Article 67

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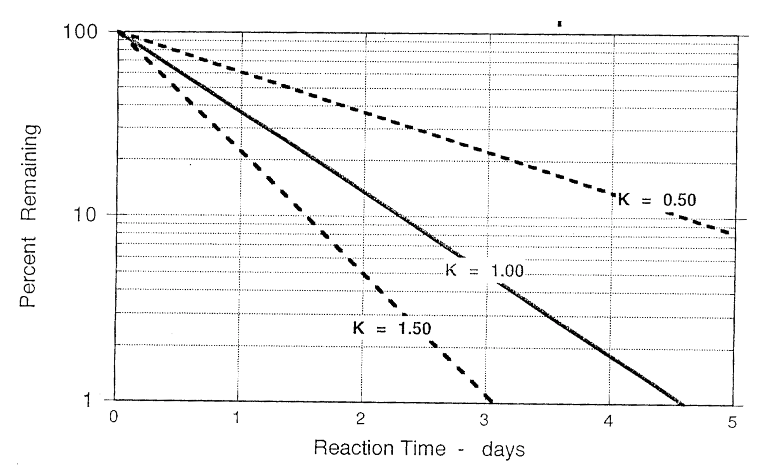
Microbes and Urban Watersheds: Ways to Kill 'Em

Managing microbes from urban watersheds can be a daunting task, as bacteria are usually present in high concentrations during storms, come from many different sources, and follow many complex pathways to reach receiving waters. In this article, we examine whether it is technically feasible to reduce microbes in urban stormwater to maintain drinking water, water contact recreation and shellfish consumption uses. The article begins with a discussion of the causes of bacteria mortality, and then reviews what is currently known about bacteria removal provided by stormwater best management practices, stream buffers, and source controls. The major focus is on fecal coliform bacteria, as this indicator has been used in nearly all performance studies conducted to date.

The review concludes that current stormwater practices, stream buffers and source controls have a modest potential to reduce fecal coliform levels, but cannot reduce them far enough to meet water quality standards in most urban settings. It is also argued that current watershed practices have even less capability to remove protozoans in stormwater runoff, such as *Giardia* and *Cryptosporidium*. The last section examines several design improvements that might enhance the bacteria removal performance of watershed management practices.

Figure 1: Effect of Different Die-off Rates (k) on Bacteria Mortality (Hydroqual, Inc., 1996)



Sources of Bacteria Mortality

Most fecal coliform bacteria thrive in the digestive systems of warmblooded animals, but do not fare well when exposed to the outside world. Over time, most fecal coliforms gradually “die-off.” Key factors and practices that can be manipulated to increase bacteria die-off include the following:

- Sunlight (ultraviolet light)
- Sedimentation
- Sand filtration
- Soil filtration
- Chemical disinfection
- Growth inhibitors

The term “die-off,” however, is not as final as it would appear. Often, researchers actually only measure the “disappearance” of bacteria from the water column. Bacteria and viruses settle from the water column to the bottom sediments. Given the warm, dark, moist and organic-rich conditions found in bottom sediments, many coliform bacteria can survive and even multiply in this environment. A number of researchers have documented this behavior in the sediments of storm drains, catch basins, ditches and channels. If these sediments are resuspended by turbulent stormwater flows, the bacteria can reappear in the water column.

Researchers and engineers have examined the “die-off” rates for many different microbes in fresh waters (Mancini, 1978). Bacteria die-off can be modeled as a first-order decay equation, using a k value of about 0.7 to 1.5 per day (Figure 1). In practical terms, “k” values in this range mean that about 90% of bacteria present will disappear from the water column within two to five days. The die-off rate is generally much faster in marine and estuarine waters than freshwater (Thoman and Mueller, 1987).

Exposure to Sunlight

Bacteria are a lot like vampires in that they generally can’t stand the light of day. Bacteria are killed when exposed to a very specific and narrow band of the light spectrum (254 nm—ultraviolet UV light). Consequently, exposure to sunlight is one of the most important factors causing bacteria die-off. Maximum die-off requires clear water, however, and the turbidity and organic matter

Table 1: Comparison of Die-Off Rates and Treatment Effectiveness for Different Microbes

Microbial Indicator	Light?	Settling?	Surface filtration?	Die off rates (k)	Ability to Multiply	Survival in sediments?
Total coliforms	Yes	Yes	Yes	1/day	Yes	Moderate
Fecal coliforms	Yes	Yes	Yes	0.7 - 1.0/day	Yes	Days
Fecal Streptococci	Yes	Yes	Yes	1/day	Low	Weeks
Escherichia Coli	Yes	Yes	Yes	1/day	Low	Months
Salmonella spp.	Yes	Yes	Yes	1.5/day	Yes	Weeks to months
Psuedonomas aeruginosa	Yes	Partial	Yes	?	Yes	Months
Crytospoidium spp.	No	Partial	Partial	1.5/day	No	Months
Giardia spp.	No	Partial	Partial	1.5/day	No	Months

found in urban runoff can greatly interfere with the sunlight effect (Bank and Schemhel, 1990).

UV light has been utilized by water utilities to disinfect drinking water and wastewater effluent. In recent years, this technique has been used for end-of-pipe runoff treatment at combined sewer and stormwater outfalls in a few settings including Toronto, New York, and Florida (O'Shea and Field, 1992). These initial applications indicated that substantial stormwater treatment is needed to remove suspended solids before UV light is effective. Sophisticated telemetry and energy are also needed to calibrate the "dosage" of intensive UV light to the rapidly changing flow conditions in stormwater.

Sedimentation

Individual fecal coliform bacteria cells are very small particles (as small as a single micron in diameter), but they frequently adsorb to sediment particles or attach to other bacterial cells. Schillinger and Gannon (1982) reported that about 15 to 30% of fecal coliform cells present in stormwater are adsorbed to larger suspended particles, most of which were greater than 30 microns in diameter. Fecal coliform bacteria that do adsorb to these larger particles can settle rapidly out of the water column (Schillinger and Gannon, 1982; Auer and Niehaus, 1993).

Bacteria that do not attach or adsorb to particles are much harder to settle. Schillinger and Gannon (1982) note that 50% of fecal coliform bacteria in stormwater suspensions were not attached. These cells are only one to two microns in diameter and effectively act like fine clay particles in terms of surface transport and settling characteristics (Coyne *et al.*, 1995). Such small particles have very slow settling velocities, and may remain in suspension for days or even weeks.

Auer and Niehaus (1993) computed a combined settling velocity for unattached and attached coliform bacterial cells in urban stormwater of about two to four feet per day, depending on the relative proportion of small and large bacteria "particles." Using this settling rate, about 90% of bacteria would settle out from a typical stormwater pond in about two days under ideal conditions. This finding is consistent with the one log bacteria removal consistently achieved in stabilization ponds utilized for wastewater treatment which typically yields a fecal coliform effluent of about 1,000 MPN per 100 ml (Godfrey, 1992).

Sand Filtration

Sand filtration has traditionally been used by water utilities to ensure the purity of drinking water, after chemical pretreatment and sedimentation are employed. Coliform removal rates of 97 to 99.5% can be expected in a properly operated treatment plant (Viessman and Hammer, 1993), but drop to about 60% without prior chemical pretreatment.

Sand filtration has been adapted to treat stormwater runoff (Claytor and Schueler, 1996), but it is important to recognize that stormwater sand filters are different in many ways from those used to treat drinking water. First, sand filters employed to treat drinking water use several layers of filter media to promote more consistent filtration (e.g., anthracite and garnet). Second, drinking water filters are designed to enable daily "back flushing" that drives trapped sediments and microbes backup through the filter bed and thereby prevents microbial breakthrough in the filter media. Lastly, drinking water filters employ chemical pretreatment to remove larger solids before they ever reach the filtration bed.

Most stormwater sand filters lack these characteristics—particularly the ability to back flush. This is worth noting, since individual bacterial cells are only a few microns in size and may not be fully strained out by passing through sand grains that are much larger in size (45 to 55 microns). Thus, since stormwater filters are not regularly back-flushed, it is likely that microbes and pollutants migrate through the filter bed over time. Consequently, most field studies of sand filters remove only 50 to 65% of carbon and bacteria, although solids removal can approach 90% (article 64).

Soil Filtration

Bacteria can be effectively treated by filtering and straining water through the soil profile. Indeed, a home septic system relies on soil filtration. In this traditional method for onsite sewage disposal, wastewater is distributed through a subsurface drain field and allowed to percolate through the soil (after larger solids have been trapped in a septic tank). Soil filtration is similar to sand filtration, but can result in greater bacteria removal rates since the higher organic matter and clay content of most soils increases potential bacteria adsorption (Robertson and Edberg, 1997). When properly located, installed and maintained, septic systems can achieve virtually complete bacteria removal over a distance of 50 to 300 feet (but not necessarily complete removal of much smaller enteric viruses). A number of factors can cause soil filtration to fail (e.g., clogging, macro pores, hydraulic overloading, thin soils, excessively permeable soils or bedrock fractures). In these cases, wastewater breaks out or through the soil profile with little or no treatment.

Several stormwater practices also utilize some degree of soil filtration to aid in pollutant removal. Examples include infiltration practices and bioretention areas that divert runoff through the soil profile. To a lesser degree, grass swales allow for some soil filtration if runoff infiltrates into the channel during smaller storms. No data are available to assess the performance of stormwater practices that utilize soil filtration, but it is reasonable to assume that their bacteria removal rates are comparable to septic systems if the soil filter is deep enough.

Chemical Disinfection

Bacteria can be rapidly killed through chemical disinfection. The most common approach is to add chlorine or related compounds to wastewater. While chlorine can be very effective in killing bacteria, it needs to be added at the right dosage. If too little chlorine is added, some bacteria will survive, particularly those adsorbed to solid particles (Field *et al.*, 1993). If too much chlorine is added, environmentally harmful chlorine residuals can be released downstream. Precise dosing is possible within the highly controlled conditions of a water supply or wastewater treatment plant, but is very difficult to attain when flow and turbidity are highly variable. Thus, chemical disinfection of stormwater has been largely restricted to combined sewer overflow abatement facilities and a few Canadian beach outfalls (Field and O'Shea, 1992).

Growth Inhibitors

A series of factors can slow the growth of bacteria in surface waters and sediments. While these factors do not technically kill bacteria, they do slow their growth, reduce survival and increase predation. Major factors that can inhibit the growth of bacteria include colder water temperatures, low nutrient levels, low carbon supplies, low pH levels and moisture loss (Oliveri *et al.*, 1977). While it is difficult for a watershed manager to control these factors, they can sometimes be manipulated in the design of stormwater practices and open channels to achieve greater bacteria removal.

Sources of Protozoan Mortality

Protozoans such as *Cryptosporidium* and *Giardia* appear to be harder to control than fecal coliform bacteria. This is somewhat surprising given that cysts and oocysts can be five to 10 times larger than individual bacterial cells, and therefore should settle or filter more rapidly. The cysts and oocysts of these protozoans, however, are not affected by sunlight, and because of their persistence and durability they can last for many months in wet sediments (Bagley *et al.*, 1998). Soil filtration does appear to be a promising method, as protozoans are not very mobile in soils (Robertson and Edberg, 1997).

Sand filtration at drinking water plants has not been found to be fully effective in removing all cysts and oocysts according to Lechevalier and Norton (1995), although it is not clear whether the cysts that pass through sand filters remain viable. (Indeed, a strong debate rages on the proper methods to monitor viable *Cryptosporidium* and *Giardia*). A series of studies have found that back flushing of sand filters at drinking water treatment plants resuspend protozoa, and can become a significant source of cysts/oocysts (States *et al.*, 1997; Lechevalier and Norton, 1995). Wastewater effluent is also one of the major sources of protozoa to surface waters, particularly for *Cryptosporidium* (States *et al.*, 1997; Lechevalier *et al.*, 1991; Stern, 1996).

Chemical disinfection can inactivate cysts and oocysts, but typically requires chemical pretreatment, higher doses, and longer contact times than when used to inactivate fecal coliforms. Researchers are beginning to study the best ways to inactivate cysts and oocysts. Physical abrasion, ammonia, low moisture content, freeze-thaw conditions, and very high temperatures (25-30 degrees C) have all been found to inactivate protozoa to some degree.

There is no monitoring data to assess whether stormwater practices can effectively remove *Giardia*, *Cryptosporidium* or *Salmonella*. Given that few effective removal mechanisms exist for these durable pathogens, it is speculated that it will be much harder to remove them compared to fecal coliform bacteria. Additional research is needed to answer this question.

Ability of Watershed Practices to Treat Bacteria Sources

Effectiveness of Stormwater Practices

Urban stormwater practices must be extremely efficient if they are to produce storm outflows that meet the 200 MPN standard for fecal coliform bacteria from a site. Assume for a moment that a site experiences a fecal coliform concentration equivalent to the national mean of 15,000 per 100 ml during a storm. A stormwater practice would need to achieve a 99% removal rate for fecal coliform to meet the standard. To date, performance monitoring research has indicated that no stormwater practice can reliably achieve a 99% removal rate of any urban pollutant on a consistent basis.

To date, only 24 performance monitoring studies in our database have actually measured the input and output of fecal coliform bacteria from stormwater practices during storm events. The Center's stormwater pollutant removal database includes ten ponds, nine sand filter and five swales (Table 2). The majority of performance studies have focused on fecal coliform or fecal strep as bacterial indicators, with just a few observations for *Psuedonomas* and *E. coli*. It should be noted that fecal coliform monitoring does not lend itself to automated monitoring techniques because of holding time limitations. Consequently, estimates of efficiency are typically based on grab sampling.

For the 10 stormwater ponds, mean fecal coliform removal efficiency was about 65% (range -5 to 98%). The mean removal efficiency calculated for nine sand filters was lower (about 50%), and these practices had a wider range in removal (-68 to +97%). It should be noted that most sand filter performance data has been collected during warm seasons and most sites were in Texas. No performance monitoring data were available to assess the capability of infiltration practices or stormwater wetlands on coliform removal.

Most researchers report a few episodes of negative fecal coliform removal during the course of their sampling efforts. Figure 2 provides a typical example of the variability in bacteria removal in a North Carolina wet pond monitored by Borden and his colleagues (1996). The limited data on fecal streptococci and *E. coli* removal appears to fall within the same range as fecal coliform removal (Table 2).

Outflow Concentrations from Stormwater Practices

Pollutant removal performance can be strongly influenced by the variability of the pollutant concentrations in incoming stormwater. If inflow concentrations are near an "irreducible level," a low or negative removal can be recorded, even though outflow concentrations discharged from a stormwater practice are still relatively low (see article 65). This behavior may explain the high concentration of bacteria often found in stormwater pond outflows. Table 3 compares outflow concentra-

Table 2: Comparison of Mean Bacteria Removal Rates Achieved by Different Stormwater Practices

Stormwater Management Practice	Fecal coliform	Fecal streptococci	*E. coli*
Ponds	65% (n=10)	73% (n=4)	51% (n=2)
Sand filters	51% (n=9)	58% (n=7)	No data
Swales	–58% (n=5)	No data	No data

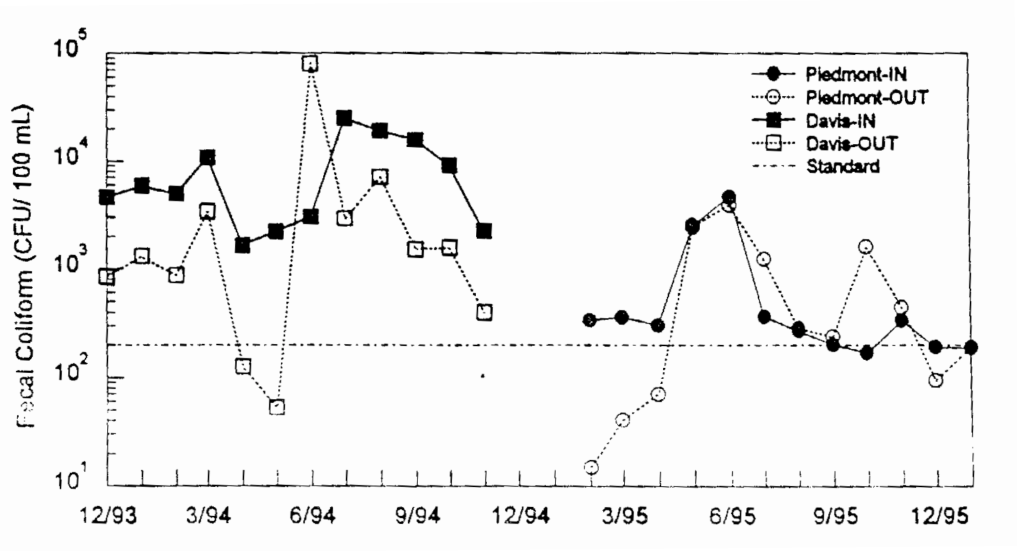


Figure 2: Inflow and Outflow Bacteria Levels in a North Carolina Wet Pond (Borden *et al.*, 1996)

tions among stormwater practices and suggests that most practices discharge fecal coliform bacteria in the ranges of 2,500 to 5,000 colonies per 100 ml, or about 12 to 25 times the water contact recreation standard.

Effectiveness of Stream Buffers

Our current knowledge about the bacteria removal capability of stream buffers is rather sparse. Indeed, at the present time, no data exist on the performance of either forested stream buffers or grass filter strips in removing bacteria from urban stormwater runoff. Some indication of their potential effectiveness, however, can be inferred from the performance of grass filter strips used to control runoff from crops and livestock operations. Taken together, these studies suggest that grass filter strips have only a modest capability to remove fecal coliforms from runoff.

For example, Coyne *et al.* (1995) found that grass filter strips were able to remove 43 to 70% of fecal coliforms in two experimental grass filter plot studies, while Young *et al.* (1980) reported 70% coliform removal from a 100-foot grass filter strip. Two other researchers, however, found that grass filter strips had essentially no ability to remove fecal coliform due to short flow lengths (Dickey and Vanderholm, 1981) or extremely high influent concentrations (Schellinger and Clausen, 1992).

It is very doubtful whether an urban stream buffer could exceed the 70% maximum removal rate observed for agricultural stream buffers, given coliform sources within stream buffers such as wildlife, plants and even soils, the relatively narrow band of adjacent land that

Table 3: Comparison of Mean Bacteria Removal Rates (Colonies/100ml) Achieved by Different Stormwater Practices

Stormwater Management Practice	Fecal coliform	Fecal streptococci	*E. coli*
Ponds	5,144 (n=9)	3,381 (n=4)	869 (n=2)
Sand filters	5,899 (n=9)	16,088 (n=7)	No data
Swales	2,506 (n=3)	No data	No data

can be effectively treated, and the tendency to create channelized flows.

Another line of evidence suggests that urban stream buffers or filter strips may have little potential to remove fecal coliforms from urban stormwater. Five researchers have examined whether grass channels can effectively filter or trap bacteria as stormwater passes through them. Depending on storm size, the swales exhibited shallow concentrated flow, or more rarely, sheetflow conditions. As a group, the grass swales were found to have no ability to reduce fecal coliform levels, with zero or negative changes in concentration reported in four out of five studies (see Table 2 and article 116). Pet droppings, in-situ multiplication and short travel times were all cited as reasons for the poor performance of swales. Swales had a geometric mean outflow concentration of about 2,500 MPN per 100 ml (Table 3). It should be noted that these performance studies did not account for bacteria reduction by soil filtration under the swale.

Effect of Source Control in Reducing Bacteria Levels.

Source control seeks to reduce or eliminate sources of bacteria in urban watersheds before they come into contact with stormwater. Common source control programs focus on pet waste cleanup, proper disposal of kitty litter, pumpouts of boat sewage, septic system maintenance, discouraging resident waterfowl and general urban housekeeping. While source control is desirable, very little monitoring has been conducted to determine if it can actually reduce watershed bacteria levels. One study that evaluated the effectiveness of source control in urban watersheds was conducted by Lim and Oliveri (1982), who reported that bacterial densities were generally lower in well-maintained Baltimore alleys compared to alleys in poor condition (e.g., trash and refuse piles).

The ultimate effectiveness of any bacteria source control effort is dependent on four factors. First, how prevalent is the behavior that education programs seek to modify? Second, how effective are education or enforcement programs in reaching the target population? Third, what specific educational or enforcement techniques are effective in actually changing the behavior of the target population? Finally, what realistic bacteria reductions in a watershed could be expected if the target population actually changed its behavior?

Consider for a moment the most common bacteria source control program: getting pet owners to clean up after their dogs. A recent phone survey of dog owners in the Chesapeake Bay indicated that 59% of respondents claimed to clean up after their dog most or all of the time, while 38% of the respondents reported that they rarely or never did so (CWP, 1999). Most dog walkers understood the water quality or public health consequences of their behavior: 65% agreed with the statement that pet waste can be a source of bacteria and nutrients to nearby streams (27% disagreed). Interestingly, the walkers who didn't always clean up after their dogs showed little interest in changing their behavior. Factors that might prompt them to clean up more often were complaints by neighbors (21%), a simple sanitary collection method (17%), convenient disposal locations along trails or parks (17%) and fines (7%). One-third of all dog walkers, however, indicated that none of these factors would induce them to change their behavior. Clearly, pet waste source control programs will need to be very creative to alter these deeply rooted attitudes.

Would these "bad actors" respond more to the stick of an enforcement approach or the carrot of an education approach? What outreach techniques really attract their attention? How much bacteria do they generate in a watershed, and what realistic bacterial reductions could result if some or all of the bad actors changed their behavior? Until we can answer these questions, it is very difficult to craft effective source control programs, and virtually impossible to assign a "watershed bacteria reduction" for source control.

Effect of Improving Wastewater Disposal and Conveyance.

In watersheds where untreated wastewater is a documented source of bacteria, basic repairs to the wastewater system can produce impressive local reductions in bacteria levels. For example, several communities have measurably reduced bacteria levels by connecting homes with failing septic systems to sanitary sewer lines, rehabilitating aging sanitary sewer lines, eliminating illicit/illegal connections, providing pumpouts of recreational sewage, and treating combined sewer overflows (Field and O'Connor, 1997; NRDC, 1999). While these measures can be an effective strategy for reducing extremely high bacteria levels in dry and wet weather flows in urban watersheds, they do not address bacteria contributed by stormwater.

Improving Bacteria Treatment By Watershed Practices

Stormwater Practices

Few stormwater regulations provide specific guidance on how to design or select stormwater practices for greater bacteria removal. Several design enhancements are provided below that might be able to enhance the performance of the current generation of stormwater practices.

- Create high light conditions in the water column of stormwater ponds or wetlands. For example, storage can be provided in a series of separate and rather shallow cells. The last cells should have lower turbidity and therefore permit greater UV light penetration.

- Provide additional retention or detention time in stormwater ponds to promote greater settling (i.e. two to five days). Alternatively, engineers could size ponds based on a smaller minimum design particle (say 15 microns).
- Design inlet and outlet structures of stormwater ponds to prevent bacteria-laden bottom sediments from being resuspended and exported. Reducing turbulence is essential for "dry" extended detention ponds that do not have a "pool barrier" to trap and retain bottom sediments.
- Reduce turf and open water areas around stormwater ponds so that resident geese and waterfowl populations do not become established and become an internal bacterial source.
- Add shallow benches and wetland areas to stormwater ponds to enhance the plankton community and therefore increase bacterial predation.
- Infiltration practices can play a role in reducing bacteria yields to surface waters where soil conditions permit. Optimal soil infiltration rates range from 0.5 to 2.0 inches. Even when infiltration is not feasible at a site, designers should endeavor to achieve as much soil filtration as possible through the use of filter strips, rooftop disconnection and open channels.
- If filtering practices are used, employ finer-grained media in the filter bed with a small diameter (say, 15 microns), or at least provide a finer-grained layer at mid-depth in the filter profile. The typical "concrete-grade" sand used in most sand filters may be too coarse-grained to prevent coliform breakouts. The use of finer-grained media, however, could lead to more chronic clogging of the filter bed. In any event, sand filters are not likely to achieve high bacteria removal unless the process for pretreatment and/or filtration is extended for 40 hours or more. This is most easily done by extending the detention time in the sedimentation chamber used for pretreatment.
- Remove trapped sediments from filter pretreatment chambers on a more frequent basis during the growing season. In addition, "dry" pretreatment chambers may be more desirable since bacteria-laden sediment would be subject to both sunlight and desiccation. In general, sand filters should be oriented to provide maximum solar exposure.
- Consider using bioretention, infiltration and dry swale practices that employ soil filtration. Given sufficient pretreatment and soil filtering depth, these practices have the potential to achieve bacterial removal rates comparable to functioning septic systems. Their actual performance monitoring and longevity in the field, however, needs more study before stormwater "soil filters" are recommended for bacteria-limited watersheds.
- Avoid creating internal bacterial sources in the stormwater conveyance system, such as ditches, catch basins, swales, or sediment storage within the storm drain network. In bacteria-limited catchments, conveyance systems should be designed to be either self-cleansing or promote maximum sediment retention. Dry swales, which employ soil filtration and have an under drain, are probably superior to grass swales from a bacteria reduction standpoint.
- Locate new stormwater outfalls to maximize distance from any water intakes, beaches or shellfish beds.

Research is needed to determine what, if any, additional bacteria removal could be produced by these design enhancements. In addition, performance monitoring is urgently needed to evaluate whether *Giardia* or *Cryptosporidium* can be removed by current or enhanced stormwater practices. Clearly, there are upper limits on what gravity-driven stormwater practices can actually achieve. Even an advanced secondary wastewater treatment that filters its effluent still discharges fecal coliform at the 10^3 to 10^5 levels before final chemical disinfection (ASCE, 1998). This suggests that more advanced disinfection techniques may need to be incorporated into stormwater practices if they ever will be able to meet bacterial standards in urban waters.

Stream Buffers

The ability of urban stream buffers to remove bacteria has never been tested in the field, so the following design enhancements are based solely on engineering theory and bacteria behavior. An ideal stream buffer might be composed of three lateral zones: a stormwater depression area that leads to a grass filter strip that in turn leads to a forested buffer. The stormwater depression is designed to capture and store stormwater during smaller storm events and bypass larger stormflows directly into a channel. The captured runoff within the stormwater depression can then be spread across a grass filter designed for sheetflow conditions for the water quality storm. The grass filter then discharges into a wider forest buffer designed to have zero discharge of surface runoff to the stream (i.e., full infiltration of sheetflow).

The outer zone of a stream buffer must be engineered in order to satisfy these demanding hydrologic and hydraulic conditions. In particular, simple structures are needed to store, split and spread surface runoff within the stormwater depression area. Although past efforts to engineer urban stream buffers were plagued by hydraulic failures and maintenance problems, recent experience with similar bioretention areas has been much more positive (Claytor and Schueler, 1996). Consequently, it may be useful to consider elements of bioretention design for the outer zone of an urban stream buffer (shallow ponding depths, partial under drains, drop inlet bypass, etc.).

Even when stream buffers cannot be engineered, they can be managed for bacterial source control. For example, grazing within a urban stream buffer should not be permitted, and livestock should be excluded from stream buffers adjacent to hobby farms and horse pastures.

Source Control

Bacteria source control remains in its infancy as a watershed practice. While the value of source control efforts such as pet waste cleanup is obvious, it is not always clear how to improve its effectiveness. Several lines of research are probably worth pursuing:

- Catchment scale monitoring to directly link pets to pollution
- Attitude surveys that profile the psychology of pet owners for devising better ad campaigns
- Buffer training for dogs
- Research to develop a more convenient and sanitary product to retrieve and dispose of pet wastes

Summary

Current stormwater, buffer and source control practices do not appear capable of removing enough fecal coliform bacteria to meet the 200 MPN water contact recreation standard in stormwater discharges, unless the receiving water is well-mixed and diluted with cleaner water. The 50 to 75% bacteria removal reported for stormwater and buffer practices falls well short of the 99% removal needed to meet standards. Considering that the outflow concentration from stormwater practices is on the order of 2,500 to 5,000 MPN/100 ml, it is probable that bacterial concentration will always exceed pre-development conditions in most urban watersheds, even if stormwater treatment and buffer practices are fully implemented and all wastewater discharges are eliminated.

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References denoted by an asterisk ( ) were used in the bacteria removal performance analysis provided in Tables 2 and 3.*

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