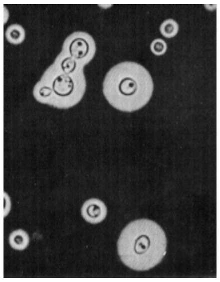


Microbes and Urban Watersheds

II. Concentrations, Sources, and Pathways

Microbes are problematic. They are small and include hundreds of groups, species, biotypes and strains. They are ubiquitous in the environment, found on nearly every surface of the earth. They exist within us, on us, on plants, soils and in surface waters. They grow rapidly, die-off, survive or multiply depending on a changing set of environmental conditions. Some microbes are beneficial to humans, while others exert no impact at all. Other microbes cause illness or disease, and a few can even kill you.

The presence of some types of microbes indicates a potential risk for water contamination, while other microbes are pathogens themselves (i.e., they are known to cause disease). Microbes are nearly always present in high concentrations in stormwater, but are notoriously variable. They are produced from a variety of watershed sources, such as sewer lines, septic systems, livestock, wildlife, waterfowl, pets, soils and plants, and even the urban drainage system itself.

Fecal coliform levels in urban stormwater routinely exceed standards by a factor of 50 to 75.

It is little wonder that many watershed managers are thoroughly confused by the microbial world. This article seeks to provide enough background to help a watershed manager assess bacteria problems. It contains a national review and analysis of microbial concentrations, sources, and pathways in urban watersheds. The major focus is on fecal coliform bacteria, for which the most urban watershed data is available, but reference is also made to protozoa, such as *Cryptosporidium* and *Giardia*.

The article begins with a field guide to the bacteria found in urban waters. It compares the frequency of detection, origin, indicator status and measurement units of different microbes. The next section presents a national assessment of bacteria levels in urban stormwater. The last section profiles the many different human and nonhuman bacteria sources that can potentially occur in an urban watershed.

Field Guide to the Microbes

The complex microbial world is confusing to most, therefore, worth a moment to understand some of the terminology used to describe it. The term *microbes* refers to a wide range of living organisms that are too small to see with the naked eye. *Bacteria* are very simple single celled organisms that can rapidly reproduce by binary fission. Of particular interest are *coliform bacteria*, typically found within the digestive systems of warm-blooded animals. The coliform family of bacteria includes total coliforms, fecal coliforms and the group *Escherichia coli (E. coli)*. Each of these can indicate the presence of fecal wastes in surface waters, and thus the possibility that other harmful bacteria, viruses and protozoa may be present. Fecal streptococci (a.k.a., *Entercocci*) are another bacteria group found in feces which, under the right conditions, can be used to determine if a waste is of human or nonhuman origin. As such, all coliform bacteria are only an *indicator* of a potential public health risk, and not an actual cause of disease.

A *pathogen* is a microbial species that is actually known to cause disease under the right conditions. Examples of bacterial pathogens frequently found in stormwater runoff include *Shigella spp.* (dysentery), *Salmonella spp.* (gastrointestinal illness) and *Pseudonomas auerognosa* (swimmer's itch). Some subspecies can cause cholera, typhoid fever and "staph" infections. The actual risk of contracting a disease from a pathogen depends on a host of factors, such as the method of exposure or transmission, pathogen concentration, incubation period and the age and health status of the infected party.

Protozoa are single-celled organisms that are motile. Two protozoans that are common pathogens in surface waters are *Giardia* and *Cryptosporidium*. To infect new hosts, these protozoans create hard casings known as cysts (*Giardia*) or oocysts (*Cryptosporidium*) that are shed in feces, and travel through surface waters in search of a new host. The cysts or oocysts are very durable and can remain viable for many months. The protozoan emerges from its hard casing if and when a suitable host is found.

Table 1 provides a general comparison of the many microbes found in urban stormwater runoff, in terms of their frequency of detection, origin, indicator status, measurement units and information use.

Public health authorities have traditionally used fecal coliform bacteria to indicate potential microbial risk, and to set water quality standards for drinking water, shellfish consumption and water contact recreation. Some typical fecal coliform standards are pro-

Table 1: Comparison of Microbes found in Urban Stormwater

Microbial Indicator	Found in Urban Runoff?	Fecal Origin?	Non-Human Sources?	Indicator or Pathogen	Units of Measurement [a]	Information Use [b]
Total coliforms	All samples	Most	Animals, plants, soil	Neither	Counts per 100 ml	Historical, seldom used
Fecal coliforms	All samples	Most	Animals, plants, soil	Indicator	Counts per 100 ml	Water contact, shellfish, drinking water
Fecal streptococci	All samples	Yes	Warm-blooded animals	Indicator	Counts per 100 ml	Sometimes used to ID waste source [c]
Escherichia coli	Nearly all samples	Yes	Mammals, some found in soils	Indicator, some are pathogen	Counts per 100 ml	Water contact, shellfish, drinking water
Salmonella spp.	About half	Yes	Mammals (esp. dogs)	Pathogen	Counts per 10 ml	Food safety
Psuedonomas aeruginosa	All samples	Yes	Mammals	Pathogen	Counts per 100 ml	Drinking water
Crytospoidium spp.	Less than half	Yes	Mammals (esp. livestock)	Pathogen	Oocysts per liter	Drinking water
Giardia spp.	Less than half	Yes	Mammals (esp. dogs and wildlife)	Pathogen	Cysts per liter	Drinking water

[a] *Research use many different terms and sampling methods to describe their bacterial counts, including MPN (most probable number), colony forming units (CFU), colonies, or organisms.*
[b] *See Table 2 for a more thorough discussion on bacteria and protozoan standards.*
[c] *It is important to note that fecal strep is a poor method for urban stormwater (see Lalor and Pitt, this issue)*

vided in Table 2. Fecal coliforms are an imperfect indicator and regulators continually debate whether other bacterial species or groups are better indicators of potential health problems and how low indicator levels must be to ensure "safe" water. The debate, however, remains largely academic, as over 90 percent of the states still rely of fecal coliform in whole or in part as their recreational water quality standards (USEPA, 1998).

Fecal Coliform Levels in Urban Stormwater Runoff

Coliforms are ubiquitous —about 20 percent of all water quality samples at U.S. Geological Survey's main sampling stations across the country exceeded the 200 MPN/100 ml fecal coliform standard in the 1980's (Smith et al., 1992 Note: Most samples were conducted in dry weather conditions and in larger watersheds.) The highest fecal coliform levels were routinely collected in agricultural and urban watersheds. Forested and pastured watersheds had much lower fecal coliform levels (about 50 to 100 MPN per 100 ml).

The vast majority of urban stormwater monitoring efforts utilize fecal coliform as the primary microbial indicator. A small handful of researchers have measured other coliforms or other specific pathogens (e.g., *Salmonella*, *Pseudonomas*, etc.). Some caution should be exercised when evaluating storm concentrations of fecal coliforms, as most represent a "grab" sample rather than a true flow-composite sample. This, along with differences in how samples are counted and averaged, produces the notorious variability that is associated with stormwater fecal coliform data.

Table 2: Typical Coliform Standards for Different Water Uses

Water use	Microbial Indicator	Typical water standards
Water contact recreation	Fecal coliform	<200 MPN per 100 ml
Shellfish bed	Fecal coliform	<14 MPN per 100 ml
Drinking water supply	Fecal coliform	<20 MPN per 100 ml
Treated drinking water	Total coliform	No more than 1% coliform positive samples per month
Freshwater swimming	*E. coli*	<126 MPN per 100 ml
Marine swimming	*E. coli*	<35 MPN per 100 ml

Important Note: *Individual state standards may employ different sampling methods, indicators, averaging periods, averaging methods, instantaneous maximums and seasonal limits. MPN=most probable number. Higher or lower limits may be prescribed for different water use classes. Please consult your state water quality agency or USEPA (1998) to determine bacteria standards used in your community.*

Pitt (1998) reports a mean fecal coliform concentration in stormwater runoff of about 20,000 colonies per 100 ml based on 1,600 storm runoff samples largely collected during the Nationwide Urban Runoff Program (NURP) in the early 1980's. He also reports a nearly identical mean fecal coliform concentration of about 22,000 colonies per 100 ml that was derived from a second database containing 25 additional stormwater monitoring studies conducted since NURP.

Arid and semi-arid regions experience higher fecal coliform levels.

The Center for Watershed Protection has recently developed a third database containing 34 more recent urban stormwater monitoring studies. An analysis of the Center database indicates a slightly lower mean concentration of fecal coliform in urban stormwater of about 15,000 per 100 ml. The Center fecal coliform database is profiled in Figure 1. Nearly every individual stormwater runoff sample in the database exceeded bacteria standards, usually by a factor of 75 to 100. Some indication of the enormous storm to storm variability in fecal coliform bacteria can be seen in Figure 1, with concentrations often spanning five orders of magnitude at the same sampling location. Other data for fecal streptococci and *E. coli* are provided in Figures 2 and 3.

Arid and semi-arid regions of the country often experience higher fecal coliform levels. For example, Chang (1999) computed a flow-weighted mean fecal coliform concentration of 77,970 MPN/100 ml in 21 small urban watersheds in Austin, Texas.

It should be noted that the most extreme bacteria concentrations in stormwater runoff from larger catchments (10^5 -10^6) are usually associated with an inappropriate human discharge (e.g., failing septic system, sanitary sewer overflows or illicit connections) (Pitt,1998).

Fecal coliform levels are generally much lower in stream baseflow than during storms, unless an inappropriate sewage discharge is present upstream (Gannon and Busse, 1989; USEPA, 1983). This is most evident at runoff monitoring stations at recently developed suburban watersheds that have few suspected sewage discharges. For example, Varner (1995) sampled fecal coliform samples at 11 stations in suburban catchments in the City of Bellevue, WA. Overall, the mean stormflow concentration of fecal coliforms (4,500 MPN/100 ml) was about nine times greater than mean baseflow concentrations (600 MPN/100 ml) for all stations.

Watershed managers should systematically assess dry weather flows from stormwater outfall pipes, however, before they conclude that dry weather bacteria concentrations are not a concern. In some communities, as many of 10 percent of all pipe outfalls have dry weather flow. Even if only a few of these flows contain sewage, they can produce very high bacteria concentrations because of low instream flow.

Fecal coliform levels are about 90 percent lower in runoff that occurs in winter than during the summer months, although bacteria levels can increase sharply during snowmelt events (USEPA, 1983 and Figure 4). Researchers have occasionally correlated bacteria levels with factors such as rainfall, rainfall intensity, antecedent rainfall, turbidity and suspended solids within individual urban watersheds. Few of these relationships, however, appear to be transferable from one watershed to another. Other watershed variables that may better predict bacteria levels include population density (Glenne, 1984), age of development and percent residential development (Chang, 1999).

Unlike many pollutants, fecal coliforms do not appear to be directly related to subwatershed impervious cover. For example, Hydroqual (1996) evaluated fecal coliform concentrations for seven small subwatersheds of different impervious cover in the Kensico watershed, a small drinking water reservoir for New York City. Undeveloped subwatersheds with 4 percent impervious cover had fecal coliform concentrations well below the 200 MPN standard, whereas watersheds ranging from 20 to 65 percent imperviousness exceeded the standard handily (Figure 5). While developed watersheds nearly always had greater fecal coliform concentrations than undeveloped watersheds, more impervious cover in a developed watershed was not observed to increase fecal coliform concentrations.

Protozoan Levels in Urban Runoff

Until recently, the major sources of protozoa in surface waters were generally thought to be human sewage, dairy runoff and wildlife sources. The only study to date that has measured *Cryptosporidium* or *Giardia* in stormwater runoff found high levels of both protozoans (Stern et al., 1996). David Stern and his colleagues monitored a series of agricultural and urban watersheds within the New York City water supply reservoir system, and found urban subwatersheds had slightly higher rates of *Giardia* and *Cryptosporidium* detection than agricultural subwatersheds, and a higher rate of confirmed viability (Table 3 and Stern et al., 1996).

States et al. (1997) also found very high levels of *Cryptosporidium* and *Giardia* in storm samples collected from combined sewers in the Pittsburgh region (geometric means of 28,881 cysts/100 ml for *Giardia* and 2,013 oocysts/100 ml for *Cryptosporidium*) The protozoa were detected in virtually every sample collected from the combined sewer overflows. Sampling of protozoa is complicated by durability of their cysts and oocysts in the environment (i.e., some *Cryptosporidium* and *Giardia* cysts and oocysts persist, but are no longer viable of infecting another host). Much more sampling is needed in other regions to determine if stormwater and combined sewer runoff are major sources of *Cryptosporidium* and *Giardia*.

Figure 1: Fecal Coliforms in Urban Stormwater Runoff

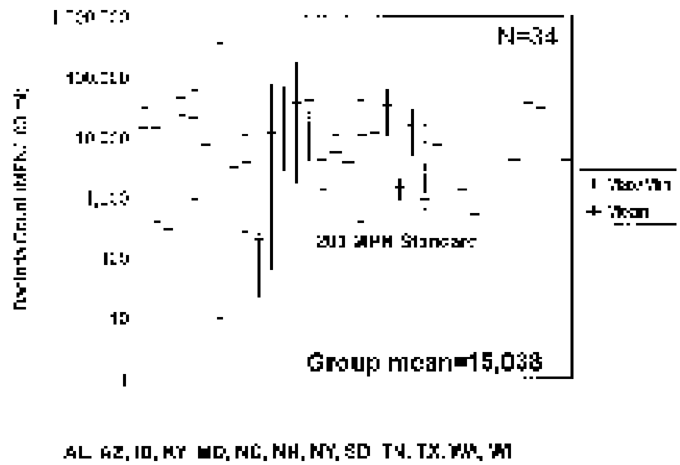


Figure 2: Fecal Streptococci in Urban Stormwater Runoff

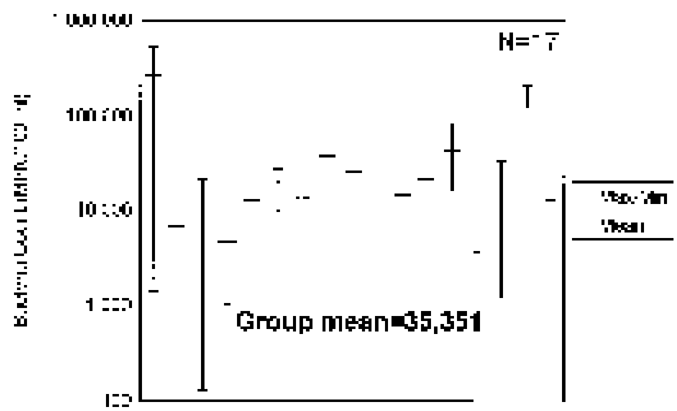


Figure 3: *E. coli* in Urban Stormwater Runoff

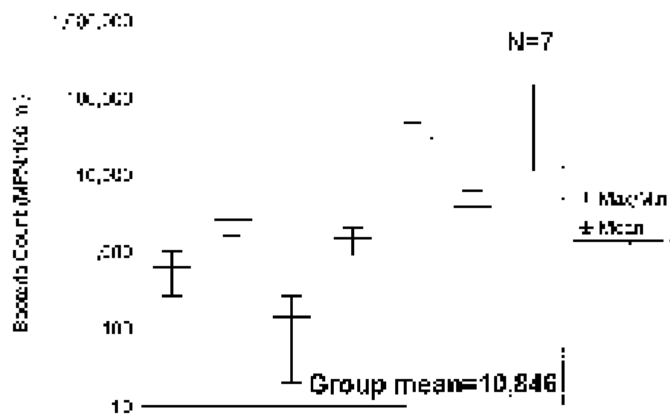


Figure 4: Fecal Coliforms in Winter Runoff

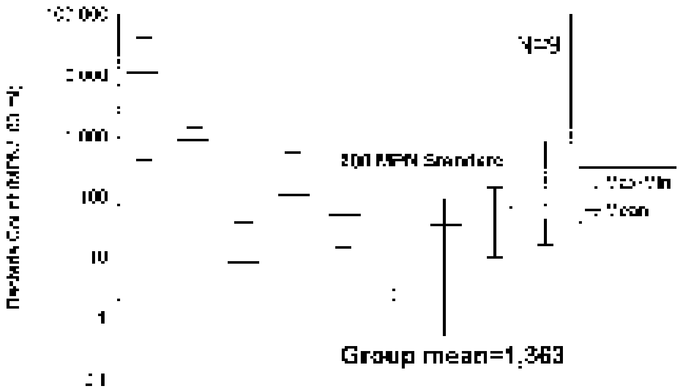
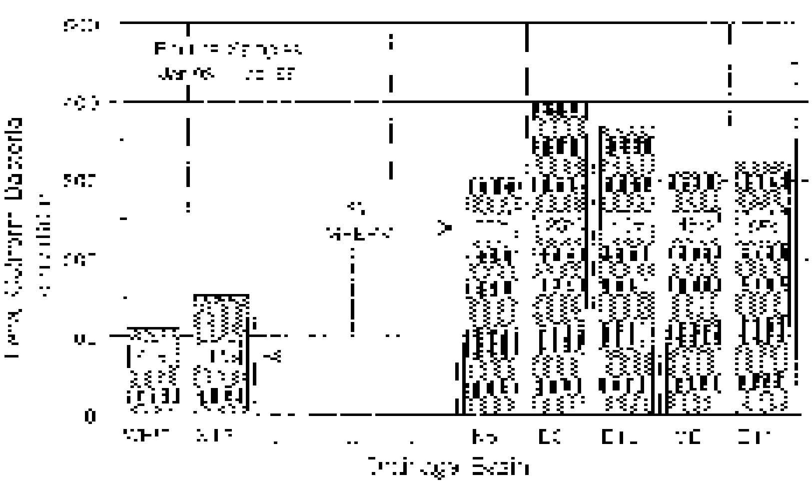


Figure 5: Fecal Coliform Levels in Watersheds of Different Impervious Cover ***(Source: Hydroqual, Inc., 1996)***



Bacteria Sources in Urban Watersheds

The high concentrations of bacteria in stormwater are derived from many possible human and non-human sources. Consequently, watershed managers must investigate many different sources and source areas in order to develop an effective strategy for bacteria control. Some of the more likely bacteria sources are described in Table 4, and are discussed below.

Human Sources of Bacteria

The major source of bacteria in most urban waters was human sewage until the advent of modern wastewater treatment. Wastewater is now generally collected in a central sewer pipe and sent to a municipal plant for treatment in most urban watersheds. Ideally, wastewater treatment provides more efficient collection, conveyance, and treatment of wastewater than septic systems or package plants. In reality, many sewer systems are still an episodic or chronic source of bacteria. Potential pathways of human sewage to surface waters include combined sewer overflows, sanitary sewer overflows, illegal sanitary connections to storm drains, transient dumping of wastewater into storm drains and failing septic systems.

The potential significance of sewage as a bacteria source can be quickly grasped from Table 5, which compares typical coliform levels from several waste streams, including raw sewage, combined sewer overflows, failed septic systems, stormwater and forest runoff. Raw sewage typically is about two to three orders of magnitude "stronger" than stormwater runoff in terms of coliform production, and is four to five orders of magnitude "stronger" than forest runoff that is influenced only wildlife sources. As a general rule, human sources of sewage should be suspected when fecal coliform concentrations are consistently above 10^5 (Pitt, 1998).

Table 3: Percent Detection of *Giardia* cysts and *Cryptosporidium* oocysts in Subwatersheds and Wastewater Treatment Plant Effluent in the New York City Water Supply Watersheds *(Source: Stern et al., 1996)*

	Percent Detection			
Source water sampled *(No. of sources/No. of samples)*	**Total *Giardia***	**Confirmed *Giardia***	**Total *Cryptosporidium***	**Confirmed *Crytosporidium***
Wastewater effluent *(8/147)*	41.5	12.9	15.7	5.4
Urban subwatershed *(5/78)*	41.0	6.4	37.2	3.9
Agricultural subwatershed *(5/56)*	30.4	3.6	32.1	3.6
Undisturbed subwatershed *(5/73)*	26.0	0.0	9.6	1.4

- *Combined sewer overflows (CSO's)*

  Many older cities have a sewer system that carries both wastewater and stormwater. During some storms, the capacity of the treatment system is exceeded, and diluted wastewater is discharged directly into the surface waters without treatment. As seen in Table 5, CSOs have extremely high bacteria levels and deserve immediate attention as a bacteria source when they are found in any watershed.

- *Sanitary sewer overflows (SSO's)*

  Human sewage can be introduced into surface waters even when storm and sanitary sewers are separated. Leaks and overflows are common in many older sanitary sewers where capacity is exceeded, high rates of infiltration and inflow occur (i.e., outside waters gets into pipes, reducing capacity), frequent blockages occur, or are simply falling apart due to poor joints or pipe materials. Power failures at pumping stations are also a common cause of SSO's. The greatest risk of a SSO occurs during storm events; however, little comprehensive data is available to quantify SSO frequency and bacteria loads in most watersheds. The Association of Metropolitan Sewage Agencies (AMSA, 1994) estimates that about 140 overflows occur per one thousand miles of sanitary sewer lines each year (a thousand miles of sewer serves a population of about 250,000). The AMSA survey also found that 15 to 35 percent of all sewer lines were over capacity and could potentially overflow during storms.

- *Illicit connections to storm sewers*

  Sewage can be introduced into storm sewers by accident or design. The hundreds of miles of storm and sanitary sewer pipes in a community creates a confusing underground spaghetti of utilities, so it should not be surprising that im-

Table 4: Potential Sources of Coliform Bacteria in an Urban Watershed

Human sources

Sewered watershed

- Combined sewer overflows
- Sanitary sewer overflows
- Illegal sanitary connections to storm drains
- Illegal disposal to storm drains

Non-sewered watershed

- Failing septic systems
- Poorly operated package plant
- Landfills
- Marinas and pumpout facilities

Non-human sources

Domestic animals and urban wildlife

- Dogs, cats
- Rats, raccoons
- Pigeons, gulls, ducks, geese

Livestock and rural wildlife

- Cattle, horse, poultry
- Beaver, muskrats, deer, waterfowl
- Hobby farms

Table 5: Comparison of Bacterial Densities in Different Waste Streams (MPN/100 ml)
(Sources: Pitt, 1998; Lim and Oliveri, 1982; Smith et al., 1992, Horsely & Witten, Inc., 1995)

Waste stream	Total coliform	Fecal coliform	Fecal streptococci
Raw sewage	2.3×10^7	6.4×10^6	1.2×10^6
Combined sewer overflow	$10^4 - 10^7$	$10^4 - 10^6$	10^5
Failed septic systems	$10^4 - 10^7$	$10^4 - 10^6$	10^5
Urban stormwater runoff	$10^4 - 10^5$	2.0×10^4	$10^4 - 10^5$
Forest runoff	$10^2 - 10^3$	$10^1 - 10^2$	$10^2 - 10^3$

proper connections are made to the wrong sewer (*See Feature Article V in this issue*). For example, Johnson (1998) reported that just under 10 percent of all businesses in Wayne County, MI had illicit connections, with an average of 2.6 illicit connections found at each detected business. While most illicit connections did not contain raw sewage (e.g., floor drains, sinks), 11 percent of the Wayne County illicit connections include toilet discharges. Schmidt and Spencer (1986) found a 38 percent rate of illicit connections in Washtenaw County, MI, primarily among automobile-related and manufacturing business. It is not clear how many of these illicit connections involved sewage, as compared to wash water. Pitt and McClean (1986) detected illicit connections in about 12 percent of storm sewers in Toronto, and Pitt (1998) found that 18 percent of storm outfalls surveyed that had dry weather flow were contaminated by human sewage in a small Alabama subwatershed.

- *Illegal dumping into storm drain system*

  There is quite a bit of anecdotal evidence of illegal transient dumping of raw sewage into storm drain from septage vac trucks (i.e, honey wagons), recreational vehicles and portable toilets (Johnson, 1998). In addition, there may be inadvertent dumping from moving vehicles, such as livestock carriers and recreational vehicles. The overall significance of illegal or inadvertent dumping as a watershed bacteria source, however, is hard to quantify.

- *Failing septic systems*

  About one-fourth of all American households rely on on-site septic systems to dispose of their wastewater, which translates to about 20 million individual systems (Wilhelm et al., 1994). After solids are trapped in a septic tank, wastewater is distributed through a subsurface drain field and allowed to percolate through the soil. Bacteria are effectively removed by filtering and straining water through the soil profile, if the septic system is properly located, installed and maintained. A large number of septic systems fail, however, when wastewater breaks out or passes through the soil profile without adequate treatment. The regional rate of septic system failure is reported to range from 5 to nearly 40 percent, with an average of about 10 percent (Table 6).

  The causes of septic system failure are numerous: inadequate soils, poor design, siting, testing or inspection, hydraulic overloading, tree growth in the drain field, old age, and failure to clean out. When investigating whether septic systems are likely to be a major bacteria source in a watershed, managers should consider the following risk factors: septic systems that are older than 20 years, situated on smaller lots, service second homes or provide seasonal treatment, are adjacent to shorelines or ditches, are located on thin or excessively permeable soils, or are close to bedrock or the water table. The design life of most septic systems is 15 to 30 years, at which point major rehabilitation or replacement is needed.

Table 6: Failure Rate for Septic Systems

Geographic location	Source	Failure rate (%)
Frederick County, MD	Tuthill, 1998	30+
Detroit, MI	Johnson, 1998	20
Wayne County, MI	Johnson, 1998	21
Oakland County, MI	Johnson, 1998	39
Florida	Hunter, 1998	5
Mason County, WA	Glasoe and Tompkins, 1996	12
Puget Sound, WA	Smayda et al., 1996	10 to 25

Tuthill et al. (1998) detected coliforms in 30 to 60 percent of shallow wells in Frederick County, MD, with the highest concentration found on lots of a half acre or less served by septic systems. Glasoe and Tompkins (1996) reported a much higher failure rate for septic systems situated near waterfront as compared to more upland areas. Duda and Cromartie (1982) reported a very strong relationship between the density of septic systems and shellfish bed closure in the flat coastal plain of North Carolina.

Non-Human Bacteria Sources

Unless an inappropriate human sewage discharge is present in an urban watershed, most of the bacteria present in storm runoff are generally assumed to be of nonhuman origin. Recent genetic studies by Alderiso et al. (1996) and Trial et al. (1993) independently concluded that 95 percent of fecal coliform found in urban stormwater were of nonhuman origin. Recent microbial tracking by Samadpour and Checkowitz (1998) also confirms that nonhuman sources (dogs and livestock from hobby farms) were the primary source of bacterial contamination in a lightly developed Washington watershed, although septage effluent was a secondary source.

Documented nonhuman sources of fecal coliform bacteria in urban watersheds are dogs, cats, raccoons, rats, beaver, gulls, geese, pigeons and even insects. Dogs in particular appear to be a major source of coliform bacteria and other microbes, which is not surprising given their population density, daily defecation rate, and pathogen infection rates. According to van der Wel (1995), a single gram of dog feces contains 23 million fecal coliform bacteria. Dogs have also been found to be significant hosts for *Giardia* and *Salmonella* (Pitt, 1998). The *Salmonella* infection rate for dogs and cats ranges from 2 to 20 percent according to Lim and Oliveri (1982), who also noted that dog feces were the single greatest source contributing fecal coliform and fecal strep bacteria in highly urban Baltimore catchments. Trial et al. (1993) reported that cats and dogs were the primary source of fecal coliforms in urban subwatersheds in the Puget Sound region. In addition, Davies and Hubler (1979) found 13 percent of cats and 25 percent of dogs were infected with *Giardia*. Pitt (1998) notes that prior studies have indicated that dogs are a significant host of *Pseudonomas aureginosa*.

Urban wildlife can also be a significant bacterial source. In highly urban areas, rats and pigeons can be a major source of bacteria (Lim and Oliveri, 1982). In more suburban watersheds, raccoons have adapted to an underground habitat within storm drain pipes, and use ledges in storm drain inlets on a temporary basis. Blankenship (1996) reported that exceedance of *E. coli* standards in a Virginia coastal area was due to the local raccoon population.

Beaver are gradually recolonizing many urban stream habitats where they had previously been extirpated (Kwon, 1997). Numerous studies have fingered beavers as a key source of *Giardia*. For example, Monzingo and Hibler (1987) detected giardia in an average of 44 percent of beavers sampled in a Montana lodge, and also documented *Giardia* cysts in beaver ponds, pond sediments and downstream waters. Other researchers have found lower infection rates. For example, Frost et al. (1980) found *Giardia* in 10 percent of the beaver population and 40 percent of the muskrat population, while Davies and Hubler (1979) reported an 18 percent *Giardia* infection rate among beavers in Ohio.

Dogs are a major source of fecal coliform, *Giardia* and *Salmonella*.

Geese, gulls and ducks are speculated to be a major bacterial source in urban areas, particularly at lakes and stormwater ponds where large resident populations become established. Levesque et al. (1993) detected an increase in *E. coli* concentrations from flock of gulls roosting near a reservoir, which is not to surprising given that they have very high bacteria excretion rates (Table 7). Relatively little data is available to quantify whether geese and ducks are a major source of fecal coliforms or pathogens. Moorhead et al. (1998) did find high *E. coli* concentrations in a series of stormwater impoundments in West Texas that were heavily utilized by waterfowl, and other stormwater researchers often attribute high coliform levels to upstream geese or duck populations (Pitt et al., 1988). Bacteria production from waterfowl are expected to be greatest in small impoundments and concrete water storage reservoirs.

Livestock can still be a major source of fecal coliform in unsewered urban watersheds, particularly those areas of the urban fringe that have horse pastures, "hobby" farms and ranchettes (Samadapour and Checkowitz, 1998). Although these operations are very small, the stocking density is often very high, and grazing and riparian management practices are seldom applied.

Bacterial Survival and Growth in the Urban Drainage System

It is commonly assumed that most fecal coliform bacteria rapidly die off in the outside world in a few days. Research, however, has shown that many bacteria merely disappear from the water column and settle to bottom sediments, where they can persist for weeks or months in the warm, dark, moist and organic-rich conditions found there (Burton et al., 1987). Fecal coliform levels in stream and lake sediments are routinely three to four orders of magnitude higher than

Table 7: Bacterial Densities in Warm-Blooded Animals Feces
(Sources: Pitt, 1998; Godfrey, 1992; Geldrich et al., 1962)

Waste stream	Fecal coliform *(Density/gm)*	Fecal streptococci	Unit discharge *(lbs/day)*
Human	1.3×10^7	3.0×10^6	0.35
Cats	7.9×10^6	2.7×10^7	0.15
Dogs	2.3×10^7	9.8×10^8	0.32
Rats	1.6×10^5	4.6×10^7	0.08
Cows	2.3×10^5	1.3×10^7	15.4
Ducks	3.3×10^7	5.4×10^7	0.15
Waterfowl	3.3×10^7	-	0.18 - 0.35

those in the overlying water column (Van Donsel and Geldrich, 1971).

The same behavior has recently been noted in the bottom sediments of stormwater ponds and urban lakes (Pitt, 1998). Other researchers have documented that fecal coliform bacteria can survive and even multiply in the sediments in urban streams, ditches and drains (Burton et al., 1987; Marino and Gannon, 1991). Some evidence of fecal coliform survival has been observed in catch basins (Butler et al., 1995; Ellis and Yu, 1995) and also within roadway curb sediments (Sartor and Boyd, 1977; Bannerman et al., 1996). Coliform bacteria also have been found to survive and grow in moist soils and leaf piles (Oliveri et al., 1977). This may explain why grass swales and ditches frequently have high bacteria levels.

The strong evidence that fecal coliform bacteria can survive and even multiply in sediments indicates that the drainage network itself can become a major bacterial sink and/or source during storm events if sediments are flushed or resuspended.

Bacterial Source Area Research

Several researchers have sampled small source-areas within the urban landscape to determine where the major nonhuman sources of fecal coliforms are found. The two most recent studies have been conducted in Madison, Wisconsin (Bannerman et al., 1993) and Marquette, Michigan (Steuer et al., 1997). While the bacteria levels were widely different in the two studies, both indicated that residential lawns, driveways and streets were the major source areas for bacteria (Table 8). As might be expected, rooftops and parking lots were usually smaller source areas.

The source area data lend some credence to the "Fido" hypothesis—areas of the urban landscape that are used by dogs and other pets tend to generate higher bacteria levels. In addition, both studies reported end-of-pipe bacteria concentrations that were at least an order of magnitude higher than any source area in the contributing watershed, which suggests that the storm drain system was the greatest bacterial source in the watershed, possibly as a result of the resuspension of storm drain sediments or an undetected illicit connection. The tendency for end-of-pipe bacteria levels to exceed contributing source area levels was also documented in stormwater source area monitoring in Toronto conducted by Pitt and McClean (1986).

Priorities for Watershed Research.

Our ability to manage bacteria problems on a watershed basis are handicapped by some major data gaps, particularly with respect to pathogen levels, bacterial source areas and the linkage between indicators and human pathogens. The following priority research areas would help to fill these gaps and be of practical value to watershed managers:

- More epidemiological research on the public health risk associated with limited exposure to urban stormwater (wading, canoeing, tubing, etc.).
- Expanded monitoring for *Giardia* and *Cryptosporidium* in stormwater runoff from sewered and unsewered catchments.
- Development of better, faster and more robust bacteria indicator tests that can reduce analysis time from the current 48 hours to two hours or less. Not only would such tests provide early warning of public health risks, but they would allow researchers to collect automated storm samples which is currently not recommended due to holding times.
- Sampling of *Cryptosporidium*, *Giardia* and *Sal-*

Table 8: Concentrations (geometric mean colonies per 100 ml) of Fecal Coliforms from Urban Source Areas *(Steuer et al., 1997; Bannerman et al., 1993)*

Geographic location	Marquette, MI	Madison, WI
No. of storms sampled	12	9
Commercial parking lot	4,200	1,758
High traffic street	1,900	9,627
Medium traffic street	2,400	56,554
Low traffic street	280	92,061
Commercial rooftop	30	1,117
Residential rooftop	2,200	294
Residential driveway	1,900	34,294
Residential lawns	4,700	42,093
Basin outlet	10,200	175,106

monella infection rates for different populations of dogs, cats, and other urban wildlife.

- More systematic monitoring of the frequency and volume of sanitary and storm sewer discharges to determine bacteria contributions during sanitary sewer overflows and dry weather flows.
- Development of better, faster and more accurate field methods to determine how frequently septic systems fail, and the potential bacterial load they contribute to a watershed. In addition, a standard protocol for defining septic system "failure" needs to be adopted.
- Systematic sampling of bacteria sources and reservoirs within a network of storm drains and stormwater practices should be done.
- Development of watershed models or statistical tools that can better project and quantify bacteria sources and dynamics.

Summary

This review of bacteria levels and sources leads to four troubling conclusions. The first is that it is exceptionally difficult to maintain beneficial uses of water in the face of even low levels of watershed development, given the almost automatic violation of bacterial water quality standards during wet and dry weather. Thus, if a watershed manager has a beach, shellfish bed or drinking water intake to protect, they can expect that even a modest amount of watershed development is likely to restrict or eliminate that use.

The second troubling conclusion is that bacteria levels in urban stormwater are so high that watershed practices will need to be exceptionally efficient to meet current fecal coliform standards during wet weather conditions. Given stormwater fecal coliform levels equivalent to the national mean of 15,000 per 100 ml, watershed practices may need to achieve nearly a 99 percent removal rate to meet standards. The ability of current stormwater practices, stream buffers and source controls to attain this daunting performance level is reviewed in the next article.

The third troubling conclusion is that watershed managers will need to perform a lot of detective work to narrow down the lengthy list of potential bacteria suspects. Considerable monitoring resources will need to be applied to isolate the unique mix of bacteria sources that cause water quality problems in each specific watershed, and more importantly, identify sources that are most controllable.

Lastly, it is very troubling that we understand so little about the actual relationship between bacterial indicators and the risk to public health in urban watersheds. Fecal coliform remains an imperfect indicator, yet no better alternative has yet to emerge to replace it. A great deal more research is needed to fully indicate the real public health risk of urban stormwater.

—TRS

References

References denoted by an asterisk ( ) were used in the Center's bacteria database and are the sources for Figures 1 through 4.*

Alderiso, K., D. Wait and M. Sobsey. 1996. Detection and characterization of male-specific RNA coliphages in a New York City reservoir to distinguish between human and nonhuman sources of contamination. In *Proceedings of a Symposium on New York City Water Supply Studies*, ed. McDonnell et al. TPS-96-2. American Water Resources Association. Herndon, VA.

AMSA. 1994. *Separate sanitary sewer overflows: what do we currently know?* Association of Metropolitan Sewerage Agencies, Washington, DC.

Bannerman, R., D. Owens, R. Dodds, and N. Hornewer. 1993. Sources of pollutants in Wisconsin stormwater. *Water Science and Technology* 28(3-5):241-259.

Bannerman, R., A. Legg and S. Greb. 1996. *Quality of Wisconsin stormwater 1989-1994*. USGS Open File Report 96-458. U.S. Geological Survey, Reston, VA.*

Blankenship, K. 1996. Masked bandit uncovered in water quality theft. *Bay Journal*. Vol 6. No. 6. Alliance for the Chesapeake Bay.

Brabets, T. 1987. *Quantity and quality of urban runoff from the Chester Creek Basin, Anchorage, Alaska*. USGS Water Resources Investigations Report 86-5312. U.S. Geological Survey, Reston, VA.*

Burton, A, D. Gunnison and G. Lanza. 1987. Survival of pathogenic bacteria in various freshwater sediments. *Applied and Environmental Microbiology* 53(4) 633-638.

Butler, D., Y. Xiao, S. Karunaratne and S. Thedchanamoorthy. 1995. The gully pot as a physical, chemical and biological reactor. *Water Science Technology* 31(7): 219-228.

Chang, G. 1999. *Personal communication*. Austin TX Environmental and Conservation Services Dept. City of Austin, TX.

Chang, G., J. Parrish and C. Soeur. 1990. *Removal efficiencies of stormwater control structures*. Environmental Resources Management Division, Environmental and Conservation Services Department, Austin, Texas. *

Davies, R. and C. Hubler. 1979. Animal reservoirs and cross-species transmission of Giardia. In *Waterborne transmission of giardia*. W. Jablonski and J. Huff (eds.). U.S. Environmental Protection Agency, Cincinnati, OH. pp. 104-125.

Duda, A. and K. Cromartie. 1982. Coastal pollution from septic tank drain fields. *Journal of the Environmental Engineering Division*. American Society of Civil Engineer. 108 EE6.

Ellis, J. and W. Yu. 1995. Bacteriology of urban runoff: the combined sewer as a bacterial reactor and generator. *Water Science Technology* 31(7): 303-310.

Evaldi, R. and B. Moore. 1992. Stormwater data for Jefferson County, Kentucky. USGS Open File Report 92-638. *

Fossum, K and R. Davis. 1996. *Physical, chemical biological and toxicity data for the study of urban stormwater and ephemeral streams, Maricopa County, AZ. Water years, 1992-1995*. USGS Open File Report 96-394. U.S. Geological Survey, Reston, VA.*

Frost, F., B. Plan and B. Liechty. 1980. Giardia prevalence in commercially trapped animals. *Journal of Environmental Health*. 42: 245-249.

Gannon, J. and M. Busse. 1989. E. coli and enterococci levels in urban stormwater, river water and chlorinated treatment plant effluent. *Water Resources* 23(9): 1167-1176.

Geldrich, E., R. Borden, C. Huff, H. Clark and P. Kabler. 1962. Type distribution of coliform bacteria in the feces of warm-blooded animals. *Journal Water Pollution Control Federation* (34): 295

Glasoe, S. and J. Tompkins. 1996. Sanitary surveys in Mason County. *Puget Sound Notes* 39: 1-5

Glenne, B. 1984. Simulation of water pollution generation and abatement on suburban watersheds. *Water Resource Bulletin* 20(2).

Godfrey, A. 1992. Sources and fate of microbial contaminants. In *Recreational Water Quality Management Volume 2: Freshwaters.* eds. D. Kay and R. Hanbury. Ellis Horwood, New York NY, pp. 137-154.

Harms, L., M. Smith and K. Goddard. 1983. *Urban runoff control in Rapid City, South Dakota. Final Report*. Nationwide Urban Runoff Program. U.S. Environmental Protection Agency. Washington, DC.*

Hoos, A. 1990. *Effects of stormwater runoff on local groundwater quality, Clarksville, TN.* USGS Water Resources Investigation Report 90-4044. U.S. Geological Survey, Reston, VA.*

Horsley & Witten, Inc. 1995. *Identification and evaluation of nutrient and bacterial loadings to Maquoit Bay, Brunswick and Freeport, Maine*. Final Report: Casco Bay Estuary Project, Portland, ME.

Hunter, R. 1998. *Personal communication*. Septic system failure rates in Florida. Florida Dept. of Health.

Hydroqual, Inc. 1996. *Design criteria report: Kensico watershed stormwater best management facilities. Appendix C*. Report prepared for City of New York. Dept. of Environmental Protection. 240 pp.

Johnson, B. 1998. *The impact of on-site sewage systems and illicit connections in the Rouge River Basin.* Unpublished manuscript. Rouge River Program Office. Camp Dresser and McKee. Detroit, MI.

Jones, S. and R. Langan. 1996. *Assessment of the effectiveness of permanent stormwater control measures*. Final report to New Hampshire Office of State Planning. University of New Hampshire. Portsmouth, NH 22 pp. *

Kjelstrom, L. 1995. *Data for an adjusted regional regression models of volume and quality of urban stormwater runoff in Boise and Garden City, Idaho: 1993-1994.* USGS Water Resources Investigations Report 95-4228. U.S. Geological Survey, Reston, VA.*

Kwon, H. 1997. Return of the beaver. *Watershed Protection Techniques* 2(3): 455-461.

Levesque, et al. 1993. Impact of Ring-billed gull on the microbiological quality of a reservoir. *Applied Environmental Microbiology* 59(4): 1128-42.

Lim, S. and V. Olivieri. 1982. *Sources of microorganisms in urban runoff*. Johns Hopkins School of Public Health and Hygiene. Jones Falls Urban Runoff Project. Baltimore, MD 140 pp. *

Marino, R. and J. Gannon. 1991. Survival of fecal coliforms and fecal streptococci in storm drain sediment. *Water Resources* 25(9): 1089-1098.

Monzingo, D. and C. Hibler. 1987. Prevalence of giardia in a beaver colony and the resulting environmental contamination. *Journal of Wildlife Disease* 23: 576.

Moorhead, D., W. Davis and C. Wolff. 1998. Coliform densities in urban waters of West Texas. *Journal of Environmental Health* 60(7): 14-28.

Olivieri, V.P., Kruse, C.W., Kawata, K., Smith, J.E., 1977. *Microorganisms in urban stormwater*. USEPA Report No. EPA-600/2-77-087 (NTIS No. PB-272245). Environmental Protection Agency, Washington, DC.

Pitt, R. and J. McLean. 1986. *Toronto Area Watershed Management Study*. Humbar River Pilot Watershed Project. Ontario Ministry of the Environment.

Pitt, R. 1998. Epidemiology and stormwater management. In *Stormwater Quality Management*. CRC/ Lewis publishers. New York, NY.

Samadpour, M. and N. Checkowitz. 1998. Little Soos Creek microbial source tracking. *Washington Water RESOURCE,* Spring, 1998. University of Washington Urban Water Resources Center.

Schmidt, S. and D. Spencer. 1986. Magnitude of improper waste discharges in an urban system. *Journal WPCF* 58(7): 744-758.

Smayda, T., N. Pollison and A. Law. 1996. Towards the standardization of sanitary sewer methods: fecal coliform sampling and criteria. *Puget Sound Notes* 39:5-10.

Smith, R., R. Alexander and K. Lanfear. 1992. *Stream water quality in the coterminous United States—status and trends of selected indicators during the 1980's. National Water Summary 1990-1991*. pp. 11-140 in USGS Water Supply Paper 2400. U.S. Geological Survey, Reston, VA.*

States, S., K. Stadterman, L. Ammon, P. Vogel, J. Baldizar, D. Wright, L. Conley and J. Sykora. 1997. Protozoa in river water: sources, occurrence and treatment. *Journal AWWA* 89(9): 74-83.

Steuer, J., W. Selbig, N. Hornewer and J. Prey. 1997. *Sources of contamination in an urban basin in Marquette, Michigan and an analysis of concentrations, loads and data quality*. USGS Water Resources Investigation Report 97-4242, Middleton, MI. 26 pp.

Stern, D. 1996. Initial investigation of the sources and sinks of *Cryptosporidium* and *Giardia* within the watersheds of the New York City water supply system. In *Proceedings of a Symposium on New York City Water Supply Studies*. Eds. McDonnell et al. TPS-96-2 184 pp. American Water Resources Association. Herndon, VA.

Tuthill, J., D. Miekle and M. Alavanja. 1998. Coliform bacteria and nitrate contamination of wells in major soils of Frederick, Maryland. *Journal of Environmental Health* 60(8): 16-21.

Trial, W. et al. 1993. Bacterial source tracking: studies in an urban Seattle watershed. *Puget Sound Notes*. 30:1-3.

USEPA, 1983. *Results of the nationwide urban runoff program*. NTIS PB-84-185552. Office of Water, Environmental Protection Agency, Washington, DC.

USEPA, 1998. *Bacteria water quality standards for recreational waters (freshwater and marine); status report*. EPA-823-R-98-003. Office of Water, Environmental Protection Agency, Washington, DC.

van der Wel, B. 1995. Dog pollution. *The Magazine of the Hydrological Society of South Australia*, 2(1)1.

Van Donsel, D and E. Geldreich, 1971. Relationship of salmonellae to fecal coliforms in bottom sediments. *Water Resources* 5: 1079-1087.

Varner, P. 1995. *Characterization and source control of urban stormwater quality*. City of Bellevue Utilities Department. City of Bellevue, Washington. *

Wilhelm, S., S. Schiff, and J. Cherry. 1994. Biogeochemical evolution of domestic wastewater in septic systems: 1. Conceptual model. *Groundwater* 32: 905-916.