Proposed Evaluation Methodology for Predicting Groundwater Contamination Potential from Storm water Infiltration Activities

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Abstract- Infiltration is gaining acceptance, and is even being encouraged, as a practical way to manage storm water on site. To prevent potential groundwater contamination, though, tools are required to predict the potential for contamination due to this infiltration for many site conditions. Infiltration should be encouraged in areas having the least potential for causing groundwater contamination. Factors that influence contamination potential include the pollutant concentration in the runoff directed to the infiltration device (after any necessary pre-treatment) and the ability of the underlying soil to remove the pollutant. This paper presents two levels of modeling for predicting whether groundwater contamination is a concern and whether pre-treatment should be considered. The potential effects of storm water on groundwater quality was estimated based on the likely presence of problem constituents in the storm water, their mobility through soils, the type of treatment received before infiltration, and the infiltration method used. The constituents of most concern include chloride, certain pesticides (lindane and chlordane), organic toxicants (1,3-dichlorobenzene,pyrene and fluoranthene), pathogens, and some heavy metals (nickel and zinc). Reported instances of groundwater contamination associated with storm water was rare in residential areas where infiltration occurred through surface soils (except for chloride), but was more common (especially for toxicants) in commercial and industrial areas where subsurface infiltration was used.

Index Terms- Groundwater contamination, storm water, infiltration, Nutrients; Toxicants

I. INTRODUCTION

With urbanization, the permeable soil surface area where infiltration and subsequent groundwater recharge has historically occurred, is reduced, while the available soils usually have their infiltration capacity dramatically reduced due to compaction. This has resulted in much less groundwater recharge and greatly increased quantities of surface runoff. In addition, the waters available for recharge carry increased quantities of pollutants compared to natural conditions. Infiltration has been viewed by the engineering community as a way to address the need to restore the natural hydrologic cycle and that will improve groundwater recharge. What is not available is good guidance on predicting whether infiltration is appropriate and what levels of pre-treatment are required prior to infiltration. The intention of this paper is to identify known storm water contaminants as to their potential to adversely affect groundwater. This potential is evaluated based on pollutant abundance in storm water, pollutant mobility in the vadose zone, the treatability of the pollutants, and the infiltration procedure used. Published observations of roundwater contamination in areas of storm water recharge are also provided in this review paper, along with suggestions to minimize potential contamination problems. Because urban hydrogeology is an active research field, there are many new papers continuously becoming available containing new case studies. The purpose of this paper is to assemble a collection of information relating to potential groundwater problems that is of great interest to storm water managers responsible for the design and implementation of infiltration devices and who may be uncertain of these potential problems. Prior to urbanization, natural groundwater recharge resulted from infiltration of precipitation through pervious surfaces, including grasslands and woods. This infiltrating water was relatively uncontaminated. With urbanization, the permeable soil surface area through which recharge by infiltration could occur was reduced. This resulted in much less groundwater recharge and greatly increased surface runoff. In addition, the waters available for recharge generally carried increased quantities of pollutants. There are many types of articial storm water infiltration mechanisms that have been used in urbanizing areas in order to decrease discharges of storm water to surface waters and to help preserve groundwater recharge. These are described in many storm water design manuals. The following infiltration techniques are most commonly used. Recent evaluations, using a computer-based vadose zone model, were performed as part of a Water Environment Research Foundation (WERF)-sponsored project on developing guidance for storm water managers considering infiltration as a management practice (Clark, *et al*. 2006). The complete description of these two levels of modeling, in addition to two case studies, is available in Clark and Pitt (2007).

- surface infiltration devices (grass filters and grass lined drainage swales; infiltration is usually dominant storm water treatment mechanism; infiltration occurs through turf and surface soils, providing the most opportunities for pollutant trapping before the water reaches groundwater)
- French drains or soak-aways (small source area subsurface infiltration pits, most typically used for infiltrating drainage from roofs; usually simple gravel-filled dug holes, but can be an empty perforated container)

- porous pavements or grid pavers (replace impervious pavements, overlain on a relatively thick storage layer of coarse material; may include drainage pipes to collect excess water that cannot be infiltrated into underlying soil)
- drainage trenches (collect and infiltrate runoff€ from adjacent paved areas; generally long, moderately wide, and shallow in dimensions; filled with coarse gravel to provide storage)
- infiltration wells, or dry wells (deep, relatively small diameter holes allowing storm water to be discharged to deep soil horizons, sometimes directly into saturated zones, commonly located at storm drainage inlet locations serving up to a few hectares of drainage area, with over¯ows discharged to storm or combined drainage system)
- percolating sewerage (conventional separate storm drainage, but with perforations through pipe or gaps between pipe segments; usually wrapped in geotextile fabric with coarse gravel used as trench backfill material);
- dry (percolating) basins (usually large storage areas typically located at end of drainage system before discharge into receiving water; commonly used as recreation facilities during dry weather; also provides infiltration through turf and surface soils).

All infiltration devices redirect runoff€ waters from the surface to the sub-surface environments. Therefore, they must be carefully designed using sufficient site specific information to protect the groundwater resources and to achieve the desired water quality management goals.

1. Groundwater contamination associated with storm water pollutants:

1.1. Nutrients

While nitrate is one of the most frequently encountered contaminants in groundwater (AWWA, 1990), groundwater contamination by phosphorus has not been as widespread, or as severe. Nitrogen loadings are usually much greater than phosphorus loadings, especially from nonagricultural sources (Hampson, 1986). Nitrogen occurs naturally both in the atmosphere and in the earth's soils. Natural nitrogen can lead to groundwater contamination by nitrate. As an example, in regions with relatively unweathered sedimentary deposits or loess beneath the root zone, residual exchangeable ammonium in the soil can be readily oxidized to nitrate if exposed to the correct conditions. Leaching of this naturally occurring nitrate caused groundwater contamination (with concentrations greater than 30 lg=l) in non-populated and non-agricultural areas of Montana and North Dakota (Power & Schepers, 1989). Forms of nitrogen from precipitation may be either nitrate or ammonium. Atmospheric nitrate results from combustion, with the highest ambient air concentrations being downwind of power plants, major industrial areas, and major automobile activity. Atmospheric ammonium results from volatilization of ammonia from soils, fertilizers, animal wastes and vegetation (Power & Schepers, 1989). In the United States, the areas with the greatest nitrate contamination of groundwater include heavily populated states with large dairy and poultry industries, or states having extensive agricultural irrigation. Extensively irrigated areas of the United States include the corn-growing areas of Delaware, Pennsylvania and Maryland; the vegetable growing areas of New York and the Northeast; the potato growing areas of New Jersey; the tobacco, soybean and corn growing areas of Virginia, Delaware and Maryland (Ritter, Humenik & Skaggs, 1989); the chicken, corn and soybean production areas in New York (Ritter, Scarborough & Chirnside, 1991); the western Corn Belt states (Power & Schepers, 1989); and the citrus, potato and grape vineyard areas in California (Schmidt & Sherman, 1987). Roadway runo€ has been documented as the major source of groundwater nitrogen contamination in urban areas of Florida (Hampson, 1986; Schifer, 1989; German, 1989). This occurs from both vehicular exhaust onto road surfaces and onto adjacent soils, and from roadside fertilization of landscaped areas. Roadway runoff also contains phosphorus from motor oil use and from other nutrient sources, such as bird droppings and animal remains that has contaminated groundwaters (Schifer, 1989). Nitrate has leached from fertilizers and affected groundwater's under various turf grasses in urban areas, including at golf courses, parks and home lawns (Petrovic, 1990; Ku & Simmons, 1986; Robinson & Stephen Snyder, 1991). Leakage from sanitary sewers and septic tanks in urban areas can contribute significantly to nitrate-nitrogen contamination of the soil and groundwater (Power & Schepers, 1989). Nitrate contamination of groundwater from sanitary sewage and sludge disposal has been documented in New York (Ku & Simmons, 1986; Smith & Myott, 1975), California (Schmidt & Sherman, 1987; Chang, Page, Pratt & Warneke, 1988),Narbonne, France (Razack, Drogue & M'Baitelem 1988), Florida (Waller, Howie & Causaras, 1987) and Delaware (Ritter et al., 1989).

1.1.1. Removal processes in soil

Whenever nitrogen-containing compounds come into contact with soil, a potential for nitrate leaching into groundwater exists, especially in rapid-infiltration wastewater basins, storm water infiltration devices, and in agricultural areas. Nitrate is highly soluble and will stay in solution in the percolation water, after leaving the root zone, until it reaches the groundwater. Therefore, vadose-zone sampling can be an effective tool in predicting nonpoint sources that may adversely affect groundwater (Spalding & Kitchen, 1988). Nitrogen containing compounds in urban storm water runoff€ may be carried long distances before infiltration into soil and subsequent contamination of groundwater (Robinson & Stephen Snyder, 1991). The amount of nitrogen available for leaching is directly related to the impervious cover in the watershed (Butler, 1987). Nitrogen infiltration is controlled by soil texture and the rate and timing of water application (either through irrigation or rainfall) (Petrovic, 1990; Boggess, 1975). Landfills, especially those that predate the RCRA Subtitle D Regulations, often produce significant nitrogen contamination in nearby groundwater, as demonstrated in Lee County, Florida (Boggess, 1975). Studies in Broward County, Florida, found that nitrogen contamination problems can also occur in areas with older septic tanks and sanitary sewer systems (Waller et al., 1987). Nutrient leachates usually move vertically through the soil and dilute rapidly down gradient from their source. The primary factors affecting leachate movement are the layering of geologic materials, the hydraulic gradients, and the volume of the leachate discharge (Waller et al., 1987; Wilde, 1994). Once the leachate is in the soil/groundwater system, decomposition by denitrification can occur, with the primary decomposition product being elemental nitrogen (Hickey & Vecchioli, 1986). As an example, deep well injection of organonitriles and nitrates in a limestone aquifer acts like an anaerobic filter with nitrate respiring bacteria being the dominant microorganism. These bacteria caused an 80% reduction of the waste within one hundred meters of injection in the Floridan aquifer, near Pensacola (Ehrlich et al., 1979b). Gold and Groffman (1993) reported groundwater leaching losses from residential lawns to be low for nitrates (typically <2 mg/l), when using application rates recommended for residential lawn care. During percolation through the soil, some nutrients are removed and the nutrient concentrations affecting the groundwater are significantly reduced. Phosphorus, in the form of soluble orthophosphate, may be either directly precipitated or chemically adsorbed onto soil surfaces through reactions with exposed iron, aluminum or calcium on solid soil surfaces (Crites, 1985). Phosphorus fixation is a two-step process, sorption onto the soil solid and then conversion of the sorbed phosphorus into mineraloids or minerals. If the sorption sites are filled either with phosphate anions or another ion, phosphorus sorption will be low. The sorption of phosphorus per unit of percolation liquid decreases with each year of recharge (White & Dornbush, 1988). Downward movement of phosphorus in different soils was found to be directly related to the reactivity index measured for each soil, especially for surface-applied phosphorus fertilizer. In Washington, a difference in depth of penetration was noted, however, between sandy- and clayey-textured soils, with sandy-textured soils showing the greater depth of penetration. If the fertilizer was surface applied, instead of sprinkler applied, and the soil was not inverted, most of the phosphorus remained within the top 5±7.5 cm of the surface (Lauer, 1988). If the nitrogen is not used by the plant, it will leach through the soil toward the groundwater, with some being removed in the soil prior to its reaching the aquifer. Under certain conditions, losses of dissolved nitrate and nitrite can be described by zero-order kinetics (Hampson, 1986). In general, however, the process is regulated by so many limiting factors that such a simplified description is not possible. Residual nitrate concentrations were found to be highly variable in soil due to factors such as soil texture, mineralization, rainfall, irrigation, organic matter content, crop yield, nitrogen fertilizer/sludge application rate, denitrification, and soil compaction (Ferguson, Eisenbauer, Bockstadter, Krull & Buttermore, 1990). Nitrates flow to groundwater from storm water infiltration is controlled by the rate and volume of infiltration, horizontal and vertical groundwater flow, the depth to the water table, and the existence of areas/channels of preferential flow. Once the nitrate has reached the groundwater, its concentration may be reduced by dispersion and diffusion with uncontaminated groundwater (Wilde, 1994). The amount of ammonia volatilization is influenced by the position of the nitrogen in the soil/turf grass after application. This position is highly influenced by rainfall and/or irrigation (Bowman, Paul, Davis & Nelson, 1987) as reported by Petrovic (1990).

Phosphorus concentrations generally decrease with depth in agricultural soils because phosphorus is adsorbed to soil minerals and also precipitates readily with calcium, iron, or aluminum (Lauer, 1988; Ragone, 1977). The dominant precipitation reactions are pH dependent, forming mostly iron and aluminum phosphates in acid soils and calcium phosphates under alkaline conditions. In neutral soils, the precipitation reactions are strongly rate-limited, so that the apparent solubility of the phosphate compounds is higher than under either acid or alkaline conditions (Bouwer, 1985).

1.2. Pesticides

Pesticides are used in urban areas, primarily for weed and insect control in houses, along roadsides, railroad rights of way, in parks, on golf courses, and on private lawns (Racke & Leslie, 1993). The pesticide loading in runoff water has been correlated to the amount of impervious cover and to the distance the runoff will travel prior to infiltration or decomposition, as demonstrated Lager (1977) and confirmed in Austin, Texas by Butler (1987). Urban pesticide contamination of groundwater in central Florida likely resulted from municipal and homeowner use of these chemicals for pest control and their subsequent collection in storm water runoff. Samples from the upper part of the Floridan aquifer have contained detectable amounts of diazinon, malathion, 2,4-D, ethion, methyl trithion, silvex, and 2,4,5-T (German, 1989). In California, chlordane groundwater contamination has been traced to its application adjacent to residential foundations where it had been used for termite and ant control (Greene, 1992). Atrazine and simazine groundwater contamination was related to their use to control weeds along roadways (Domagalski & Dubrovsky, 1992). In Arizona, diazinon, dacthal, and dioxathion were detected in stormwater runoff entering urban dry wells that recharge the aquifer (Wilson, Osborn, Olson, Maida & Katz, 1990). Diazinon (at 30 lg/l) and methyl parathion (at 10 µg/l) were detected in groundwater below municipal waste treatment plants in Florida which used land spreading or well injection of wastes (Pruitt, Troutman & Irwin, 1985). Gold and Groffman (1993) reported groundwater leaching losses from residential lawns to be low for dicamba and 2,4-D (< 1 µg/l), when using application rates recommended for residential lawn care. In contrast, groundwater below Fresno, California, stormwater recharge basins contained only one of the organ phosphorus pesticides, diazinon. None of the ten chlorinated pesticides (aldrin, chlordane, endosulfan I, endosulfan II, endosulfan sulfate, DDD-mixed isomers, DDT-mixed isomers, DDE-mixed isomers, gamma- BHC, and methoxychlor) and none of the chlorophenoxy herbicides were found (Nightingale, 1987b; Salo, Harrison & Archibald, 1986). The Technical University of Denmark (Mikkelsen, Madsen, Rosgjerg & Harremo□es, 1996a; Mikkelsen, Arngjerg-Nielson & Harremoes, 1996b) has been involved in a series of tests to examine the effects of storm water infiltration on soil and groundwater quality. They found that heavy metals and PAHs present little groundwater contamination threat, if surface infiltration systems are used. However, they express concern about pesticides which are much more mobile.

1.2.1. Removal processes in soil

Heavy repetitive use of mobile pesticides, such as EDB, on irrigated and sandy soils likely contaminates groundwater. Fungicides and nematocides must be mobile in order to reach the target pest and hence, they generally have the highest contamination potential. Pesticide leaching depends on patterns of use, soil texture, total organic carbon content of the soil, pesticide persistence, and depth to the water table (Shirmohammadi and Knisel, 1989). A pesticide leaches to groundwater when its residence time in the soil is less than the time required to remove it, or transform it to an innocuous form by chemical or biological processes. The residence time is controlled by two factors: water applied and chemical adsorption to stationary solid surfaces. Volatilization losses of soil-applied pesticides can be a significant removal mechanism for compounds having large Henryo's constants (Kh), such as DBCP or EPTC (Jury, Spencer & Farme, 1983). However, for mobile compounds having low Kh values, such as atrazine, metolachlor, or alachlor, it is a negligible loss pathway compared to the leaching mechanism (Alhajjar, Simsiman & Chesters, 1990).

1.2.2. Mobility.

Estimates of pesticide mobility can be made based on the three removal mechanisms affecting organic compounds (volatilization, sorption, and solubility), as shown on Tables A (Armstrong & Llena, 1992). Application methods and formulation state can also play a significant role in pesticide mobility. Residues of foliar-applied water soluble pesticides appear in high concentrations in runoff (Pierce & Wong, 1988).

Table A: Mobility class definition

Class	K_d	MI
I-Mobile	<.1-1.0	1-1.0
II-Intermediate Mobility	1.0-10.0	0.01-0.1
III-Low Mobility	10.0-100.0	0.001-0.01
IV-Very Low Mobility	>100.0	<0.001

K_d is the soil adsorption coefficient, ml/g and M1 is the mobility index (ratio of pollutant's migration velocity to migration velocity of water under saturated flow).
Source: modified from Armstrong and Llena (1992).

Infiltration Evaluation Methodology and Model Results:

The design of an appropriately-functioning infiltration device, including the prevention of groundwater contamination, requires three steps: (1) determining the concentrations and forms of the pollutants entering and leaving the device; (2) determining the characteristics of the soil that affect water quality; and (3) predicting the potential for groundwater contamination. The goal of an effective screening methodology to evaluate groundwater contamination potential is to incorporate locally-derived data and the available body of research on storm water quality and soils into an evaluation method that can be used to determine if storm water infiltration is feasible at a site.

Step 1: Evaluate Pollutant Loadings and Chemical Forms

Once it is determined which pollutants are found in the storm water runoff for which infiltration is planned, an important consideration for fate and transport is whether or not pollutants of concern are associated with particulates or are in dissolved (ionic) or colloidal forms. Ionic/dissolved or colloidal pollutants are more likely to penetrate into the vadose zone and require a chemical interaction between the soil and the pollutant to prevent transport. Particulate associated pollutants are more likely to be trapped on the infiltration device's surface, or in the near-surface soils.

Sources of Data for Pollutant Concentrations. Using locally-derived data to evaluate the appropriateness of infiltration is preferable; however, there are often financial and time constraints that preclude local sampling. When local storm water quality data is absent, using regional or land-use-specific data may be the best option. Many Municipal Separate Storm Sewer Systems (MS4s) have monitored their storm water outfalls as part of their permitting process. Outfall data from the site's watershed may prove to be a valuable source of runoff characterization data, assuming the predominant watershed land use is similar to that of the site. Other sources include land-use-specific data cited in the literature. It has been well-documented that several land uses are more likely to generate specific pollutants of concern, *e.g.*, hydrocarbons from highways and maintenance yards; metals from watersheds with substantial quantities of galvanized roofing; lawn care chemicals from well-maintained landscaped areas, etc. When regional or land-use-specific data is absent, the data collected as part of the US EPA's storm water permit program, and summarized in the National Storm water Quality Database (NSQD), is available (Maestre and Pitt 2005). The full database, including summary tables showing median concentrations for different land uses [industrial, commercial, residential, freeway, open space, etc.], is located at http://unix.eng.ua.edu/~rpitt/Research/ms4/mainms4.shtml, along with several published papers describing the database features and example evaluations). The NSQD database can provide a first estimate of end-of-pipe concentrations of the pollutants of interest.

Step 2: Evaluation of the Soil for Infiltration:

Soil Chemical Characteristics. One important aspect of soils that affects pollutant movement is the soil's organic content, which ranges from less than 0.05% to greater than 80%, but is most often between 2 and 5%. Greater amounts of organic matter decrease the movement of many pollutants of concern through the soil. In addition, the multitudes of microorganisms present in the vadose-zone soils fix nitrogen and degrade organic matter and various pollutants. A second important aspect is the pore volume between the grains, which may be filled with water or air.

Infiltration Rate and Capacity. The infiltration capacity of soil is the maximum rate at which infiltration can occur under specific conditions of soil moisture. The infiltration capacity of a soil depends on soil texture, the water content of the soil, its compaction (density), and the presence of macropores and cracks.

Step 3: Predicting Groundwater Contamination Potential Below Infiltration Basins

The prediction of groundwater contamination potential can be very complex – depending on the concentration and form of the pollutant, the characteristics of the soil, and the rate at which water moves through the soil. Mobility is compound-specific and depends on the soil matrix (mostly the soil texture, and associated permeability, and organic content). Other soil characteristics, such as pH, also play an important role in pollutant movement. Two types of models have been developed by the authors to assist stormwater managers with evaluating the potential for groundwater contamination. The first is a simplified method that links in a chart the mobility of the pollutant, the fraction in the filterable (dissolved) phase, and the concentration of the pollutant. This information is combined with the information on the soil type and general soil reactivity to provide a mobility class depending on the type of infiltration device used. The second method described uses a vadose-zone model, developed for predicting pollutant movement beneath a landfill. This model, unlike the simplified method, predicts pollutant concentrations in the groundwater at various depths in the vadose zone after different infiltration time periods, given input parameters of rainfall amount, soil chemistry, and pollutant concentrations of the infiltrating water.

Simplified Method for Predicting Groundwater Contamination

The Groundwater Recharge Committee of the National Academy of Science (Andelman, *et al*. 1994) examined risks associated with recharging groundwater with waste waters (including storm water). General causes of concern included the following:

- High mobility (low sorption potential) in the vadose zone,
- High abundance (high concentrations and high detection frequencies) in storm water, and
- High soluble fractions (small fraction associated with particulates that could be removed at the soil surface by straining or by common sedimentation treatment).

It is possible to assess the need for pre-treatment to reduce the runoff pollutant loadings before infiltration. Results of that analysis (the simplified method predicting groundwater contamination potential) are shown in Clark and Pitt (2007). This simplified method is based on the following assumptions. The contamination potential is the most critical rating of the influencing factors. As an example, if no pretreatment was to be used before percolation through surface soils, the mobility and abundance criteria are most important. The filterable fraction is not as important since no pretreatment is being used. If sedimentation pretreatment is to be used before surface infiltration, then some of the pollutants will likely be removed before infiltration. In this case, all three influencing factors (mobility, abundance in storm water, and soluble fraction) are important. If subsurface injection (with minimal pretreatment) is used, then only abundance is significant. If the pollutant is present in high concentrations, it will likely have an adverse effect on the groundwater. Attenuation through the vadose zone may be insignificant as the water would bypass it if using direct injection. Table 1 is only appropriate for initial estimates of contamination potential because of the simplifying assumptions made, such as the likely worst-case mobility conditions for sandy soils having low organic content.

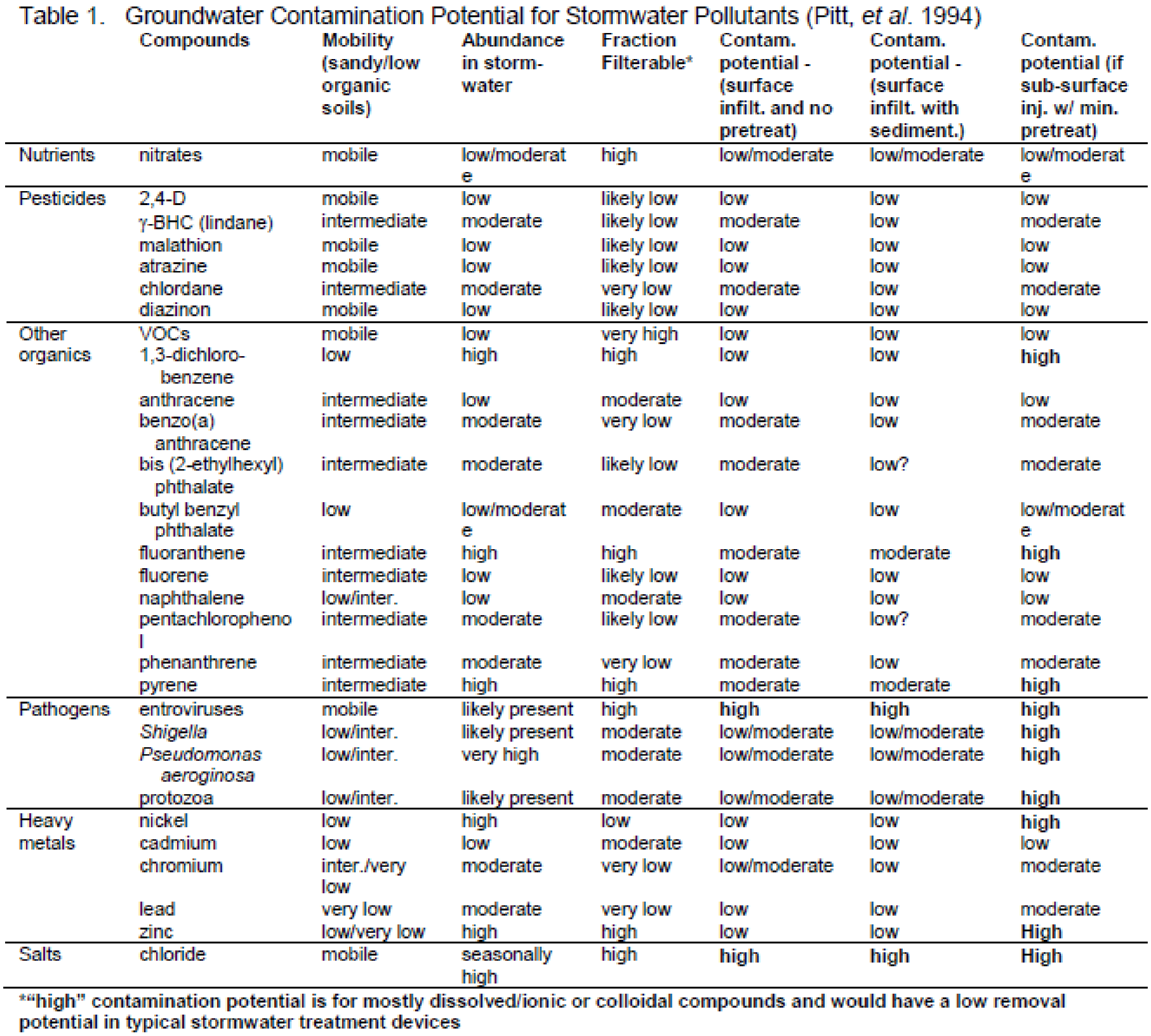

Table 1. Groundwater Contamination Potential for Stormwater Pollutants (Pitt, *et al.* 1994)

	Compounds	**Mobility (sandy/low organic soils)**	**Abundance in storm-water**	**Fraction Filterable***	**Contam. potential - (surface infilt. and no pretreat)**	**Contam. potential - (surface infilt. with sediment.)**	**Contam. potential (if sub-surface inj. w/ min. pretreat)**
Nutrients	nitrates	mobile	low/moderate	high	low/moderate	low/moderate	low/moderate
Pesticides	2,4-D	mobile	low	likely low	low	low	low
	γ-BHC (lindane)	intermediate	moderate	likely low	moderate	low	moderate
	malathion	mobile	low	likely low	low	low	low
	atrazine	mobile	low	likely low	low	low	low
	chlordane	intermediate	moderate	very low	moderate	low	moderate
	diazinon	mobile	low	likely low	low	low	low
Other organics	VOCs	mobile	low	very high	low	low	low
	1,3-dichloro-benzene	low	high	high	low	low	**high**
	anthracene	intermediate	low	moderate	low	low	low
	benzo(a) anthracene	intermediate	moderate	very low	moderate	low	moderate
	bis (2-ethylhexyl) phthalate	intermediate	moderate	likely low	moderate	low?	moderate
	butyl benzyl phthalate	low	low/moderate	moderate	low	low	low/moderate
	fluoranthene	intermediate	high	high	moderate	moderate	**high**
	fluorene	intermediate	low	likely low	low	low	low
	naphthalene	low/inter.	low	moderate	low	low	low
	pentachlorophenol	intermediate	moderate	likely low	moderate	low?	moderate
	phenanthrene	intermediate	moderate	very low	moderate	low	moderate
	pyrene	intermediate	high	high	moderate	moderate	**high**
Pathogens	entroviruses	mobile	likely present	high	**high**	**high**	**high**
	Shigella	low/inter.	likely present	moderate	low/moderate	low/moderate	**high**
	Pseudomonas aeroginosa	low/inter.	very high	moderate	low/moderate	low/moderate	**high**
	protozoa	low/inter.	likely present	moderate	low/moderate	low/moderate	**high**
Heavy metals	nickel	low	high	low	low	low	**high**
	cadmium	low	low	moderate	low	low	low
	chromium	inter./very low	moderate	very low	low/moderate	low	moderate
	lead	very low	moderate	very low	low	low	moderate
	zinc	low/very low	high	high	low	low	**High**
Salts	chloride	mobile	seasonally high	high	**high**	**high**	**High**

***"high" contamination potential is for mostly dissolved/ionic or colloidal compounds and would have a low removal potential in typical stormwater treatment devices**

Computer Models to Predict Vadose Zone Contaminant Transport

Over the last fifteen years, computer models for the vadose zone have become readily available. Many of these models were developed initially to predict plume migration beneath leaking landfills. They typically focused on the behavior of either organic or inorganic pollutants in the vadose zone. One model, SESOIL (Seasonal Soil compartment model), is capable of modeling both organic and inorganic pollutants (RISKPRO 2003; Clark, *et al.* 2006).

As described earlier, the specific type of soil and its properties have a profound effect on the movement of water and pollutants. Three main properties were identified during modeling tudies conducted by Clark, *et al.* (2006): intrinsic permeability, organic content, and pH. Other factors beyond the soil itself also affect pollutant movement and groundwater contamination potential, including pollutant concentrations of the infiltrating water, rainfall, and vadose zone thickness. The primary objective of the research conducted by Mikula (2005) and Clark, *et al.* (2006) was to determine which controlling factors have the greatest influence on the movement of zinc and sodium chloride in the vadose zone beneath a typical infiltration device. A case study illustrating the use of a vadose zone model can be found in Clark and Pitt (2007).

II. CONCLUSIONS AND RECOMMENDATIONS

Many types of storm water infiltration approaches have been used in urban areas to decrease surface discharges of storm water and restore groundwater recharge. The most common include the following:

- Surface infiltration devices (e.g., grass filters, grass-lined drainage swales, percolating basins, bioretention/biofiltration cells) – infiltration occurs through turf and surface soils, providing the best opportunity for pollutant trapping in the surface soils and vadose zone. The devices listed below discharge stormwater below organic soils, allowing increased pollutant movement to the groundwater.
- French drains or soak-aways (e.g., source area infiltration pits, roof runoff infiltration pits

- Porous pavements or grid pavers
- Drainage trenches
- Infiltration wells or dry wells
- Percolating pipes

When selecting the appropriate infiltration device for a site (or for determining whether infiltration is a viable option), it is crucial to evaluate the potential for groundwater contamination below the device. As described above, the prediction of the vulnerability of groundwaters to contamination from surface water infiltration is a three-step process. The first step is determining the pollutants of concern and the concentrations and chemical forms of these pollutants. The storm water pollutants of most concern (those that may have the greatest potential
Adverse impacts on groundwaters) include the following:

- Nutrients – possibly nitrates in areas having high stormwater nitrate concentrations;
- Pesticides – Lindane and chlordane;
- Other organics – 1,3-dichlorobenzene;
- Pathogens – Enteroviruses and possibly other pathogens, including *Shigella*, *Pseudomonas aeruginosa*, and various protozoa;
- Heavy metals – Nickel and zinc, followed by chromium and lead.
- Salts – Chloride in northern areas where de-icing salts are used for traffic safety.

Identifying the soil characteristics for a particular site affecting pollutant migration is the second step. The information required includes the following:

- Soil texture – Sand, silt, clay, loam, or a combination of these
- Intrinsic permeability
- Hydraulic conductivity
- pH
- Organic content
- Cation exchange capacity

The third step requires using the information determined in the first two steps to predict the potential for groundwater contamination. Two approaches were described in detail in Clark and Pitt (2007). In general, to prevent groundwater contamination below infiltration devices, surface devices (such as grass swales, bioretention/biofiltration cells, and percolation ponds) that have a substantial depth of underlying organic-rich soils above the groundwater, are preferable to using subsurface infiltration devices (such gravel trenches or French drains, and especially injection wells), unless the runoff water is known to be relatively free of pollutants. Infiltration of stormwater from residential areas is also safer than from more contaminated areas, unless suitable pre-treatment is used. Pre-treatment to remove solids and particulate-associated pollutants will also reduce the required maintenance frequency of the infiltration component of the treatment train.

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