
Barium	Circulatory system effects	0.07
Cadmium	Kidney effects	0.002
Chromium	Liver and kidney effects	0.05
Fluoride	Skeletal damage	1.5
Lead	Central and peripheral nervous system damage, kidney effects, highly toxic to infants and pregnant women	0.01
Mercury	Central nervous system disorders, kidney effects	0.001
Nitrate and Nitrite	Methemoglobinemia (blue baby syndrome)	50, 3

4.2.2.6 Viruses

Viruses are infectious agents that have simple acellular structures and patterns of reproduction [Prescott et al., 1999, pp. 337]. A complete virus particle contains molecules of RNA or DNA within a layer of protein and a virus cannot reproduce independent of living cells. Viruses can be found in sewage, rivers, lakes, groundwater and water used for drinking and swimming [NHMRC, 1996]. Beder [1997, pp. 137] stated that sewage could contain up to 110 different viruses. Water borne transmission of viruses to humans mostly occurs when water contaminated with human fecal material containing viruses is consumed. Common viruses are discussed below.

Adenoviruses can cause acute infectious gastroenteritis and conjunctivitis. They can be transmitted to humans as a result of drinking water contaminated with fecal material, inhalation of aerosols containing the virus or by eye contact with water containing with the virus. Children are more susceptible to the virus and infection is most likely to occur in poorly maintained swimming pools [NHMRC, 1996].

Enteroviruses can be responsible for rashes, sore throats, aseptic meningitis, paralysis, cardiac symptoms, conjunctivitis and gastrointestinal symptoms [NHMRC, 1996]. The virus can be transmitted to humans via ingestion of water contaminated with fecal materials, consumption of unwashed foods or the consumption of foods that have been touched by houseflies carrying the virus on their feet.

Several different viruses cause Hepatitis. Hepatitis A and Hepatitis E can be transmitted to humans via ingestion of water contaminated with fecal materials that contain Hepatitis A or Hepatitis E viruses. Infections caused by Hepatitis A and Hepatitis E viruses can result in infections of the liver, lassitude, anorexia, weakness, nausea, vomiting, headache, abdominal discomfit, fever and jaundice [NHMRC, 1996].

The Norwalk virus causes rapid, self-limiting gastroenteritis which can last 24 – 48 hours. The virus is transmitted to humans via ingestion of water contaminated with fecal materials that contain Norwalk virus [NHMRC, 1996]. Outbreaks of Norwalk virus induced infections have been attributed to drinking water supplies contaminated by fecal material, recreational bathing water contaminated by sewage and consumption of shellfish grown in water contaminated by sewage.

Rotaviruses, Para-Rotaviruses and Reoviruses are transmitted to humans via ingestion of water contaminated with fecal materials that contain Rotaviruses, Para-Rotaviruses and Reoviruses [NHMRC, 1996]. Reoviruses may cause respiratory illnesses and gastroenteritis. Rotaviruses have caused severe diarrhoea in infants and small children and caused gastroenteritis in the elderly. Para-Rotaviruses have been responsible gastroenteritis in adults.

Masters [1991, pp. 228] explained that all human fecal material contains Coliform bacteria whilst the excreta from only a small number of individuals will contain pathogens including viruses. Robeck et al. [1962] calculated the virus to Coliform ratios in sewage and polluted surface waters (Table 4.5).

Table 4.5: Calculated virus to Coliform ratios in sewage and polluted surface water

Medium	**Viruses**	**Coliforms**	**Virus / Coliform ratio**
Sewage	500 / 100 mL	46×10^6 / 100 mL	1:92,000
Polluted surface water	1 / 100 mL	5×10^4 / 100 mL	1:50,000

Table 4.5 shows that the chance of finding viruses in sewage and polluted surface water is small. Thus the risk of contracting an illness from a virus in drinking water is small.

4.2.3 Indicator Organisms

It is currently difficult, expensive and time consuming to monitor bacterial, viral and protozoan pathogens [NHMRC, 1996 and Prescott et al., 1999]. Indeed extensive testing may fail to detect the presence of pathogens. Contamination of drinking water with human or animal feces containing pathogens is a major cause of disease (including Salmonella, Shigella, Typhoid and Cholera). Coliform bacteria are common to the human gastrointestinal tract and relatively simple to isolate in tests [NHMRC, 1996; Prescott et al., 1999 and Feachem et al., 1980]. Thus Coliform bacteria are used as an indicator of recent fecal contamination of drinking water and the possible presence of pathogens in the water.

Total Coliforms are used in drinking water standards because they are a highly sensitive indicator of fecal contamination. Unfortunately they are also the least specific indicators of fecal contamination. Coliforms occur naturally in soil and vegetation therefore they may be present in the absence of fecal contamination of water. Coliforms are also present in biofilms in pipes and on fixtures in water distribution systems, can multiply in unpolluted water and are most likely to be present in untreated water supplies [NHMRC, 1996; Prescott et al., 1999 and Feachem et al., 1980]. The presence of Coliform bacteria is suggestive but not conclusive evidence of fecal contamination of water [NHMRC, 1996].

Fecal (thermotolerant) Coliforms that convert tryptophan to indole at 44.5°C are regarded as *E. Coli* in the Australian Drinking Water Standards [NHMRC, 1996]. The chance of *E. Coli* multiplying in unpolluted water is small and the presence of *E. Coli* is therefore a reliable indicator of recent fecal contamination. The presence of *E. Coli* in water will indicate recent fecal contamination by humans, animals or birds indicating that there may be a health risk.

The use of Fecal Coliforms is a fairly reliable method to indicate the possible presence of bacterial pathogens in water that originate from fecal contamination by humans, animals and birds. There is unfortunately some uncertainty with the use of Fecal Coliforms as an indicator of fecal contamination of water because aerobic heterotrophic bacteria such as *Aeromonas Spp.* that are naturally occurring in the environment can present as Fecal Coliforms during tests. Also many authors including Prescott et al. [1999], NHMRC [1996] and Feachem et al. [1980] explain that the indicator organisms cannot discriminate between humans, animals and birds as the origin of fecal contamination. Different sources of fecal contamination will pose different risks of exposure to pathogens. The use of Fecal Streptococci is recommended as a secondary indicator to reveal the presence of animal feces. Bacterial indicators of fecal contamination of water (such as Total and Fecal Coliforms) are limited predictors of the presence of pathogens. Feachem et al. [1980] explain that bacterial indicators of fecal contamination may be poor predictors of the presence of nonbacterial pathogens such as viruses and protozoa. Importantly nonbacterial pathogens may survive longer in the environment than bacterial indicator organisms such as Total or Fecal Coliforms. Failure to locate Fecal or Total Coliforms in water does not necessarily indicate the absence of pathogens.

It is clear that reliance on testing using bacterial indicator organisms is not a guarantee that a water supply will be free of pathogens. The water storage and distribution systems will need to be carefully maintained to minimise the risk of pathogens entering or remaining in the system. Heterotrophic Plate Counts can be used to determine the presence of all heterotrophic bacteria in water providing a general indication of water quality. Detection of large numbers of heterotrophic bacteria (>100 CFU/ml for disinfected water and >500 CFU/ml for undisinfected water) can indicate that the quality of water has deteriorated [NHMRC, 1996].

The majority of studies that found that rainwater stored in tanks was of poor quality made this claim on the basis of the presence of Coliform bacteria in the water (Section 4.1). The presence of Coliform bacteria is assumed to indicate recent fecal contamination of water that may indicate the presence of pathogens. However Coliform bacteria occur naturally in the environment and are most likely to be found in untreated waters. The isolation of Coliform bacteria in rainwater is unlikely to indicate recent fecal contamination and even less likely to indicate the presence of pathogens. Moreover the majority of water-borne pathogens originate from human fecal material (Section 4.2). Citizens do not defecate on roofs or even in household yards. It is highly improbable that the majority of pathogens can be transported from roofs to adequately sealed above ground tanks. It is also unlikely that pathogens from roofs and household yards can be transported to adequately sealed underground tanks. Pathogens are rarely found in rainwater tanks (Section 4.2). Claims that rainwater is unsafe due to the presence of Coliform bacteria are questionable. Given that rainwater is unlikely to be contaminated by sewage more intensive testing is required to determine the presence of pathogens in rainwater.

4.3 The Water Treatment Chain

The supply of water of a quality acceptable of drinking or other uses involves the use of multiple protection barriers [Maher et al., 1997 and NHMRC, 1996]. A water treatment chain for mains and rainwater supply systems is needed. The water treatment chain for a mains water system includes catchment management, screening of debris, flocculation, settlement, filtration and disinfection. The treatment chain for a rainwater supply system can include management of the roof gutter system, first flush separation, screening to remove debris, flocculation, settlement and biological removal of contaminants in the rainwater tank, disinfection of rainwater in the hot water service and drinking water filters or ultraviolet disinfection.

The quality of mains and rainwater supplies is dependent on the adequacy of the water treatment chain. Conversely the water quality requirements of the end uses for the water supply will dictate the elements required in the treatment chain. In this section the mains water treatment chain is discussed and the elements of the rainwater treatment chain are examined and compared to the mains water treatment chain. The efficacy of the rainwater treatment chain in terms of human health is examined and acceptable water uses are determined.

4.3.1 Mains Water Treatment

The mains water treatment chain begins with effective catchment management. This will include control of industrial, mining, forestry, agricultural and human activities within water supply catchment boundaries. There have been notable failures of mains water supplies resulting in public health epidemics caused by discharge of sewage or chemicals to a water supply catchment (including a viral outbreak originating from sewage contamination that affected thousands of people in Sunbury in Victoria and the Milwaukee *Cryptosporidium* outbreak in the USA that affected 400,000 people) [Maher et al., 1997]. Catchment management is of paramount importance for the maintenance of water quality. Failures of centralised water supply systems can result in widespread public health epidemics.

Stormwater runoff from the water supply catchment is generally stored in a reservoir (or aquifer) for subsequent use for water supply. The raw water is screened to remove large floating and suspended debris and, depending on the suspended solids content, is stored in a sedimentation basin until the remaining large suspended particles settle out. The water is then mixed with alum and lime to facilitate coagulation of microorganisms, organic matter, toxic contaminants and suspended fine particles [Prescott et al., 1999 and Masters, 1991]. The net negative charge of the suspended particles repels other particles in water causing the particles to remain separate. The addition of a coagulant (alum or lime) neutralises the charge allowing the particles to join together forming flocs. This is called flocculation.

The raw water is then stored in a settlement basin where some of the flocs containing microorganisms, organic matter, toxic contaminants and suspended fine particles settle to the bottom of the basin and may be removed from the water. The water is then passed through a filtration unit that is usually a rapid sand filter that will remove up to 99% of remaining bacteria by physically trapping flocs and fine particles.

The processes of flocculation, settlement and filtration remove the majority of contaminants including bacteria from the water. The final step in the treatment chain is disinfection to eliminate any pathogens remaining in the water. The water is then stored and distributed via a network of pipes to urban areas. Unfortunately most centralised water supplies rely on lengthy pipe networks to distribute water to households. The amount of disinfectant added to the water supply is dependant on the length of the pipe system. Disinfection residual must be maintained throughout the distribution system to ensure pathogens are eliminated.

The internal surfaces of the pipe systems are usually colonised by layers of microorganisms known as biofilms. In pipe distribution systems biofilms can neutralise the effect of disinfection, revive bacteria that have been injured by disinfection and with the assistance of the flow rate in a pipe release bacteria into the water supply [LeChevallier, 1989]. Bacteria in biofilms are highly resistant to disinfection residuals. In aging pipe distribution systems that contain established biofilms large doses of disinfectants are required to maintain water quality but disinfection by-products are potentially carcinogenic [Morris and Naumova, 2000] and may cause birth defects [Bove, 2000]. Current centralised disinfection practices are not suited to mains water distribution systems.

4.3.2 The Roof

The water supply catchment in the domestic rainwater supply system is the household roof. The quality of runoff from the roof will be dependant on the materials used to construct the roof, the types of material deposited on the roof and maintenance. A roof catchment coated with lead paint or with lead fittings can contribute unacceptably high levels of lead contamination to stored rainwater [Gee, 1993; Cunliffe, 1998 and Simmons et al., 2001]. Roof catchments in major urban and industrial centres can be subject to increased deposition of contaminants including heavy metals and chemicals that are derived from heavy traffic, industry, incinerators and smelters [Cunliffe, 1998]. In some cases the air quality in a region may dictate that roof runoff is used for purposes other than drinking.

It is improbable that human feces or significant amounts of animal feces will contaminate the roof catchment. Therefore the risk of transmitting pathogens that are responsible for major water borne diseases (such as Cholera, Typhoid, Shigellosis and Salmonellosis) to the rainwater tank is minimal. However the roof catchment can be contaminated with bird and small animal feces, dust and leaves. Indeed these contaminants can concentrate on the roof surface during dry periods. Ultraviolet radiation kills all varieties of microorganisms due to its short wave length [Prescott et al., 1999, pp. 131-132]. Even visible light, in sufficient intensity, such as sunlight can kill or injure microorganisms. Some water borne pathogens including *Campylobacter jejuni* are also susceptible to drying [USFDA, 1999]. Exposure to sunlight on roofs during dry periods may eliminate a considerable amount of harmful microorganisms from roof catchments. Rainfall runoff from roof catchments will, in most cases, contribute bacteria and moderate levels of inorganic chemicals to stored rainwater. However it appears that the risk of transporting pathogens from roof surfaces to rainwater appears to be small.

4.3.2.1 The Roof Gutter System

Rainfall runoff from the roof catchment is collected in a gutter system and discharged via downpipes to the rainwater tank. The roof gutter system is an efficient collector of rainwater, sediments, bird and animal feces, leaves and debris. The accumulation of these materials in the roof gutter system can encourage bacterial growth [Cunliffe, 1998] that may contribute to stored water, may attract birds and rodents thereby increasing fecal contamination of the roof catchment, and decrease the volume of rainwater that can be harvested [Duncan and Wight, 1991]. Regular inspection and cleaning of the roof gutter system should be undertaken to limit contamination of rainwater [Cunliffe, 1998 and Gee, 1993].

Duncan and Wight [1991] found that gutters that were not cleaned in over two years provided comparable water quality to gutters that were regularly cleaned. However they recommend regular inspections of gutters and annual cleaning of gutters as a conservative measure. There are a number of roof systems available that exclude leaves and sediments from discharge to the rainwater tank. Mobbs [1998] used these gutters on a house in an inner suburb of Sydney and reported rainwater quality compliant with the Australian Drinking Water Guidelines from the majority of samples taken from the rainwater tank.

4.3.3 The First Flush Device

Many authors including Jenkins and Pearson [1978], Clarke [1987] and Yaziz et al. [1989] have found that the quality of roof runoff improves with increasing accumulated rain depths. A similar result was also found during the Figtree Place experiment (Chapter 2). Yaziz et al. [1989] suggested that the first 0.33 mm of rainfall should be separated from roof runoff and Jenkins and Pearson [1978] recommended that the first 0.25 mm of rainfall should be separated from roof runoff to minimise contamination of stored rainwater. However Yaziz et al. [1989] explained that the quality of roof runoff will vary as a function of rainfall depth, intensity and antecedent dry periods. The results from the Figtree Place experiment (Table 2.7) suggest that at least the first 1 mm of rainfall on a roof should be separated from inflow to a rainwater tank.

The separation of a fixed volume of roof runoff will remove a variable amount of contamination from entry to the rainwater tank. Also a first flush device may not remove all contamination during the designated first flush volume and subsequent roof runoff may carry further contamination to the rainwater tank. A final year project in the Department of Civil, Surveying and Environmental Engineering at the University of Newcastle was carried out to evaluate the efficiency of various first flush separation devices in the laboratory. Lindsay [1999] tested a number of different designs. Three of those first flush device designs (shown in Figure 4.3) are discussed here.

The first flush devices (Figure 4.3) were designed to store the first portion of inflow (that may be contaminated) from a roof in a chamber that is 500 mm long, 386 mm wide and 300 mm deep. When the chamber is full rainwater overflows into a rainwater tank. Rainwater stored in the chamber slowly leaks through a small hole in the base eventually emptying the chamber.

The three designs (Figure 4.3) included a basic configuration, the use of a baffle and an extended inlet pipe. Each device was tested for three different inflow rates of 0.5 L/s, 1 L/s and 1.5 L/s. In order to test each device's ability to separate dissolved solids from inflow to a rainwater tank a known mass of salt was injected into the inflow. The proportion of salt discharged to the rainwater tank was recorded (shown as mass out in Table 4.6). To test the first flush 300 Litres of the salt concentration was discharged into the empty devices and to test the "second flush" the salt concentration was discharged into the devices that had been filled with clean water. The results are shown in Table 4.6.

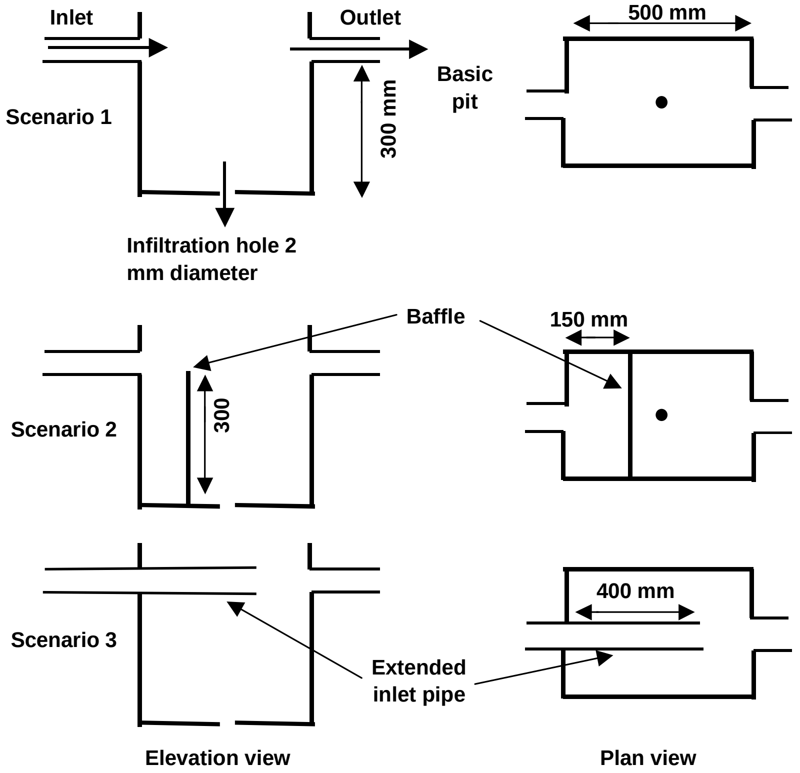

Figure 4.3: Configuration of the three first flush devices tested by Lindsay [1999].

Table 4.6: Efficiency of the first flush devices for the removal of dissolved solids

	First flush						**Second flush**		
Discharge (L/s)	**0.5**	**1**	**1.5**	**0.5**	**1**	**1.5**	**0.5**	**1**	**1.5**
Design	**Mass out (%)***			**Mass out (%)****			**Mass out (%)*****		
1 Basic	46	78	76	46	87	85	89	92	95
2 Baffle	62	82	78	62	91	89	74	89	94
3 Extended pipe	6	9	17	6	13	28	98	97	88

* evaluated after 250 L of inflow

** evaluated after 500 (0.5 L/s), 400 (1 L/s) and 300 (1.5 L/s) seconds

*** evaluated after 350 (0.5 L/s), 350 (1 L/s) and 300 (1.5 L/s) seconds

The results (Table 4.6) show that the first flush devices removed more dissolved solids from low flows (0.5 L/s) and that the extended pipe configuration was most effective at removing dissolved solids from the first flush. Importantly the first flush devices did not remove all of the dissolved solids because some of the dissolved solids remain suspended in the water and are entrained into the outflow from the device. The second flush event would represent the ability of the devices to remove dissolved solids from inflow to a rainwater tank during a rain event. As anticipated, all devices were relatively ineffective at removing dissolved solids from the “second flush”. An identical experiment was conducted using fine grained sand rather than salt to test the effectiveness of the first flush devices at removing suspended solids from inflow to a rainwater tank. The results are shown in Table 4.7.

Table 4.7: Efficiency of the first flush devices for the removal of suspended solids

	First flush			**Second flush**		
Discharge (L/s)	**0.5**	**1**	**1.5**	**0.5**	**1**	**1.5**
Design	**Mass out (%)**			**Mass out (%)**		
1 Basic	20	35	38	41	43	46
2 Baffle	16	32	32	23	44	45
3 Extended pipe	3	6	12	64	67	67

The results (Table 4.7) show that the first flush devices were very effective, particularly at low inflows, at removing suspended solids from the first flush. Once again it is important to note that the first flush devices do not remove all suspended solids from inflow to a rainwater tank because some of the suspended solids are entrained into the outflow from the first flush device. The first flush devices will also remove a proportion of suspended solids from inflow to a rainwater tank during a rain event (the second flush result). The extended pipe design was shown to be the most effective at removing dissolved and suspended solids from the first flush and the least effective at removal from the second flush.

The first flush device can potentially remove 11 % - 94% of dissolved solids and 62% - 97% of suspended solids from the first flush into a rainwater tank. It can also remove 5% - 26% of dissolved solids and 33% -77% of suspended solids inflow to a rainwater tank during a rain event after it has filled. The first flush device can be designed to remove large a proportion of contaminates from entry to a rainwater tank making it an important part of the rainwater supply treatment chain. Importantly, the device once filled can also remove a proportion of contamination from inflow to a rainwater tank during a storm event. It is important to note that the traditional first flush devices recommended by many authors including Duncan and Wight [1991], Mobbs [1998] and Cunliffe [1998] involving a ball that floats to the top of a storage with a given volume will not remove contaminants from inflow to a rainwater tank during a rainfall event following the first flush.

4.3.4 The Rainwater Tank

A roof catchment management program involving regular inspection and cleaning of roof gutter systems, and the use of a first flush device will significantly reduce the amount of dissolved and suspended material entering the rainwater tank as part of roof runoff. Nevertheless runoff from roof catchments will, in most cases, contribute bacteria and moderate levels of inorganic chemicals to stored rainwater.

Authors such as Duncan and Wight [1991], Gee [1993], Bell [personal communication, 1999], James [personal communication, 1999] and Ariyabandu [2000] report that the quality of roof runoff improves in rainwater tanks. The Figtree Place and Maryville experiments (Chapters 2 and 3) also found that the quality of roof runoff improves in rainwater tanks. It was also found that the quality of rainwater in a tank varied from the water surface to the point of supply near the base of the tank. The rainwater quality at the point of supply in the rainwater tank was found to be significantly better than at the water surface. Bell [personal communication, 1999] and James [personal communication, 1999] also report this phenomenon.

Duncan and Wight [1991] suggested that a rainwater tank will act as a clarifier of rainwater allowing contaminants to settle to the bottom of the tank. Gee [1993] found that the sediments in rainwater tanks contained high concentrations of heavy metals although the concentrations of heavy metals at the water surface were well within the Australian Drinking Water Guidelines. Similarly, during the Figtree Place experiment it was found that although roof runoff contained exceedances of the Australian Drinking Water Guidelines for Coliforms, Iron and Lead the values of these parameters were considerably less at the water surface, and high concentrations of the parameters were found in the sediments. The values of these parameters were found to be least at the point of supply near the bottom of the tank. Bell [personal communication, 1999] and James [personal communication, 1999] reported similar results.

Rodents, frogs and reptiles can enter rainwater tanks that do not have screens on all inlet and outlets contributing pathogens to the stored water that may cause illness if the water is used for drinking [Taylor et al., 1999]. Modern rainwater tanks are supplied with screens on all inlets and outlets. Maintenance of these screens should eliminate the risk of disease caused by rodents, frogs and reptiles entering the tank. Careful installation (construction) and maintenance of a rainwater tank will ensure that soils, leaves and debris do not enter the tank and compromise water quality.

It is assumed that a number of processes operate to improve water quality in a rainwater tank including accumulation of microorganisms at the surface air-water interface (the water surface microlayer), flocculation and settlement in the tank, and the action of biofilms. A description of those processes follows.

4.3.4.1 The Water Surface Microlayer

Many authors including Woodcock [1948], Blanchard [1970] and Prescott et al. [1999, pp.852-883] report that certain types of bacteria concentrate at the surface microlayer of water. Prescott et al. [1999, pp. 860] explain that, in low nutrient environments (such as rainwater tanks), microorganisms form flocs to increase surface areas allowing greater capture of nutrients. Aquatic environments contain gradients of microorganisms in the water column that are dependant on the concentration of Oxygen and nutrients [Prescott et al., 1999, pp. 853]. Clearly aerobic microorganisms will concentrate at the water surface in a rainwater tank to utilise Oxygen from the atmosphere and nutrients as they enter the tank at the water surface.

The concentration of some microorganisms at the water surface prevents those organisms from being supplied to the household because water is drawn from a point near the base of the rainwater tank. This process can eliminate the transfer of bacteria that colonise water surfaces such as *Legionella Spp*. from household water supplies.

4.3.4.2 Flocculation and Settlement

Organic materials are regularly discharged in roof runoff to rainwater tanks. Nutrients and microorganisms tend to accumulate on the surface of organic materials in low nutrient aquatic environments [Prescott et al., 1999, pp. 855]. It is proposed that the presence of microorganisms on the surfaces of organic materials allows the organic materials to bind creating flocs. The presence of microorganisms on the surface of organic materials may also neutralise the negative charges that keep the materials apart. This will also allow the materials to readily form flocs. These flocs settle to the bottom of rainwater tanks removing contamination from the water.

4.3.4.3 Biofilms

Biofilms are formed when microorganisms bind together with sticky polysaccharide fibres to maximise their ability to extract nutrients and accumulate microbes from the surrounding water bodies [Prescott et al., 1999, pp.855-860, Flemming, 1993, and Christensen and Characklis, 1990]. Coliforms and *Pseudomonas Spp.* bacteria are commonly found in biofilms. More than 99% of the microorganisms on earth are living in biofilms and a majority of surfaces can be or are colonised by microorganisms including sediments and suspended particles [Fleming, 1993 and Prescott et al., 1999, pp. 855-860].

Biofilms are used in sewerage treatment. Wastewater flows over biofilms attached to rocks or other solid media in trickling filters resulting in the addition of passing nutrients, organic material and microorganisms to the biofilm thereby removing those elements from the passing sewage [Prescott, 1999, pp. 870-871]. Biofilms also form on sand grains in drinking water sand filters resulting in the removal of nutrients and microorganisms from the water [Flemming, 1993].

In low nutrient aquatic environments microorganisms will readily attach to surfaces on structures, sediments and organic materials to maximise opportunities to utilise nutrients, microorganisms and organic materials from the water column. Inflow from the roof and periodic water uses from a rainwater tank will ensure that the stored water is often slowly circulating increasing the contact between biofilms and nutrients, microorganisms and organic materials. This will maximise opportunities for biofilms to extract nutrients, microorganisms and organic materials from the water. It is hypothesised that the action of biofilms improves water quality in rainwater tanks.

4.3.5 Pasteurisation

During the Figtree Place experiment (Chapter 2) it was discovered that the microbial quality of tank water with high bacterial loads was improved in storage hot water services set at temperatures in the range 50ºC to 65ºC. Indeed the hot water quality was always compliant with the Australian Drinking Water Guidelines. It was also found that microbial quality of tank water with low bacterial loads improved by passing through an instantaneous hot water service at the Maryville house (Chapter 3).

Many authors including Michell [1994], Benenson [1995], Joyce et al. [1996], Jorgenson et al. [1998] and Prescott et al. [1999, pp.136-139] report that heating water to relatively low temperatures over a period of time will kill bacteria. This process is known as pasteurisation. Prescott et al. [1999, pp. 138] explains that moist heat readily kills bacteria, fungi and viruses. The following Table 4.8 from Prescott et al. [1999] gives the approximate conditions for moist heat killing of microorganisms.

Table 4.8: Approximate conditions for moist heat killing of microorganisms

Organism	**Temperature and time required for killing**	
	Vegetative cells	**Spores**
Yeasts	5 minutes at 50 - 60ºC	5 minutes at 70-80ºC
Molds	30 minutes at 62ºC	30 minutes at 80º
Mesophilic bacteria	10 minutes at 60-70ºC	2 – 800 minutes at 100ºC
Viruses	30 minutes at 60ºC	-

The approximate conditions for moist heat killing of microorganisms shown in Table 4.8 suggests that storage hot water services set at 60ºC will remove the majority of vegetative cells over a 30 minute period including mesophilic bacteria but may not eliminate spores from water. The majority of microorganisms and almost all human pathogens are mesophilic bacteria that are viable in the temperature range 20ºC to 45ºC [Prescott et al., 1999, pp. 127]. The resilience of vegetative spores to pasteurisation in water may indicate that there is a chance of regrowth of bacteria after water leaves the hot water service. This will require further investigation. The hot water services at Figtree Place has eliminated the majority of bacteria from the water at low temperatures (50-65ºC) and the hot water service at the Maryville house eliminates the majority of bacteria at a low temperature (55ºC) over a very short duration.

The effectiveness of the hot water services at Figtree Place and Maryville can be explained by number of processes. Prescott et al. [1999] reveals that heat readily kills microorganisms in acidic conditions. Hot water services will be more effectively kill microorganisms in rainwater that is slightly acidic (pH 5.7 – 5.9). Also the viability of different microorganisms subject to temperature varies widely. For example *Salmonella Spp.* in chicken is killed in 0.4 minutes at a temperature of 60ºC, *E. Coli* is unstable at temperatures greater than 45ºC, *Pseudomonas Spp.* is unstable at temperatures greater than 40ºC and *Cryptosporidium* is killed in two minutes at a temperature of 60ºC [Benenson, 1995 and Prescott et al., 1999].

The maximum temperature that the majority of human pathogens will tolerate is 45ºC. At water temperatures above 45ºC the majority of pathogens will begin to die off. Most pathogens are killed instantly at 65ºC [Benenson, 1995]. The pattern of microbial death is significant for the effectiveness of the hot water services at killing pathogens. The pathogen is not killed instantly upon exposure to moderate heat rather the death of the pathogen population is expected to be exponential [Prescott et al., 1999, pp. 137 and Mitchell, 1974].

A large microbial population will take longer to kill than a smaller population. A small population of microorganisms will be killed rapidly upon exposure to heat or less heat will be required to eliminate the microbes at a slower rate. Prescott et al. [1999, pp. 139] provides an example of this: *Salmonella Spp.* in chicken is killed in 0.4 minutes at a temperature of 60ºC or *Salmonella Spp.* in chicken is killed in 4 minutes at a temperature of 55ºC. The presence of organic materials (such as the chicken) will increase the temperature or period of exposure to the temperature required to kill the bacteria. Bacteria in water are likely to be rapidly killed by exposure to heat. The instantaneous hot water service at the Maryville house (Chapter 3) was probably effective at eliminating bacteria from rainwater because the hot water will have a short residence time in the household plumbing and the bacteria population sizes were small (average values: Total Coliforms 18 CFU/100 mL, Pseudomonas Spp. 1673 CFU/100 mL and Heterotrophic Plate Count 784 CFU/mL).

The use of rainwater in hot water services has been shown to produce water quality compliant with the microbial guidelines in the Australian Drinking Water Guidelines in Chapters 2 and 3. It is believed that the hot water services are pasteurising rainwater to produce hot water of an acceptable quality.

4.3.6 Acceptable Water Use from the Rainwater Tank

It is often stated that water supply from rainwater tanks is not acceptable for potable uses but over 3 million Australians drink water from rainwater tanks. If is assumed that the average household size is 2.7 people then over 1.11 million Australian households use rainwater for drinking purposes. However there are only a handful of reported cases where water from a rainwater tank in Australia has caused illness. The risk of contracting an illness from a rainwater tank appears to be very small.

Poorly maintained rainwater tanks have caused the majority of illnesses or potential health risks from drinking water from a rainwater tank. Some illnesses have been caused by drinking water from rainwater tanks located near heavy industry such as lead smelters. However it should be obvious from the above discussion that the production of mains water or rainwater for drinking purposes requires careful management of the water source. Likely sources of contamination in rainwater tanks are soil and leaves accumulated in gutters for long periods, faecal material deposited by birds, lizards, mice, rats, possums etc., and dead animals in gutters or tanks.

Acceptable water quality can be maintained in a rainwater tank provided that mesh screens cover all inlets and outlets to limit access of leaves, debris, animals and mosquitoes to the tank, a first-flush device is used to discard the first part of rainfall that may be contaminated, and roof gutters are regularly cleared of leaves and debris. Rainwater should not be collected from roofs painted with lead based paints or tar based paints or from roofs constructed using asbestos. Roofs constructed from galvanised iron, Colorbond, Zincalume, slate or ceramic tiles provide acceptable water quality, although some investigation is required to check for long-term release of potentially harmful elements. Special roof guttering in not required for rainwater collection, normal guttering is sufficient provided that the roof guttering is kept clear of leaves and debris.

Another method to eliminate possible health risks of the use of water from rainwater tanks is to use rainwater for purposes other than drinking. The designer can match different household use categories with the required water quality, frequency of use and rainfall to maximise water savings. The proportion of typical domestic household uses (from Gardner et al. [2001], Van der Wal [2000] and Chapter 2) is shown in Figure 4.4.

Figure 4.4 reveals that drinking water is a very small proportion of total household water use. It is clear that an effective strategy for rainwater reuse to reduce mains water consumption and stormwater discharges could target household consumption types with greater volumes and frequency of water use that require a lesser water quality (such as outdoor, toilet, laundry or hot water uses). Rainwater used in hot water services was shown to produce water quality compliant with the Australian Drinking Water Guidelines.

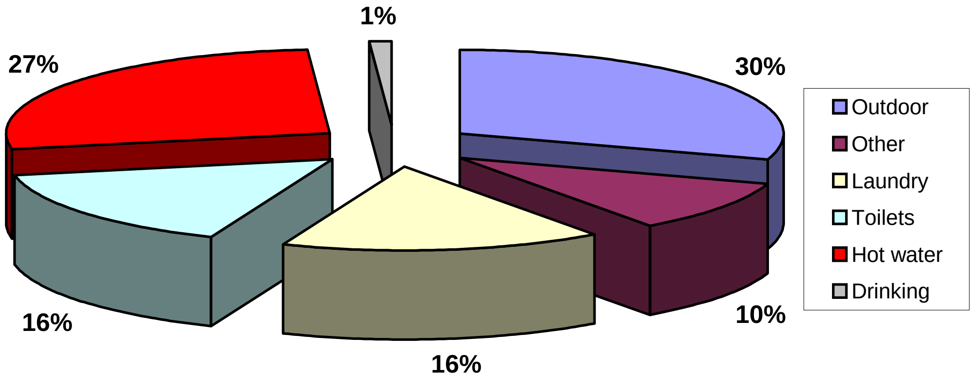

Figure 4.4: Domestic water use types by proportion

However a mistake commonly made by designers is to assume that using rainwater to supply outdoor uses will produce substantial mains water savings. The mismatch between seasonal rainfall and outdoor water use patterns can result in poor utilisation of rainwater resulting in long periods when the tanks are either empty or full. This problem can be remedied by using rainwater to supply constant indoor uses such as toilet flushing and hot water that will consistently draw down the rainwater storage allowing the rainwater to refill the storage more often. Combinations of different water use frequencies from rainwater tanks such as toilet flushing, hot water and outdoor uses can result in substantial reductions in mains water use and stormwater discharges.

It appears that the rainwater treatment chain of the roof, first flush device, rainwater tank and hot water service provides acceptable water quality for outdoor, toilet and hot water uses. The addition of an ultraviolet disinfection unit or a water filter to the rainwater treatment chain should produce water quality acceptable for all household uses.

4.4 Summary

In this chapter the literature describing the water quality that can be expected from rainwater tanks and health risks that can be derived from drinking rainwater stored in rainwater tanks was discussed. The human digestive system and common water borne diseases were examined to develop an understanding of the health risks that may result from using rainwater for household uses.

It was found that the quality of rainwater stored in tanks can be degraded by poor maintenance of the rainwater tank and in a small number of cases this has resulted in the transmittal of pathogens from human, animal or birds via fecal contamination of stored water to humans causing disease. In general the majority of water borne diseases were found to originate from fecal contamination of drinking water by humans, animals and birds.

The rainwater treatment chain of the roof, first flush device, rainwater tank and hot water service, and the human gastrointestinal tract plays significant roles in reducing the risk of disease created by pathogens. Bacterial indicator organisms Total and Fecal Coliforms are used to indicate recent fecal contamination of drinking water supplies indicating the possible presence of pathogens. Coliform bacteria occur naturally in the environment. Therefore the presence of Coliform bacteria in rainwater may not indicate the possibility of contamination of rainwater by human excreta or the presence of pathogens. Indeed the majority of studies that have found that the quality of rainwater stored in tanks was unacceptable for household uses on the basis of the presence of Coliform bacteria may have made questionable conclusions. Pathogens have rarely been found in rainwater. More detail research is required to understand the quality of rainwater stored in tanks.

The rainwater treatment chain produces acceptable water quality for outdoor, toilet and hot water uses. It appears that the quality of rainwater will allow the widespread introduction of rainwater tanks to supply toilet, hot water and indoor uses. This will have the potential to defer the need to build new dams, reduce the requirement for water supply and stormwater pipes, and reduce impacts on the environment.

The impact of installation of rainwater tanks to supplement mains water supplies on long-term domestic mains water use is examined in Chapter 6. The impact of this strategy on the provision of stormwater infrastructure is examined in Chapter 7 and the impact on the provision of new water supply dams is examined in Chapter 9.