

# Potential Water Quality Impacts of Stormwater Infiltration

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## Introduction

A significant fraction of precipitation infiltrates into the soil in an undeveloped area with natural ground cover, such as forest or meadow. This water is filtered and cooled as it travels underground. Some infiltrated water is subsequently discharged into rivers and streams as base flow, which provides a steady contribution of high quality water to lakes, streams and rivers. Some infiltrated water descends deeper underground to the water table and recharges aquifers. Groundwater recharge replenishes the supply of underground water that can be extracted for domestic and irrigation use. Another portion of precipitation is returned to the atmosphere through evapotranspiration. Evapotranspiration is a combination of evaporation and plant transpiration. Where there is natural ground cover, infiltration and evapotranspiration serve to minimize the percentage of precipitation that becomes runoff, the water that flows over that land surface into streams and other surface water bodies.

As land is developed, stormwater runoff increases in both rate and volume due to increases in impervious area and soil compaction. This development dramatically alters the hydrologic cycle by changing the relative percentage of precipitation that contributes to groundwater recharge, evapotranspiration, and runoff by adding impervious surfaces, such as pavement and rooftops. The amount of stormwater that infiltrates into the soil is reduced, resulting in decreased recharge of groundwater and eventual loss of base flow in streams and rivers.

Stormwater runoff picks up debris, sediment, and other contaminants as it seeks low areas, where it can pool and cause flooding problems. Common contaminants of stormwater runoff include sediment, nutrients, toxic substances, oxygen-demanding materials, and bacteria all of which can seriously degrade the quality of receiving waters.

Infiltration has been viewed as a solution to solving surface water problems. Many municipalities are now requiring stormwater control of both peak flow and runoff volume to help offset the potential impacts of unmanaged stormwater runoff. Structural measures have been proposed to infiltrate stormwater runoff to help restore the lost groundwater recharge and reduce the volumes of runoff that need to be managed by other stormwater practices. Many believe that if the pattern of paving and roofing over areas that once contributed to groundwater recharge continues, base flows in streams and rivers will be reduced or eliminated and irrigation and drinking water supplies will be effected. In fact, these effects can already be seen. According to the Dane County Regional Planning Commission (Dane County RPC) (1999), the Yarhara River at McFarland, Wisconsin has already suffered a greater than 50% reduction in base flow due to human activities.

If the solution to losses in groundwater recharge is to infiltrate more stormwater runoff, the quality of the water to be infiltrated must be examined. Stormwater contains many different types of pollutants, but what is important is how much of those pollutants are actually transported to the groundwater and if the pollutants do make it to the groundwater, do they cause any problems.

### **Research up to 1994**

In 1994, a literature review was published by Pitt et al. entitled “Potential Groundwater Contamination from Intentional and Nonintentional Stormwater Infiltration”. This paper was a summary of research that had been completed to that date about the potential hazards of infiltrating stormwater runoff.

Pitt and his colleagues found that urban runoff contains high concentrations of bacteria, metals, and some organic toxicants. They also found that these pollutants showed no regional differences. That is, stormwater runoff from any location in the country contains similar concentrations of pollutants. The only significant factor in the quality of urban runoff is the land use of the watershed. For example, Pitt et al. found that highest amounts of organics are found in the runoff from areas used for servicing vehicles. In contrast, sidewalks, roads, and residential areas contribute the largest amounts of bacterial contamination.

Pitt et al. examined the correlation between the contaminants in stormwater and their potential for reaching groundwater aquifers. They concluded that three factors contribute to the risk of a contaminant reaching the groundwater. The three factors are:

1. mobility
2. abundance
3. soluble fraction

The first factor, mobility, is of great importance. Some contaminants, such as heavy metals, may be in high concentration in runoff, but once they begin to infiltrate the soil they quickly adsorb to soil particles and become immobile. On the other hand, chlorides, such as road salt, are very mobile once in solution and can travel quickly to the groundwater.

In order for a pollutant to contaminate groundwater, it must be present in a high enough concentration to pose a problem. This is why abundance is also factor. Depending on the pollutant, small or large concentrations can be problematic. Chlorides, for example, may be present at significant concentration, but don't become a serious health risk until they show up at very high levels. In contrast, viruses at very low concentrations pose a high risk of contamination.

Solubility is also an important factor. Some pollutants are much more soluble and pose a greater risk for groundwater contamination. Contaminants need to be examined to

determine their solubility in the soil environment. If the soil contains a large amount of highly charged clay particles, most pollutants will not be soluble.

Although almost every known contaminant has been found in stormwater runoff, Pitt et al. concluded that pesticides, pathogens, and salts pose the greatest threat to groundwater from stormwater infiltration. These pollutants have a high risk of contamination due to their mobility, abundance, and solubility in stormwater. In addition, they also are very difficult to treat and remove from stormwater runoff.

Pitt and his colleagues recommended several steps to reduce the potential for groundwater pollution from stormwater infiltration:

- *Pretreatment* – Pretreatment of the stormwater runoff before it enters the infiltration area is critical. According to Pitt et al., the risk of groundwater contamination is sharply reduced when runoff is pretreated by sedimentation practices and is allowed to percolate through a soil layer.
- *Divert dry weather and combined sewer flows* – Dry weather and combined sewer flows should be diverted away from the infiltration area because their water quality is usually poor.
- *Divert snowmelt from roads and parking lots* – The large concentrations of chlorides from these areas cannot be effectively treated by infiltration.
- *Do not infiltrate runoff from manufacturing and construction sites* - Runoff from manufacturing sites contains high amounts of organic compounds and heavy metals. High sediment levels from construction sites can quickly clog infiltration practices.

Infiltration with the lowest risk of groundwater contamination can most successfully be accomplished in residential areas. Pitt et al. however, do still recommend that infiltration practices be protected by pretreatment. These pretreatment devices may not have to be as elaborate or complex as practices needed for other land uses, but should still be present to remove sediment from the runoff, at a minimum. Grassed buffer strips or small sediment traps are recommended.

Since the paper by Pitt et al. in 1994, there has been a lot of research on the potential hazards of contaminating groundwater by infiltrating stormwater runoff and how to reduce those hazards. This report summarizes each of the potential pollutants and discusses possible treatment methods to reduce their contamination risk.

## **Research Since 1994:**

### **Transport of Stormwater Pollutants to Groundwater**

As Pitt et al. (1994) stated, “Few pollutants ever disappear from the urban landscape. They are merely transferred from one medium to another – from air to land, land to surface water, or from soil to groundwater.” What is important when examining the potential for groundwater contamination from stormwater infiltration is the transference from the soil, where the water infiltrates, to the groundwater. It has been shown that stormwater runoff in Wisconsin contains large amounts of pollutants (Bannerman et al., 1996). If these pollutants can be transported to the groundwater in large enough concentrations, there may be significant health and public welfare concerns (Wisconsin DNR, 2001). In Dane County, Wisconsin, existing public water supply wells already show high nitrate-nitrogen levels, increasing salt concentrations and detections of organic chemicals above state drinking water standards (Dane County RPC, 1999).

Every contaminant in stormwater has its own properties, and therefore higher or lower risks to groundwater. The research that has been reported on specific pollutants in stormwater and their risks of contaminating the groundwater from infiltration will be discussed in the next section.

#### *Pathogens*

Pathogens can be a major problem for drinking water supplies when they are detected. Even small concentrations of bacteria or viruses have the ability to infect humans and livestock. Symptoms in humans of pathogen contamination are diarrhea, cramps, nausea, and possibly jaundice (Madison Water Utility, 2001). In order for drinking water to be considered completely safe, it must be completely free of bacteria and viruses (Madison Water Utility, 2001).

The risk of groundwater contamination by pathogens is dependent on their concentrations in stormwater runoff (Pitt et al., 1994). In Wisconsin, the levels of viruses and bacteria in stormwater are highly variable, depending mostly on the source of the runoff (Bannerman et al., 1996). High levels are found primarily where human and animal waste is allowed to runoff.

Hazardous bacteria, such as *P. aeruginosa*, *Shigella*, and *Pseudomonas* are commonly found in stormwater runoff, especially in runoff from sidewalks, roads, and bare ground (Pitt et al., 1994). These bacteria are particularly harmful to humans because they do not require ingestion or large doses to cause infection. *Salmonella* and other types of bacteria are usually found at much lower doses (Pitt, 1994).

Fortunately the risk of contamination of groundwater by bacteria is generally low. Bacteria tend to remain near the soil surface due to their relatively large size and adsorption by soil particles, limiting their migration to the groundwater (Pitt et al., 1994).

Viruses, on the other hand, are much different. Not only are they smaller in size, but they are also more resistant to adverse environmental conditions and disinfection measures

(Pitt et al., 1994). Viruses can be difficult to detect in water tests because they may occur without bacterial indicators. The most effective way to control virus contamination is to locate and eliminate the source (Dane County RPC, 1999).

### *Heavy Metals*

The research community has placed a large amount of attention on heavy metals when investigating groundwater contamination. This attention is most likely due to the fact that heavy metals can be highly toxic to humans and other animals and are commonly detected at high levels in stormwater runoff (Bannerman et al., 1996 and Center for Watershed Protection, 2000). Common sources for heavy metals are parking lots, streets, gas stations, and rooftops (Center for Watershed Protection, 2000 and Bannerman et al, 1996).

Heavy metals tend to be highly charged and attracted to soil particles, which keeps their movement in soil limited and potential for groundwater contamination low (Mikkelsen et al., 1997). Although metals are largely held close to the soil surface, stormwater infiltration over long periods of time can lead to significant heavy metal accumulation and soil pollution (Barraud et al., 1999).

One metal that does not remain easily attached to soil particles is zinc (Barraud et al, 1999, Mikkelsen et al, 1997, and Pitt et al., 1994). Barraud et al. found that the retention of zinc in the upper soil layers could be as low as 31%. This can be a major concern as zinc is also found at high levels in stormwater runoff (Bannerman, 1996 and Center for Watershed Protection, 2000). The combination of mobility and abundance in stormwater runoff makes zinc a high risk for groundwater contamination.

### *Nitrate-Nitrogen*

Nitrate-nitrogen is highly soluble and does not readily attach itself to soil particles (Dane County RPC, 1999). This pollutant is therefore very mobile and can easily travel into the groundwater, especially in cool wet seasons (Pitt et al, 1994). The Dane County Groundwater Protection Plan (1999) lists nitrate-nitrogen as the most common and widespread contaminant in the county's groundwater. Infants and pregnant women are susceptible to health risks from high nitrate levels, including a disorder called methemoglobinemia (commonly called "blue baby" syndrome) (Dane County RPC, 1999). A study by Thomas (2000) reported monitoring pairs of domestic wells near Detroit, Michigan showed that human activities have increased nitrate levels in 76% of the wells, to depths greater than 25 feet.

The source of nitrate-nitrogen in stormwater is believed to be primarily from lawn and agricultural fertilizer application (Dane County RPC, 1999). Nitrate-nitrogen levels in stormwater are generally low (Bannerman et al., 1996), and therefore their risk to groundwater pollution is not significant.

### *Organic Compounds*

Organic compounds such as gasoline, esters, industrial solvents, paint, and paint thinner have been detected in stormwater and pose significant health risks (Dane County RPC,

1999). Organic compounds have been known to cause nausea, dizziness, tremors, and other health related problems. Many organic compounds have also been identified as carcinogenic if a person is exposed to them for long periods of time (Dane County RPC, 1999).

Concentrated sources of organic compounds are often called “hotspots” (Center for Watershed Protection, 2000). “Hotspots” include parking lots, gas stations, industrial sites, vehicle service areas and other high traffic areas. Stormwater runoff from these areas test high for many organic compounds and other pollutants. Organic compounds in the stormwater runoff from “hotspots”, when infiltrated, can quickly travel to the groundwater causing contamination (Center for Watershed Protection, 2000).

### *Pesticides*

Many different pesticides may be found in stormwater runoff, but most are broken down quickly in the soil by microbial activity (Pitt et al., 1994). The half-life property of a specific chemical plays a major role in its potential risk to groundwater contamination. Pitt et al. (1994) reported that pesticides with half-lives of more than thirty days pose the greatest risk.

Pesticides enter stormwater from misuse, spillage, or improper storage and disposal (Dane County RPC, 1999). They pose little risk for groundwater contamination by stormwater infiltration if used and disposed of correctly.

### *Salt*

Salt is commonly used in cold climates to deice roadways and other areas, but when salt is dissolved by snowmelt or rainfall, it is nearly impossible to remove. In fact, no pretreatment or percolation practice has been found to reduce salt concentrations before stormwater is infiltrated (Pitt et al., 1994). Most other pollutants receive some filtering from soil infiltration, but soil is ineffective at removing salt.

Fortunately, salt is not considered toxic until it reaches very high concentrations. According to Public Welfare Groundwater Quality Standards for Wisconsin (Wisconsin DNR, 2001), the concentration where action must be taken is 250 mg/L. The mean salt concentration report by Bannerman et al. (1996) in Wisconsin stormwater was 10 mg/L, but since salt cannot be easily removed, it accumulates in the groundwater. There is evidence that this is already occurring in Madison, Wisconsin where increasing salt concentrations have been detected in samples of the city’s drinking water supply (Dane County RPC, 1999).

## **Treatment Options**

It has been well documented that stormwater runoff contains high concentrations of many potential contaminants that can impact groundwater if infiltrated (Bannerman et al., 1996). In order to prevent these contaminants from reaching the groundwater, it is necessary to remove or reduce their amounts from the runoff prior to infiltration, if possible. In addition to removing chemical contaminants, pretreatment devices should

also remove sediment; otherwise the infiltration practice will clog and lose effectiveness (Horner, 1999). Several researchers have studied the effectiveness of different practices to pre-treat stormwater and remove contaminants. The next section will review practices that have been proposed for this purpose.

*Sediment Basins*

Sediment basins have been used for many years as a tool to remove pollutants from stormwater runoff. Sediment basins remove contaminants by slowing runoff water and providing storage for the sediment that settles out. In this process, contaminants attached to soil particles are trapped before entering the infiltration area (Pitt et al., 1994).

The performance of sediment basins has been documented in several reports, including the National Pollutant Removal Performance Database for Stormwater Treatment Practices 2<sup>nd</sup> Edition (Center for Watershed Protection, 2000). This report is a compilation of the results from many projects that have monitored the efficiencies of urban stormwater practices. The removal efficiencies for total nitrogen, bacteria, organic compounds, copper, zinc, and lead are shown in Table 1 below. Wet ponds differ from dry ponds by having a permanent pool of water. The permanent pool increases removal efficiencies by reducing the resuspension of particles and increasing settling time (Pitt et al., 1994).

Bardin et al. (2001) investigated the long-term removal capabilities of a settling basin used as a pretreatment device to an infiltration basin. The basin was relatively large in size (1.1 hectare of surface area) and had been in service for seven years. Even though the basin had not been maintained for seven years, the removal efficiencies had not decreased (see Table 1). They reported that removals were high for heavy metals and correlated well with sediment removals, with the exception of zinc.

**Table 1.** Median Pollutant Removal (%) by Sediment Ponds

	<b>Total Nitrogen</b>	<b>Bacteria</b>	<b>Organic Compounds</b>	<b>Copper</b>	<b>Zinc</b>	<b>Lead</b>
Dry Ponds <sup>1</sup>	25	78	NA	26	26	43
Wet Ponds <sup>1</sup>	33	70	81	57	66	73
Pretreatment Settling Basin <sup>2</sup>	NA	NA	NA	48	25	59

- Sources: 1. Center for Watershed Protection, 2000.  
 2. Bardin et al., 2001.

Although these reports show removal of nitrogen, bacteria, organics, and heavy metals, they do not include monitoring data on the other contaminants in stormwater. It is likely that other contaminants would also be removed at high rates, in connection with trapping sediment.

### *Vegetative Buffers*

Vegetated buffers have been proposed as pretreatment devices for small infiltration areas. The Center for Watershed Protection (2000) stated that vegetated areas do have significant removal capacities if the drainage area diverted to them is small. They found removal efficiencies of 38% for total nitrogen, 49% for copper, 88% for zinc, 62% for organic compounds, and 0% for bacteria (some results actually showed bacteria exported). Similar to sediment ponds, most of the removals are attributed to trapping sediment. Pretreatment devices, such as vegetated buffers, should be used at small sites to protect the infiltration areas from failing prematurely due to clogging (Pitt et al., 1994).

### *Filtration*

Filtration of stormwater runoff as a pretreatment device for infiltration can be separated into two categories: structural practices, such as sand and compost filters, and filtration by the soil itself.

Structural practices that filter water have been attempted in many geographical locations in the world. Several studies from Europe have investigated the removal efficiencies of pretreating stormwater runoff with sand filters prior to infiltration. Bardin et al. (2001) found limited long-term removal efficiencies from a sand filter system in southeast France. Removals of heavy metals were less than 17%, much less than the removals of other practices. There has also been experience with structural filtration in the United States. The Center for Watershed Protection (2000) reported results of a monitoring study of a system of sand filters in Austin, Texas. They found that the system removed relatively high amounts of heavy metals and organics, but did poorly in removing nitrate, nitrogen, and dissolved solids. Bacteria removal from the Austin site was extremely variable, with the filters at times acting as a source of bacteria. The Center for Watershed Protection (2000) also explored using filters comprised of organic material, such as peat and compost. In this investigation they found that the organic material helped to increase the removals of some dissolved contaminants, but not by very much. Table 2 shows removal results of stormwater contaminants utilizing different filtering methods.

**Table 2.** Median Pollutant Removal (%) by Structural Filtration Practices

	<b>Total Nitrogen</b>	<b>Bacteria</b>	<b>Organic Compounds</b>	<b>Copper</b>	<b>Zinc</b>	<b>Lead</b>
Organic Filter <sup>1</sup>	41	NA	NA	66	89	NA
Vertical Sand Filter <sup>1</sup>	5	NA	NA	32	56	NA
Surface Sand Filter <sup>1</sup>	32	37	84	49	80	71
Pretreatment Sand Trap <sup>2</sup>	NA	NA	NA	17	2	11

Sources: 1. Center for Watershed Protection, 2000.  
2. Bardin et al., 2001.

Many infiltration practices rely solely on the soil’s natural filtration capacity, with no other pretreatment. Soil is able to remove significant amounts of stormwater contaminants by chemical and biological filtration, and to a lesser extent, mechanical filtration (Bardin et al., 2001). The capability of individual soils to remove contaminants is a function of the physical and chemical properties of the soil and site conditions. This in part explains the differences in removal rates from several monitoring studies that are shown in Table 3.

**Table 3.** Median Pollutant Removal (%) by Infiltration through Soil

<b>Monitoring Study</b>	<b>Total Nitrogen</b>	<b>Copper</b>	<b>Zinc</b>	<b>Lead</b>
Barraud et al., 1999 (New Soakaway)	NA	NA	54-88	98
Barraud et al., 1999 (Older Soakaway)	NA	NA	31	NA
Bardin et al., 2001	NA	48	25	59
Center for Watershed Protection, 2000	51	NA	99	NA

There are potential hazards by not using other practices along with soil filtration. If sediment is not controlled from the infiltration area, small particles will clog the top layers of soil, reducing infiltration rates (Horner, 1999). In addition, it is difficult to maintain and remove the soil layers that have captured the contaminants. Mikkelsen et al. (1997) found that concentrations of adsorbable contaminants can eventually reach critical levels and pose a solid waste problem. Another concern is that, in certain situations, pollutants can migrate downward into the groundwater over time (Barraud et al., 1999). These are some of the reasons that it is recommended other practices to treat stormwater be installed prior to the infiltration area.

#### *Oil and Grease Separators*

Oil and grease separators are becoming more popular as municipal regulations have begun to require oil and grease control from high vehicle traffic areas. Studies have been conducted to quantify their removal efficiencies for specific stormwater contaminants. In a summary of several monitoring projects, the Center for Watershed Protection (2000) reported that the median removals of copper and zinc to be -11% and 17% respectively. Copper has a negative removal rate because during the monitoring period the separator acted as a source. In addition, Bardin et al. (2001) found that an oil and grease separator used as a pretreatment device to an infiltration practice showed no evidence of removing any contaminants. The current technology available for oil and grease separators is ineffective at removing contaminants from stormwater prior to infiltration.

## Conclusions and Recommendations

When discussing the quality and protection of our groundwater resources, it is necessary to examine the levels of contaminants that are deemed acceptable. As discussed earlier in this paper, numerous studies have shown that stormwater runoff contains large concentrations of pollutants that are known to cause health and public welfare problems. Depending on the specific pollutant, their risk of contaminating the groundwater varies. Table 4 shows the national and state average concentrations of contaminants in stormwater compared to applicable groundwater and drinking water standards.

**Table 4.** Average Stormwater Contaminant Concentrations and Applicable Standards

Contaminant	Units	National Average Concentration in Stormwater <sup>1</sup>	Wisconsin Average Concentration in Stormwater <sup>2</sup>	Public Health Groundwater Quality Standard <sup>3</sup>	EPA Drinking Water Standard <sup>4</sup>
Total Nitrogen	mg/l	.53	9.68	2	10
Copper	mg/l	11.1	26	.13	1.3
Lead	mg/l	50.7	48	.0015	.015
Zinc	mg/l	129	200	2.5	5
BOD	mg/l	11.5	18	25	NA
COD	mg/l	44.7	69	25	NA
Fecal Coliform	col. per 100 ml	15000	30000	0	0
Fecal Strep	col. per 100 ml	35400	NA	0	0
Chloride	mg/l	116	64	125	250

- Sources:
1. Center for Watershed Protection, 2001.
  2. Bannerman et al., 1996.
  3. Wisconsin Department of Natural Resources, 2001.
  4. United States Environmental Protection Agency, 2001.

In order to ensure safe drinking water, contaminants must be removed from stormwater before it reaches groundwater aquifers. Although soil is a tremendous natural filter, it cannot treat contaminated stormwater runoff forever. As was shown, pretreatment practices have a wide range of removal rates for different contaminants. This why it is important to design and implement practices to remove pollutants that take into account

the potential contaminants in stormwater, site specific conditions, and maintenance needs.

Proper infiltration of stormwater has many benefits; including being the only stormwater practice that controls the volume of stormwater runoff once it has been generated. Several researchers have pointed out that stormwater infiltration practices that have been designed correctly pose little threat to the groundwater (Mikkelsen et al. , 1997, Barraud et a., 1999, and Pitt et al., 1994). There is evidence, however, that careful design has not always been carried out, as Thomas (2000) found in his study near Detroit, Michigan.

Even the best practices do not remove all of the contaminants from stormwater. This is why the source of the contaminants must also be targeted. If the source cannot be controlled, stormwater runoff from these sites should not be intentionally infiltrated. Examples of these sites are “hotspots” as noted by the Center for Watershed Protection (2000) and include gas stations, high traffic areas, and parking lots. Unfortunately, “hotspots” are also the areas that produce high rates of runoff. Until technology exists that can remove more contaminants from stormwater, these areas should be diverted and not infiltrated.

## References

- Bannerman, R., Legg, A., and Greb, S., (1996), *Quality of Wisconsin Stormwater, 1989-94*, U.S. Geological Survey Water Resources Investigation Report 96-458. With the Wisconsin Department of Natural Resources. Madison, WI.
- Bardin, J., Gautier, A., Barraud, S., and Chocat, B., (2001), *The Purification Performance of Infiltration Basins Fitted with Pretreatment Facilities: A Case Study*, Water Science and Technology, Vol. 43, No. 5, Elsevier Science Ltd., Great Britain.
- Barraud, S., Gautier, A., Bardin, J., and Riou, V., (1999), *The Impact of Intentional Stormwater Infiltration on Soil and Groundwater*, Water Science and Technology, Vol. 39, No. 2, Elsevier Science Ltd., Great Britain.
- Center for Watershed Protection, (2000), *Hydrocarbon Hotspots in the Urban Landscape*, Stormwater Manager's Resource Center (SMRC) Website, [www.stormwatercenter.net](http://www.stormwatercenter.net), Ellicott City, MD.
- Center for Watershed Protection, (2000), *Is Rooftop Runoff Really Clean?*, Stormwater Manager's Resource Center (SMRC) Website, [www.stormwatercenter.net](http://www.stormwatercenter.net), Ellicott City, MD.
- Center for Watershed Protection, (2000), *National Pollutant Removal Performance Database for Stormwater Treatment Practices 2<sup>nd</sup> Edition*, Center for Watershed Protection, Ellicott City, MD.
- Center for Watershed Protection, (2001), *New York State Stormwater Management Design Manual*, New York State Department of Environmental Conservation, Albany, NY.
- Dane County Regional Planning Commission, (1999), *Dane County Groundwater Protection Plan*, Appendix G of the Dane County Water Quality Plan, Dane County Regional Planning Commission, Madison, WI.
- Horner, R., (1999), *Infiltration Facilities for Stormwater Quality Control*. Managing Stormwater Runoff Workshop, University of Wisconsin – Extension, Milwaukee, WI.
- Madison Water Utility, (2001), *2001 Annual Drinking Water Quality Report*, Water Quality Section, Madison Water Utility, Madison, WI.
- Mikkelsen, P., Hafliger, M., Ochs, M., Jacobsen, P., Tjell, J., and Boller, M., (1997), *Pollution of Soil and Groundwater from Infiltration of Highly Contaminated Stormwater – A Case Study*, Water Science and Technology, Vol. 36, No. 8-9, Elsevier Science Ltd., Great Britain.

Pitt, R., Parmer, K., Clark, S., and Field, R., (1994), *Potential Groundwater Contamination from Intentional and Nonintentional Stormwater Infiltration, 1993 Research Project*, Cooperative Agreement No. CR819573 EPA/600/SR-94/051, United States Environmental Protection Agency, Cincinnati, OH.

Thomas, M., (2000), *The Effect of Residential Development on Ground-Water Quality Near Detroit, Michigan*, Journal of the American Water Resources Association, Vol. 36, No. 5, American Water Resources Association, Middleburg, VA.

United States Environmental Protection Agency, (2001), *Current Drinking Water Standards*, United States Environmental Protection Agency Website, [www.epa.gov/safewater/mcl.html](http://www.epa.gov/safewater/mcl.html), Washington D.C.

Wisconsin Department of Natural Resources, (2001), *Groundwater Quality*, Administrative Code 433, Chapter NR 140.