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Water Quality Performance of Dry Detention Ponds with Under-Drains

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16. Abstract (Limit: 200 words)

This research is a field evaluation of the water quality performance of dry water quality ponds with under-drains. The evaluation is performed in terms of pollutant retention by measuring concentrations in the inflow and outflow from the pond. Three dry detention ponds, Mn/DOT pond 4012-03, Mn/DOT pond 4012-04 and a pond operated by Carver County, were investigated for their ability to remove total phosphorus, dissolved phosphorus, total suspended solids and volatile suspended solids.

The measured influent concentrations of most parameters in storm water runoff at the Carver County dry detention pond with under-drains were substantially lower than concentrations typically mentioned in other studies throughout the nation and influenced the pollutant retention efficiency of the pond. This study confirmed that dry detention ponds with under-drains are an option for water quality control. The results of this study indicate that various storm water pollutants can be removed by dry detention ponds with under-drains.

A comprehensive comparison of pollutant retention efficiencies of various dry detention ponds throughout the nation is also carried out in this study. Comparison of these values with the retention efficiencies of this study indicated that the pollutant retention performance of the Carver County pond was below the average expected performance of dry detention ponds but well within the expected variation, even with the low influent concentrations at the Carver County pond. This is an indication that the under-drains do provide improved pollutant retention when used with a dry detention pond.

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Water Quality Performance of Dry Detention Ponds with Under-Drains

Final Report

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Executive Summary

Dry detention ponds have been used to temporarily store storm water runoff, but have not qualified for NPDES II designation as a “Best management practice” (BMP) in Minnesota because they have not been demonstrated to remove sufficient storm water pollutants. One concept is to have the major storm water runoff filter through media of either sand or soil and discharge through under-drains. This research is a field evaluation of the water quality performance of dry water quality ponds with under-drains. The evaluation is performed in terms of pollutant retention by measuring concentrations in the inflow and outflow from the pond. This study may allow designers to expand their choices when selecting a storm water management practice in order to meet water quality objectives, and will provide them with information on the treatment effectiveness of dry ponds with underdrains.

Three dry detention ponds, Mn/DOT pond 4012-03, Mn/DOT pond 4012-04 and a pond operated by Carver County, were investigated for their ability to remove total phosphorus, dissolved phosphorus, total suspended solids and volatile suspended solids. Storm water monitoring equipment was installed at the inlet and outlet of each of three dry detention ponds with under-drains. Automated flow-weighted sampling was initiated in May of 2004 and results were reported through August 2, 2005. Twelve storm events were monitored at Carver County pond during this period for flow and various water quality parameters. Sampling from two Mn/DOT ponds did provide an experience base with lessons about monitoring and maintenance, but did not achieve any reportable results. Flow weighted samples were collected at the Carver County pond and analyzed to obtain influent and effluent event mean concentrations. Pollutant retention efficiencies for each storm event were calculated by comparing the influent and effluent pollutant concentrations.

The measured influent concentrations of most parameters in storm water runoff at the Carver County dry detention pond with under-drains were substantially lower than concentrations typically mentioned in other studies throughout the nation and influenced the pollutant retention efficiency of the pond. The mean total phosphorus influent event mean concentrations (EMC’s) of six different dry detention pond studies from the literature was found to be 0.65 mg/L which was about three times higher than the mean influent total phosphorus concentrations (0.184 mg/L) obtained at Carver County dry detention pond. The average dissolved phosphorus event mean concentration for twelve monitored storms at Carver County was found to be 0.097 mg/L which is one half of the mean influent dissolved phosphorus concentrations of six different dry detention pond studies. It is believed that settling of sediment bound phosphorus in the pre-treatment pond and grassy swales resulted in the low influent event mean concentrations at Carver County dry detention pond.

This study confirmed that dry detention ponds with under-drains are an option for water quality control. Carver County pond provided moderate storm water treatment, even with low influent concentrations. The total load-based retention efficiency for

twelve monitored storms at Carver County dry detention pond with under drains were 88% for total suspended solids, 81% for volatile suspended solids, 58% for total phosphorus, and 52% for dissolved phosphorus, These retention efficiencies are most relevant to site specific, total pollutant load studies. This load-based efficiency incorporates infiltration as a water quality treatment, which was substantial at the Carver County pond. Retention efficiencies can also be based upon the reduction of pollutant concentration, rather than reduction of pollutant load, and will thus consider only the treatment that the effluent flow receives. The average concentration-based retention efficiencies for twelve monitored storms were 38% for total suspended solids, 32% for total volatile solids, 26% for particulate phosphorus and 16% for total phosphorus. The dissolved phosphorus average retention efficiency was 3%, which is expected because the mechanisms to remove dissolved phosphorus in a dry detention pond are of minimal importance. These average retention efficiencies are more comparable to the literature, because they do not incorporate infiltration, which is a site-specific parameter. The results of this study indicate that suspended solids and particulate phosphorus in storm water can be removed by dry detention ponds with under-drains. If combined with infiltration capacity, dry detention ponds can be an effective treatment technology at all influent concentrations.

A comprehensive comparison of pollutant retention efficiencies of various dry detention ponds throughout the nation is carried out in this study. This comparison illustrates that dry detention ponds were efficient in removing total suspended solids. Average concentration-based total suspended solid retention efficiency for the dry detention ponds included in this comparison is found to be 50% with a standard deviation of 34%. Similarly, average total phosphorus retention efficiency for all studies is found to be 29% with a standard deviation of 19%. However, average dissolved phosphorus retention efficiencies of 16% with a standard deviation of 24% indicate that dry detention ponds are less effective in removing dissolved phosphorus than total suspended solids and total phosphorus. Comparison of these values with the concentration-based retention efficiencies of this study indicated that the pollutant retention performance of the Carver County pond was below the average expected performance of dry detention ponds but well within the expected variation, even with the low influent concentrations at the Carver County pond.

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1. Introduction

A. Impacts of Storm Water Runoff

Natural forests and farmland have been replaced by impervious surfaces due to a higher trend of urbanization in the last few decades. This has resulted in reduced vegetative cover in watersheds and increased storm water runoff to the receiving water bodies. The threat of frequent flooding is greater than before due to reduced time to peak flow as more smooth and impervious land surfaces increase the hydraulic conveyance efficiency and thus the velocity of storm water runoff. Human activities also produce different types of pollutants and sediments which are deposited on the impervious surfaces. These pollutants and sediments are transported to receiving water bodies by storm water runoff and hence degrade the water quality of our streams and lakes.

Typically, increased imperviousness has two basic impacts on runoff: the degradation of water quality and increased volume and rate of runoff from impervious surfaces. These impacts can cause significant changes in hydrology and water quality that result in a variety of problems, including increased flooding, decreased aquatic biological diversity, increased sedimentation and erosion and habitat modification. It has been found that at any given rainfall intensity, impervious lands can increase the peak discharge by a factor of 2 to 5 and duration of flow by a factor of 5 to 10 (Booth and Jackson, 1997). Impervious cover of 15 to 30 percent has, in some watersheds, produced 10 times the frequency of the small flood events and has doubled the volume of large flood events (Maxted and Shaver, 1996) The high velocities of storm water runoff from impervious surfaces not only decreases the time to peak flow but also can produce high energy flows which cause stream bank and streambed erosion due to scouring.

The amount of pollutants transported by storm water runoff usually depends on the percentage of impervious land present in any given watershed and the mass of available pollutants. These pollutants often are classified as aquatic plant nutrients, which may increase the biological production of the surface waters, increase eutrophication processes and hence cause degradation of receiving waters. The extent of the environmental damage caused by pollutants is also related to the characteristics of the watershed, such as soil type, topography and the frequency and intensity of precipitation. Many studies have been done to determine the type and mass of pollutants present in storm water runoff. Phosphorus, nitrogen, zinc, lead, copper and cadmium are commonly found pollutants in many studies (Stanley, 1996; Kluesener and Lee, 1974; Ferrara and Witkowski, 1983; Yu et al, 1991; Schueler, 1987).

Typically, phosphorus is a nutrient of concern because it is a limiting nutrient in most receiving water bodies. It occurs in storm water as dissolved phosphorus contributed from different fertilizers, highway runoff conveyance, animal wastes and particulate phosphorous including that incorporated in organic matter or bound to sediments. Dissolved phosphorus exists mostly in the form of orthophosphate, which is available immediately for uptake by algae and can cause serious aesthetic problems. On the other hand, sediment bound particulate phosphorus and organic materials eroded during surface runoff provide a variable source of phosphorus to algae in water bodies. When additional phosphorus is introduced via runoff, eutrophication may be accelerated.

Suspended solids are a second pollutant of primary concern in storm water runoff, because the solids will reduce clarity of a water body, settle in the water body and carry pollutants such as metals, nutrients and hydrocarbons. Typical solids are sand, silt and organic material that washes off with soil or leaves. Reduction of suspended solids in storm water are important for the esthetics and quality of a water body.

B. Overview of Storm Water Management Practices:

The significance of storm water runoff in affecting water quality in the United States has become an increasing concern in recent years. Storm water management practices are structural or nonstructural practices designed to minimize the impacts of water pollution from non-point sources by using the most effective means of achieving water quality goals (http://www.pca.state.mn.us/water/pubs/sw-bmpmanual.html, July 30, 2004). Detention basins have been used for decades to mitigate peak storm water discharges from urban areas. However, the environmental impacts of storm water on the downstream watershed portions have not been well understood. After implementation of National Clean Water Act in 1972, more concern has been raised about effects of storm water on the quality of receiving water bodies. In 1998 the EPA reported that nutrients, suspended solids and heavy metals are the primary source of pollution in urban and rural storm water. Of particular interest in Minnesota are the reduction of nutrients and sediments in storm water. Dry detention basins with under-drains may be able to achieve these goals. The National Pollutant Discharge Elimination System (NPDES) Phase II regulations, implemented by Minnesota Pollution Control Agency (MPCA) in compliance with the National Clean Water Act has not yet included the use of various stormwater best management practices (BMPs) other then wet detention ponds into their permitting processes. This study is focused towards the performance evaluation of dry detention basins with under-drains in terms of nutrient and sediment retention.

Typical structural storm water management facilities include dry detention, wet detention, dry detention with filtration, infiltration, etc. Dry detention ponds are storm water control ponds that do not have a continuous pool of water. These are the storm water basins with pond bottom above the groundwater table. They are used to control and temporarily store the storm water. Typically, they are designed to drain within 48 hours after a storm so that they remain dry between the storm events (MPCA 2005). The Minnesota Department of Transportation (Mn/DOT) uses this type of system to treat highway runoff. Dry basins also slowdown the velocity of storm water runoff and reduce channel erosion and downstream sedimentation. Dry detention ponds help to prevent sudden flooding as they improve the time to peak flow for downstream conveyance structures. During the temporary storage of the storm water, suspended solids settle down at the bottom of the ponds and increase the storm water quality. If total suspended solid retention in a detention basin is good, the retention of other pollutants that bind to particles is generally good, as well (Stanley, 1996). Dry detention ponds with under-drains are often designed with 18 to 24 inches of filter media. Storm water passes through the filter media and pollutants are trapped by the filter and enhanced storm water quality is achieved. In this sense, they are a combination of an infiltration basin and a filter with effluent.

Dry detention ponds are typically easier and less expensive to construct as compared to wet detention ponds. They are also more flexible in maintenance and inspection. They are considered at least 25 to 40 % less expensive than wet detention ponds.
(http://www.georgiaplanning.com/watertoolkit/Documents/WatershedPlanningTools/17_DryPonds.pdf, August 2nd, 2004.)
Moreover, unlike wet ponds, dry detention ponds do not require a permanent pool of water for operation. This characteristic of dry detention ponds has made them an attractive option for designers and users as continuous ponding of water can lead to many serious problems like algal growth, mosquito breeding, drowning, difficult access for cleaning, bad odors, etc. Wet detention ponds can be replaced by dry detention ponds wherever a lack of sufficient storm water supply would prevent the use of wet ponds. Dry detention ponds also provide multiple benefits as they can be used for all kinds of recreational activities during dry periods. Some portions of dry ponds which do not get wet very often can be landscaped or utilized for other purposes.

C. Objectives

Strict environmental regulations with a greater focus on non-point source pollution have highlighted the achievement of maximum treatment levels with minimum available resources. The Minnesota Department of Transportation (Mn/DOT) and different counties in Minnesota have designed and built many dry detention ponds in rural areas, particularly in District 7 around Mankato. The main objective of this research is to evaluate the storm water quality performance of dry detention ponds with under-drains. The evaluation is performed in terms of total suspended solids, volatile suspended solids, total phosphorus and dissolved phosphorus retention by measuring concentrations in the inflow and outflow from the pond.

More storm water management organizations are taking it upon themselves to evaluate the performance of their own management practices. This study has attempted to consolidate the available performance evaluations and fill in the gap posed by dry detention ponds preferred by Mn/DOT and water resource management organizations. Moreover, this study provides a basic understanding of the performance of dry detention ponds with under-drains and may allow designers to expand their choices when selecting a storm water management practice in order to meet water quality objectives. This research will directly help those who are responsible for limiting the runoff of suspended and dissolved pollutants from receiving water bodies. The benefit of this work will be a very basic understanding of the performance of dry detention ponds in terms of their efficacy to remove certain pollutants. The users of this research include Mn/DOT, state and county highway engineers, city and consulting engineers, water resource management organizations such as Soil & Water Conservation Districts, Watershed Management Organizations and watershed districts, and regulators.

2. Review

A. Storm Water Pollutants and Treatment Practices

Nutrients and suspended solids are major pollutants present in storm water runoff. Phosphorus is typically the most common limiting nutrient in receiving waters. High phosphorus concentrations in storm water runoff degrade the water quality of lakes and streams through eutrophication. Different forms of phosphorus also attach to the sediment at the bottom of the pond through the adsorption process. Shammaa and Zhu (2002) indicated that total suspended solids (TSS) can increase the turbidity level and inhibit plant growth of receiving water bodies. It has also been found that suspended solid loading can affect river biota and reduce the number of different fish species (Scheuler, 1996). There are two ways to minimize the impacts of these pollutants on streams or lakes. One possible solution is to stop the pollutants from entering into the receiving water bodies by limiting them at the source. The second strategy is to treat the storm water runoff. Different storm-water treatment practices can be employed to achieve the latter strategy. Typically, grassy swales, constructed wetlands, buffer strips, retention or detention ponds and infiltration devices are used to treat storm water runoff.

Dry detention and retention ponds are the most common storm water treatment practices used for flood mitigation and water quality improvement. The concept of “detention” and “retention” has been used interchangeably by many researchers and scientists in the past. Detention ponds collect and provide temporary storage for storm water with subsequent gradual discharge to downstream rivers or lakes. Retention ponds subsequently dispose storm water by infiltration into the ground or evaporation without any release to downstream receiving waters (Harper, 1993). Detention ponds are also classified into various types such as, dry detention, extended dry detention and wet detention ponds etc. Both dry and extended dry ponds remain dry between the storm events but discharge through an extended dry pond is at a lower rate than dry ponds. On the other hand, wet ponds maintain a permanent pool of storm water and remain wet between storm events.

Different studies have indicated variable pollutants retention efficiencies for dry detention and wet detention ponds. Some studies claim that wet detention ponds are considered to provide better pollutant retentions than dry detention ponds (Winer, 2000). However, there are studies which do not support the idea that wet ponds have better retention rates than dry ponds. Bartone and Uchrin (1999) have reported an interesting comparison of a dry and a wet detention pond. This comparison showed that dry ponds provided much better retention rates than wet pond for total nitrogen, total phosphorus, dissolved phosphorus, particulate phosphorus and total suspended solids. Moreover, Harper et al. (1999) studied a dry detention pond that provided extremely effective retention rates for total phosphorus, dissolved phosphorus and total suspended solids.

Even though dry detention ponds with filtration systems are used throughout the nation for storm water pollution abatement, few field studies have been conducted to verify their performance in terms of sediment and pollutant retention. Studies that provided information about actual field measurements of inflow and outflow from a dry detention pond with filtration systems are included in this literature review. It is difficult to compare all studies as there are differences in pond configuration and morphology, sediment composition, residence times, runoff characterization and monitoring equipment.

B. Pollutant Retention Mechanism

Dry detention ponds can provide reduction of storm water pollutants in many different ways. Sedimentation is considered to be the primary mechanism of pollutant retention in dry ponds. Dry ponds are typically designed in such a way that they can hold the water for a period of up to 2 days. In the case of dry detention ponds with under-drains, storm water runoff flows through the outlet after passing through the small perforations in the under-drains which collect the filtered storm water. This process reduces the velocity of storm water and provides sufficient time for settling and filtration of the particulate matter present in the runoff. Finally, infiltration is a third mechanism by which dry detention ponds reduce dissolved pollutant load to the receiving water body. As settling of particles primarily depend on size, shape and density of the particles, different studies have yielded inconsistencies in settling rates. It has been found that about 50 % of the particulate matter settles within first 1 to 2 hours of detention (Driscoll, 1989). Papa and Adams (1999) considered particle settling as a function of pond depth and detention time and indicated less efficient settling velocities.

Some nutrients present in storm water runoff, like particulate phosphorus attached to the suspended sediments, are also removed through the process of settling or sedimentation. As there is no direct relationship between settling of suspended solids and dissolved pollutant retention, it is unlikely that dissolved pollutants would be removed at the same rate as sediments. Stanley (1996) reported retention efficiency of 71% for total suspended solids, 14% for total phosphorus and 26% for dissolved phosphorus. Similarly, a dry detention pond in Oakhampton, Maryland obtained retention efficiencies of 87%, 26% and -12% for suspended solids, total phosphorus and dissolved phosphorus, respectively (Winer, 2000). The same trend was observed for the Stedwick, Maryland pond with 70% retention for suspended solids and 14% retention for total phosphorus (Winer, 2000). Hence, it is difficult to assume that a dry detention pond with high total suspended solids retention can provide high retention efficiencies for total and dissolved phosphorus.

Pollutant retention mechanisms in dry detention ponds also include processes like adsorption, absorption and biodegradation. Two factors are very important to initiate these processes in the dry detention ponds. One factor is the contact between the aquatic organisms and pollutants as no biological activity can start without their contact. The second factor is the time required to complete the biological process (Athanas, 1988).

Dry detention ponds may maintain a pool of water for up to several days which may allow algae and phytoplankton to develop in the ponds.

The temporary pool provided by dry detention ponds also helps in pollutant retention through the adsorption process. This process occurs between the water column and sediment at the bottom of the pond and results in binding of phosphorus to the soil or sediment. Van Buren (1994) indicated that the adsorption processes can significantly affect the retention of nutrients and metals from ponds. He also mentioned that if a detention time of two weeks under aerobic conditions is provided then a considerable amount of dissolved and total phosphorus can be removed by adsorption of these pollutants to sediment. However, sediment may release adsorbed pollutants under anaerobic conditions. Similarly, Martin (1986) observed significant dissolved phosphorus retention in a pond in Orlando, Florida and concluded that algae and phytoplankton consumed most of the dissolved phosphorus. He also speculated that the adsorption processes at the interface of water column and bottom sediment and plant uptake through roots may also contribute to dissolved phosphorus retention.

Vegetative growth in ponds can also improve the water quality to some extent by utilizing dissolved phosphorus (Athanas, 1988). Results of a dry detention pond with a filtration system constructed adjacent to Lake Tohopekaaliga in Florida also support this hypothesis. Samples from six storm events at three different locations within the pond from November 1985 to November 1986 were collected from the Lake Tohopekaaliga dry detention pond. Three units of automated storm water samplers were installed at the inlet, outlet and within the pond prior to the filter berm. The filtration system of the pond consisted of two sets of filter berms which were provided with the six inch perforated under-drains at the bottom of the media. The filter media was clogged with fine particles soon after construction was completed. As shown in Table 2.1, Cullum and Dierberg (1990) reported that the input concentrations of dissolved phosphorus and total phosphorus decreased 77-78% respectively during migration through the pond before reaching the filter berms. It was concluded that this reduction in pollutants was due to standing crops of Typha species within the pond. However, dissolved phosphorus increased 68% while traveling through the filter. This may be a result of desorption of the organic dissolved phosphorus which can occur under anaerobic conditions. However, it is also possible that the point measurements in the pond are not representative of the mean value. Holler (1990) observed that the filter media stabilized as the system aged because there was a substantial increase in the retention of orthophosphorus in the last three (out of six) monitored storm events.

Table 2.1: **Results of storm event monitoring at Lake Tohopekaliga (Mean of 6 storm events) (Cullum & Dierberg, 1990)**

Parameter	Units	% Change in Pond	% Change in Filter	Total % Change in System
SRP (S.E# 1 - 3)	mg/l	-78	183	-38
SRP (S.E# 4- 6)	mg/l	-77	-35	-85
SRP (6 Events)	mg/l	-77	68	-62
Total P	mg/l	-78	-33	-85
Turbidity	NTU	-88	50	-81

It is believed that isolation of change in the pond from the change in filter is misleading because the one sample location does not represent a mean value for the pond. However, on an overall basis, the pond showed a retention of 62% for dissolved phosphorus, 85% for total phosphorus and 81% for turbidity for six storm events as shown in Table 2.1.

C. Performance of Dry Detention Ponds in Terms of Retention Efficiencies:

Performance and effectiveness of storm water detention ponds are usually expressed in terms of retention efficiencies. However, large variability is observed in retention efficiencies for different studies. According to EPA (1983), the most common method used to measure the retention efficiencies in urban runoff is the event mean concentration (EMC) efficiency. The event mean concentration is the flow weighted mean concentration of the entire storm event. EMC efficiency is calculated by determining the flow weighted inflow and outflow concentrations of all storm events, as follows:

$$\text{EMC efficiency (\%)} = [(\text{Conc}_{in} - \text{Conc}_{out})/\text{Conc}_{in}] * 100 \quad \ldots\ldots\ldots\ldots \quad (2.1)$$

Where:

Conc_{in} is the flow weighted mean concentration at inflow.
Conc_{out} is the flow weighted mean concentration at outflow.

EMC efficiency does not account for rainfall inputs directly on the pond so adjustments should be made for rainfall. It does also not account for a reduction of total load in the effluent by infiltration losses in the dry detention pond.

A comprehensive comparison of pollutant retention efficiencies of various dry detention ponds throughout the nation is shown in Table 2.2. However, an exact comparison is not possible as included studies showed differences in pond design, method used to determine pollutant retention efficiency and monitoring methodologies. Although dry detention ponds have been used for decades throughout the nation, most of the current literature discusses wet detention ponds. Winer (2000) summarized the retention efficiencies of only six dry detention ponds (out of 139 BMP's in general with 59 for ponds) in the national pollutant retention performance database for storm water treatment practices (STP)(2nd edition). In order to satisfy the new criteria of the database (2nd edition; Winer, 2000), all storm-water treatment practice (STP) studies incorporated into the database must have been monitored for five or more storm events, automated samplers that enable flow or time based composite samples must have been used and the method used for computation for retention efficiency must have been documented. Out of the existing six studies documented in the database, five were already reported by Stanley (1996). All six studies from the database along with the studies reported by Stanley (1996) are included in Table 2.2. Retention efficiencies included in the database illustrate that dry detention ponds were efficient in removing total suspended solids. The total and dissolved phosphorus retention efficiencies were generally lower than that for total suspended solids, however.

Mean and standard deviation of total suspended solids, total phosphorus and dissolved phosphorus retention efficiencies of all the sites included in Table 2.2 are also calculated due to high variability involved in the reported data. Average total suspended solid retention efficiency for the dry detention ponds included in Table 2.2 is found to be 50% with a standard deviation of 34%. Similarly, average total phosphorus retention efficiency for all studies is found to be 29% with a standard deviation of 19%. However, average dissolved phosphorus retention efficiencies of 16% with a standard deviation of 24%, indicate that dry detention ponds are less effective in removing dissolved phosphorus than total suspended solids and total phosphorus.

Performance of dry detention ponds in terms of pollutant retention efficiencies is variable. Some dry detention pond studies have reported significant pollutant retention (Harper, 1999; Stanley, 1996) and some studies have shown that dry ponds increased the amount of pollutant in the storm water runoff (Bartone and Uchrin, 1999). If the filter media used in the dry ponds reaches its retention capacity limit then it may start contributing nutrients instead of removing them resulting in poor or negative retention efficiencies.

Table 2.2: **Comparison of pollutant retention efficiencies of dry detention ponds through out the United States**

	Detention pond	**Watershed (Acres)**	**Average Hours to Drain**	**Storms Monitored**	**Retention Efficiencies (%)**		
#					**TSS**	**TP**	**Ortho P**
1	Lake Tohopekaliga,FL[4] (With UD)*	122	N/A	6	N/A	85	62
2	Debary, FL[5] (With UD)*	23.86	N/A	35	93	13	25
3	Hawthorn Ditch, OR[a]	512	N/A	11	47	21	N/A
4	Monroe County, NY[6]	N/A	N/A	N/A	83.8	32	28.6
5	Morris County, NJ[2]	22.3	N/A	4	-10.5	37	-6.3
6	Oakhampton, MD[1a]	17	N/A	N/A	87	26	-12
7	Stedwick, MD[1a]	34	6--12	25	70	13	N/A
8	Washington,DC[7]	N/A	N/A	N/A	77	26.2	27.4
9	Lakeridge, North VA[1]	88	1--2	28	14	20	-6
10	Charlottesville, VA[3]	7.9	N/A	8	50	40	N/A
11	London, North VA[1a]	11	<10	27	29	40	N/A
12	Lawrence, Kans[1]	12	6--16	19	3	19	0
13	Greenville, NC[1a]	200	75	8	71	14	26
14	Maple run, TX[1a]	28	9	17	30	18	N/A
	Mean of all sites				**50**	**29**	**16**
	Standard Deviation				**34**	**19**	**24**
	Carver County, MN	**45**	**118**	**6**	**39**	**16**	**3**

[1] Reported by Stanley1996

[a] Reported in the National Pollutant Retention Performance Database for Storm water Treatment Practices summarized by Winer (2000)

[2] Bartone and Uchrin, 1999

[3] Yu, et al, 1994

[4] Cullum and Dierberg, 1990;

[5] Harper, et al, 1999

[6] Zarriello and Sherwood, 1993

[7] Randall, 1982

N/A, not available

* Detention ponds with under drains are noted by (With UD)

Stanley (1996) computed retention efficiencies for total suspended solids, nitrogen, phosphorus, and selected metals and compared them with other studies. A large variability was observed in his comparison for retention efficiencies of total suspended solids (3 – 87 %). According to Pope and Hess (1988), the reason for low total suspended solid retention (3%) in a Lawrence, Kansas pond was the result of resuspension of previously deposited suspended solids at the bottom of the pond. On the other hand, the Greenville pond (Stanely, 1996) showed satisfactory total suspended retention of 71%. One possible explanation made by Stanley regarding the better performance of the Greenville pond was its longer detention times (75 hrs). However, it is difficult to conclude that this pond's performance was enhanced due to larger detention times as the Stedwick, Maryland pond showed almost the same suspended solid retention efficiency (70%) with a very short detention time (6-12 hrs). Stanley concluded that overall the Greenville pond's storm water retention efficiencies for total phosphorus and ortho-phosphorus are slightly better (in a few cases) than other ponds of the same type. Moreover, the only noticeable maintenance problem mentioned was the growth of excessive or woody vegetation on the bottom and embankments of the ponds which might have actually improved the suspended solid retention efficiency of the pond.

The first flush in storm water runoff, which has been stated to carry a disproportionately large amount of the pollutants load, has been suggested as an important parameter which defines the volume of runoff that must be captured and treated in order to remove a given percentage of pollutant from a storm. If the first 20% of the storm runoff contains 80% or more of the total pollutant load then it is considered to be a strong exhibition of first flush (Stanely, 1996). Results from the Greenville detention pond did not exhibit a first flush as the first 20% of the storm runoff from it carried only about 25% of total particulate pollutant load and 23 – 37 % of the total dissolved pollutant load (Stanley, 1996).

A field study was conducted in Debary, Florida from August 1997 to March 1998 to compute the hydraulic and water quality performance of a dry detention pond (Harper, 1999). Overall system retention efficiencies for this dry detention pond were calculated over a period of six months. High mass or load retention efficiencies of 99%, 84% and 86% were reported for total suspended solids, total phosphorus and dissolved phosphorus respectively. Harper (1999) indicated that only a small percentage of influent left the pond through the under drain outflow. He indicated that it should not be inferred from his study that all dry detention ponds can provide such high pollutant retention efficiencies. It was observed that almost 70% of the influent was lost due to the ground water seepage through the pond bottom which carried a corresponding mass of pollutants (Harper, 1999). It is believed that very high mass retention efficiencies were obtained due to significant seepage losses (70%), which does not represent the real performance of the Debary, Fl pond in terms of pollutants retention. However, concentration based retention efficiencies were also calculated for the Debary, Fl pond. On a concentration basis, the pond showed retention efficiencies of 93%, 13% and 25% for total suspended solids, total phosphorus and dissolved phosphorus, respectively.

A hydraulically modified dry detention pond in Charlottesville, Virginia, was monitored to evaluate its performance in terms of storm water pollution abatement (Yu et al, 1994). Samples were collected for each storm event and examined for total suspended solids, total phosphorus, chemical oxygen demand and zinc. It was found that the pond showed reasonable retention efficiencies with an average pollutant retention efficiency of 50 % for total suspended solids and 40 % for total phosphorus (Yu et al, 1994). A specific trend between total suspended solids retention efficiency and volume of rainfall was observed and it was found that retention efficiency decreased as the volume of rainfall increased. Yu et al. (1994) concluded that the Charlottesville pond retention efficiency was reasonable when compared with the results obtained from other ponds of same type.

Dry detention ponds have been used to capture the total and dissolved forms of phosphorus. As phosphorus has great affinity for binding with the sediments present in the runoff through the adsorption process, sedimentation is considered to be an important retention mechanism of phosphorus in dry detention ponds. Papa and Adams (1999) developed a statistical model as shown in Figure 2.1 which expresses the total suspended solids retention as a function of drawdown time. They also discussed the influence of pond depth and particle settling velocities on total suspended solids retention. Figure 2.1 also indicates that the basins with the worst retention of total suspended solids also had a low drawdown time.

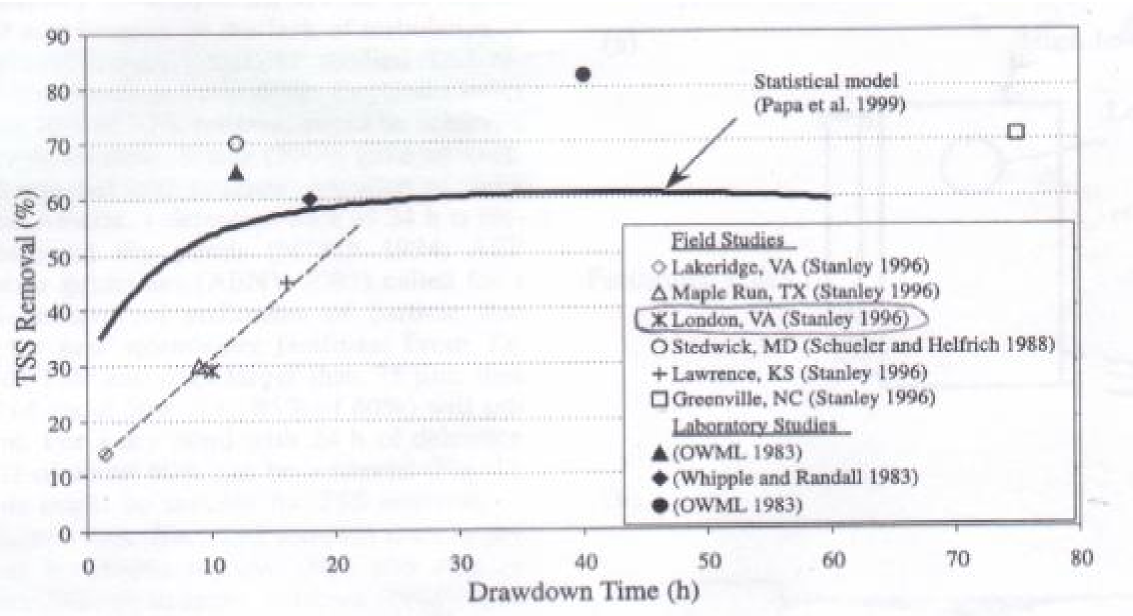

Figure 2.1: **TSS retention as a function of draw down time (Papa et al, 1999)**

Load based efficiency was also used in this study as a measure of the performance of the pond. Load based efficiency enables analysis of infiltration losses of various pollutants. As shown in equation 2.2, load base efficiency can be calculated by determining the percent change of total pollutant loading through the pond.

$$\text{Load efficiency (\%)} = [(Conc_{in} * V_{in} – Conc_{out} * V_{out})/Conc_{in} * V_{in}] * 100 \quad ……. (2.2)$$

Where:

$Conc_{in}$ is the flow weighted mean concentration at inflow.
$Conc_{out}$ is the flow weighted mean concentration at outflow.
V_{in} is the influent volume over the inlet weir.
V_{out} is the effluent volume discharge from the pond.

The primary difference between load based efficiency and EMC efficiency is that the load based efficiency incorporates the losses due to infiltration as though the infiltrated water is treated to 100% efficiency. Filtration through the soil is usually an effective treatment mechanism, however, and the load based efficiency may give the most accurate overall treatment of storm water.

D. Maintenance:

Maintenance of dry detention ponds is an important issue. According to Harper (1999), variable hydraulic performance was observed by the under-drain filter system of Debary, Florida pond. The original filter under drain system was found to be inoperable and was replaced in August 1997. However, filter media provided good hydraulic performance for only two weeks after reconstruction and was totally clogged within a period of one month. To restore the hydraulic performance of the filter media, backwashing was performed in September 1997 but the filter media showed better performance for only two to three weeks and its hydraulic conductivity decreased rapidly (Harper, 1999). The filter media was again backwashed in October and November 1997, but it was observed that the filter media became channelized due to repeated backwash which allowed the water to enter the under-drain system without passing through the filter media. Harper (1999) also claimed that significant ground water loss helped the dry detention pond to remain dry within the storm events, otherwise hydraulic performance of the under-drain system was insufficient to keep the water below the 100 year weir overflow elevation.

It has been found that dry detention ponds sometimes don’t work as designed due to poor maintenance. There can be many potential reasons for malfunctioning of this storm water management practice. Nnadi, et al, (1996) has carried out a study to investigate the performance evaluation of three non-functioning dry detention ponds with under drains in Central Florida. A survey of the as-built elevations of the inlet, outlet and under drain structures, and pond bottom revealed that ponds were not constructed to design elevations. It was found that the groundwater table stayed above the under drain elevations throughout the monitoring period. Soil samples were taken from three ponds and the permeability of each sample was found by laboratory testing. These rates ($1.63x10^{-4}$, $7.47x10^{-5}$ & $4.5x10^{-3}$cm/sec) were found to be lower than the standard permeability of 10^{-2} cm/sec (FDOT Design Standards, 1996). Moreover, all the three ponds were not maintained according to recommended guidelines and cattails and grass clippings were observed at the pond bottom which may have increased the organic loading in the pond.

Nnadi, et al, (1996) concluded that use of low permeability soils, under sizing due to change in the design criteria, elevations that differed from design elevations and poor maintenance were the primary causes of the failure of the three dry detention ponds. They suggested some corrective measures (Table 2.3) based on the problems identified in the ponds and a set of field investigation procedures was also developed. These items can be used to identify problems and retrofit a nonfunctioning dry detention pond with under drain.

Table 2.3: **Suggested corrective action (Nnadi, 1996)**

Problems	**Suggested Corrective Action**
Sediment trap clogged	Clean out or Replace Sediment Trap and/or Skimmer
Inlet clogged	Clean out or Dredge Inlet
Under drain clogged	Backwash Under drains
Outlet clogged	Clean out or Remove Clogging Materials
Unacceptable sieve analysis results	Scrapping & Retention of Low Permeability Soils
Is GWL > Pond Bottom Elevation	Decision based on Identified Problems, Possibly Redesign
Are Structures built to design	Decision based on Identified Problems, Possibly Redesign
Is Under drain crushed	Decision based on Identified Problems, Possibly Redesign
Layers of non homogeneous soils	Decision based on Identified Problems Possibly Redesign
Clogging of filter fabric	Decision based on Identified Problems Possibly Redesign
Under drain perforations clogged	Decision based on Identified Problems Possibly Redesign
None of the above	Possibly Replace Filter media

Galli (1992) analyzed the performance and longevity of 12 extended dry detention ponds in Prince George’s County, Md. It was found that a few of them did not meet their expected design life as they stopped functioning as designed within a period of 1.2 to 43 months. Very high detention times were observed in a few of the ponds as the filter media clogged soon after installation. As a result these ponds were behaving like wet ponds. Lindsey et al (1992) also surveyed 116 dry detention basins in Baltimore, Md. He reported that, although these dry ponds were not maintained properly, 62 out of 116 inspected dry detention ponds were functioning as designed. The most common problems reported for these ponds were excessive sedimentation, inappropriate ponding of water and clogging of the outflow structure. Parker (2002) surveyed four dry detention ponds with under drains in the Minneapolis – St. Paul, Minnesota metropolitan area. Three of them were reported to be working as designed. The one non-functioning pond experienced clogging of filter media and continuous standing water was observed.

3. Methods

A. Site Selection Criteria

The site selection criteria included the following elements:

1) Under-drains: Storm water is stored in dry detention ponds and primary source of evacuation of storm water is infiltration and evaporation. In order to evaluate the performance of filter media in dry ponds by comparing the influent and effluent concentrations, under drains must be provided beneath soil or sand media. Since this study focuses on the performance of dry detention ponds with under drains, all the ponds selected for it include an under drain system. Storm water after passing through the filter media enters into the perforated under drain (drain tile) and leaves the pond.

2) Single Inflow and Outflow: Many dry detention ponds have multiple inflow locations and some have multiple outflows. Since monitoring equipment is relatively expensive, and the possibility of having equipment that is not operating properly increases with number of monitoring stations. A single inflow and outflow were important criteria for the pond selection. All the ponds selected for this study have single inflow and outflow location.

3) Ease of Monitoring Equipment Placement: Primary measuring devices like weirs and flumes play an important role in providing accurate influent and effluent measurements for dry detention ponds with under-drains. However, sometimes it is difficult to install these weirs due to intricate geometry of the inlet and outlet structure of dry detention ponds with under drains. Moreover, there are some sites where monitoring equipment placement would be difficult, and require extensive construction. Therefore, installation of monitoring equipment and weirs were considered as important factors when selecting sites for this study and sites with better or easy installation conditions were preferred.

4) Accurate Flow Measurements: Accurate flow measurement is difficult at some sites. Most sites require adaptations to measure discharge with the desired degree of accuracy. Overland flow can allow the water to enter the pond without passing through the inlet structure and can disturb the mass balance of the whole system. Therefore, ability to adapt the inflow/outflow to meet the needs of accurate flow measurements was an important criteria for pond selection.

5) Access to the pond: Vegetation trends in dry detention basins should also be considered as dry detention ponds with excessive vegetation can create access problems and may require high amounts of rainfall to produce significant effluent runoff through the under-drains. Generally, maintenance and access to the ponds are not a problem because dry detention ponds are typically owned by a public entity that is helpful and willing to assist in a monitoring program.

6) Safety and Distance between the Ponds: Safety was also considered during site selection as some ponds are located in highway interchanges or at locations that would require significant safety precautions, which this project was unprepared to supply. Moreover, distance between the ponds is also an important factor while selecting multiple ponds as it would be difficult to monitor the sites regularly if they are located far apart from each other.

B. Site Description

Three dry detention ponds were selected for this study. All of them have under drains and single inlet and outlet structures. The first two ponds selected for this research study were built by Minnesota Department of Transportation (Mn/DOT) in district 7 (near Mankato) of Minnesota. The Mn/DOT designation given to these ponds are Mn/DOT pond 4012-03 and Mn/DOT pond 4012-04. Their plan views are shown in Figure 3.1. Mankato is a city of approximately 33,000 people located 85 miles south west of Minneapolis - Saint Paul. Ponds 4012-03 and 4012-04 are located on the east and west side of the intersection of State Highway 22 and County Road 102, respectively. They are equipped with under-drains and are situated parallel to each other, which allow monitoring during the same storm events. A special seed mixture at a rate of 16 kg/acre was sprinkled after construction of both ponds for plant growth.

Pond 4012-04 is approximately 0.2 acres in size and is surrounded by single family houses on the south side and by County Road 102 on the north-west side (Figure 3.1). It was constructed in 1999 and has a drainage area of about 7 acres. Two swales, one parallel to County Road 102 and other parallel to the State Highway 22, convey the storm water runoff to the inlet of the pond 4012-04. Storm water runoff enters the pond through a 142 ft long reinforced concrete culvert (24 inch diameter) under County Road 102. No specific details are provided about the return period of the design storm event for pond 4012-04. However, according to Mn/DOT, all the storm treatment practices including dry ponds are designed for a two year event as a minimum. Most of them, however, can handle a much larger event and would not be overwhelmed until a 50 or 100 year storm event. After passing through the culvert, runoff flows down a rock channel (rip rap) into the pond. The sides of the pond are covered by thick grass and the pond bottom is sheltered with Elymus, Rye Grass (Perennial) and Alfalfa (Creeping) along with some other native plant species. Native soils are used as filter media for pond 4012-04 and a rock filled trench holds 67 ft long (6 inch diameter) perforated polyethylene under drain pipe is installed at the bottom of the pond. Two 6 inch diameter drop inlets are provided to draw down the water level in the pond, if desired. Perforated stand pipes were installed over the drop inlets to regulate the direct entrance of the storm water runoff in to the under drain pipe. An outlet structure built at the south-east corner of the pond 4012-04 receives storm water runoff through 6 inch under-drain pipe. The outlet structure is 4 ft deep and has a top diameter of 27 inches and discharges storm water downstream to a grass waterway through a 2 ft diameter pipe.

Pond 4012-03 has an area of approximately 0.19 acres, a drainage area of approximately 10 acres, and was built in 1999. A stream runs parallel to the east side of the pond and shares a steep slope with the southern boundary of the pond (Figure 3.1). Erosion was observed at the south-east corner of the pond in 2003 and rip rap cover was provided over the affected area as a remedial measure to stop the direct inputs of the runoff from the pond into the stream. Two swales/ditches convey the storm water runoff to the inlet of the pond. A 90 ft long, 2 ft diameter reinforced concrete culvert discharges the runoff into the pond. Unlike pond 4012-04, little vegetation was observed at the bottom of the pond 4012-03. However, the sides of pond 4012-03 are covered with heavy grass. The detention pond 4012 -03 is constructed with an under drain system and a total of 151 ft long (4 inch diameter) perforated polyethylene under drain pipe is installed at the bottom of the pond. Native soils are used as filter media which surround the under drain pipe without any gravel bed protection. At the south corner of the pond 4012-03, an under drain pipe was connected to a six inch outlet pipe which discharged the runoff in to the downstream water body.

The third pond selected for this research study was built by Carver County, Minnesota in 2002 and will be referred to as “Carver County dry detention pond”. Carver County is located in central Minnesota and cities and towns included in it are Carver, Chanhassen, Chaska, Cologne, Mayer and Norwood. Carver county dry detention pond is located along Highway 212 and lies one mile West of Cologne in the Carver Creek watershed. It drains a watershed that encompasses the corner of the Carver County’s new public works facility site. Carver County public works facility site consists of 45 acres with impervious area on the site totaling approximately 10.2 acres. The first phase of construction consisted of Carver County public works facility. Future construction of County facilities may occur on the remainder of the site.

Carver County dry detention pond is approximately 3 acres in size with a slope of 1% from inlet to outlet. It is designed to provide storage up to a 100 year – 24 hour event on the site. Storm water runoff is directed through grass waterways to a small pretreatment pond (forebay) before it enters the pond. After entering into the detention pond the storm water runoff infiltrates through the under drains. A series of rock filled trenches holding perforated drain tile acts as an under drain for the pond. Eight sets of 8 inch diameter perforated polyethylene under drain pipes (Y-shaped) are joined together by 8 inch × 8 inch × 4 inch polyethylene laterals oriented at 45 degree. Every set of under drain consisted of two arms, each 30 ft long with a diameter of 4 inches. A total of 140 ft of 8 inch diameter under drain pipe and 480 ft of 4 inch diameter under drain pipe were installed within the detention pond as shown in Figure 3.2.

A cross section of Carver County pond under drain system is shown in the Figure 3.3. The under drain pipe was surrounded by a mixture of soil and ASTM C33 fine sand which was used as filter media for Carver County dry detention pond. Carver county dry detention pond is unique compared to the other two ponds in this study because a filter fabric was used to wrap the soil-sand filter media and under drain pipe. A layer of six inches of native soils (typically tighter clays for Carver County) was used to burry the filter fabric to avoid its exposure at the surface. The under drains collect the infiltrated storm water and drain it into the outlet structure. The outlet structure of the Carver County dry detention pond is 5 ft in diameter and receives infiltrated runoff through an 8 inch under drain pipe as shown in Figure 3.4. This large outlet structure was provided so that the rainfall in excess of the design storage volume could discharge downstream. A 18 inch (inner diameter) reinforced concrete pipe takes the runoff from the outlet structure and discharges it into the downstream watershed. Native plants were planted on the site including the grass waterways (ditches) and areas around the parking lot.

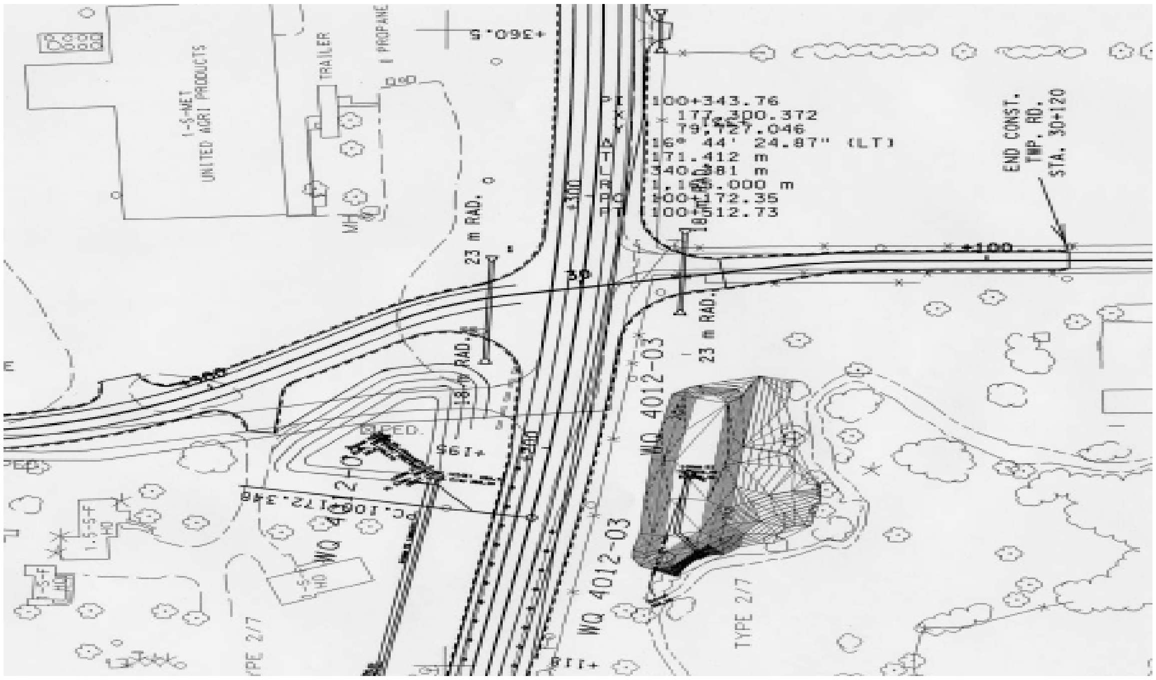

Figure 3.1: Plan view of Mn/DOT pond 4012-03 and Mn/DOT pond 4012-04

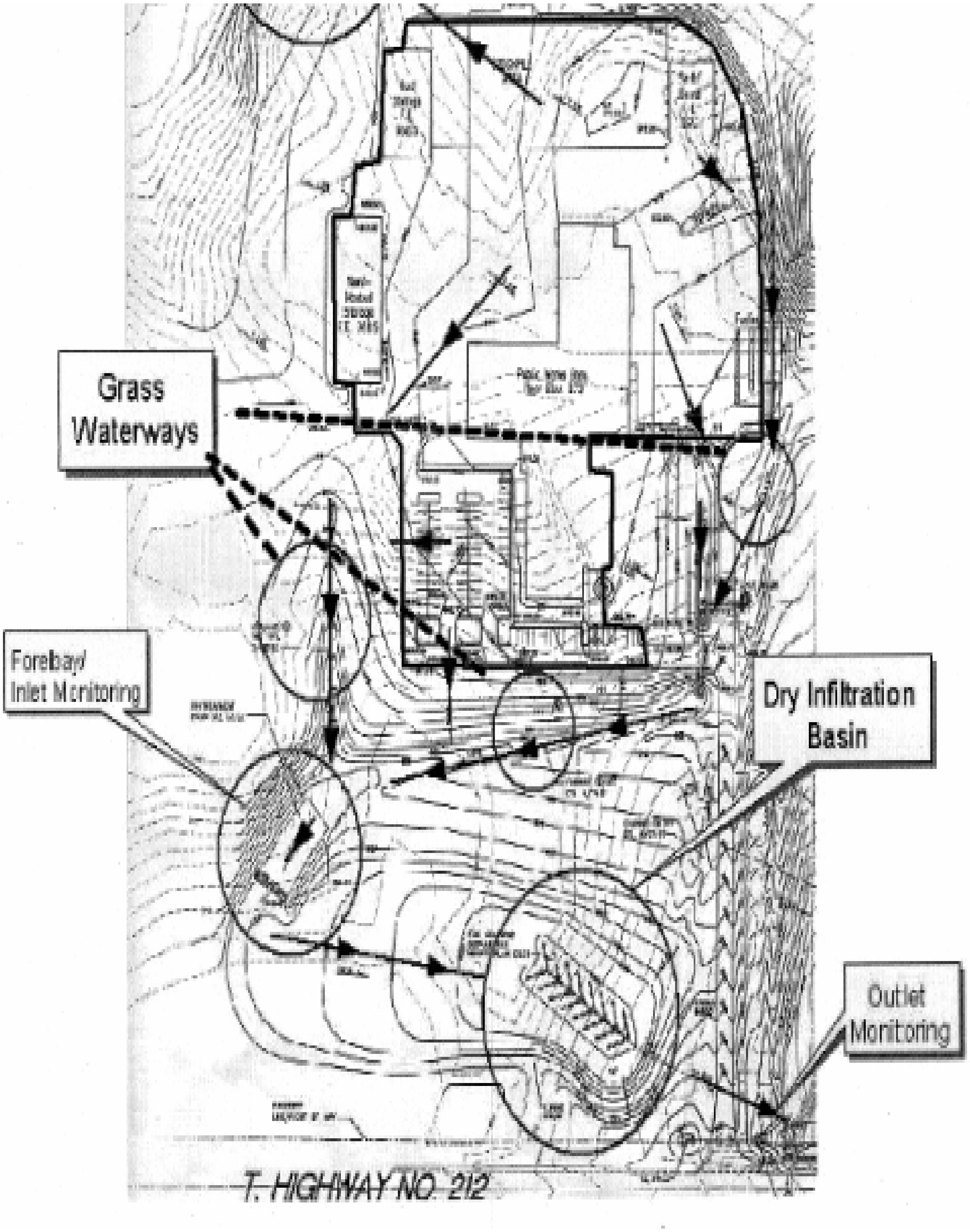

Figure 3.2: Plan view of Carver County dry detention pond

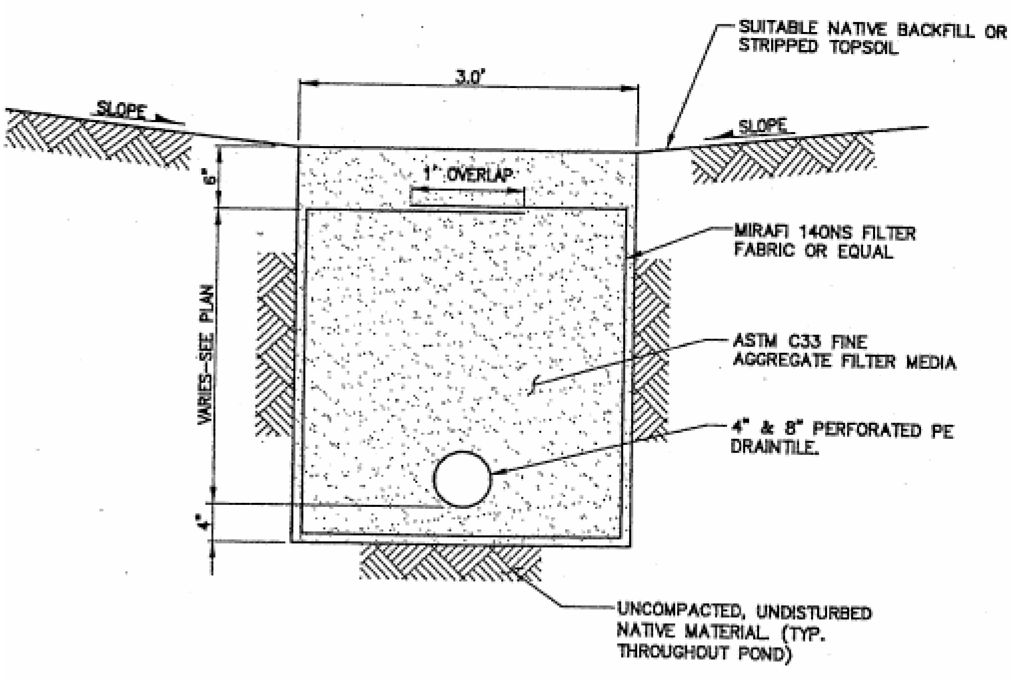

Figure 3.3: Cross section of Carver County pond under-drain system

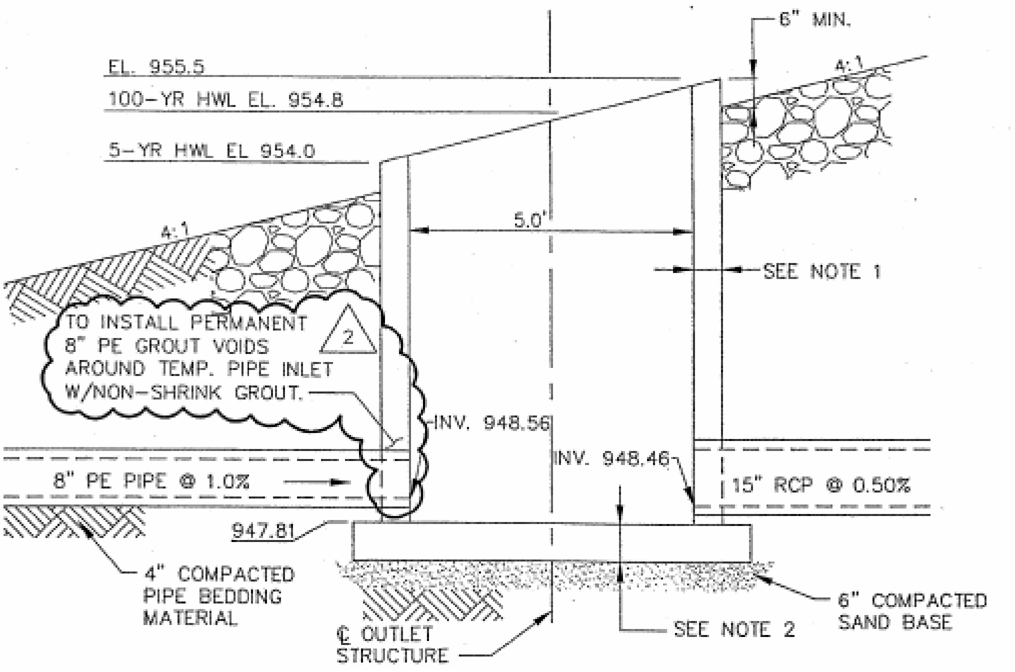

Figure 3.4: Outlet structure of Carver County dry detention pond

C. Instrumentation & Field Sampling

Storm water runoff monitoring provides information about the quantity and quality of runoff. One objective of this study is to monitor storm water runoff and evaluate the concentration of pollutants present in the runoff. This goal was achieved by collecting and analyzing representative samples from different storm events at the three ponds previously discussed. Automated storm water quality sampling requires particular equipment to be installed at the sites. A complete survey of different brands (Isco Inc, NE; American Sigma Inc, CO and Global Water Instrumentation, CA) of storm water monitoring equipment was carried out before obtaining any equipment. Different types of automated samplers and flow meters (ISCO) were installed at the sites to obtain continuous records of inflow and outflow from the selected ponds. Isco Flowlink 4 software was used at all three sites for advanced data management and helped in computation of different hydraulic parameters using the recorded measurements.

Field sampling was carried out by applying simple sampling strategies. Typically, flow or time interval between samples and minimum flow depth threshold are the two important factors considered during programming the equipment. Since flow based sampling provides a better representation of storm events because the percentage of samples taken at high flow rates is greater (Miller et al, 2000), all the equipment used in this study was programmed to provide continuous flow weighted storm water samples. A specific minimum flow threshold was also programmed according to each site based upon experience. When the flow depth exceeded the minimum level threshold and the flow interval condition was met, the sampler was triggered to take samples. Different flow intervals were used at the inlet and outlet of three sites during the field sampling.

There are two different ways to collect the samples using automated samplers, discrete sampling and composite sampling. Discrete sampling involves one sample per bottle and provides a detailed picture of pollutant concentrations in a storm event over time. Composite sampling provides more than one sample per bottle and permits larger magnitude events to be sampled. However, it decreases the number of samples representing a storm event and increases the percentage of errors in load estimates (Miller et al, 2000). In this study, a 24 bottle configuration was used to collect discrete samples at all the selected sites. However, all the automated samplers were programmed to take 4 samples per bottle. Hence a composite-type discrete sampling technique was used to collect samples for longer durations and higher magnitude storm events than would have otherwise been possible.

(1) Calibration of Discharge Measurements

Compound V-notch Weir

Compound V-notch weirs were used at all three of the monitored dry detention ponds in this study. These weirs allow for accurate measurements at low flow rates while accommodating high flows with the rectangular stage. While there has been research in the past on this type of weir (Bergmann, 1963), it was not sufficient for the purposes of this study.

An experimental setup was introduced in St. Anthony Falls Laboratory to develop a water level to discharge relationship. A 3 inch deep V-notch with 4 inch extensions on either side was tested. Point gauges were utilized to measure water levels at the weir and for the rectangular weir upstream used for the calibration. Raw data from the USBR Bergmann (1963) report was also used to expand the amount of data available for a curve fit.

It was hypothesized that the equation could be formed by simple addition and subtraction of the different flow relationships for V-notch weirs and rectangular weirs. The basic equations for the V-notch and rectangular weirs follow in equation 3.1 and 3.2 (MPCA 2006):

$$Q_{V-notch} = \sqrt{2g}\frac{8}{15}C_d H^{2.5} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

$$Q_{rec\tan gular} = \sqrt{2g}\frac{2}{3}C_d L H^{1.5} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

Where:

g = gravitational acceleration
C_d = coefficient of discharge for a specific weir
H = water level above weir
L = total length of horizontal crest of rectangular weir

Typical coefficients of discharge for V-notch weirs and rectangular weirs are .58 and .62 respectively. These coefficients are incorporated to account for various types of losses. Thus it would follow that we can combine these equations and determine new coefficients of discharge to define a general compound weir equation.

To develop a general equation for the compound weir, section 2 was subtracted from section 1 to account for the V-notch weir and all flow above it, then section 3 was added to account for the rectangular portion of the weir, as given in equation 3.3.

$$Q_{compound} = Q_1 - Q_2 + Q_3 \qquad \ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

Where:

$Q_{compound}$ = Discharge of entire compound weir
Q_1 = Discharge of V-notch weir
Q_2 = Total discharge of sections 2
Q_4 = Total discharge of sections 3

Figure 3.5 shows these different sections of flow.

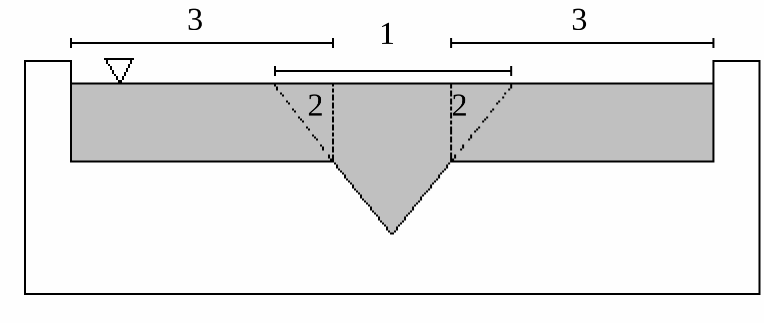

Figure 3.5: Hypothesized flow sections for compound weir.

Substituting equations 3.1 and 3.2 into equation 3.3 appropriately, the following general equation for a compound weir is obtained:

$$Q_{compound} = \sqrt{2g}\left[\frac{8}{15}C_{d1}H_1^{2.5} - \frac{8}{15}C_{d2}H_2^{2.5} + \frac{2}{3}C_{d3}LH_2^{1.5}\right] \quad \text{........ (3.4)}$$

Where:

$Q_{compound}$ = Discharge of compound weir
H_1 = Head above the invert of the V – notch (Figure 3.6)
H_2 = Head above the horizontal crest(Figure 3.6)
L = Combined length of the horizontal portions of the weir (Figure 3.6)

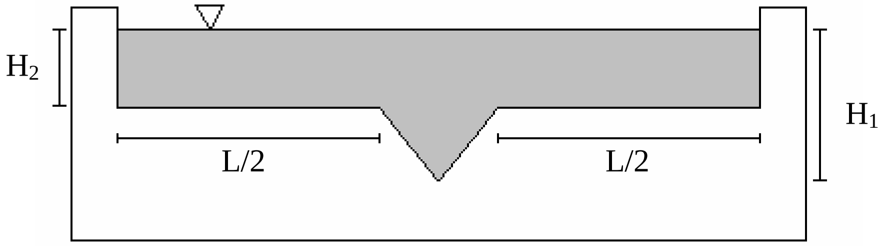

Figure 3.6: Significant physical measurements of a compound weir.

The data obtained from the weir calibration experiment was combined with data from Bergmann's USBR report. A Matlab script was written to iterate on discharge coefficients (C_{d1}, C_{d2}, C_{d3}) combinations in our hypothesized equation. The combination with the lowest standard fraction error was selected. This combination yielded less than 2% error for both Bergmann's data and the data collected in our experiment. It is important to note that this equation is non-dimensional and only requires the user to be consistent with selected units. The coefficients:

$C_{d1} = .57$
$C_{d2} = .55$
$C_{d3} = .64$
resulted in the following fitted equation:

$$Q_{compound} = \sqrt{2g}\left[0.30H_1^{\ 2.5} - 0.29H_2^{\ 2.5} + 0.43LH_2^{\ 1.5}\right] \qquad \text{……..}\ (3.5)$$

Circular Weir

Continuous outflow hydrographs were recorded by the automatic sampler with a flow module from May 2004 to November 2004 and May 2005 to August 2005 at the outlet of the Carver County dry detention pond. The early storms were not included in this study because the sampler at the outlet of the Carver County pond did not collect samples due to low depth of flow in the outflow pipe. Analysis of these three storms indicated that no velocity was recorded by the area velocity sensor located in the outlet pipe. On the other hand, the sensor did record continuous outputs of water level in the pipe. The maximum depth recorded for these storms was less than 2 inches. Research about the performance characteristics of the Isco area velocity sensor revealed that the depth of water over the sensor in the conduit should be greater than 2.5 inches to record any velocity. To overcome this difficulty, a 3.5 inch high plastic circular weir was installed down stream of the sensor in the outlet pipe to raise the depth of the water over the area velocity sensor (Personal Communication with ISCO, May 2004). The Isco 750 area velocity flow module provided continuous records of velocity profile after the installation of circular weir. Later, during effluent data analysis, it was found that effluent discharges calculated by the Isco area velocity flow module exceeded the influent discharges by 2 to 5 times for different storm events. These exceptionally large effluent discharges as compared to influent discharges through the outlet pipe initiated research to identify the cause of the problem.

An experimental setup was introduced at the Saint Anthony Falls Laboratory to simulate the field conditions at the outlet of the Carver County dry detention pond. The 6700 Isco sampler along with the Isco 750 area velocity flow module was brought to the laboratory from the outlet of the Carver County pond. A 3 inch high plastic circular weir was installed down stream of the area velocity sensor in a 10 ft long polyethylene pipe with an internal diameter of 15 inches. A river water intake was connected to one end of a paddle type flow meter which was calibrated for flow measurements. The other end of the paddle type flow meter discharged into the pipe to supply the flow for measurement by the area-velocity sensor. A series of thirteen experiments of different durations (1-24 hours) were performed at flow rates ranging from 0.03cfs to 0.33cfs, a range typical of outflow from the Carver County dry detention pond. A calibration factor was computed by comparing the discharges recorded by the paddle type flow meter and area velocity flow module.

The experimental results are given as the ratio of the area velocity sensor-measured flow volume to calibrated flow volume versus flow rate in Fig. 3.7. It is evident from the figure that the area velocity flow sensor over-predicted the discharge through the pipe. The extent of error in discharge measurements was found to be greater at lower flow rates. Further laboratory experiments revealed that the area velocity sensor measured the water level to a reasonable accuracy, as water levels in pipe during different tests were manually measured and compared to the recorded levels. This indicated that the velocity recorded by the sensor was not accurate.

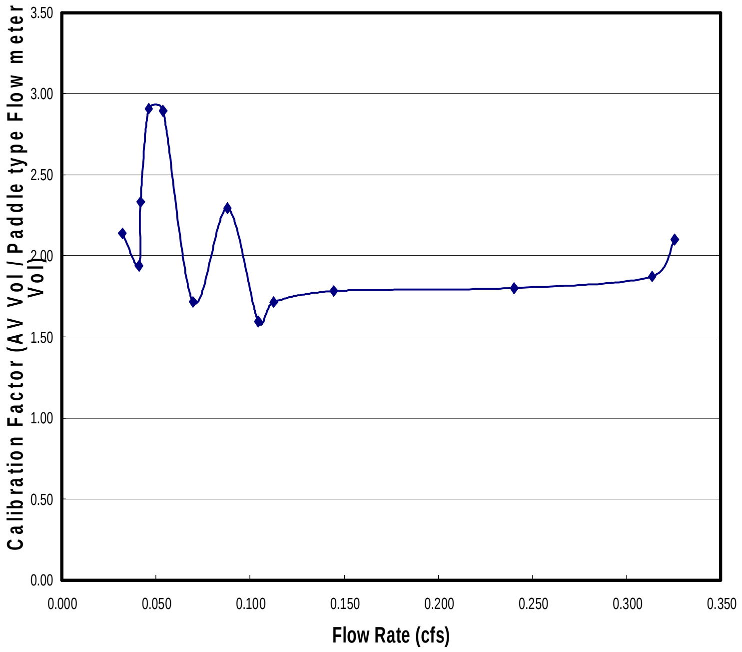

Figure 3.7: Comparison of effluent volumes recorded by calibrated paddle type flow meter and Isco area velocity flow module at Saint Anthony Falls Laboratory.

The accurate water level measurements combined with the circular weir meant that discharge could still be computed if an accurate head versus discharge relation could be developed. Previously an equation had been available which would measure discharge at flow rates that did not overtop the circular weir (Herbert Addison, 1941, page 91). When this equation was used at high flows the flow rate would diverge as the water level increased above the top of the weir, causing difficulties at determining the flow through the pond. Most flows in 2005 overtopped the weir at some point, thus a new discharge equation was required.

An additional experiment was conducted at the Saint Anthony Falls Laboratory to develop a circular weir equation. A 17.5 inch pipe was connected to a high volume water line and fitted with several weir sizes to allow for calibration of semi-circular weirs when water levels exceed the upper edges of the weir.

It was determined through modeling and further experimental analysis that the equation for any specific combination of a circular weir and pipe is highly dependent upon the ratio of the weir height to the diameter of the pipe (Fig. 3.8), that is:

$$C = \frac{d_0}{D} \qquad \text{…………..} \quad (3.6)$$

Where:
d_o = weir height
D = inside pipe diameter
C = constant based on pipe/weir combination.

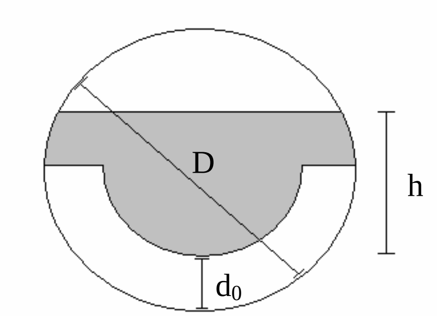

Figure 3.8: Cross-section of outlet pipe with circular weir and definitions used in Eqs. 3.6 and 3.7.

An equation was found that functioned for an 18 inch pipe with a weir to dipe diameter ratio of C = .194. The equation showed sufficient accuracy, and could be used through the entire range of water levels provided that open channel flow it maintained. The equation developed for the pipe in the outlet of the Carver County detention pond is as follows:

$$\frac{Q}{\sqrt{g}D^{2.5}} = .4882\left(\frac{h}{D}\right)^{1.98} \qquad \text{…………..} \quad (3.7)$$

Where:
Q = Discharge in cubic feet per second
g = Gravity
h = Water level above bottom edge of weir

Since this equation provided an appropriate fit for flow calibration, it was used to determine the effluent flow for all storms. It should be noted that this equation is good for all ranges of h, provided that open channel flow is maintained.

The head-discharge curve comparison for the experimental data and the standard semi-circular weir equation are shown in Figure 3.9, which illustrates that the circular weir expression provided a sufficiently close approximation of the calibrated real discharges obtained during the laboratory experiments. Cumulative total effluent volume was also calculated for each of the twelve storm events and used in preparation of a volume budget for the Carver County dry detention pond. The volume budget showed effluent volumes to be approximately half of their corresponding influent volumes. This is reasonable since dry detention ponds often exhibit significant amounts of infiltration.

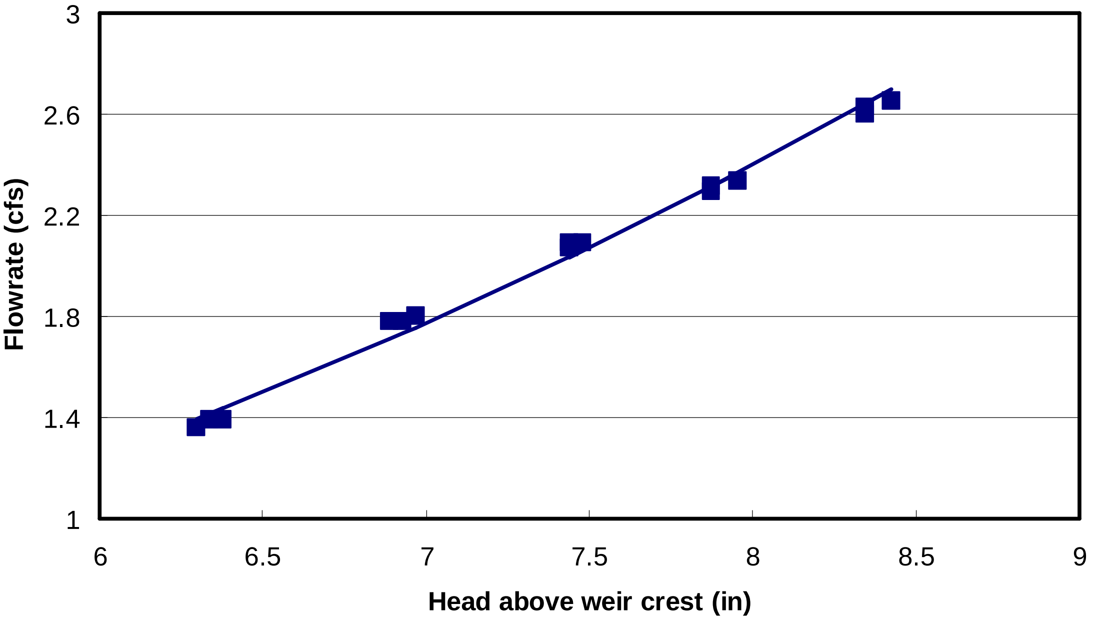

Figure 3.9: Head-Discharge relationship of Eq. 3.7 compared to experimental data.

(2) Instrumentation and modifications at Mn/DOT pond 4012-04:

Pond 4012-04 is owned and maintained by Minnesota Department of Transportation. It was monitored from July 2004 to November 2004. A 2700 series Isco portable sampler was installed at the inlet and outlet of the pond 4012-04. They were programmed to collect flow weighted storm water samples in 24, 1 liter wedge shaped bottles. Similarly, Isco 4230 bubbler flow meters were installed at the inlet and outlet of pond 4012-04 to pace the sampler to collect flow proportioned samples. Monitoring equipment enclosed in an environmental cabinet at the inlet of pond 4012-04 is shown in Figure 3.10. The Isco 4230 bubbler flow meter uses an internal air compressor to supply a metered amount of air in the channel through a tube, called a bubble line. One end of the bubble line is connected to the differential pressure transducer in the flow meter and the other end is submerged in the channel. The level of water in the channel was determined by measuring the pressure required to force the air bubbles out of the bubble line. The level measurements are then converted to flow rate by the flow meter at the inlet and outlet of pond 4012-04.

A compound weir, with a 5 ft wide rectangular crest and 1 ft deep, 90 degree V-notch, was installed at the inlet of the pond 4012-04 (Figure 3.11). Similarly, a 3 ft wide and 1 ft deep compound weir was installed at the outlet of the pond 4012-04 (Figure 3.12) in the manhole. The V-notch portion of the compound weir might easily handle the normal range of discharges at the inlet of the pond. However, the rectangular portion of the compound weir will account for occasional high discharges.

Figure 3.10: Storm water monitoring equipment at the inlet of the Mn/D0T dry detention pond 4012-04

Figure 3.11: Compound weir, bubble line and suction line at the inlet of the Mn/D0T dry detention pond 4012-04

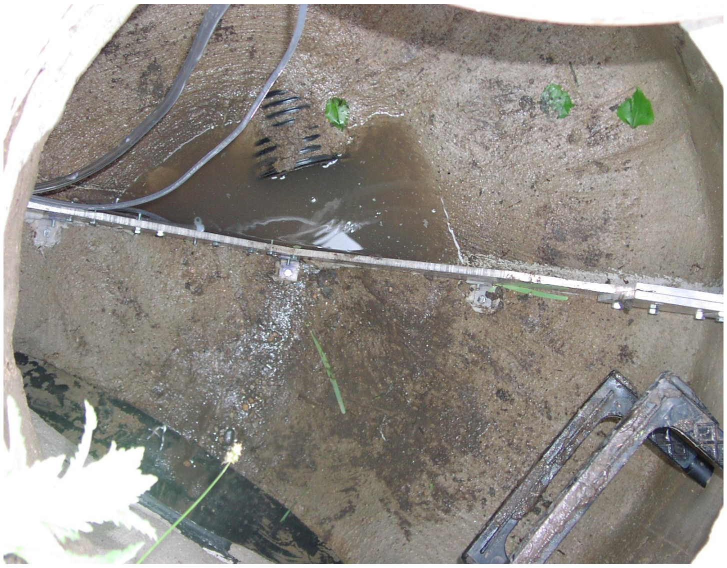

Figure 3.12: Top view of the compound weir, bubble line and suction line at the outlet of the Mn/D0T dry detention pond 4012-04

A bubble line was attached to the Isco 4230 bubbler flow meter and a suction line was connected to the Isco 2700 sampler. Both the lines were installed upstream of the compound weirs at the inlet and outlet of pond 4012-04. A simple garden rain gauge was used at the outlet of the pond 4012-04 to estimate approximate rainfall measurements.

(3) Instrumentation and modifications at Mn/DOT pond 4012-03:

Pond 4012-03 is also owned and maintained by Minnesota Department of Transportation. It was selected for this research study and was monitored from July 2004 to November 2004. A 2100 series Isco portable sampler was installed at the inlet and outlet of Pond 4012-03 to collect flow based samples. For this purpose, an Isco 4120 Submerged Probe Data Logger was connected with samplers at the inlet and outlet to pace the samplers and store all the all the hydraulic inputs and outputs from the pond. The Isco 4120 contains a differential pressure transducer to measure the level which is used to determine the discharge using programmed level to flow conversions. Unlike flow meters, submerged probe data loggers were programmed using a laptop computer loaded with Isco Flowlink 4 software.

Pond 4012-03 experienced some erosion and infiltration problems in 2004. Originally, there was one under drain in pond 4012-03. However, when it was selected for this study, addition of two new under drains was recommended during a site visit by the Technical Advisory Panel (a panel comprised of 7 practicing engineers) of the project to improve the infiltration mechanism of the pond. As a result, the Minnesota Department of Transportation, Mankato office, installed two new 200 ft long 6 inch polyethylene perforated under drain pipes at the bottom of pond 4012-03. Almost half of the existing (original 4 inch, 151 ft long) under drain was removed during the installation of new under drains. Hence, a total of 400 ft, 6 inch diameter and 75 ft, 4 inch diameter under drains were installed at the pond 4012-03. All three under drains combined together in a junction box at the extreme south corner of the pond and a new outlet structure was also installed. The outlet structure was a 1 ft wide and 8 ft deep AgriDrain® box which was buried in the berm at the southern corner of the pond (Figure 3.13). One 6 inch diameter pipe was installed to convey the infiltrated runoff from the junction of three under drains to the outlet structure of the pond.

A compound weir with a 1 ft deep 90 degree V-notch cut into a rectangular notch of 5 ft, was installed at the inlet of pond 4012-03 (Figure 3.14). A 6 inch V-notch weir was placed at the bottom of the outlet structure of the pond 4012-03 for accurate flow measurements. Suction lines and submerged probe sensors were attached to the bottom of the weirs at the inlet and outlet of the pond 4012-03.

All the monitoring equipment at the inlet and outlet of pond 4012-04 and pond 4012-03 was powered by deep cycle marine batteries (Figure 3.10). Seven ft tall, 3.6 ft wide and 2.1 ft deep steel cabinets were anchored to a concrete base by Minnesota Department of Transportation. These Cabinets housed the monitoring equipment at the inlet and outlet of pond 4012-04 and pond 4012-03. Four Global Tech (PRO 5W) solar powered battery chargers were attached to the top of the steel cabinets at the inlet and outlet of both ponds to continuously charge the marine batteries. A laptop PC loaded with Isco Flowlink 4 software was used to retrieve the data from the inlet and outlet of pond 4012-04 and pond 4012-03.

Figure 3.13: AgriDrain ® Outlet structure and environmental cabinet at the outlet of the Mn/D0T dry detention pond 4012-03

Figure 3.14: Compound weir at the outlet of the Mn/D0T dry detention pond 4012-03

(4) Instrumentation and modifications at the Carver County dry detention pond:

The Carver County dry detention pond is owned and maintained by Carver County. To officially take over the monitoring of Carver County dry detention pond for this study, an agreement was signed between the Saint Anthony Falls Laboratory and Carver County in the beginning of 2004. Carver County pond was monitored from May 2004 to November 2004 and May 2005 to August 2, 2005, and twelve storm events were recorded during this period. A 6700 series portable Isco water quality sampler, owned by Carver County, was installed at the inlet of Carver County dry detention pond. A complete set of 24, wedge shaped 1 liter bottles were installed inside the sampler to preserve the storm water runoff samples. The unit was programmed to collect samples on a flow-weighted basis and to provide hydraulic inputs into the pond with measurements stored in the internal memory at 10 minute intervals. A tipping bucket Isco rain gage was available at the inlet of pond. It provided information on rainfall such as total rainfall amount, antecedent dry days and rainfall intensity for each storm event.

A five ft wide rectangular sharp crested weir was installed at the inlet of Carver County pond to enable accurate inflow measurements to be made (Figure 3.15). The weir was installed by a Carver County Public Works crew in 2003. Later, an insert was installed to turn the weir into a compound weir (Figure 3.16). An Isco 710 Ultrasonic Flow Module was plugged directly into a 6700 series sampler at the inlet of the pond. The sensor on the 710 Ultrasonic module was installed above the water surface in the flow channel at the inlet of the Carver County dry detention pond. It transmitted a sound pulse which was reflected by the water surface of the channel. The elapsed time between sending the pulse and receiving an echo determined the depth of the liquid in the channel. The level/depth measurements were then used to calculate the total discharge through the inlet of the pond. The combination of sampler, ultrasonic module and tipping bucket rain gauge provided a continuous hydrograph of inputs (level, flow rate and rainfall) for the inlet of Carver County dry detention pond.

At the outlet of Carver County pond, a 6700 series portable sampler was programmed to take flow based storm water runoff samples. Unlike the inlet, a 750 Area Velocity Flow Module was directly connected to the sampler at the outlet of the pond. The Area Velocity Flow Module sensor was installed in the outlet culvert using a circular spring ring to keep the sensor attached to the bottom of the culvert pipe. The module uses Doppler technology to measure the average velocities in the pipe. An integral pressure transducer which is also enclosed in the Area Velocity sensor measured water depths to determine flow area. The 6700 sampler then calculated the discharge by multiplying the recorded average velocities and corresponding flow areas. As mentioned earlier, the probe was used, in this case, as just a pressure transducer and used with a 3.5 inch circular weir inside the outlet pipe.

The monitoring systems at both the inlet and outlet of Carver County dry detention pond were powered by heavy duty deep cycle marine batteries. Global Tech (PRO 5W) solar powered battery chargers/maintainers were also installed at the inlet and outlet of the pond (Figure 3.17). They kept the marine batteries in fully charged condition and virtually eliminated the need to visit the site for periodic battery replacements. 6700 Isco samplers and 700 series Isco modules are water- tight, corrosion resistant, and can be installed without additional protection. However, all the monitoring equipment at the inlet and outlet of the Carver County pond was enclosed in lockable wooden environmental cabinets (Figure 3.17). A laptop PC equipped with Isco Flowlink 4 software was used to retrieve the data from the 6700 samplers at the inlet and outlet of the pond. Flowlink software not only allowed for the review and analysis of the data at site but also generated a variety of graphs and reports.

Carver County Public Works office staff monitored the storm water runoff at Carver County dry detention pond during 2003 but as indicated by the data, it appeared there was no discharge at the outlet of the pond. The same trend was observed in the beginning of May 2004. It was discovered that velocity measurements were not recorded by the 750 Area Velocity sensor. Research about the performance of the Area Velocity sensor revealed that it requires more than 2 inches of water depth to measure the velocity profile. As discharge through the under drain pipe of Carver County dry detention pond was typically not adequate to generate a 2 inch depth over the sensor, an artificial head of water was created in the pipe by installing a 3.5 inch high circular plastic weir that fit the inside dimensions of the outlet pipe (Figure 3.18). The Area Velocity sensor was then installed 6 inches upstream of the circular plastic weir. The Area Velocity sensor started recording the velocity readings immediately after installation of the plastic plate.

It was observed during the sampling season 2004 that the rectangular weir at the inlet of the Carver County pond was too wide to provide accurate flow measurements. Therefore, in October 2004, the 5 ft wide rectangular weir was modified into a sharp crested compound weir which could more accurately measure flow rates at low discharges.

Figure 3.15: Rectangular weir at the inlet of Carver County dry detention pond

Figure 3.16: Rectangular weir with v-notch insert at the inlet of Carver County dry detention pond

Figure 3.17: Wooden environmental cabinet & solar panel at the outlet of Carver County dry detention pond

Figure 3.18: 3.5 inch high plastic circular weir at the outlet (culvert) of the Carver County dry detention pond

D. Laboratory Analysis:

All the selected sites were visited periodically for monitoring from May 2004 to November 2004 and May 2005 to August 2, 2005. Storm water samples collected by the samplers at the sites were transported to Saint Anthony Falls Laboratory (SAFL) after each storm event. Samples contained in 1 liter bottles were refrigerated after returning to the laboratory until analysis. Storm runoff samples were analyzed at SAFL to determine the total phosphorus, dissolved phosphorus, total suspended solid and total volatile solid concentrations.

Each sample was subdivided and 5 replicates were made for total and dissolved phosphorus analysis. Each replicate consisted of a 5 ml sample contained in U-shaped test tubes. Since phosphorus in storm water runoff may occur in combination with organic matter, the persulfate digestion method was used to oxidize the organic matter to release phosphorus in the form of orthophosphates. 1.04 ml (0.05 g solid) potassium persulfate was added to all the 5 ml samples for total phosphorus analysis. The potassium persulfate converts particulate phosphorus into dissolved form during the digestion process. All the samples were then digested in an autoclave at approximately 105 kPa for about 30 minutes (APHA, 1998). For dissolved reactive phosphorus analysis, five replicates of each sample were made by filtering 5 ml of sample through 0.45 *m*m syringe driven Millipore filter (33mm diameter). Digested total phosphorus samples and filtered dissolved phosphorus samples were then analyzed calorimetrically by a HACH spectrophotometer with infrared phototube at 880 nm as explained in Standard Methods for examination of water and waste water (APHA, 1998). All the glassware used in the analyses through out the season was acid washed in a 10% HCl acid bath according to procedure explained in Standard Methods (APHA, 1998).

Typically, the natural color of water does not interfere at high wavelength of 880nm. However, for highly colored waters, a turbidity correction must be applied (APHA, 1998). Therefore, turbidity corrections were applied to all the influent samples for total phosphorus by measuring the blank absorbance and subtracting it from absorbance of each sample. Individual calibration curves within the phosphate ranges indicated in 4500 – P.E.1c (APHA, 1998) were then prepared by plotting absorbance versus phosphate concentration.

Total suspended solid concentrations (TSS) for all the storm water samples were determined by filtering a well mixed sub-sample through a Whatman 934-A glass microfibre filter (25 mm diameter). A large oval chamber muffle furnace was programmed to dry the residue retained on the filter to a constant weight at 105^{o}C. Total volatile solid (TVS) concentrations were determined by filtering solids in the same way as described for the total suspended solids and then igniting the filter to a temperature of 550^{o}C. The procedures adopted for total suspended solid and total volatile solid analysis are described in Standard Methods 2540 D and 2540 E (APHA, 1998), respectively.

E. QA/QC & Data Analysis

As mentioned previously, five (5) replicates of each storm water sample were analyzed for total and dissolved phosphorus to increase the precision of nutrient analyses. Mean, standard deviation and 95 % confidence interval of five replicates for all storm events were also computed. To verify the accuracy of our results, influent and effluent samples from one storm event were sent to the Research Analytical Laboratory (RAL) at the Department of Soil Science, University of Minnesota. The comparison of the results between our laboratory (SAFL) and RAL indicated an average percentage difference of 1 % for influent total phosphorus samples. However, an average percent difference of 30% was observed for effluent total phosphorus comparison (Table 3.1). This large difference was due to a comparison between low effluent concentrations, close to the limit of detection (0.01 mg/L). In general, accuracy suffers when the limit of detection is approached.

Table 3.1: Comparison of influent and effluent Total Phosphorus analysis results between Saint Anthony Falls Laboratory and Research Analytical Laboratory (RAL) at the University of Minnesota.

			Total Phosphorus (mg/L)			
SE # 5	**SAFL1 (mg/L)**	**SAFL 2 (mg/L)**	**SAFL 3 (mg/L)**	**SAFL Mean**	**RAL**	**Difference**
Inlet 1	0.310	0.316	0.364	0.306	0.315	-2.857%
Inlet 3	0.508	0.514	0.47	0.364	0.36	1.111%
Inlet 4	0.567	0.551	0.532	0.416	0.44	-5.455%
Inlet 5	0.300	0.31	0.293	0.257	0.24	7.083%
Inlet 7	0.298	0.285	0.279	0.243	0.23	5.652%
					Average % Diff	1.11%
Outlet 1	0.079	0.081	0.077	0.077	0.05	54.00%
Outlet 3	0.128	0.13	0.123	0.128	0.11	16.36%
Outlet 5	0.073	0.073	0.071	0.071	0.06	18.33%
Outlet 7	0.071	0.071	0.067	0.069	0.05	38.98%
Outlet 9	0.063	0.063	0.065	0.062	0.05	24.00%
					Average % Diff	30.34%

F. Pollutant Retention Computations

The chemical analysis of storm water samples determined the mean influent and effluent concentrations of the five replicates for total and dissolved phosphorus. The event mean concentration (EMC) was then computed by averaging the mean concentration of all flow weighted samples collected for an entire storm event. The event mean concentration represents a flow weighted average concentration for the entire storm event and provides a simple way of comparing the change in concentration between the inflow and outflow of the ponds.

The performance of the dry detention pond in terms of pollutant retention was reported by computing retention efficiencies. The pollutant retention efficiency is a measurement of the percent of a pollutant removed from the water between the inflow and outflow of a pond (Winer, 2000). The pollutant retention efficiencies were determined by using the following relation:

$$\text{Pollutant Retention Efficiency (\%)} = [(\text{Conc}_{in} - \text{Conc}_{out})/\text{Conc}_{in}] * 100 \ldots(3.7)$$

Where:

Conc_{in} is the flow weighted mean concentration at inflow.
Conc_{out} is the flow weighted mean concentration at outflow.

The dilution of the influent concentration due to precipitation falling directly into the pond is an important factor which may significantly affect the retention efficiencies (Winer, 2000). Evaporation from the pond during periods when the pond contains water is negligible. Since the concentration based retention efficiencies do not account for rainfall inputs, adjustments to the influent concentrations were made for rainfall. To achieve this goal, the volume of rainfall that fell in the pond was computed by multiplying the total precipitation of a storm event by the total area of the pond and adding to the original recorded inflow volume.

The total load of the entire storm event was also determined by multiplying the event mean concentration by the total influent volume. The adjusted influent concentrations were then obtained by dividing the total load for each storm by the total volume (sum of rainfall volume and original influent volume). The equations used are as follows:

$$PL_{in} = C_{in} \times V_{in} \qquad \ldots\ldots\ldots\ldots\ldots. \ (3.8)$$

$$Adjusted\ C_{in} = \frac{PL_{in}}{V_{in} + V_R} \qquad \ldots\ldots\ldots\ldots\ldots. \ (3.9)$$

Where,
PL_{in} = Influent pollutant loads (mg),
C_{in} = Influent Mean Concentration (mg/L),
V_{in} = Influent Volume (L), and
V_R = Rainfall Volume (L).

The influent and effluent flow rates and runoff volumes of the dry ponds were computed by using the results of flow measurement devices. For the inlet discharge, an ultrasonic flow module provided continuous inputs of elevation relative to the weir, which were converted to a discharge by using the sharp crested rectangular weir equation or the compound weir equation after the weir was converted. Thus, flow rates throughout a storm event were obtained. A volume conversion was then performed in Isco Flowlink Software which multiplied the flow rate by the respective time span (10 min interval for this study) to determine the corresponding influent flow volumes. Rainfall volumes for each storm event generated by the direct input of the precipitation on the pond itself were then added to measured influent volumes to obtain total influent volumes at the Carver County dry detention pond. At the outlet of the pond, discharge was determined using a the sharp crested weir equation described previously in this chapter.

4. Results and Discussion

Attempts were made to characterize the dry detention ponds with respect to water quality measurements, residence time and water budget. These attempts were successful for one of the ponds. The lessons learned on the other two ponds, however, were significant and helpful. Rainfall and runoff measurements are summarized for every storm event and pollutant concentrations of storm water samples are presented with respect to water quality standards. Performance of dry detention ponds is reported in terms of pollutant retention efficiencies for all measured constituents during storm events. The mean, minimum and maximum pollutant concentrations and pollutant retention efficiencies are also compared to the other storm water dry detention ponds reported in the literature.

A. Performance of Mn/DOT Dry Detention Pond 4012-03 and 4012-04 with Under-Drains

Mn/DOT pond 4012-03 and Mn/DOT pond 4012-04 were designed, maintained and owned by Minnesota Department of Transportation. Pond 4012-03 was reconstructed by Mn/DOT Mankato in June/July of 2004 and additional under-drains were installed at the bottom of the pond to improve its drainage capacity. However, immediately after reconstruction, it was observed that the pond was unable to drain any of the influent discharge through the outlet structure (Fig 4.1). The intake structure (weir and culvert) worked efficiently to allow the storm water to enter the dry detention pond. However, the outlet structure at pond 4012-03, which was continuously monitored after every storm event, did not show any discharge. Overall, what began as a dry detention pond evolved to be a wet detention pond.

As a consequence of the poor performance of pond 4012-03, the pond was investigated and different possible solutions were explored. It was speculated that perhaps the new under-drains are not aligned properly with the outlet structure. However, after discussing the issue with Mn/DOT Mankato, it was concluded that the elevation mismatch between under-drain and intake of outlet structure was unlikely (Scott Morgan and Andrew Olmanson, Personal communication, August, 2004). Almost 8 inches of storm water was standing in pond 4012-03 after the first two storm events. This standing water eventually evaporated and infiltrated across the boundaries of the pond.

Further research was done in which the design of ponds 4012-03 and 4012-04 were explored. A comparison was made between the installation techniques adopted for the under-drains in pond 4012-03 and pond 4012-04. It was found that the under-drains were installed at pond 4012-03 by simply burying them under the native soil without using a gravel bed surrounding the under drains (Andrew Olmanson, Personal communication, November, 2004). However, the gravel bed technique was used at pond 4012-04 and this pond provided discharge through the outlet structure. It is possible that the thin openings in the polyethylene under-drain pipe at pond 4012-03 were blocked by the soil surrounding the pipe and as a consequence the storm water started to infiltrate across the boundaries of the pond instead of discharging through the outlet structure via under drains. It was also observed that the soil was not opened up by the plant root structure to allow drainage before filling as a wet pond. The following maintenance procedures have been recommended to the Mn/DOT Mankato District:

- Temporarily remove the riser on the overflow drain to allow pond to dry after storms.
- Mix gypsum or other soil-working agent into the soil surface.
- Seed a wetland species mix in the pond, which will take root under both wet and dry conditions
- Reinstall the riser on the overflow drain after the plants have taken root and pond is functioning well.

If these maintenance procedures are unsuccessful, it may be necessary to replace the filter media and reinstall the under drain system to alleviate the problems associated with the Mn/DOT dry detention pond 4012-03.

Figure 4.1: Mn/DOT dry detention pond 4012-03 after a few storms in August 2004.

Instrumentation was completed at pond 4012-04 in June of 2004 and it was continuously monitored from June 2004 through August 2005. The influent samples were collected for the first two storm events at the pond 4012-04 and the influent event mean total and dissolved concentrations were .86mg/L and.46 mg/L respectively. However, no effluent samples were taken by the samplers for these two storm events. As a result, another investigation was done to identify the source of the problem and modifications were implemented at the outlet of the pond 4012-04.

The design of the compound weir installed at the outlet structure of the pond 4012-04 was modified to satisfy the hydraulics of the under drain system. The compound weir was installed only 1 ft downstream of the under drain pipe due to the space restrictions in the concrete outlet structure (manhole). To ensure a proper notch across the weir, the height of the notch crest above the channel bottom was six (6) inches. The diameter of the under drain pipe was also six (6) inches and hence a backwater effect was caused by the weir. In August 2004 the V-notch of the compound weir at the outlet of the pond 4012-04 was redesigned and machined to 1.25 ft deep (original 1 ft deep) to avoid the back water effect. This modification in the weir design allowed the water to pass over the V-notch portion of the weir. No sample at the outlet was collected from August through October of 2004 due to insufficient rainfall to produce effluent discharge.

A noticeable change was observed in the pond bottom surface of dry detention pond 4012-04 throughout the growing seasons of 2004 and 2005 due to heavy vegetation. Elymus, Rye Grass, Alfalfa and some other local plant species (approximately 5 – 6 ft tall) completely covered the bottom as well as most of the side banks of the dry pond. These plants utilized a substantial amount of storm water and hence decreased the amount effluent discharge. It was observed that storm events with a total precipitation of one half inch were not adequate to produce a significant discharge through the outlet of the pond 4012-04. The pond is apparently operating effectively as a bio-retention/infiltration facility for storms of up to 1/2 inch precipitation.

During the 2005 monitoring season, samples were obtained from both ponds, however several issues were encountered which made their analysis problematic. The most significant issue was the lack of corresponding inlet and outlet samples. Corresponding inlet and outlet samples were only obtained in one instance at pond 4012-04. This lack of corresponding samples was most likely caused by a lack of sufficient precipitation to produce an effluent through the under drain. That is, most runoff entering the pond infiltrated without exiting through the effluent pipe. The second issue was water entering through the perimeter of the 4012-04, washing out large portions of the banks of the pond, filling in the dry detention pond and possibly clogging the sand filter during the later half of the 2005 season. This would result in unrealistic TSS and TP concentrations because of additional sediment from the pond banks. Thus, the corresponding samples that were taken were compromised. The final issue was vandalism and theft. Entire power systems were stolen from two of the cabinets on two separate occasions, at times causing the equipment to miss large storms. This can be an important consideration for monitoring at remote locations with minimal security. The following recommendations were made to Mn/DOT to remedy these problems:

- Fill and pack the wash to prevent any further erosion of the pond banks in pond 4012-04. Additional rip rap may also be necessary to reduce the possibility of further erosion in the future.
- The bottom of pond 4012-04 should be cleaned out and returned to its original level to allow for proper draining of the pond during storm events.
- More secure environmental cabinets should be installed at both pond 4012-03 and 4012-04 to prevent further damage and theft of equipment.

B. Winter Sampling at Mn/DOT Dry Detention Pond 4012-04:

Winter sampling attempts were made at pond 4012-04 to determine the difficulties in capturing the snow melt runoff. Winter sampling is of interest because of the potential for high pollutant concentration in low discharges that constitute snow melt. There are often many of these melting events during a winter, especially for the detention ponds that collect runoff from roads and highways. Chloride and suspended sediment concentration related to salt and sand use on roads is of special interest. The phosphorus that comes with the suspended sediments may also be usually high. There are, however, no reported attempts to sample during snow melt periods in northern U.S. climates, to our knowledge, in the literature.

An attempt to explore the potential challenges of winter sampling in Minnesota was thus undertaken. The first step was to keep all the monitoring equipment charged and in operable condition under extremely cold weather. The solar panels were originally installed at pond 4012-04 on the top of the environmental cabinets facing vertically upward. A steel stand was used to change the orientation (facing south at 15 degrees off of vertical) of solar panels to receive a greater amount of sunlight in the winter and to avoid the collection of snow over the solar panels. This was successful. The solar panels provided enough energy to keep the deep cycle marine batteries fully charged throughout the winter season.

The electronics of the equipment in the field cabinet performed well. No heater was required to keep the equipment operating properly, even though the Isco 2700 samplers are considered to be fairly old. This is consistent with experience involving weather monitoring equipment: the electronics work fine as long as they are enclosed. However, while analyzing the winter data recorded by Flowlink, it was observed that a number of samples were taken at certain time intervals but the 2700 Isco sampler did not contain any physical samples in the bottles. The Isco 4230 bubbler flow meter uses a compressor to pump the air into the channel by means of a bubble line (tube) which sits upstream of the inlet and outlet compound weirs. The other end of the bubble line is connected to the differential pressure transducer in the flow meter. When the pressure inside the bubble line is sufficient to counteract the hydrostatic pressure of the flow channel, the first bubble of air is released into the channel. The pressure transducer inside the flow meter senses this pressure and converts it into a depth. When the programmed level threshold is met, the flow meter sends a pulse to the Isco sampler to take a sample. However, during the winter season, solid ice covered the bubble line and the pressure transducer took the back pressure against the ice as hydrostatic pressure and sent a pulse to the sampler instructing it to take a sample. Under this scenario, the sampler pumped in only air. Thus the Flowlink data showed a number of samples but no actual sample was taken. This is the only issue encountered with winter sampling at the 4012-04 pond. If an improved pressure measurement method is possible during winter at this site, winter sampling may be viable.

Some manual samples of snow, ice and water were taken at pond 4012-04 site during a snow melt. The location selected for manual sampling included spill over inlet weir, surface and bottom ice near the inlet weir, along highway, ditch along highway, pre-treatment pond and detention pond. These samples were analyzed for total suspended solids, volatile suspended solids and chloride.

The total suspended solid, volatile suspended solid and chloride concentrations varied among the samples as shown in Figure 4.2. The sample taken along the highway showed highest concentrations for total suspended solids and volatile suspended solid. The lowest total suspend solid and volatile suspended solid concentrations were found in the sample with spill over the inlet weir. The pre-treatment pond sample showed higher total suspended and volatile suspended solid concentrations. The highest chloride concentration was found in the sample with spill over the inlet and the sample along the highway showed lowest chloride concentration. This is likely due to the high mobility rate of chloride in snow and ice melt runoff. When water freezes, contaminants such as chloride are exuded because they do not fit into the crystalline matrix. The chloride, then, is pushed to the surface of the snow or ice crystal and will be washed off in the early portion of the snow melt event. The sample taken from the detention pond showed minimum levels of chloride concentration and moderate amount of total and volatile suspended solids.

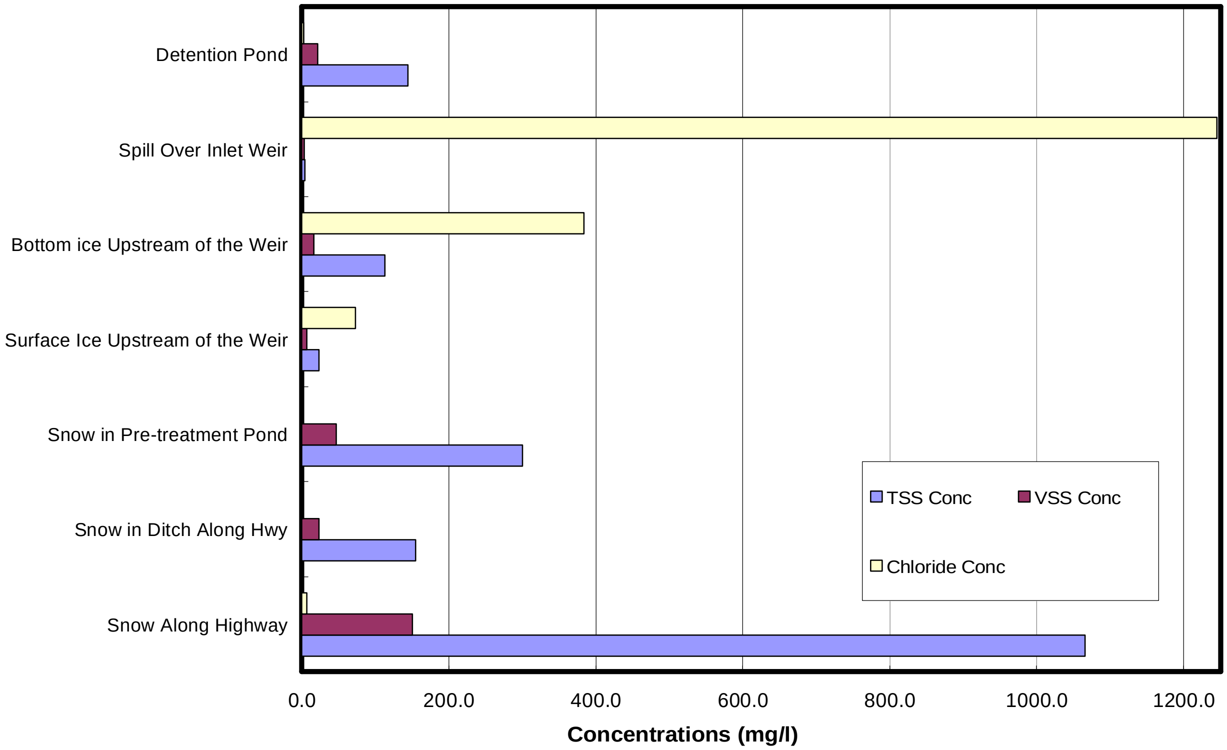

Figure 4.2: Comparison of total suspended solids, volatile suspended solids and chloride concentrations for different samples of snow, ice and melt water from upstream to downstream flow points.

C. Performance of Carver County Dry Detention Pond with Under-Drains:

(1) Rainfall characteristics

The twelve storms monitored at the Carver County dry detention pond from May 27, 2004 to September 14, 2004 and May 1, 2005 to August 2, 2005 each encompassed a record of rainfall characteristics and antecedent conditions. For each individual storm event, information on total rainfall, storm event beginning time, storm event duration, antecedent dry days, average rainfall intensity and residence time are included in Table 4.1. Storm #2 was unusually intense with overtopping of the storm water runoff into the outlet structure, resulting in incomplete treatment of a portion of the effluent. Additional small storms in 2004 and 2005 did not produce outlet samples and thus are not included in the results.

Table 4.1: Rainfall Characteristics and Antecedent Conditions for Six Monitored Storms at Carver County Dry Detention Pond with Under-drains

Storm #	Beginning Date	Total Rainfall	Event Duration	Dry Days Preceding Storm	Average Rainfall Intensity	Hours to Drain
		(in)	(hr)		(in/hr)	
1	27-May-04	4.10	53	1	0.077	328
2	10-Jun-04	2.23	2	0	1.115	64
3	5-Jul-04	0.70	25	1	0.028	60
4	10-Jul-04	2.25	6	4	0.375	109
5	5-Sep-04	1.58	13	6	0.122	51
6	14-Sep-04	1.39	18	7	0.077	97
7	7-Jun-05	1.67	96	0	0.017	138
8	12-Jun-05	.41	23	1	0.018	66
9	20-Jun-05	1.16	6	4	0.193	48
10	27-Jun-05	.40	9	5	0.043	20
11	29-Jun-05	.51	16	0	0.032	42
12	3-Jul-05	.18	2	2	0.103	12

Total event rainfall for twelve monitored storms ranged from 0.18— 4.1 inches, with a mean of 1.38 inches per storm event. Antecedent dry conditions varied between 1 to 7 days. Average rainfall intensity was calculated as the total rainfall divided by the event duration. Event duration was defined as the time span between the first amount of rainfall and the last significant amount of rainfall. It was observed that the Carver County pond did not drain completely after storm 1 and some water was already in the pond at the initiation of the exceptionally intense storm 2.

It is recommended by the Minnesota Pollution Control Agency that dry detention ponds fully drain within 48 hours of a storm (MPCA 2005). Thus the Carver County dry detention pond did not exhibit satisfactory residence times for most of the monitored storms. It was unable to drain storm 1 completely even after approximately two weeks. A similar trend was noticed for storm event 4, 6, and 7. The design drainage time of 2 days was not met for large storms.

(2) Storm water inputs and outputs at the Carver County dry detention pond

Continuous inflow hydrographs were recorded from May 2004 to November 2004 and May 2005 to August 2005 for the Carver County pond. A complete listing of measured influent storm water is exhibited in Appendix A and contains continuous inflow hydrographs along with information on different flow rates at 10 min intervals, average flow rates and cumulative total volume for individual storm events.

An estimation of rainfall-runoff relationships at the Carver County pond for six storm events is exhibited in Table 4.2. Total rainfall volume for the entire watershed was measured at the detention pond site by multiplying the total rainfall for each respective storm event by the contributing watershed area (45 acres). The product represents the total amount of rainfall volume which fell within the watershed during each storm event. Total influent volume was computed by adding the sampler measured influent discharge and total rainfall volume that fell directly into the pond.

Table 4.2: Summary of rainfall-runoff relationship for six storm events monitored at Carver County dry detention pond with under-drain

Storm	Total Rainfall	*T.R.V of Watershed	Measured Influent Volume	**Direct Rain Input	Total Influent Volume	Total Effluent Volume	*** R_v
#	(in)	(ft3)	(ft3)	(ft3)	(ft3)	(ft3)	
1	4.10	669,412	76,182	43,050	119,232	70,062	0.178
2	2.23	364,095	15,586	23,415	39,001	24,744	0.107
3	0.70	114,290	12,138	7,350	19,488	3,837	0.171
4	2.25	367,360	39,752	23,835	63,587	32,281	0.173
5	1.58	257,969	31,075	16,800	47,875	8,796	0.186
6	1.39	226,947	11,312	14,175	25,487	18,967	0.112
7	1.67	272,795	39,181	18,186	57,367	30,420	0.210
8	0.41	66,974	9,280	4,465	13,745	5,184	0.205
9	1.16	189,486	25,574	12,632	38,206	32,470	0.202
10	0.40	65,340	4,980	4,356	9,336	2,158	0.143
11	0.51	83,309	8,630	5,554	14,184	6,926	0.170
12	0.18	29,403	1,247	1,960	3,207	220	0.109
						Mean R_v	0.164

* Total rainfall volume which fell within the watershed
** Direct rainfall input into the pond
*** Average Runoff Coefficient value

Finally, an average runoff coefficient value”R_v” was computed by dividing total influent volume by the total rainfall volume of the entire watershed, as given in Equation 4.1.

$$R_V = \frac{TIV}{TRV} \qquad \text{…………} \quad (4.1)$$

Where:
TIV = Total Influent Volume
TRV = Total Rainfall Volume

The computed rainfall coefficient values ranged from a low of 0.107 for storm event 2 in June to a high of 0.210 for storm event 7 in June 2005, with an average runoff coefficient of 0.164. The runoff coefficient values given in Table 4.2 represent the Carver County dry pond. The average R_v value of the Carver County dry pond is lower than the runoff coefficient value of 0.29 for Greenville, N.C dry pond (Stanley, 1996). However, the watershed of the Carver County dry pond had a 22% impervious area, while the Greenville watershed had 31% impervious surface. This indicates that a significant portion of the runoff volume was lost due to infiltration and evapotransporation in the Carver County dry pond watershed. Further, a Debary, FL study (Harper et al, 1999) had an R_v value of 0.121 with an impervious area of 60%, which is considered to be a very low value for a watershed runoff coefficient under these conditions. The estimation of the average rainfall coefficient of the Carver County dry pond site/watershed is used in a subsequent section to model accumulation rates of sediments in the dry detention basin.

It should be noted that the storm water outputs were roughly half the magnitude of the storm water outputs (Fig. 4.3). This indicates that a significant amount of the storm was infiltrated. A large portion of the pollutant load most likely infiltrated as well, causing a large amount of loss of the pollutant load.

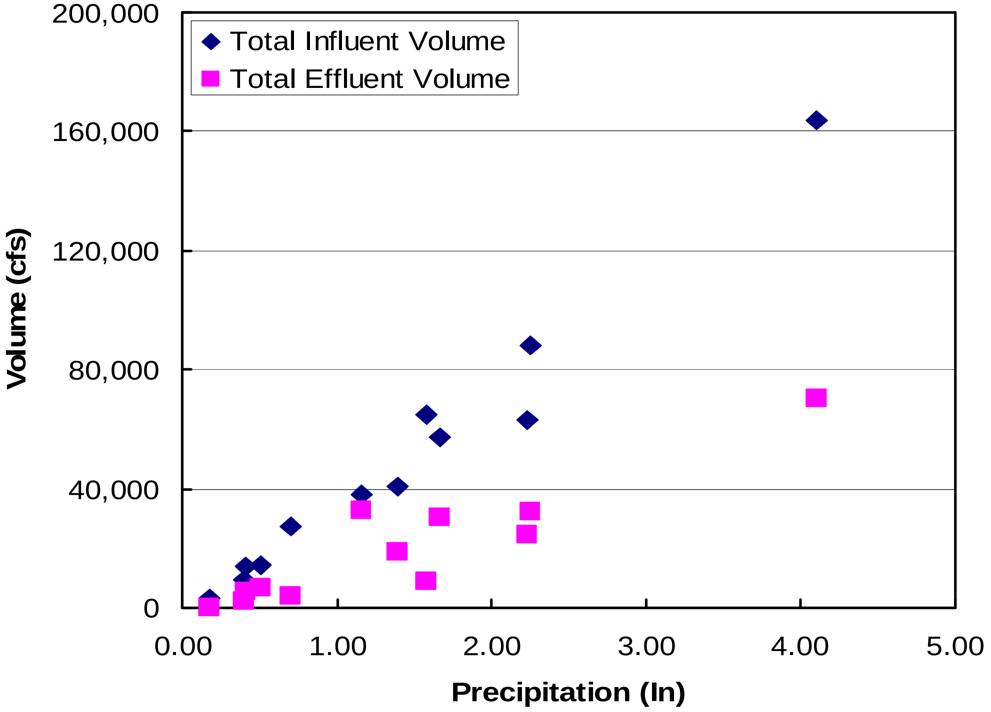

Figure 4.3: Comparison of total influent and total effluent volumes for six storms at Carver County dry detention pond with under-drain.

(3) Storm Water Pollutant Data

Summation of Loads – individual storms

Summation of loads for individual storm events allows for the calculation of the total mass of the influent pollutant load that is removed. When using discrete sampling, it is equal to the sum of each concentration multiplied with its corresponding flow volume. Where composite sampling is used, it is simply the overall flow weighted average pollutant concentration multiplied by the total corresponding volume (equation 4.2).

$$M_{pollutant} = C_{ave} * V \qquad \text{............} \quad (4.2)$$

As can be seen in Table 4.3 total suspended solids (TSS) and volatile suspended solids (VSS) efficiencies for each storm using summation of loads averaged 72% and 69%, respectively. It should be noted that summation of loads assumes that all infiltrated water has 100% pollutant removal. Infiltration is subtracted from the effluent load, and therefore is counted as treatment. In Table 4.4, total phosphorus and dissolved phosphorus summation of loads average efficiencies are 62% and 57%. Summation of loads may be useful when analyzing a storm water practice for TMDL's. Infiltration, however, needs to be considered separately for each practice.

Table 4.3: Summary of TSS and VSS loads and efficiencies at Carver County.

Storm	TSS Load in	TSS Load Out	Efficiency	VSS Load In	VSS Load Out	Efficiency
SE 1	194.473	19.839	90%	18.232	5.357	71%
SE 2	873.237	76.163	91%	106.794	10.93	90%
SE 3	10.595	0.978	91%	4.304	0.467	89%
SE 4	116.678	24.864	79%	23.768	6.033	75%
SE 5	15.59	1.32	92%	8.812	0.946	89%
SE 6	4.042	1.289	68%	2.093	0.752	64%
SE 7	29.851	21.74	27%	8.453	6.973	18%
SE 8	6.32	0.692	89%	2.002	0.294	85%
SE 9	9.656	8.101	16%	2.414	1.861	23%
SE 10	2.417	0.495	80%	1.209	0.217	82%
SE 11	4.276	2.277	47%	1.833	1.062	42%
SE 12	0.245	0.011	96%	0.13	0.005	96%
		Average:	72%		Average:	69%

Table 4.4: Summary of Total Phosphorus and Dissolved Phosphorus loads and efficiencies at Carver County.

Storm	TP Load in	TP Load Out	Efficiency	DP Load In	DP Load Out	Efficiency
SE 1	0.547	0.175	68%	0.209	0.101	52%
SE 2	0.273	0.106	61%	0.041	0.028	31%
SE 3	0.058	0.009	85%	0.038	0.006	83%
SE 4	0.418	0.190	54%	0.254	0.117	54%
SE 5	0.359	0.046	87%	0.226	0.030	87%
SE 6	0.123	0.083	33%	0.070	0.048	31%
SE 7	0.278	0.194	30%	0.175	0.109	38%
SE 8	0.078	0.018	77%	0.033	0.010	71%
SE 9	0.285	0.218	23%	0.179	0.150	16%
SE 10	0.041	0.008	80%	0.026	0.005	81%
SE 11	0.065	0.028	57%	0.033	0.015	53%
SE 12	0.007	0.001	92%	0.004	0.000	89%
		Average:	62%		Average:	57%

Efficiency Ratio – individual storms

Efficiency ratios can be calculated for each individual storm event to determine the improvement that occurs in water quality. Unlike summation of loads, efficiency ratios do not account for infiltration losses of pollutant loads. The efficiency ratio is calculated by determining the percentage reduction in pollutant concentration from the influent to the effluent of the device. Flow weighted concentrations should be used, which can be calculated from either discrete samples or flow weighted composite samples. The ratio can then be calculated using the following equation:

$$ER = 1 - \frac{Eff_{effluent}}{Eff_{\inf luent}} \qquad \text{…………} \quad (4.3)$$

Table 4.5: Summary of TSS and VSS concentrations and overall efficiencies at Carver County.

Storm	TSS Conc. In	TSS Conc. Out	Efficiency	VSS Conc. In	VSS Conc. Out	Efficiency
SE 1	57.6	10	83%	5.4	2.7	50%
SE 2	790.7	108.7	86%	96.7	15.6	84%
SE 3	19.2	9	53%	7.8	4.3	45%
SE 4	64.8	27.2	58%	13.2	6.6	50%
SE 5	11.5	5.3	54%	6.5	3.8	42%
SE 6	5.6	2.4	57%	2.9	1.4	52%
SE 7	18.4	25.2	-37%	5.2	8.1	-56%
SE 8	16.2	4.7	71%	5.1	2	61%
SE 9	8.9	8.8	1%	2.2	2	9%
SE 10	9.1	8.1	11%	4.6	3.5	24%
SE 11	10.6	11.6	-9%	4.6	5.4	-17%
SE 12	2.7	1.8	33%	1.4	0.8	43%
		Average:	38%		Average:	32%

Table 4.6: Summary of Total Phosphorus and Dissolved Phosphorus concentrations and overall efficiencies at Carver County.

Storm	TP Conc. In	TP Conc. Out	Efficiency	DP Conc. In	DP Conc. Out	Efficiency
SE 1	0.162	0.088	46%	0.062	0.051	18%
SE 2	0.247	0.151	39%	0.037	0.040	-8%
SE 3	0.105	0.082	22%	0.069	0.059	14%
SE 4	0.232	0.208	10%	0.141	0.128	9%
SE 5	0.265	0.183	31%	0.167	0.120	28%
SE 6	0.171	0.155	9%	0.097	0.0990	7%
SE 7	0.171	0.225	-31%	0.108	0.127	-18%
SE 8	0.201	0.125	38%	0.084	0.065	22%
SE 9	0.263	0.237	10%	0.165	0.163	1%
SE 10	0.157	0.136	13%	0.099	0.080	19%
SE 11	0.162	0.142	12%	0.082	0.078	4%
SE 12	0.077	0.086	-12%	0.048	0.077	-60%
		Average:	16%		Average:	3%

Summation of Loads – Long Term

Summation of loads can also be used for long term analysis. It is calculated by summing each influent load and each effluent load, and then calculating the total retention of pollutants from the influent to effluent values (eq. 4.4). Once again, this is well suited for TMDL's, but the drawback of this method is that it emphasizes larger storms with large loads. Thus, the uncertainty of one storm can affect the uncertainty of the summation-of-loads long-term efficiency.

$$Eff = 1 - \frac{\sum M_{effluent}}{\sum M_{\inf luent}} \qquad \ldots\ldots\ldots\ldots \quad (4.4)$$

Table 4.7: Summary of TSS and VSS loads and overall efficiencies.

Storm	TSS Load in	TSS Load Out	VSS Load In	VSS Load Out
SE 1	194.473	19.839	18.232	5.357
SE 2	873.237	76.163	106.794	10.93
SE 3	10.595	0.978	4.304	0.467
SE 4	116.678	24.864	23.768	6.033
SE 5	15.59	1.32	8.812	0.946
SE 6	4.042	1.289	2.093	0.752
SE 7	29.851	21.74	8.453	6.973
SE 8	6.32	0.692	2.002	0.294
SE 9	9.656	8.101	2.414	1.861
SE 10	2.417	0.495	1.209	0.217
SE 11	4.276	2.277	1.833	1.062
SE 12	0.245	0.011	0.13	0.005
Sum	1267.38	157.769	180.044	34.897
efficiency		88%		81%

Table 4.8: Summary of total phosphorus and dissolved phosphorus loads and overall efficiencies.

Storm	TP Load in	TP Load Out	DP Load In	DP Load Out
SE 1	0.547	0.175	0.209	0.101
SE 2	0.273	0.106	0.041	0.028
SE 3	0.058	0.009	0.038	0.006
SE 4	0.418	0.190	0.254	0.117
SE 5	0.359	0.046	0.226	0.030
SE 6	0.123	0.083	0.070	0.048
SE 7	0.278	0.194	0.175	0.109
SE 8	0.078	0.018	0.033	0.010
SE 9	0.285	0.218	0.179	0.150
SE 10	0.041	0.008	0.026	0.005
SE 11	0.065	0.028	0.033	0.015
SE 12	0.007	0.001	0.004	0.000
Sum	2.533	1.075	1.289	0.620
efficiency		58%		52%

Efficiency Ratio – Long Term

An efficiency ratio can be calculated for long term analysis by calculating an average of the individual storm efficiency ratios that are calculated for each storm. This method weights all storms equally and does not emphasize large storms. As with efficiency ratio for individual storms, long term efficiency ratio does not incorporate treatment that occurs through infiltration.

Average efficiency ratios for TSS, VSS, total phosphorus, and dissolved phosphorus are calculated and shown in table 4.5 an 4.6. Average efficiencies for TSS and VSS are 38% and 32% respectively. The average efficiencies for total phosphorus and dissolved phosphorus are 16% and 3%. Efficiencies for each of these pollutants were less than that of the summations of loads methods, further indicating that significant infiltration occurred at the Carver County Dry Detention Pond.

Effluent Probability – Long Term

Effluent probability is a method that can be used to determine the irreducible concentration of a specific BMP practice (Geosyntec 2002). This method involves plotting the EMC concentrations of a specific pollutant versus 1 – exceedance probability on a normal probability plot. Both influent and effluent data should be plotted in this manner. The effluent data and influent data should create two roughly straight lines except for lower concentrations which should taper together. This taper will indicate the irreducible concentration at the point where the lines come together. As can be seen in figure 4.4 and 4.5 the curves never meet and a treatment is always shown. This means that no irreducible concentration was exhibited in the Carver County dry pond.

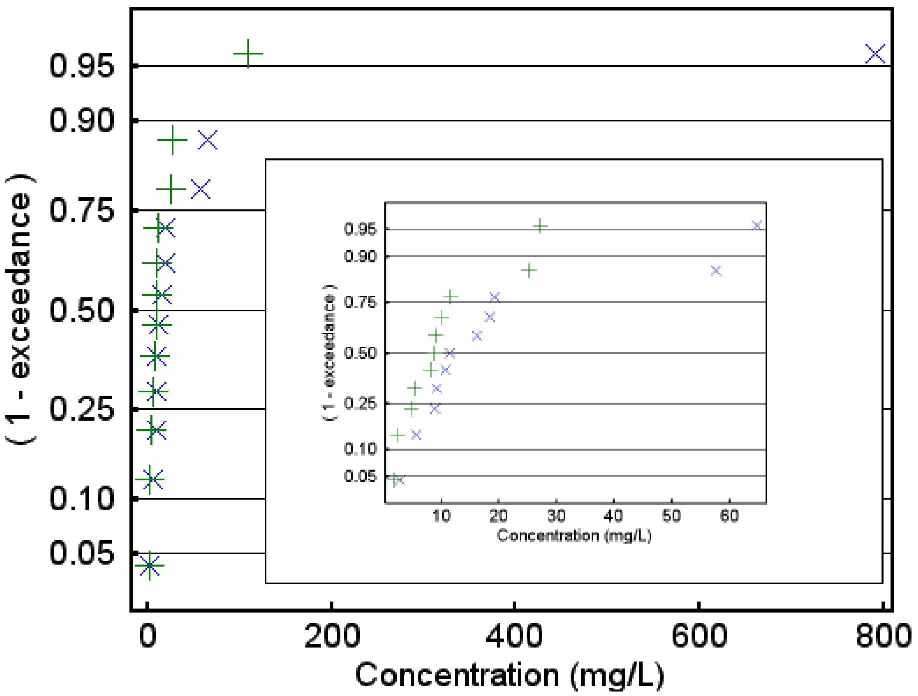

Figure 4.4: TSS Effluent Probability Plot.

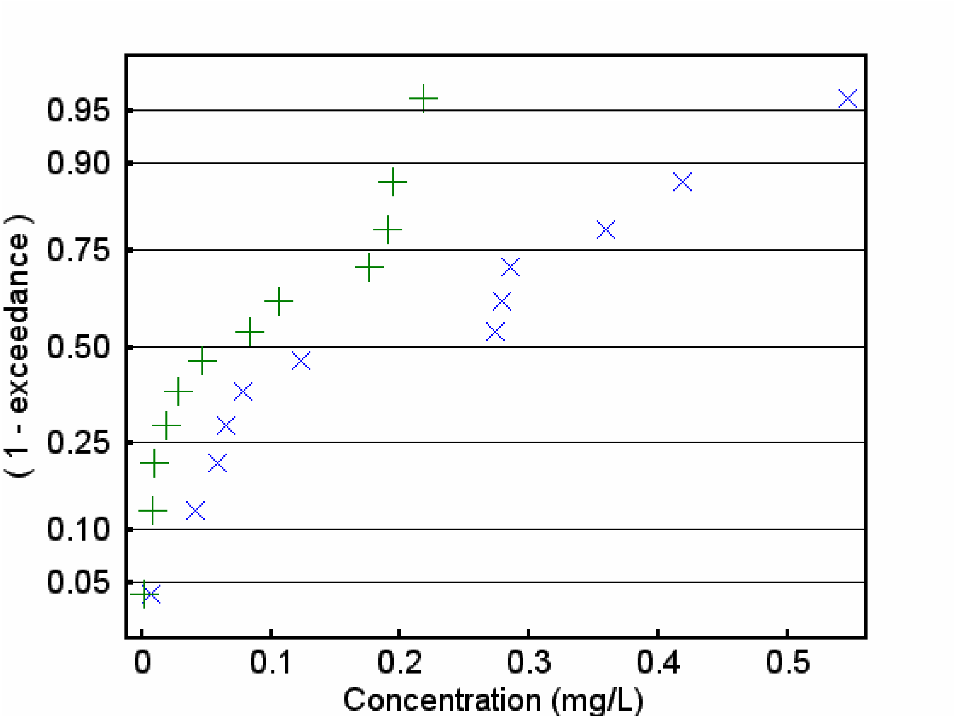

Figure 4.5: Total Phosphorus Effluent Probability Plot.

(4) Effectiveness of Carver County dry detention pond

Figure 4.6 provides rainfall intensity versus VSS and TSS EMC influent solids concentrations. It appears that the concentrations can be approximated as being fairly constant up to an average rainfall intensity of .1 in/hr while higher intensities show a trend of increasing concentrations with increasing rainfall intensity. This trend may be due to higher rainfall or flow being capable of washing away more sediment than smaller intensity storms.

Particulate phosphorus also showed some trend similar to that of VSS and TSS, as shown in Figure 4.7. There is, however, only one data point that indicates this trend.

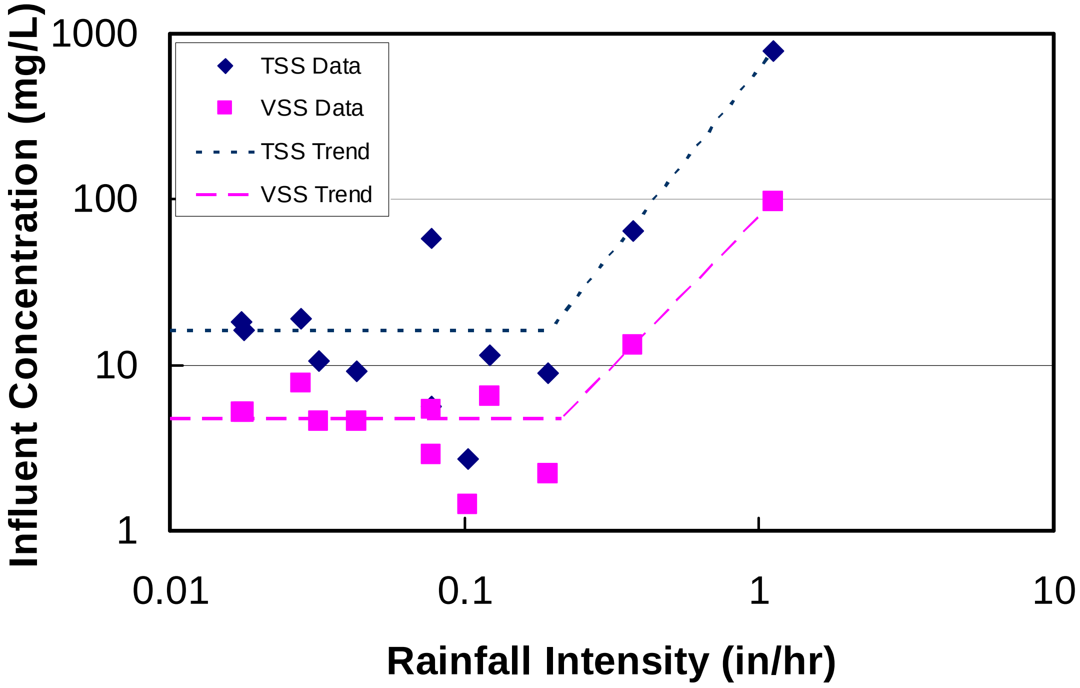

Figure 4.6: Average rainfall intensity vs. influent EMC concentration of TSS and VSS.

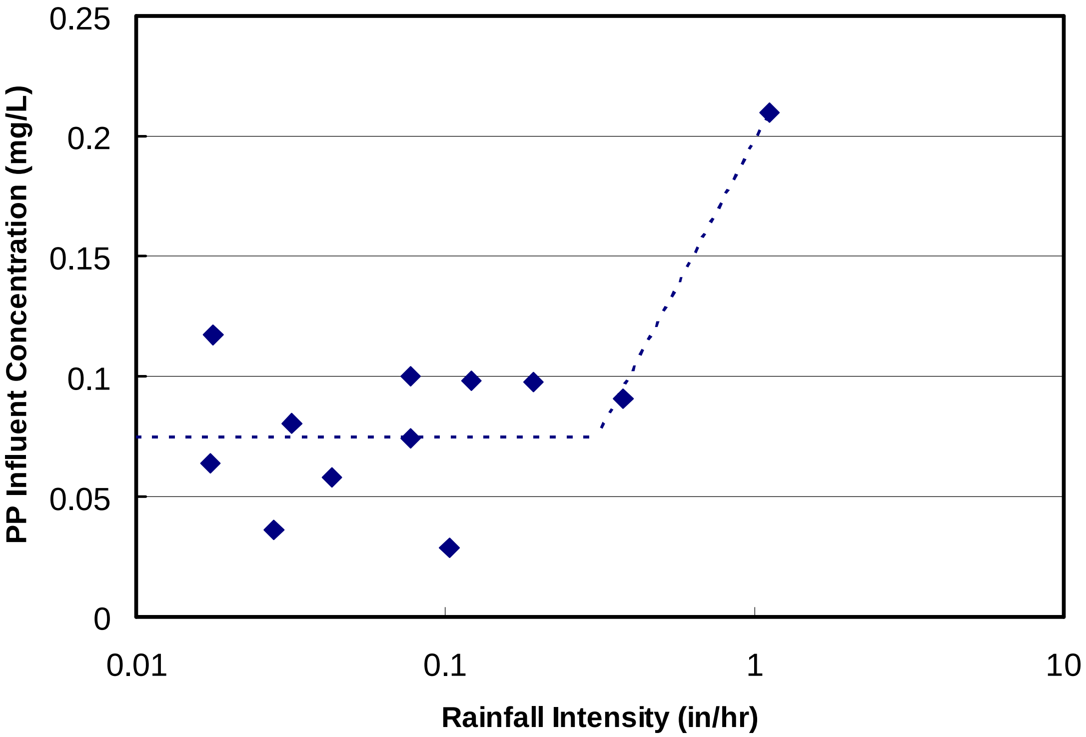

Figure 4.7: Average rainfall intensity vs. influent EMC concentration of particulate phosphorus.

The loading of pollutants should increase along with rainfall as a larger rainfall will produce larger influent volumes. Figures 4.8, 4.9, and 4.10 show this for total suspended solids, dissolved, and particulate phosphorus. It was found that greater rainfalls did indeed produce larger pollutant loading.

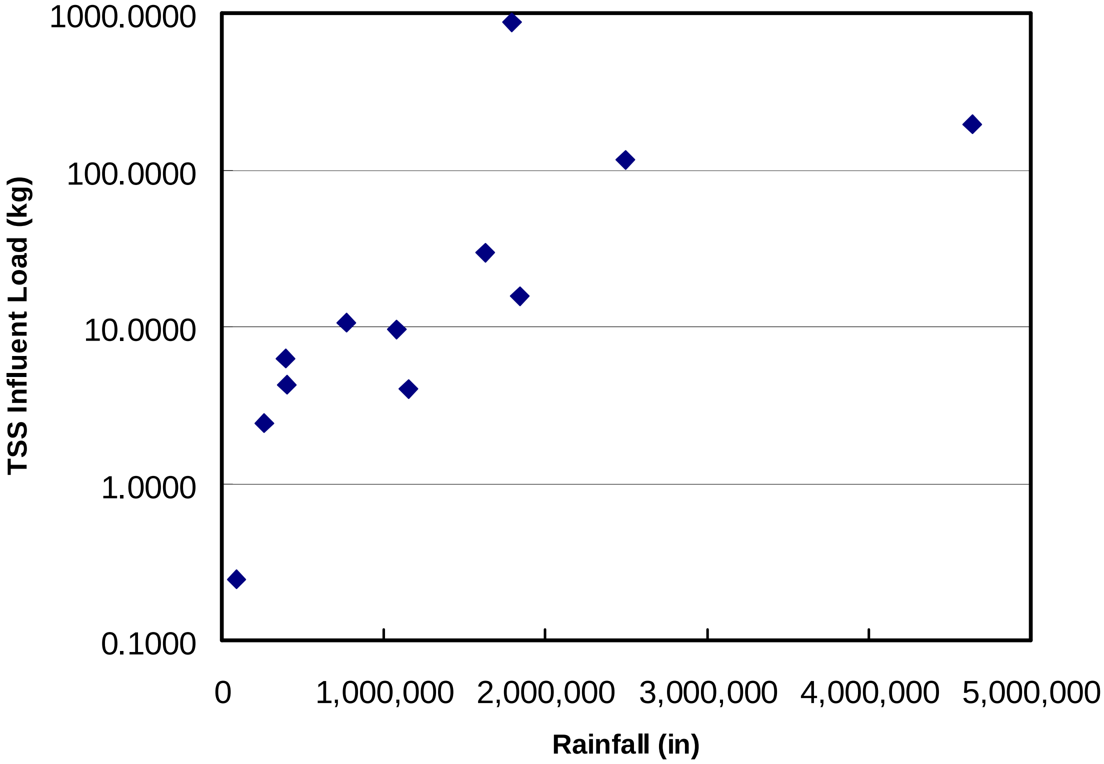

Figure 4.8: Rainfall versus total suspended solids influent load showing a proportional trend.

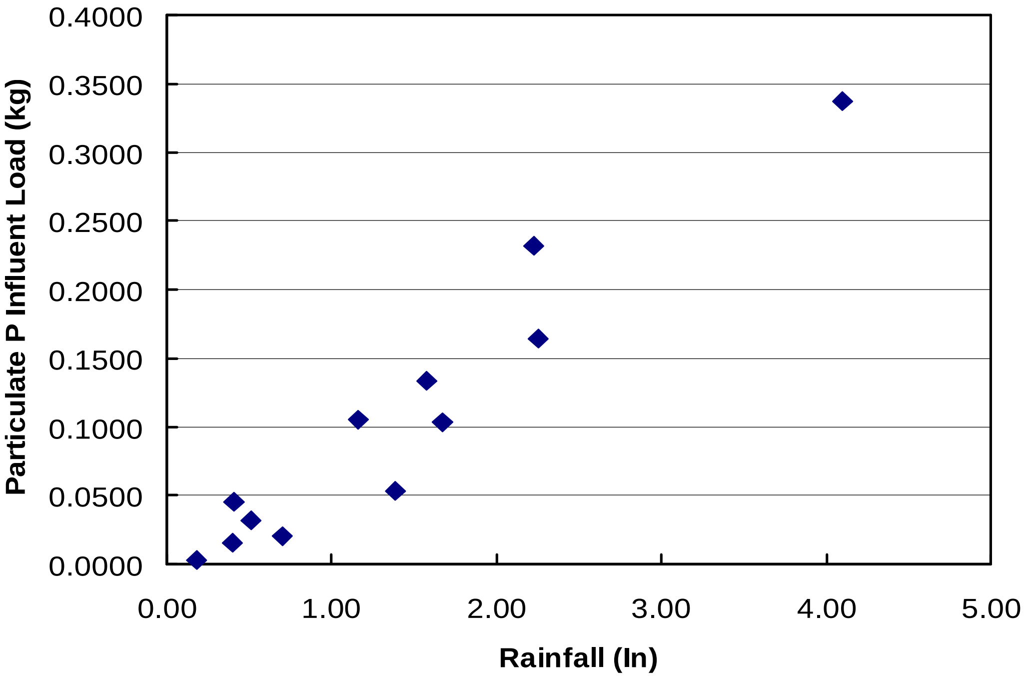

Figure 4.9: Rainfall versus particulate phosphorus influent load showing a proportional trend.

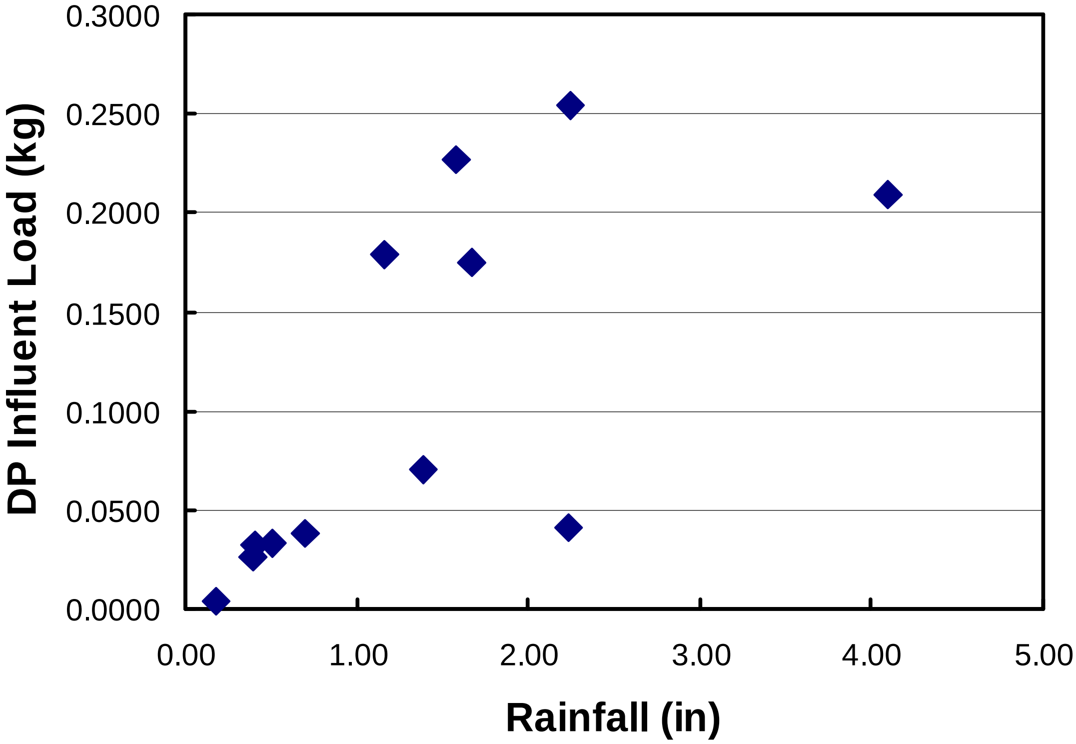

Figure 4.10: Rainfall versus dissolved phosphorus influent load showing a proportional trend.

Both load based or concentration (EMC) based retention efficiencies are used as a measure of performance for dry detention ponds. These are indicating the retention of pollutants in the storm water facility. The load based retention efficiency tends to be higher than concentration based efficiency as it incorporates the loss of pollutant through infiltration and assumes that infiltration results in complete treatment. Concentration based retention efficiency tends to take into account settling and plant uptake of pollutants but not infiltration losses. Thus load based efficiencies are generally higher than concentration based efficiencies.

Flow weighted concentration based retention efficiencies were calculated for the Carver County dry detention pond as the change between flow weighted influent concentration and the flow weighted effluent concentration discharging through the under drain system (Table 4.9). Considerable variability is observed in pollutant retention efficiencies between the monitored storms. Retention efficiencies for the particle bound contaminants were found to be higher than those for dissolved pollutants. This is expected, because a filtration system is typically not designed to remove dissolved pollutants. The highest retention efficiencies, among the analyzed parameters, were achieved for total suspended solids and volatile suspended solids with an average retention of 39% and 32% and a standard deviation of 39% and 38%, respectively (Table 4.9).

The pond was found to exhibit positive concentration retention efficiencies for most monitored storms. Negative retention efficiencies were obtained in several instances, with a possible sources being sampling errors, analysis errors or resuspension from the settled material. The Carver County dry detention pond appeared to be more effective in reducing total and particulate bound phosphorus as compared to dissolved phosphorus. Average retention efficiencies of 26%, 16% and 3% were obtained for particulate phosphorus, total phosphorus and dissolved phosphorus, respectively for this study. Dissolved phosphorus retention efficiency is typically less than total phosphorus for dry detention ponds because the main retention mechanism for pollutant retention is settling. Since dissolved phosphorus cannot settle out unless it coagulates with a solid particle, retention efficiency will be low.

Table 4.9: Estimated pollutant EMC retention efficiencies for Carver County dry detention pond with under-drain (R. Eff = pollutant retention efficiency)

	TSS R. Eff (%)	VSS R. Eff (%)	TP R. Eff (%)	DP R. Eff (%)	PP R. Eff (%)
SE 1	83	50	46	18	63
SE 2	86	84	39	-8	47
SE 3	53	45	22	14	36
SE 4	58	50	10	9	12
SE 5	54	42	31	28	36
SE 6	57	52	9	7	12
SE 7	-37	-56	-31	-18	-54
SE 8	71	61	38	22	49
SE 9	1	9	10	1	24
SE 10	11	22	13	19	4
SE 11	-9	-19	12	4	20
SE 12	34	46	-12	60	69
Mean	39	32	16	3	26
St. Deviation	39	38	22	24	33
Outflow Weighted Mean R.Eff	46	32	20	6	26

Total suspended solid retention efficiencies were high for the first two storm events. It is believed that this better performance was likely due to long detention times for storm event 1 and very high influent concentrations for storm event 2. Total suspended solid retention efficiencies for storm event 3, 4, 5 and 6 did not fluctuate much and stayed around 55%. Similarly, total volatile solid retention efficiencies for all storm events were fairly stable in 2004 except storm event 2. The retention efficiencies for total phosphorus and particulate phosphorus were highest for storm event 1 and showed a gradual decrease for remaining storm events except storm event 5. Storm event 4 and 6 exhibited poor retention efficiencies for total, dissolved and particulate phosphorus. No particular reason was found for these low pollutant retention efficiencies. Storm event 5 showed better retention for total, dissolved and particulate phosphorus retention efficiencies.

Outflow weighted mean retention efficiencies were also computed for twelve monitored storms by dividing the sum of the product of EMC pollutant retention efficiency and total outflow volume of each storm event by sum of total volume of all storm events (Table 4.9) as seen in equation 4.5.

$$R_{outflow} = \frac{\sum R_i V_i}{\sum TIV_i} \qquad \ldots\ldots\ldots\ldots \quad (4.5)$$

Where:
$R_{outflow}$ = Outflow weighted retention efficiency
R_i = EMC retention efficiency
i = storm number
TIV = Total influent volume

Outflow weighted mean retention efficiencies of 73%, 56%, 32%, 11% and 42% were obtained for total suspended solids, volatile suspended solids, total phosphorus, dissolved phosphorus and particulate phosphorus respectively. Outflow weighted mean retention efficiencies can be used to calculate pollutant load for total maximum daily load (TMDL) studies. TMDL includes non-point source pollutant contributions which are typically derived using modeling approaches. An assumed outflow weighted mean retention efficiency, based on broadly accepted statistical data can be used in a determination of total maximum daily loads for the water body at the downstream of the storm water treatment system.

Analysis of storm data for both sampling seasons was more consistent when using the load based efficiency approach. Standard deviations were generally smaller and mean retention efficiency was greater than 50% for each pollutant (Table 4.10). Overall load-based efficiencies are assumed to be preferred for total load studies. These efficiencies were 88% for total suspended solids, 82% for volatile suspended solids, 59% for total phosphorus, and 66% for dissolved phosphorus, Outflow weighted mean retention efficiencies showed slightly less treatment, with dissolved phosphorus being the only pollutant with less than 50% retention. Total suspended solids and total volatile solids both showed a treatment of 60-70% on average. It should be noted that load based retention efficiency is highly related to infiltration and that a portion of the load removed infiltrated into the local water table.

Table 4.10: Estimated load based pollutant retention efficiencies for Carver County dry detention pond with under-drain (R. Eff = pollutant retention efficiency)

SE #	TSS R. Eff	VSS R. Eff	TP R. Eff	DP R. Eff	PP R. Eff
	(%)	(%)	(%)	(%)	(%)
SE 1	90	71	68	52	78
SE 2	91	90	61	31	66
SE 3	91	89	85	83	87
SE 4	79	75	54	54	55
SE 5	92	89	87	87	88
SE 6	68	64	33	31	35
SE 7	27	18	30	38	18
SE 8	89	85	77	71	81
SE 9	16	23	23	16	36
SE 10	80	82	80	81	78
SE 11	47	42	57	53	61
SE 12	95	96	92	89	98
Mean	72	69	62	57	65
St. Deviation	27	27	24	25	25
Outflow Weighted Mean R.Eff	67	60	53	44	57
Overall Load Based Efficiencies	88	81	58	52	64

Drainage time is considered as the most important factor affecting total suspended solid retention (Shammaa et al, 2001) in dry detention ponds. Thus it was expected that storm SE1, with a 328 hour drainage time, would have the greatest retention efficiencies with the smallest storms showing lower efficiency. Total suspended solids and volatile suspended solids both showed no substantial trends of this type. (Figure 4.11, 4.12) Total phosphorus, which includes particle bound phosphorus, is expected to be similar to suspended solids. Figure 4.13 shows that no substantial trend is seen for total phosphorus or dissolved phosphorus. No trend is expected for dissolved phosphorus because the pond is intended to function as a filter and not a bio retention system.

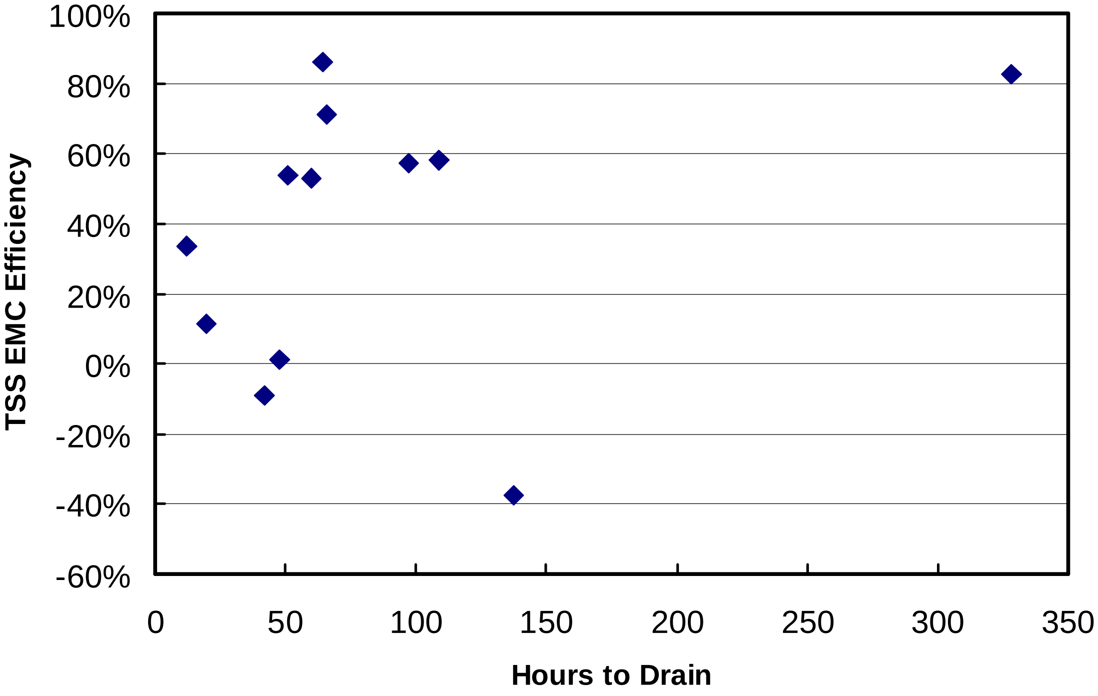

Figure 4.11: Hours to drain vs. EMC efficiency of total suspended solids.

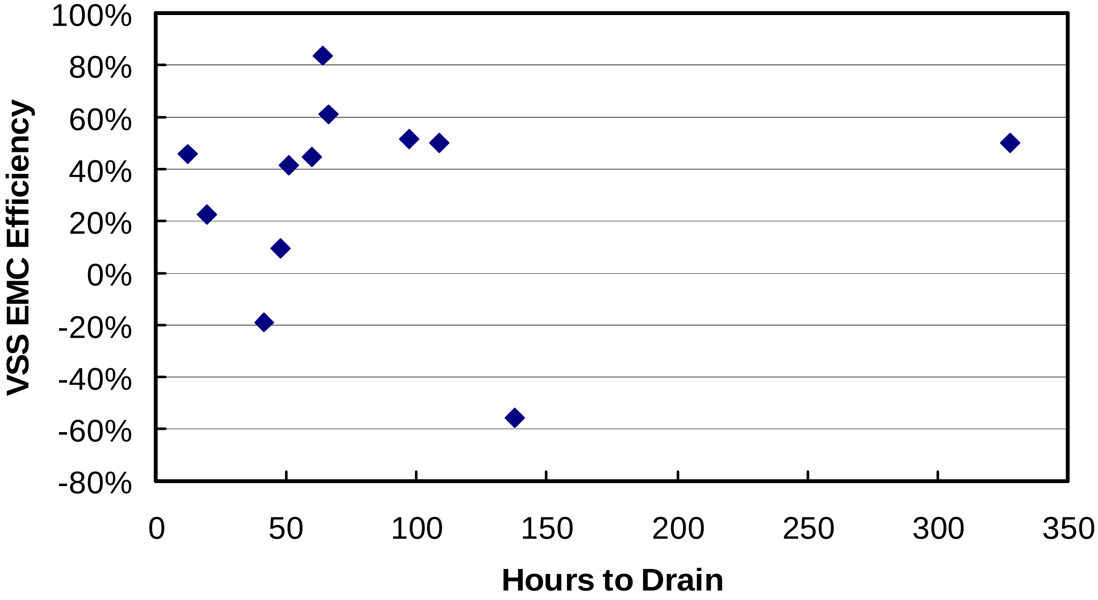

Figure 4.12: Hours to drain vs. EMC efficiency of volatile suspended solids.

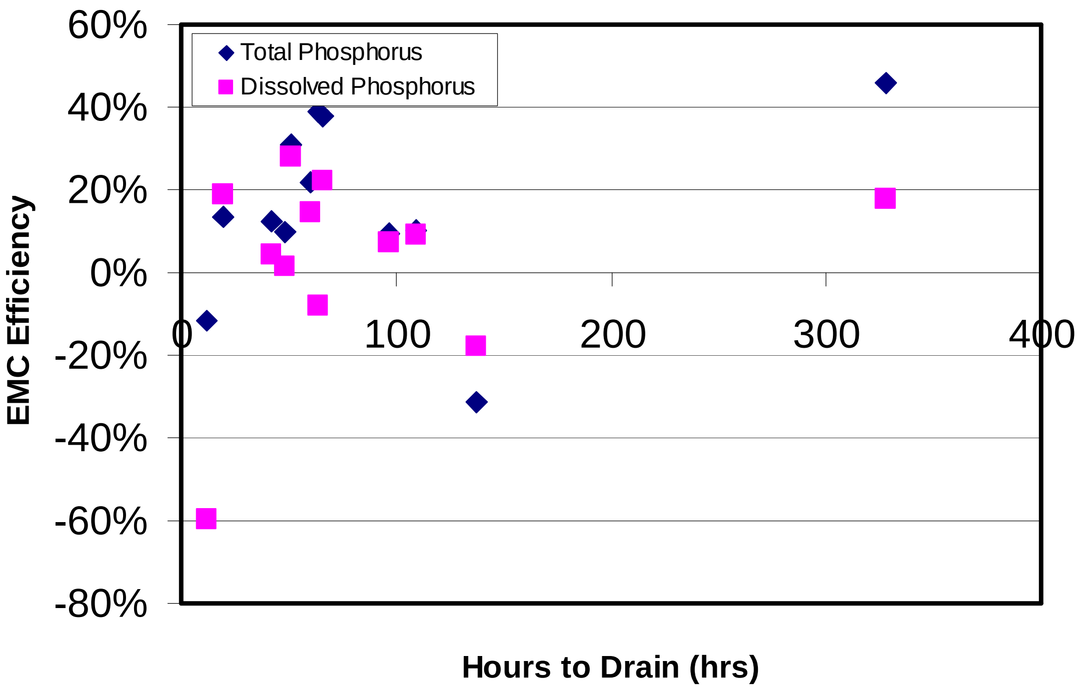

Figure 4.13: Hours to drain vs. EMC efficiency of phosphorus.

The long drainage times are of concern as it is recommended for dry detention ponds to drain within 48 hours of the storm event so that terrestrial plants can survive in the pond (MPCA 2005). The Carver County dry detention pond was designed to handle a 100 year 24 hour storm at the site, which is defined as 5.72 inches in Carver County. Storm event 1 required over 300 hours to drain with 4.1 inches of precipitation over 2 days, less than the 100 year 24 hour storm.

To remedy this problem, the layer of sediment over the sand filter should either be removed or tilled (MPCA 2005). This is a first recommendation to regain satisfactory drainage times. The effectiveness of this method should be measured by continued visual inspection of the pond after storms, with a recording of the drainage time and the rainfall of the storm.

When looking for storms which induced bypass flows, it can be useful to plot total influent volume versus a pollutant’s retention efficiency. A significant drop in retention efficiency may indicate a bypass flow. This was plotted for total suspended solids and volatile suspended solids (Figure 4.14, 4.15). The storms that show low retention efficiency are not storms that were known to bypass flow through the overflow structure. No other trends were observed when comparing the total influent volume to total and volatile suspended solids EMC efficiency.

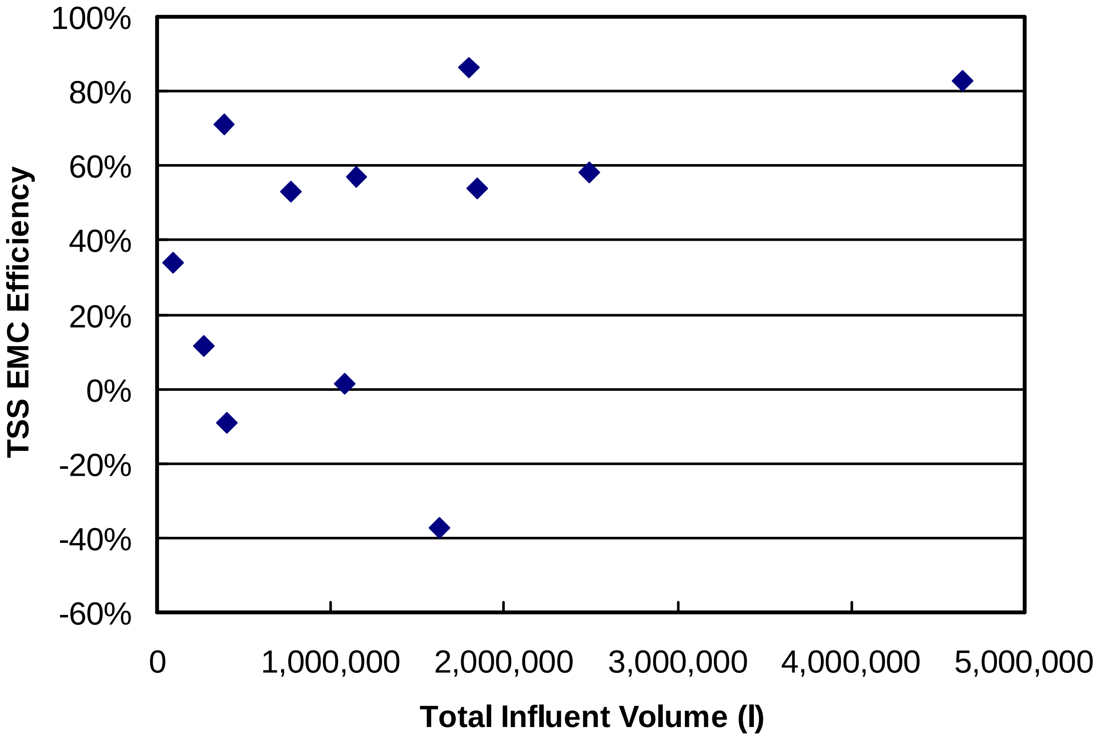

Figure 4.14: Total influent volume vs. EMC efficiency of total suspended solids.

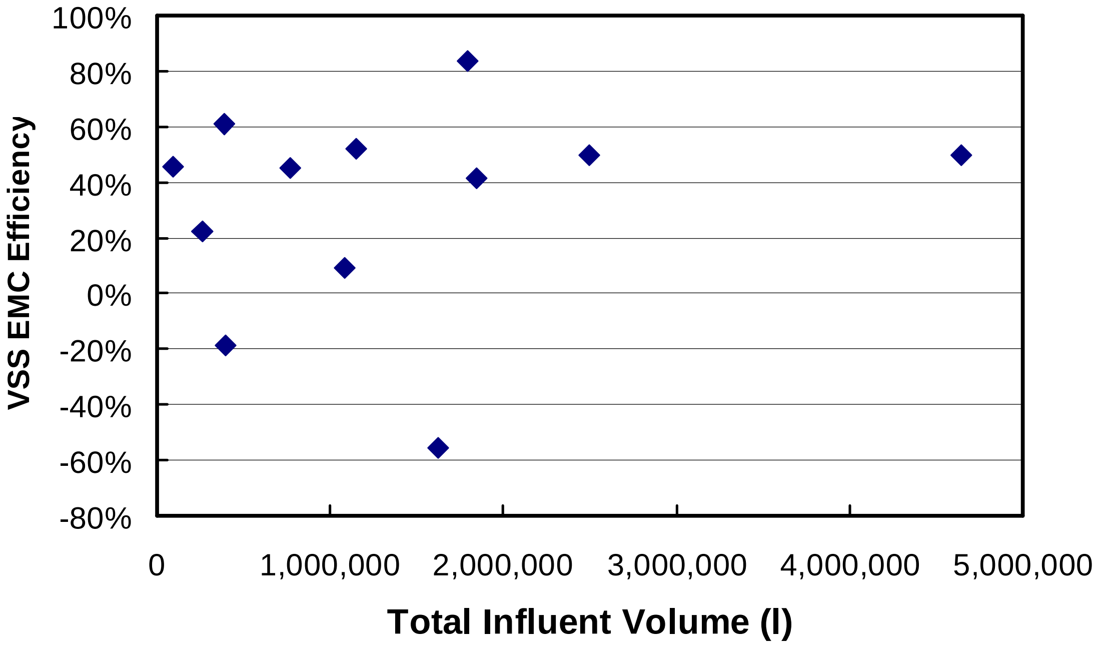

Figure 4.15: Total influent volume vs. volatile suspended solids EMC efficiency.

Load based efficiency was analyzed based on two parameters, hours to drain and total influent volume. Load efficiency is expected to increase with drainage time due to a greater opportunity for settling and infiltration. This trend was not apparent in either total suspended solid efficiencies, volatile suspended solid efficiencies, or total and dissolved phosphorus efficiencies (Figure 4.16, 4.17, 4.18).

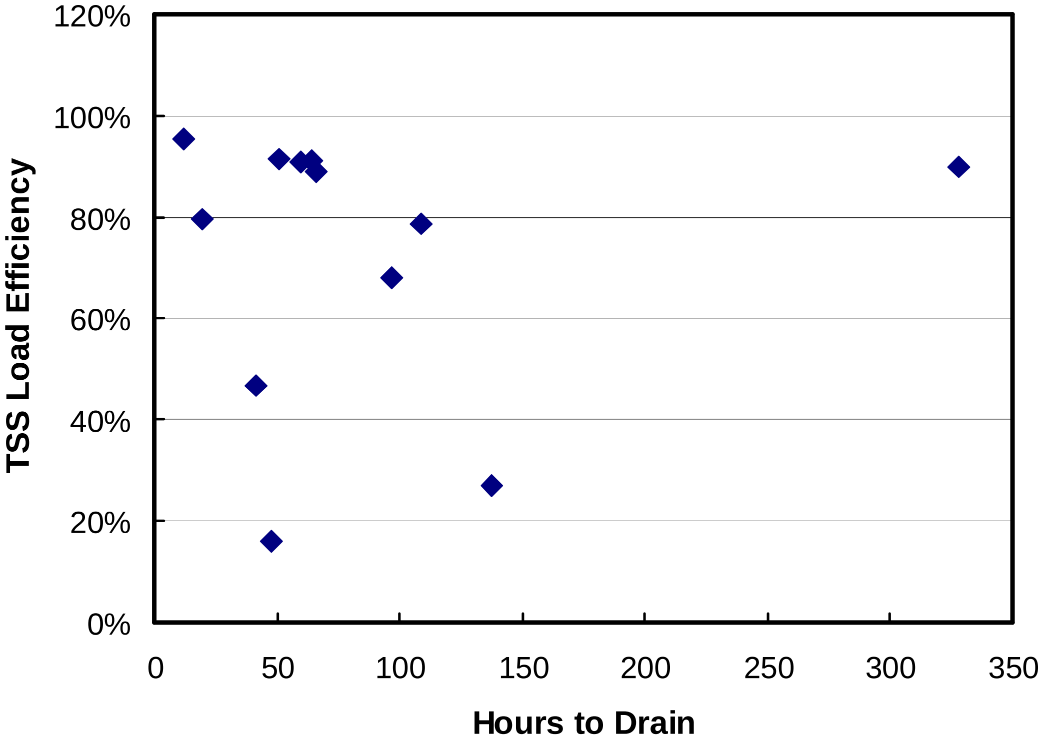

Figure 4.16: Hours to drain versus load efficiency of total suspended solids.

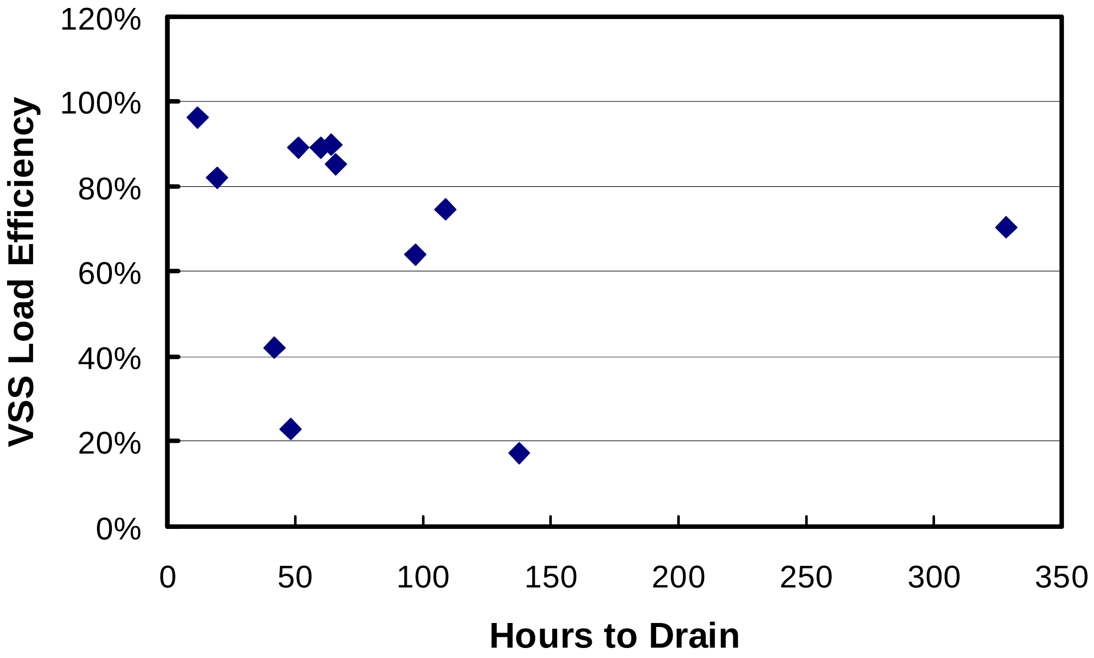

Figure 4.17: Hours to drain vs. volatile suspended solids load efficiency.

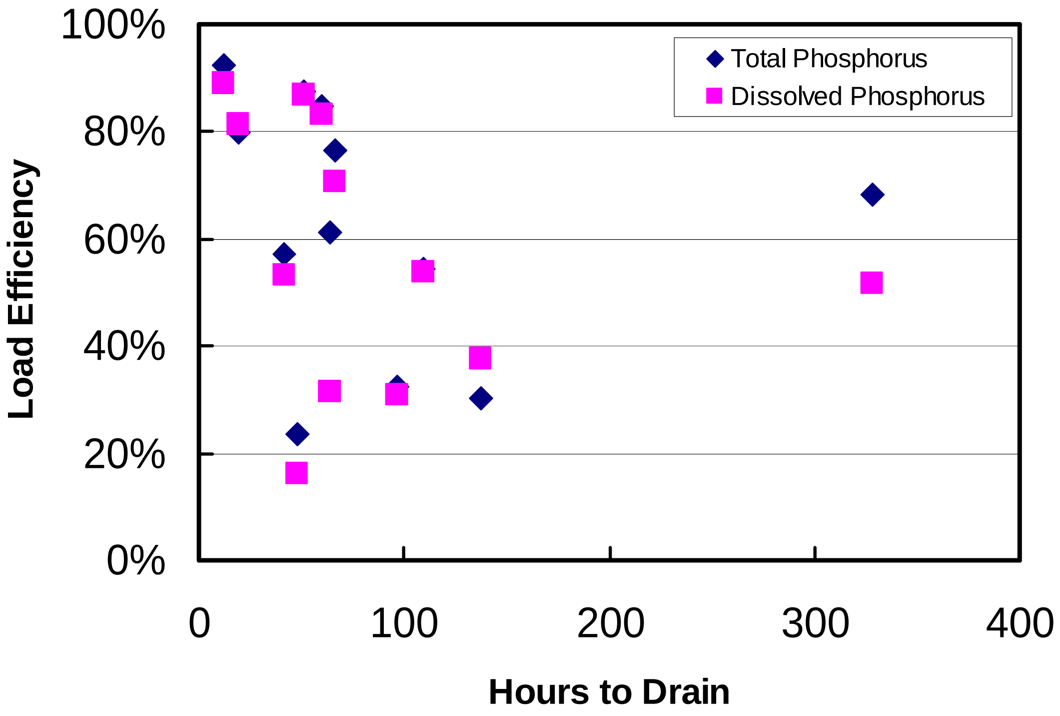

Figure 4.18: Hours to drain vs. load efficiency of total phosphorus and dissolved phosphorus.

Total influent volume also had no substantial effect on load-based efficiency of total suspended solids and volatile suspended solids (Figure 4.19, 4.20), thus the Carver County dry detention pond was able to handle all storms monitored. When the volume reaching the dry detention pond is greater than the design volume, retention efficiencies are expected to decrease as a result of bypass flows. Only one storm was known to encounter bypass flow and did not show abnormal load-based efficiency.

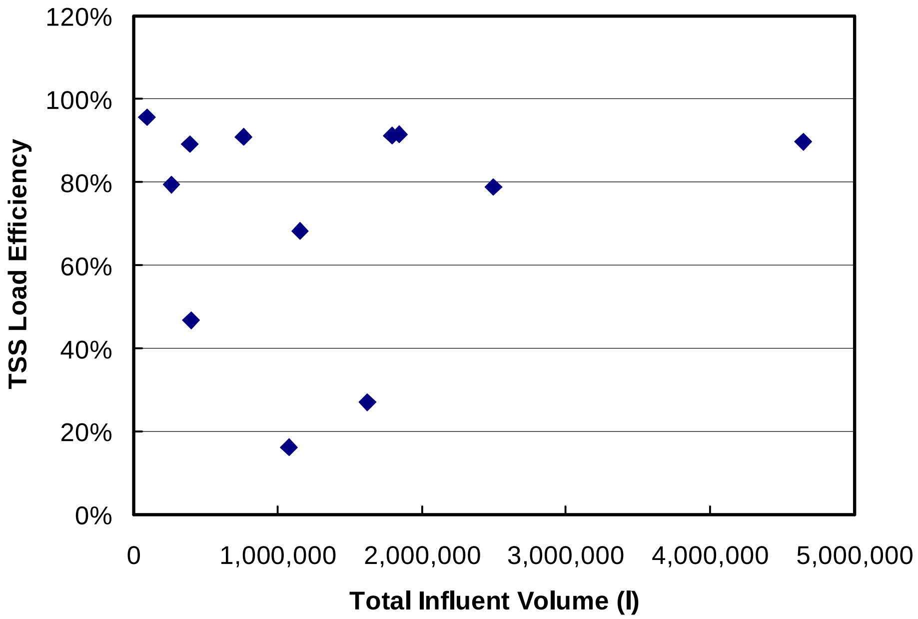

Figure 4.19: Total influent volume vs. total suspended load efficiency.

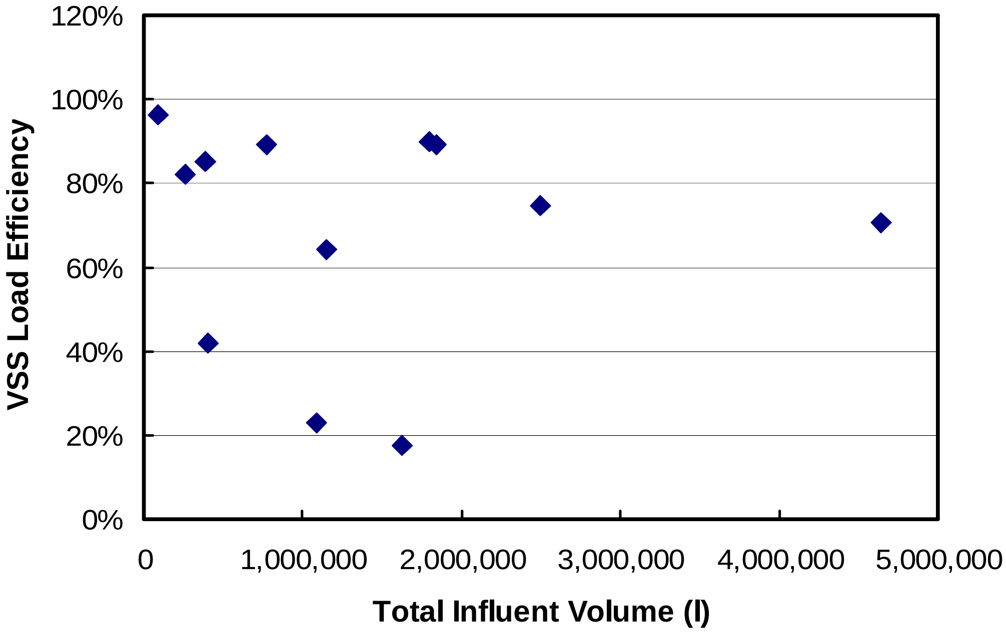

Figure 4.20: Total influent load volume vs. volatile suspended solid load efficiency.

D. Comparison of dry detention pond performance

The pollutant influent event mean concentrations of Carver County dry detention pond with under-drains are comparable to some other studies done in the USA (Table 4.7). The flow-weighted, event-mean total suspended solid concentration at Carver County pond was 109mg/L which is close to Greenville, N.C values of 127mg/L. However, total suspended solid EMC's values of 280mg/L for Madison, WI and 240 mg/L for Roseville, MN were found to be higher than obtained in this study. These lower total suspended solids EMC's at Carver County pond are likely due to the presence of a pre-treatment pond located upstream of the inlet. Moreover, two grassy ditches which conveyed the storm water runoff to the pond also provided some pre-treatment and decreased the influent concentrations. The mean total suspended solid concentration of the six sites included in Table 4.11 was 161.3mg/L with a standard deviation of 119.5mg/L. The mean total suspended solid EMC of six different dry detention pond studies mentioned in table 4.11 was compared with mean total suspended solid EMC of Carver County dry detention pond (158 mg/L). This comparison indicates that although pre-treatment at Carver County pond reduced the influent total suspended solid concentrations, its mean total suspended solid concentrations were close to the mean of six other studies.

Influent total and dissolved phosphorus event mean concentrations (EMC's) at the pond were low compared to storm water runoff values measured at other sites in the USA (Stanley 1996; Kluesener and Lee 1974; Ferrara and Witkowski 1983; Schueler 1987). The Nationwide Urban Runoff Program (NURP) study provided a comparison of storm water pollutant concentrations in different parts of the country (EPA, 1983) that are comparable to the inflow concentrations at the Carver County dry detention pond. The NURP study included pollutant concentrations measured at 81 streams and storm drains flowing through watersheds of different land use types. The median total phosphorus EMC for the NURP study was 0.38mg/L (EPA, 1983). The median total phosphorus EMC of six monitored storm events at Carver County pond was found to be 0.17 mg/L, which is almost half of the median values across the USA.

The mean total phosphorus EMC of six different dry detention pond studies was compared with mean total phosphorus EMC of the Carver County dry detention pond (Table 4.6). The mean total phosphorus influent EMC of six different studies was found to be 0.65 mg/L which was about three times higher than the mean influent total phosphorus concentrations (0.184 mg/L) obtained at Carver County dry detention pond.

Winer (2000) summarized the pollutant event mean concentrations of different dry detention ponds across the nation. The median *effluent* total phosphorus concentration for dry ponds reported by Winer was 0.18 mg/L which was almost equal to the median *influent* total phosphorus values found in this study. This indicates that the influent total phosphorus EMC's at Carver County pond were very low as compared to the other studies. It is believed that settling of sediment bound phosphorus in the pre-treatment pond and grassy swales resulted in the low influent total phosphorus EMC's at Carver County dry detention pond.

The average dissolved phosphorus event mean concentration for six monitored storms at Carver County was found to be 0.107 mg/L. Table 4.11 shows that this value is one half (1/2) of the mean influent dissolved phosphorus concentrations of six different dry detention pond studies. Only the Montgomery County, MD pond showed less dissolved phosphorus EMC values among all the locations mentioned in the Table 4.11.

A comparison of pollutant retention efficiencies of various dry detention ponds throughout the nation including Carver County dry detention pond is shown in Table 2.2. It is not possible to get a precise comparison as included studies showed differences in pond design, pond detention times, watershed areas and monitoring methodologies.

Mean total suspended solid, total phosphorus and dissolved phosphorus retention efficiencies of Carver County dry detention pond are compared with the mean of all the included studies in Table 2.2(Fig. 4.21). It was observed that retention efficiencies obtained for Carver County dry detention pond were similar to the mean efficiencies of all the sites. The average total phosphorus and dissolved phosphorus retention efficiencies for all sites included in Table 2.2 were 29% and 16%, respectively, which are higher than the 16% and 3% obtained for this study. This indicates that performance of Carver County dry detention pond in terms of pollutant retention was slightly lower than the average performance of all the dry detention pond studies included in the comparison. Carver County dry detention pond performed slightly lower than average of all other studies in terms of total suspended solids retention, with 39% retention efficiency compared to 50% retention. Retention of volatile suspended solids has not been reported in the explored literature so there is no data with which to compare this study.

Table 4.11: Comparison of Storm water Influent Pollutant EMCs from this study with those for other sites in USA.

Location	TSS (mg/L)	TP (mg/L)	DP (mg/L)
[a]NURP Median EMCs	101	0.38	0.14
[b]Greenville, NC	98	0.35	0.19
[c]Madison, Wis	280	0.98	0.57
[d]Roseville, MN	240	1.44	0.25
[e]Somerset Co., NJ	282	0.36	0.00
[f]Montgomery Co., MD	42	0.48	0.08
[g]Washington, D.C	26	0.26	0.12
Mean of 6 Sites	161.33	0.65	0.20
S.D	119.50	0.47	0.20
[h]Carver County, MN	84.62	0.184	0.097

a = U.S EPA (1983)
b = Stanley (1996)
c = Kluesener and Lee (1974)
d = Oberts and Osgood (1991)
e = Ferrara and Witkowski (1983)
f = Grizzard et al. (1986)
g = Schueler (1987)
h = This study (2004/2005)

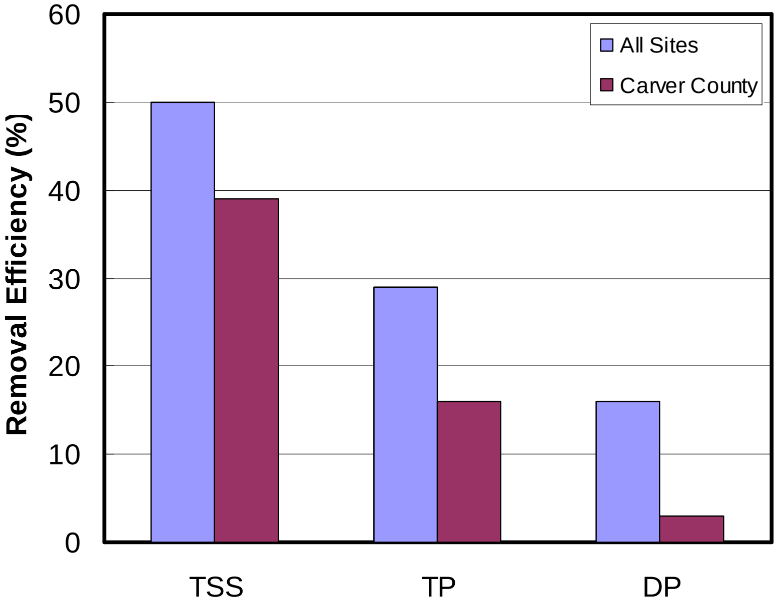

Figure 4.21: Comparison of mean total suspended solids, total phosphorus and dissolved phosphorus retention efficiencies of all sites included in table 2.2 with the Carver County dry detention pond

E. Maintenance Issues at Monitored Dry Detention Ponds with Under-Drains:

Typically, dry detention ponds are designed to drain within 48 hours (MPCA 2005). The Carver County dry detention pond did not satisfy this condition for most of the monitored storms in 2005 and 2006. In general, the drainage of storm water runoff from the pond following rain events appeared to be very slow due to the poor hydraulic performance of the filter under drain system.

A thin layer of silty clay loam was noticed at the bottom of the pond in April 2004 which may have reduced the performance of the filter media. The pond was also lacking in plant growth, which is a sign of long drainage times, because after two days the roots of most terrestrial plants begin to die off. The Carver County pond took more than 17 days to drain the first two monitored storms. Scratching the top layer of filter media at the bottom of the pond and mixing with a grain flocculent such as gypsum should improve its drainage capacity and allow terrestrial plants to germinate. The roots of terrestrial plants also tend to keep water percolation pathways open, reducing the frequency of required maintenance on a detention pond.

When field monitoring activities first began at Carver County dry detention pond in May 2004, the ditch that runs parallel (North-South) to the southern boundary of the pond was in excellent shape. However, it was noticed that side banks of the ditch experienced erosion problems and some direct input of runoff into the pond was observed. The problem appeared towards the end of the monitoring season and was fixed quickly by Carver County staff. A similar problem was seen again in 2005 with other banks, but was also repaired.

The Lower Colorado River Authority (1998) modified a sediment accumulation model developed by Schueler (1987) to result in the Modified Simple Method, as follows:

$$L\ (kg) = (P) \times (R_V) \times (C) \times (A) \times 0.1 \qquad \ldots\ldots\ldots\ldots\ldots \quad (4.6)$$

Where:

P = Rainfall per year (approximately 76 cm in Chaska, MN)
R_V = Runoff coefficient (0.154 for Carver County pond watershed)
C = Event mean concentration of pollutant (mg/L)
A = Watershed area (ha)

The Modified Simple Method was applied to the Carver County dry detention pond to determine the total suspended solid runoff load. An estimated annual total suspended solid runoff load equal to approximately 3000 kg for Carver County watershed was obtained. As the pond provided 88% long term retention efficiency for total suspended solids load, the net accumulation of sediments in the pond would be 2640 kg/yr. Assuming that one metric ton of sediment fills a volume equivalent to 0.84 m^3 (Schueler, 1987), and spreading evenly over the pond bottom , the sediment would amount to 0.07% of the pond storage volume. This indicates that the Carver County pond would not experience rapid sediment accumulation in the future and it would not be a frequent maintenance issue unless some unusual change in the watershed increases the amount of sediment in the storm water runoff. Tilling the surface, mixing in gypsum, and seeding terrestrial deep-rooted grasses such as alphalfa should allow the proper performance of the pond for 5 to 10 years.

F. Design Guidelines for Dry Detention Ponds with Underdrains

1) The MPCA Storm Water Manual (2005) should be used as a framework for designing any bmp in Minnesota. It assists in determining appropriate drainage times and design methods.
2) Native soils are often a poor choice in a dry detention pond as the infiltration rates are often unknown and inconsistent. This makes achieving desired results difficult. Engineered soils are a better option in order to achieve appropriate drainage times and infiltration rates.
3) Appropriate drainage times must be achieved to prevent vegetation die-offs. The recommended maximum drainage time of the MPCA Storm Water Manual is 48 hours. Terrestrial plants' roots die off after approximately 72 hours of continuous submersion.
4) A distance of at least 50 inches is required between the local water table and the pond's bottom surface (MPCA 2005). If this is not possible, a liner must be used to prevent infiltration into the water table.
5) Underdrains may clog easily and quickly if not placed correctly. Underdrains should be wrapped first in filter fabric, then covered in a layer of gravel and further layers of progressively finer gravels.
6) Underdrains should be treated as a part of a treatment system and not just a drainage system for a pond. Underdrains should be installed with proper surrounding materials (point 5) and be capable of conveying sufficient infiltrated water in order to meet the recommended 48 hour drainage time.

5. Lessons Learned

Mn/DOT pond 4012-03 and 4012-04 were monitored from July 2004 to August 2005. The following lessons were learned:

1) Pond 4012-03 showed poor hydraulic performance and failed to provide any discharge through the outlet. The continuous pool of water in the pond produced anaerobic soil conditions and the terrestrial vegetation in the pond died. It is recommended that Mn/DOT pond 4012-03 pond should be sprayed with a wetland seed mix to initiate the plant growth which will open the pores in the soil media. In addition, it is also recommended that a soil granulating agent (gypsum) be mixed with the surface soil.

2) The under-drains were installed at the pond 4012-03 without any gravel bed protection and native soil was used as filter media. This under drain installation technique may have caused some problems in draining the pond. The under-drain was installed with a gravel bed in pond 4012-04, it did not experience serious drainage problems.

3) The elevation (head) at the V-notch crest of the compound weir was six inches which coincided with the diameter of the outlet pipe. This caused the back water effect in the outlet pipe at pond 4012-04. The depth of the V-notch of the compound weir was increased to allow the water to run over the weir.

4) One potential problem in carrying out winter sampling is producing a continuous power supply in cold weather. The technique used in this study to install the solar panels at pond 4012-04 worked effectively and kept all the equipment in the operable condition.

5) The Isco 4230 bubbler flow meter is not ideal for winter sampling. The pressure transducer in the flow meter senses the resistance provided by the ice and thinks it is hydrostatic pressure caused by water depth and sends a signal to the sampler to take sample. Investigation in to pressure sensor probes for winter sampling is recommended.
6) Close attention should be paid to erosion on steep pond banks to prevent filling in of the affected pond. Rip rap can be an effective option for mitigating this problem.

6. Conclusions and Recommendations

Dry detention ponds have been widely used to temporarily store and treat storm water runoff, but little is known about their effectiveness in terms of pollutant retention, particularly when they are equipped with under drains. In order to learn more about their performance, three dry detention ponds with under drains were selected and monitored from May 2004 to November 2004 and May 2005 to August 2005 during this research study. The performance of these ponds in terms of pollutant retention efficiencies was estimated by comparing the influent and effluent pollutant concentrations. From the results obtained in this study, the following specific conclusions were reached:

It is recommended that a soil granulating agent should be mixed with the surface soil and wetland seed mix should be sprinkled at Mn/DOT pond 4012-03. This will help in initiating plant growth at the pond bottom. The plant growth can open up the pores in the soil and improve the draining capacity of the pond 4012-03.

Winter sampling attempts at the Mn/DOT pond 4012-04 revealed that solar panels provided sufficient power to keep the monitoring equipment in working condition. Isco 2700 samplers and Isco 4230 Bubbler flow meters did not show any electronic problem under sever cold weather. However, Isco 4230 Bubbler flow meter is not recommended for winter sampling as accumulation of ice over the bubble line can produce false hydrostatic pressures.

The measured concentrations of most parameters in storm water runoff which entered at the Carver County dry detention pond with under-drains were substantially lower than concentrations typically mentioned in other studies throughout the nation and influenced the pollutant retention efficiency of the pond. The lower values found at Carver County dry detention pond site are thought to be related to pre-treatment provided by the small pond near the inlet and also by the two grassy ditches/swales used for conveyance of storm water runoff to the detention pond site.

The use of a primary device for flow measurement is strongly recommended, especially in outlet under drain pipes. These devices (V-notch, rectangular or circular weirs, and flumes) are easy to install and can be used to provide continuous flow hydrographs using measurements of water surface level. The study revealed that an AV sensor cannot measure any velocity unless there is at least 2.5 to 3 inches of water over it, which does not often occur in under-drain outlets.

This research study confirmed that dry detention ponds with under-drains are an effective option for water quality control. The Carver County pond provided moderate storm water treatment and reduced the concentrations of total suspended solids, volatile suspended solids, particulate phosphorus and total phosphorus, even with low influent concentrations. Overall load-based efficiencies are assumed to be preferred for total load studies. These efficiencies for a total of twelve monitored storms were 88% for total suspended solids, 81% for volatile suspended solids, 58% for total phosphorus, and 52% for dissolved phosphorus, The average concentration-based retention efficiencies for twelve storms at Carver County dry detention pond with under drain were 39% for total suspended solids, 32% for total volatile solids, 35% for particulate phosphorus and 16% for total phosphorus. Retention efficiencies for dissolved phosphorus provided more variation and ranged between negative 18% to positive 60%, with an average retention efficiency of 3%. Dry detention ponds are focused on removing sediment and the associated pollutant concentration, such as particulate phosphorus. The primary retention mechanisms are not designed to retain dissolved phosphorus, so that retention is minimal.

The average concentration-based storm water pollutant retention efficiencies obtained at Carver County dry detention pond were similar to the mean of average retention efficiencies achieved at 14 other dry detention pond studies through out the country. The mean of average retention efficiencies of all other studies were 50% for total suspended solids, 29% for total phosphorus and 14% for dissolved phosphorus. Comparison of these values with the retention efficiencies of this research study indicated that the performance of the Carver County pond in terms of pollutant retention was in the range of the average expected performance of dry detention ponds.

Retention efficiencies for total suspended solids in this research study appeared to increase with increasing runoff detention time within the pond with peak retention efficiencies achieved after a detention time of 14 days. However, retention efficiencies of the other measured parameters did not show the same trend.

The results at the Carver County dry detention pond with under-drains indicate that influent pollutant concentrations influenced the pollutant retention efficiencies. Higher total suspended and volatile solids influent concentrations for storm event 2 resulted in high total suspended and volatile solids retention. Similarly, dissolved phosphorus retention efficiencies were higher at high influent concentrations and lower at low influent concentrations. However, the trend between influent pollutant concentrations and retention efficiencies for all six monitored storms at Carver County pond was not consistent.

The filter under drain system at Carver County dry detention pond exhibited poor hydraulic performance and failed to keep the pond dry between the storm events. The runoff residence time in the pond for six monitored storms ranged from a low of 2 days to a high of 17 days, with an average of 5 days. Continual maintenance is required to maintain the filter system in an operational condition. Field maintenance activities may include replacement of filter media, filter backwashing, scratching few inches from the top of the filter media or other options necessary to maintain the hydraulic performance of the filter media.

7. Implementation and Follow-up Research

This research study has been valuable in reaching the current methods being used in developing the MPCA Storm Water Assessment Protocol. The experience with assessment of a storm water BMP through monitoring has assisted us in understanding and working with the limitations in monitoring. Ultimately, this has resulted in the development of the Four Levels of Storm Water Assessment, as described below:

1) **Visual Inspection** – Visual inspection is the lowest level and least expensive form of assessment. It involves visual inspections performed and documented according to a standard checksheet.
2) **Capacity Testing –** Capacity testing is using infiltration tests to determine how quickly a device such as a detention pond or rain garden can infiltrate water.
3) **Simulated Runoff –** Simulated runoff testing involves providing water and pollutants to a storm water BMP device. This artificial storm is performed according to the parameters determined before testing and allows for any required data to be obtained for a device rather than waiting for a natural storm.
4) **Monitoring –** Monitoring is the most comprehensive method of assessment, however is also the most expensive and takes the longest amount of time. Most monitoring takes 2 years or more to have sufficient data to assess a device and requires constant attention by personnel.

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