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Recycling of Salt-Contaminated Stormwater Runoff for Brine Production at Virginia Department of Transportation Road-Salt Storage Facilities

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16. Abstract

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Laboratory and field tests were conducted using bench-scale brine generation equipment. In the laboratory phase, brine was produced using tap water while hydraulic retention times and water temperatures were varied to determine how these changes would affect the quantity and quality of brine production. Stormwater runoff from a storage pond without any previous treatment was used in the field phase to allow a better estimate of the potential effects of stormwater on the quality of the brine generated.

Results showed that the optimum conditions for brine production were low hydraulic retention time (high flow rates) and high temperatures. The total suspended solids present in the stormwater runoff did not diminish the quality of the brine in the field tests. Based on historic precipitation and chemical application data, VDOT appears to capture sufficient volumes of water to meet the majority of its potential brine production needs. Further, significant economic benefits can be obtained by applying this recycling strategy, with the greatest benefits resulting from generating brine for both direct application and pre-wetting.

Assuming average stormwater volume collection and average total NaCl application, VDOT can save approximately $3 million each year by generating brine for pre-wetting only versus approximately $6.5 million each year by generating brine for the combination of pre-wetting and direct application.

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ABSTRACT

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INTRODUCTION

Background

The Virginia Department of Transportation (VDOT) is responsible for maintaining the third largest state-maintained highway system in the United States. A significant part of this maintenance effort comprises the implementation of VDOT's snow removal and ice control program. VDOT currently stores more than 350,000 tons of NaCl distributed among approximately 300 storage facilities located throughout the state. In addition to the buildings used to stockpile the chemicals, most of the storage facilities have an adjacent impermeable pad that serves as a loading area for trucks and a stormwater storage pond or collection basin. The pad is designed to contain any chemicals that may be spilled during the loading process; the runoff from this area is directed to and stored in the nearby stormwater pond. The pond itself is designed to be impermeable to prevent infiltration of the water containing varying concentrations of anti-icing chemicals.

Evaporation rates for the ponded water are low compared to the volume of water collected (Fitch et al., 2004, 2005), and allowing the stormwater ponds containing salt water to overtop and infiltrate has obvious adverse environmental implications, ranging from salt stress on surrounding vegetation to potential groundwater contamination. As a consequence, VDOT has been forced to dispose of the salt water by one of three methods: (1) connecting directly to a publicly owned treatment works (POTW) system, (2) hiring a contractor to pump and remove the salt-laden water, or (3) applying the salt water to gravel roads. Each option has significant shortcomings. With regard to the first option, POTW systems (especially the smaller capacity facilities) are becoming increasingly averse to accepting salt water because their systems are not designed to remove salt and large influxes of NaCl can disrupt the sensitive chemical and biological reactions that make these facilities effective at removing more typical wastes. The second option is expensive and ultimately still results in the water being disposed of at a POTW. The third option is becoming less feasible as more of VDOT's gravel roads are paved each year.

Previous Research

To address the problem of salt water collection and disposal, researchers at the Virginia Transportation Research Council (VTRC) and the University of Virginia undertook a study to define more fully the extent of VDOT's salt water collection, recommend ways of reducing the volumes collected, and identify potential methods of water treatment (Fitch et al., 2004). During January, February, and March of 2004, water samples from 45 detention-pond facilities in Virginia (5 facilities in each of the state's nine transportation districts) were collected and analyzed to quantify chloride-ion concentration, total suspended solids (TSS), and oil and grease. In addition, salt-loading pad areas and pond volumes and surface areas were quantified.

The study (Fitch et al., 2004) found that chloride concentrations were considerably greater than those specified in state and federal regulatory guidelines, with concentrations routinely exceeding 1,600 mg/L (2,636 mg/L NaCl). Average concentrations of TSS and oil and grease were 20 mg/L and 9.5 mg/L, respectively. Using historic rainfall and evaporation rate data (Southeast Regional Climate Center, 2004) from 1965 through 2003 and measured impervious pad and pond areas, the quantity of stormwater collected from the loading pads and ponds during the driest, wettest, and an average rainfall year was determined. Approximately 60 MG of contaminated runoff water is generated statewide in an average rainfall year. If only the runoff generated during the 5-month winter maintenance season is considered, the volume of salt-contaminated runoff produced in an average rainfall year is about 30 MG.

Statewide, VDOT was found to pay an average cost of $0.13/gal to dispose of the salt-contaminated runoff. For an average rainfall year, this translates into a total annual disposal cost of approximately $7.8 million. This estimate assumes that all the runoff (after accounting for evaporation losses) is treated, which does not always occur. Because of the high disposal cost per gallon and the extremely large volumes of water VDOT was capturing, the researchers recommended that VDOT consider reducing the size of the loading pads where possible to reduce the volume of water captured as runoff. They also recommended that VDOT install diversion valves in the pipes leading from the drains on the loading pads to the stormwater ponds (Fitch et al., 2004, 2005). This would enable facility managers to divert water that runs off the loading pads when no salt is present. At a minimum, this would allow for the diversion of runoff from April through October, again significantly reducing the volume of water captured in the ponds.

Even with pad size reduction and the use of diversion valves, it was recognized that VDOT would still capture large volumes of water that would require disposal or treatment. Therefore, in addition to the characterization of the water captured at VDOT sites, the earlier research included an evaluation of three treatment alternatives: ion exchange, electrodialysis, and reverse osmosis (RO). The assessment was based on the findings concerning the quantity and quality of the water captured at VDOT's sites. Using this information and an assumed target chloride concentration of 250 mg/L (411 mg/L NaCl), it was determined that RO was the only technology that was potentially feasible for use (Fitch et al., 2004, 2005).

RO refers to the process wherein water containing one or more solutes is forced through a membrane that allows the water but not the dissolved solute(s) to pass. RO systems do not require caustic or acid solutions for membrane regeneration, but they do require occasional cleaning and eventual membrane replacement. RO can achieve 90% to 98% removal of dissolved solids. In theory, this removal rate is satisfactory to treat the runoff water to a chloride concentration lower than 250 mg/L, which is the U.S. Environmental Protection Agency's National Secondary Drinking Water Regulation maximum level (*Code of Federal Regulations,* 2002).

RO has been used extensively for the treatment of water in a variety of settings including the pharmaceutical, semiconductor, power generation, pulp and paper, and chemical and petrochemical industries. The U.S. Bureau of Reclamation has even proposed using RO to treat a portion of the irrigation runoff captured within the San Joaquin Valley (Landers, 2003). Despite this wide variety of uses, almost no documentation exists regarding the use of RO to treat stormwater runoff and, more specifically, runoff water containing high levels of NaCl.

Although RO appeared promising, many issues about its applicability needed to be identified before VDOT could incur the capital costs required to use it as a means of treating salt water on a large scale. To test further the practicality of using RO for the treatment of VDOT's waste salt water, a pilot study was initiated in the fall of 2004. A single, 2000 GPD RO system built by Clean Water Products was tested in the laboratory and in the field. The system used a ¾ horsepower pump to push water through a 4-in by 40-in RO membrane at 160 psi. The concentrations of NaCl in the water treated ranged from 500 mg/L to 24,000 mg/L. Upon completion of the pilot, the researchers concluded that although Cl values under 20 mg/L could be achieved, because of the wide variability in NaCl concentrations in VDOT's ponds, Cl values above 25 mg/L could be expected. In addition, the volume reduction resulting from the RO unit tested resulted in only a 50% reduction in waste water volume. A third shortcoming identified was that pre-filtering was necessary because of the high turbidity levels found in most ponds. This additional pre-filtering step significantly reduced the volume of water that could be treated by the system in a given time period. All of these factors combined resulted in the conclusion that RO was not a feasible means by which VDOT could treat its waste salt water (Fitch et al., 2006).

As a consequence, with no feasible treatment alternative identified, VDOT is still in search of an environmentally appropriate and economically feasible means of managing significant volumes of salt water captured at its maintenance facilities each year. VDOT currently uses chloride solutions ($CaCl_2$, $MgCl_2$, or NaCl) to pre-wet dry granular NaCl prior to its application. In addition, VDOT uses salt brine solution on a limited basis for direct liquid application as part of its anti-icing program (Roosevelt, 1997, unpublished data, 2008). If some fraction of the stormwater that is currently collected and disposed of as waste could be used in the making of brine solution for the purposes of pre-wetting and direct application, potentially significant volumes of water would no longer require either treatment or disposal.

PURPOSE AND SCOPE

The purpose of this study was to investigate the reuse of the salt-contaminated stormwater runoff at VDOT road-salt storage facilities as a water source for on-site brine production. Since the use of captured stormwater would likely introduce large variations in water temperature and turbidity levels during the brine making process, a better understanding of the potential effects of these changes was deemed important. More specifically, the research effort was designed to ensure that using stormwater for brine generation (1) would not have a significant effect on the quantity of brine that could be produced, (2) would not compromise the quality of the brine, (3) would not damage the brine production systems and application equipment, and (4) would be an economically feasible alternative to current disposal options.

The feasibility of this approach was quantified through bench-scale experiments in the laboratory using synthetic water samples and pond water samples collected from the field. A field test was conducted at one VDOT area headquarters (AHQ).

METHODS

To achieve the study objectives, the study team undertook three primary tasks: (1) laboratory testing of a bench-scale brine generation unit, (2) field testing of the unit, and (3) a benefit-cost (B/C) analysis of recycling stormwater runoff for brine generation.

Laboratory Testing

An 0.07-m^3 brine generation unit was built as a 1:100 scale of the ABS-1500 automatic brine generation system manufactured by GVM, Inc. A full-scale system is currently being used in a pilot study investigating on-site brine production at VDOT's Prince George AHQ (Petersburg Residency). The system consists of a rectangular (32 cm height, 80 cm width, and 28 cm depth) receptacle where the dry salt is deposited. At the bottom of the tank, two perforated polyvinyl chloride (PVC) pipes introduce the tap water from the bottom of the tank; water flows upward through the salt bed, and salt is dissolved into the water (see Figure 1, *top*). The system uses an 0.2-m^3 feed tank and a peristaltic pump to force tap water up through the dry salt bed.

A set of experiments was designed to determine the optimum hydraulic characteristics of the brine generation system and the quantity and quality of effluent from the process for influent solutions that mimic or replicate the salt-contaminated pond water. For each experiment, 62 ± 2 kg of road salt from a VDOT storage facility was used. A total of three experiments at two temperatures were conducted to obtain a minimum of 0.05 m^3 of brine (Table 1 shows the experimental conditions) using tap water as a feed solution. Salt concentrations were measured every 5 to 10 min using a saltmeter. The flow rate, height of the salt bed, and turbidity were measured every 5 to 10 min.

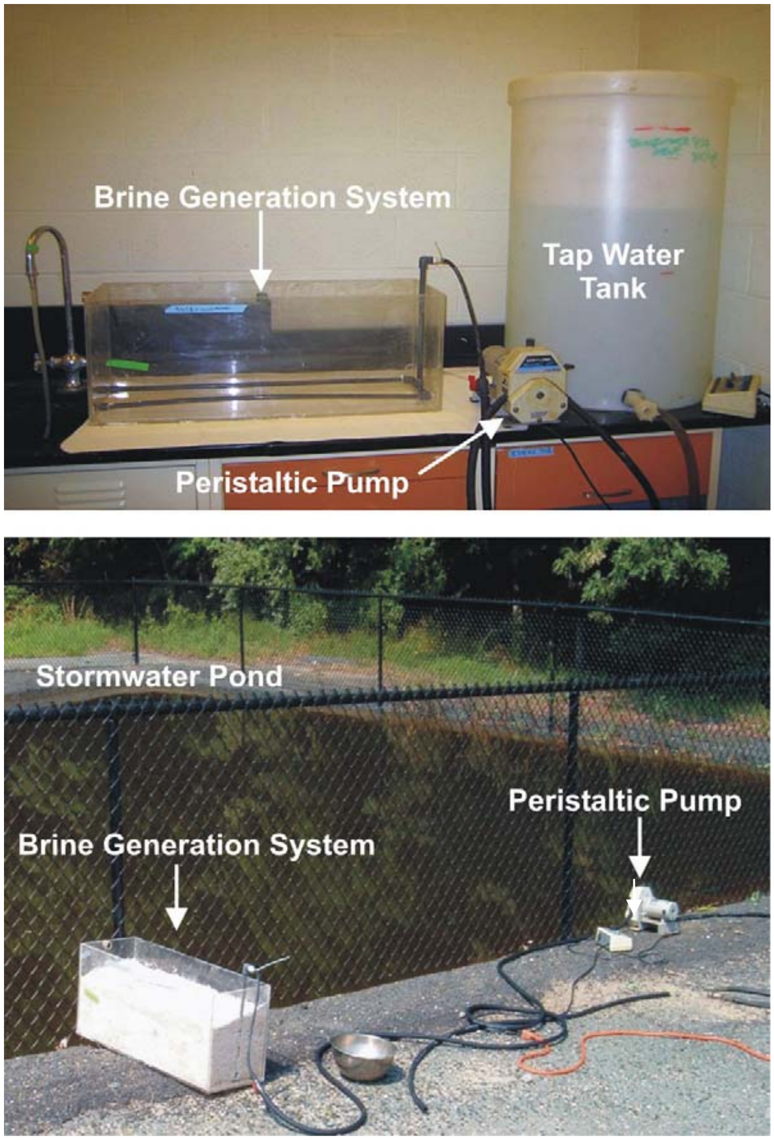

Figure 1. Setups for Laboratory Experiments *(top)* and Field Experiments *(bottom)* with Brine Generation Systems

Table 1. Operational Conditions Used for Brine Generation

Location	Water Temperature	Hydraulic Retention Time (min)
Laboratory	18 °C	17.9
		25.6
		45.0
	5 °C	21.6
		25.2
		37.0
Field	25 °C	31.8
		132.0

Field Testing

Presently, two VDOT maintenance facilities (Hanging Rock AHQ in the Salem Residency and Prince George AHQ in the Petersburg Residency) have invested in brine production equipment and have the capability to produce brine on site using municipal drinking water sources. These sites would have been logical choices for testing the effects of stormwater for brine production: however, because they do not have stormwater collection ponds, this was not feasible. Instead, the Boyd's Tavern AHQ (Charlottesville Residency) was chosen as the site for the field experiments because of its proximity to VTRC.

The field test was conducted using the same brine generation system used in the laboratory (see Figure 1, *bottom*). The Boyd's Tavern facility has a stormwater collection pond with a storage capacity of approximately 30,000 gal. Water quality analysis performed on site revealed a NaCl concentration of 110 mg/L (0.01%) and a turbidity level of 4.24 NTU.

The brine generation system was filled with approximately 62 kg of road salt collected from the salt-storage dome on site. Instead of feeding the unit with tap water, water was withdrawn from the stormwater pond using a Masterflex peristaltic pump. The influent was pumped through a coarse screen filter (mesh size 80) to remove large particles and other debris before being introduced to the brine generation system. Two operational conditions were tested (see Table 1). The brine produced was pumped back to the stormwater pond. Samples of the brine generated were collected every 5 and 15 min for the 31.8- and 132-min experiments, respectively. The samples were analyzed on site for salt content and turbidity.

Benefit/Cost Analysis

A B/C analysis of recycling stormwater runoff for brine generation was conducted assuming two methodologies for brine application (pre-wetting of dry sodium chloride and direct application of brine in conjunction with pre-wetting), different volumes of stormwater runoff potentially captured (i.e., accumulated statewide), different quantities of road salt applied during the winter season, and two disposal costs per gallon of runoff. This resulted in a total of 72 hypothetical scenarios for which benefits were calculated.

The values for maximum, average, and minimum volumes of stormwater runoff accumulated statewide were obtained from a previous study (Fitch et al., 2004) and are shown in Table 2. These values represent the estimated annual and winter runoff volumes collected in the stormwater ponds at VDOT's maintenance sites based on 38 years of rainfall data (Southeast Regional Climate Center, 2004) collected at 27 stations statewide and 30 years of evaporation data (Virginia State Climatology Office, 2001) from five regional stations.

Table 2. Annual and Winter Treatment Volumes

Value	Annual Volume (MG)	Winter Volume (MG)
Minimum	35	19
Average	59	31
Maximum	88	36

Table 3 shows the quantity of road salt purchased by VDOT from 2000 through 2005. For the purposes of the B/C analysis, the maximum, average, and minimum amounts from this 5-year period were used.

Table 4 shows the estimated costs of the brine generation unit and additional accessories required for a maintenance facility that would apply brine. These values were conservatively approximated based on equipment costs found in other anti-icing and department of transportation (DOT) synthesis studies (Alleman et al., 2004; O'Keefe and Shi, 2005). Currently, the majority of VDOT's salt spreader trucks have pre-wetting equipment (in the form of saddle tanks) to apply $CaCl_2$ or $MgCl_2$ solutions. It was assumed that this equipment would be sufficient for pre-wetting with salt brine. For this analysis, it was also assumed that one brine generation unit would be purchased for 300 VDOT maintenance facilities. (In all likelihood, VDOT would not need to purchase the full complement of equipment for each facility as some locations would be able to share equipment and other facilities may not be used in the future because of privatization of maintenance tasks.) In addition to the capital costs, the annual operational costs were estimated to be 1% of the total capital investment.

The volumes of stormwater runoff potentially used for brine generation were estimated depending on the method of application. For the pre-wetting method, a rate of 15 gal/ton of road salt was assumed based on a range of 8 to 30 gal/ton, as found in the literature (Alleman et al., 2004; Ketcham et al., 1996; Wisconsin DOT, 2005). Based on the historical granular NaCl usage values for VDOT (as taken from Table 3), it was assumed that 20% of this volume would be applied as brine using direct application. It was then assumed that the remaining 80% of granular salt applied would be pre-wet with a brine solution. Although this 20% direct brine application to 80% dry NaCl application ratio is purely hypothetical, it does fall within the ranges reported by other DOTs currently using brine for anti-icing (O'Keefe and Shi, 2005) and should be conservative for Virginia given that direct brine application is normally considered a good strategy when pavement temperatures are above 20°F (Blackburn et al., 2004). In all calculations, to obtain a brine solution at its eutectic point (23.3%), 0.44 gal of water was used to dissolve each pound of road salt.

Table 3. Road Salt Purchased by VDOT Over Recent 5-year Period

Year	Tons
2000-01	346,979
2001-02	138,706 (minimum)
2002-03	519,084 (maximum)
2003-04	341,021
2004-05	313,786
Average	331,975

Table 4. Initial per Site Capital Investment for Pre-Wetting and Direct Application of Brine

Equipment	Direct Application	Pre-wetting
Brine generation unit	$10,000	$10,000
Storage tank (5,000 gal)	$3,500	$3,500
Single line spreader	$12,700	-
Total	$26,200	$13,500

A statewide average value of \$0.13/gal was used as the first disposal cost of salt water based on the findings of earlier research (Fitch et al., 2004). Because a second disposal cost of \$0.55/gal was recently incurred at the Prince George maintenance facility, it is included here as an example of possible variance in local disposal costs from the statewide average previously determined.

The annual benefits were calculated as the difference between the costs of disposal of the total annual volume of stormwater runoff accumulated and disposal of the volume remaining after the brine production (water not used for brine generation would still need disposal at cost), plus the savings resulting from the use of the NaCl brine solution instead of $CaCl_2$ or $MgCl_2$ as the pre-wetting solution. For this analysis, a cost of \$0.50/gal for the $CaCl_2$ and $MgCl_2$ solutions was assumed although the cost of these chemicals can be much higher (O'Keefe and Shi, 2005). Put another way, the annual benefits can be calculated as forgone costs with the following equation:

$$AB = (volume_{DA} \times dc) + [volume_{PW} \times (dc + cc)]$$

where *AB* is annual benefit (\$), $volume_{DA}$ is annual direct application volume (gal), *dc* is disposal cost (\$0.13/gal), $volume_{PW}$ is annual pre-wetting volume (gal), and *cc* is the cost of other pre-wetting chemicals (\$0.50/gal). Operating costs were assumed to be negligible.

Each of the 72 scenarios was evaluated for the number of years required for forgone costs to offset exactly the initial investment in brine generation equipment (i.e., the number of years required to obtain a net present value [NPV] of zero). NPV was calculated as follows:

$$NPV = I + AB\frac{(1+i)^n - 1}{i(1+i)^n}$$

where *I* is initial investment (\$), *AB* is annual benefit (\$), and *i* is the discount rate (%). The discount rate assumed for this analysis was 5%.

RESULTS AND DISCUSSION

Laboratory Experiments

Hydraulic Retention Time and Water Temperature

Hydraulic retention time (HRT) and temperature are two key parameters for efficient brine generation in terms of the quality of the brine produced and production costs. The HRTs were selected to represent different operational conditions that might be used on site for brine preparation. The lowest HRT tested was just under 18 minutes and was based on the average flow rate and holding capacity of the ABS-1500 system previously described. This HRT for the full-scale equipment corresponds to a flow rate of about 22 m^3/h. Because some maintenance facilities may not be able to obtain such high flow rates, higher HRTs (which correspond to lower flow rates) were tested. Water temperatures between 18°C and 5°C were selected to simulate fall and winter water temperature conditions that could be expected in the stormwater ponds (as compared to the average temperature of 12°C for groundwater).

During the laboratory phase of the study, salt concentration was determined every 3 to 10 min, depending on the HRT applied. Because the effluent was discharged directly to the sewage system, a mathematical expression was used to determine the percentage of NaCl (based on mass) that would be produced in the brine if it was collected in a completely mixed storage tank:

$$Accumulative\ salt\ percentage\ (\%) = \frac{\left\lfloor \sum_{i=1}^{n} (c_{i+1} - c_i) \cdot (t_{i+1} - t_i) \cdot F \cdot 0.5 + c_{i+1} \cdot (t_{i+1} - t_i) \cdot F \right\rfloor}{\left\lfloor \sum_{i=1}^{n} (c_{i+1} - c_i) \cdot (t_{i+1} - t_i) \cdot F \cdot 0.5 + c_{i+1} \cdot (t_{i+1} - t_i) \cdot F \right\rfloor + F \cdot t_{i+1} \cdot \rho_w} \cdot 100$$

where c_i and c_{i+1} (kg/L) are the salt concentrations in the effluent of the brine generation unit measured at times t_i and t_{i+1} (min), respectively; F (L/min) is the flow rate applied; and ρ_w is the water density (kg/L) at the temperature of the experiment.

Figure 2 shows the percentage of salt in the brine produced at different hydraulic retention times and two temperatures. At both temperatures, the brine production, in terms of volume, decreased with the increase in the HRT.

Low water temperatures had a negative effect on brine production. At 5°C, the brine produced did not reach 23.3% salt at any of the HRTs. Decreasing temperature reduced the salt solubility, and the rate of dissolution decreased.

HRT and temperature also had an effect on the height of the salt in the tank as a function of time. Figure 3 shows the height of the bed of salt versus time for the different operational conditions tested. Temperature changes seemed to have a stronger effect on the amount of salt dissolved than did variation of the HRT. With two similar HRTs, 83% of the salt was dissolved after 60 min at 18˚C and only 70% of the salt was dissolved at 5˚C in the same time period. Many of the salt crystals did not dissolve, even after 300 min of operation, and they remained as a residue at the bottom of the tank. Most of these undissolved crystals were relatively large; smaller salt crystals will likely promote higher specific surface areas and higher mass transfer (dissolution) rates.

Turbidity

Turbidity was one of the major concerns with using stormwater for the creation of brine, stemming from the findings of the RO study previously conducted (Fitch et al., 2006). The investigators concluded that the high turbidity levels were the cause of the microfiltration unit clogging and ultimately restricting the throughput available for filtration by the RO filter. There was concern that these same turbidity values would (1) hinder the production of brine, (2) potentially damage the brine generation equipment, or (3) clog the brine application equipment. Figure 4 shows the turbidity values for effluent samples at each set of operating conditions. The effluent turbidity decreased rapidly from 2,000 NTU to 500 NTU after 10 min of operation in

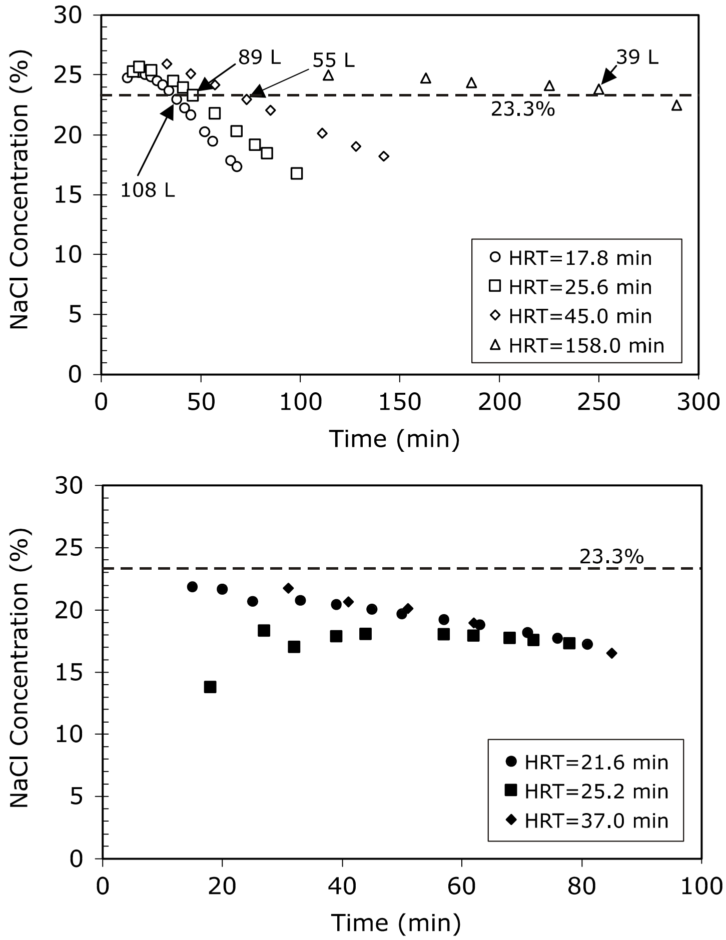

Figure 2. Percentages of Salt in Brine and Volume Produced as Function of Hydraulic Retention Time (HRT) and Temperature at 18°C *(top)* and 5°C *(bottom)*. The *horizontal dashed line* represents desired effluent salt percentage (23.3%).

every experimental condition tested. The turbidity values at the end of every experimental period were lower than 100 NTU. The high turbidity detected in the brine for each experiment originated from the high concentration of TSS in the road salt and would therefore be present regardless of the TSS from the source water. This finding was somewhat surprising but helped alleviate initial concerns that the turbidity of the stormwater runoff would hinder the brine generation process or damage the equipment since it was found in the earlier characterization study (Fitch et al., 2004) that the statewide average for TSS for water in the stormwater runoff ponds was 20 mg/L.

The turbidity values for every sample were determined again after 4 hr of settling (Figure 5). All samples analyzed had turbidity reductions greater than 95% after each settling period. The elevated content of salt in the effluent promoted the sedimentation of colloidal particles in accordance with the diffuse double layer theory. Therefore, despite the high content of TSS in the road salt, high levels of sedimentation are achieved in part because of the high salt concentration. This will result in less turbid water going to the brine application tanks and spreaders but may also require increased maintenance of the brine generation equipment.

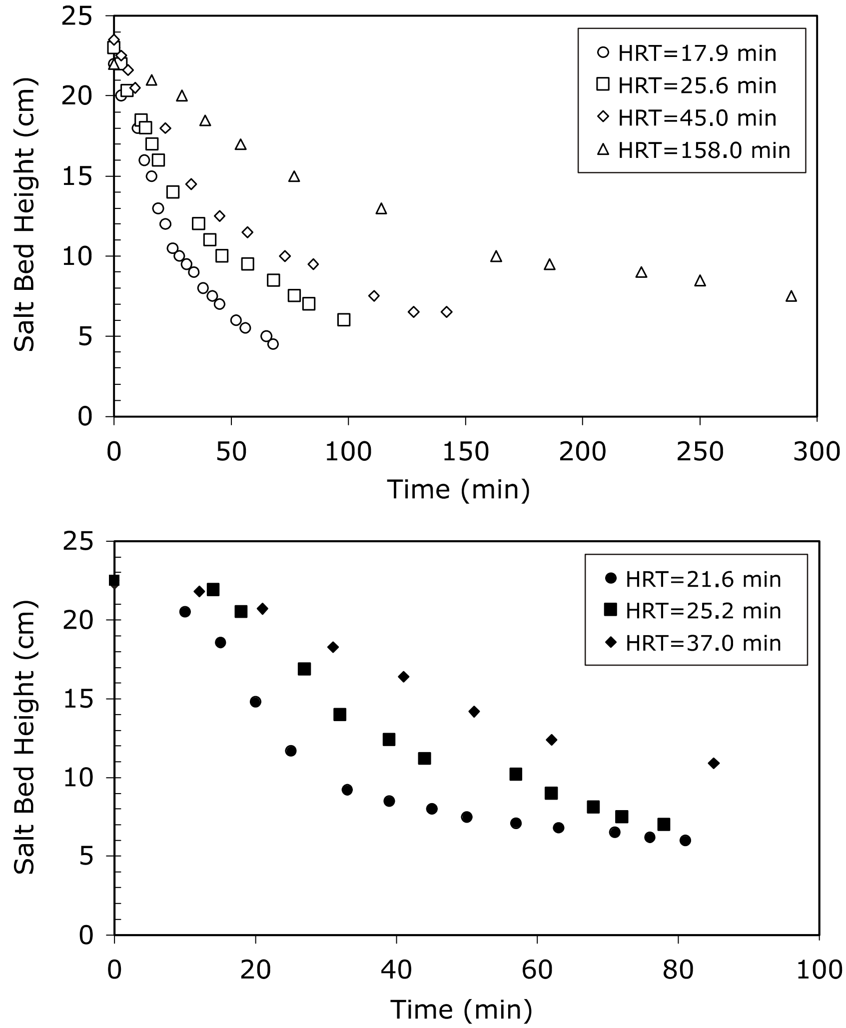

Figure 3. Height of Salt Bed as Function of Hydraulic Retention Time (HRT) and Temperature at 18°C *(top)* and 5°C *(bottom)*

Field Test

The results of the field test were similar to those of the laboratory phase. Short HRTs were found to be more effective than long HRTs for brine generation (see Figure 6). Moving more water through the system in a shorter period of time resulted in higher dissolution rates, which in turn resulted in a greater percentage of the salt in the unit being used. This was identical with what was found in the laboratory results. The dissolved NaCl in the pond water did not have a measurable effect on the final NaCl concentration in the effluent. This finding was not unexpected since the NaCl level of the pond was only 0.01% and the final concentration was approximately 23%.

As was expected based on the laboratory findings, the TSS content in the stormwater did not affect the brine generation process (because of the already high turbidity values resulting from the salt). Turbidity values obtained for the effluent and settled effluent were similar to those obtained with tap water (turbidity lower than 0.3 NTU) during the laboratory tests (see Figure 7).

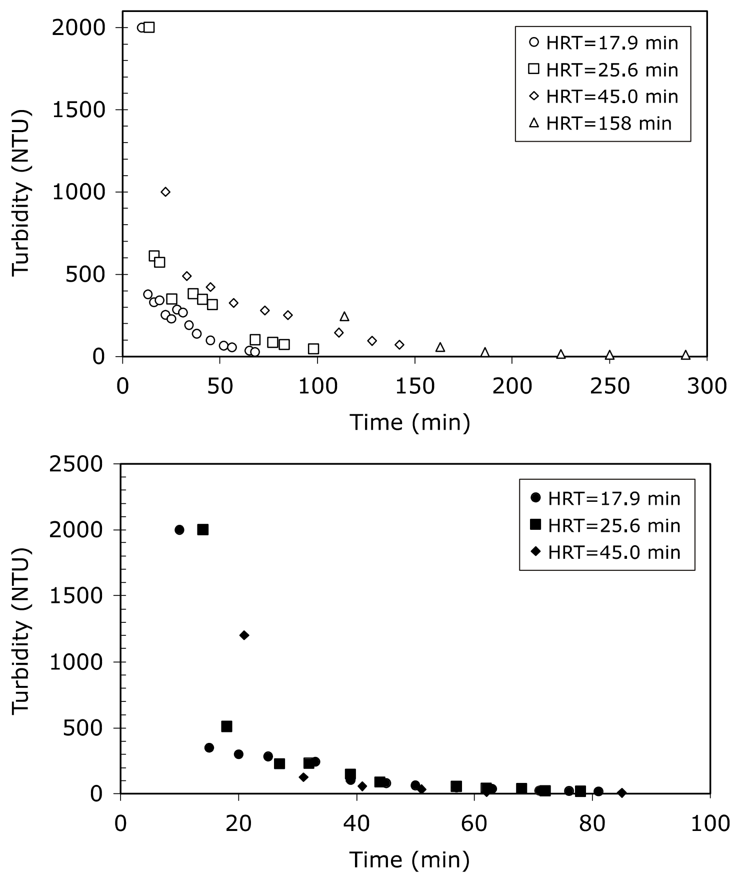

Figure 4. Effluent Turbidity as Function of Hydraulic Retention Time (HRT) and Temperature at 18°C *(top)* and 5°C *(bottom)*

Benefit/Cost Analysis

The estimated volumes of water that would be used for (1) pre-wetting only and (2) direct application in combination with pre-wetting when assuming the low, average, and high NaCl annual application rates are shown in Figure 8. Only the volume of water that would be needed for direct application for the high chemical application rate significantly exceeds VDOT's average stormwater capture volume as calculated in Fitch et al. (2004, 2005).

The estimated annual benefits for 36 brine use scenarios evaluated at the statewide average disposal cost per gallon are shown in Figure 9. The calculated values range from a low of just over $1 million to a high of over $14 million. The lowest value was calculated assuming less than 20 million gallons of stormwater are collected (the minimum winter volume, Table 2), brine created from this stormwater is used exclusively for the purposes of pre-wetting, and a minimum volume of NaCl (138,706 tons) is applied statewide. The greatest annual benefits were calculated assuming that brine is used for both direct application and pre-wetting purposes, nearly 90 million gallons of stormwater is collected (the maximum annual volume, Table 2), and the highest total NaCl volume (519,084 tons) is applied. When assuming average stormwater volume collection and average total NaCl application, the benefits calculated for pre-wetting only versus adding direct application to pre-wetting are approximately $3 million and $6.5 million, respectively.

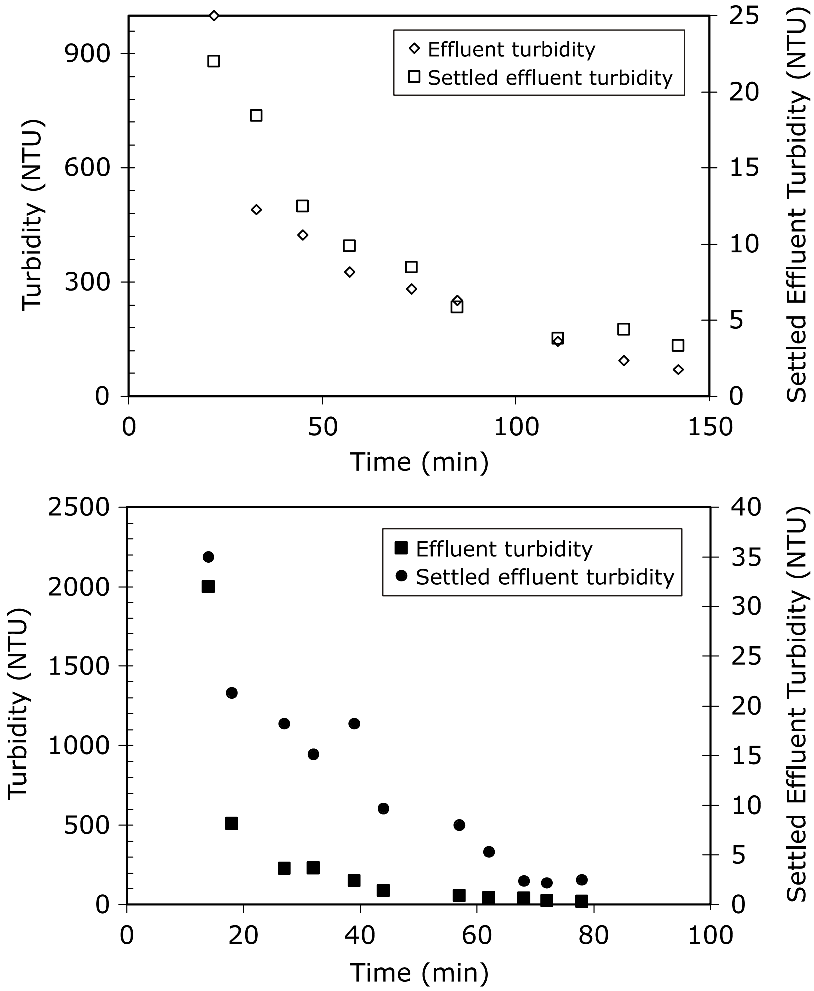

Figure 5. Comparison of Turbidity Values for Effluent Samples at Time of Collection and After 4 Hours of Settling for 18˚C *(top)* and 5˚C *(bottom)*

It is clear from this analysis that the greatest benefits are derived when direct brine application is used in conjunction with pre-wetting. It should also be noted that these benefits are primarily attributable to the reduced disposal costs of the collected stormwater. The other benefits of direct brine application and pre-wetting (i.e., reduced total chemical usage, increased level of service, etc.) as documented in the literature (Alleman et al., 2004; Ketcham et al., 1996; O'Keefe and Shi, 2005; Wisconsin DOT, 2005) were not considered in this analysis.

This analysis also revealed the approximate optimum (with respect to benefits accrued) stormwater volumes collected for each total chemical volume used and application method used. These volumes are represented by the vertical dashed lines in Figure 9. For all three salt-use scenarios where only pre-wetting is used, no additional benefits are accrued if additional stormwater is collected. This indicates that VDOT could generate all the brine used for pre-wetting with the minimum amount of stormwater captured. Conversely, assuming the maximum chemical application scenario and direct application of brine in conjunction with pre-wetting, the maximum volume of stormwater potentially collected could be used in the making of brine necessary for these two application methods.

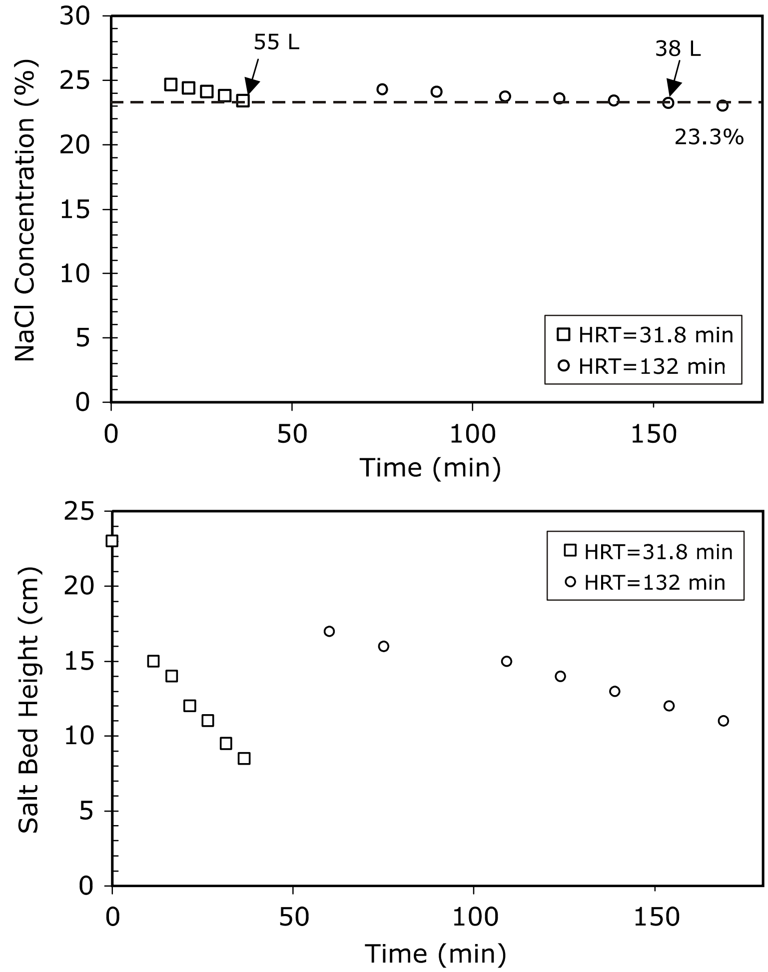

Figure 6. ***Top:*** **Percentages of Salt in Brine and Volume Produced as Function of Hydraulic Retention Time (HRT).** ***Bottom:*** **Height of Salt Bed as Function of HRT.**

Table 5 summarizes the results for how long it would take forgone disposal and chemical additive costs to offset the brine generation capital investment costs for each of the 72 scenarios. All alternatives yielded a positive return on the investment in less than 4 years. The reuse of stormwater runoff for brine to be used for pre-wetting offset the initial brine generation equipment costs more rapidly as the amount of road salt used increased, regardless of the volumes of stormwater runoff accumulated during the year or winter season. For direct application in conjunction with pre-wetting, the number of years required to recoup the capital investment was significantly reduced when compared with pre-wetting only. In addition, this alternative was more sensitive to the variation of the quantity of salt applied and to the variation of the volume of stormwater runoff accumulated. However, with all alternatives, the use of volumes of stormwater runoff higher than 30 MG and road salt application higher than 332,000 tons per year resulted in the recovery of the capital invested in less than 2 years when assuming statewide average disposal costs.

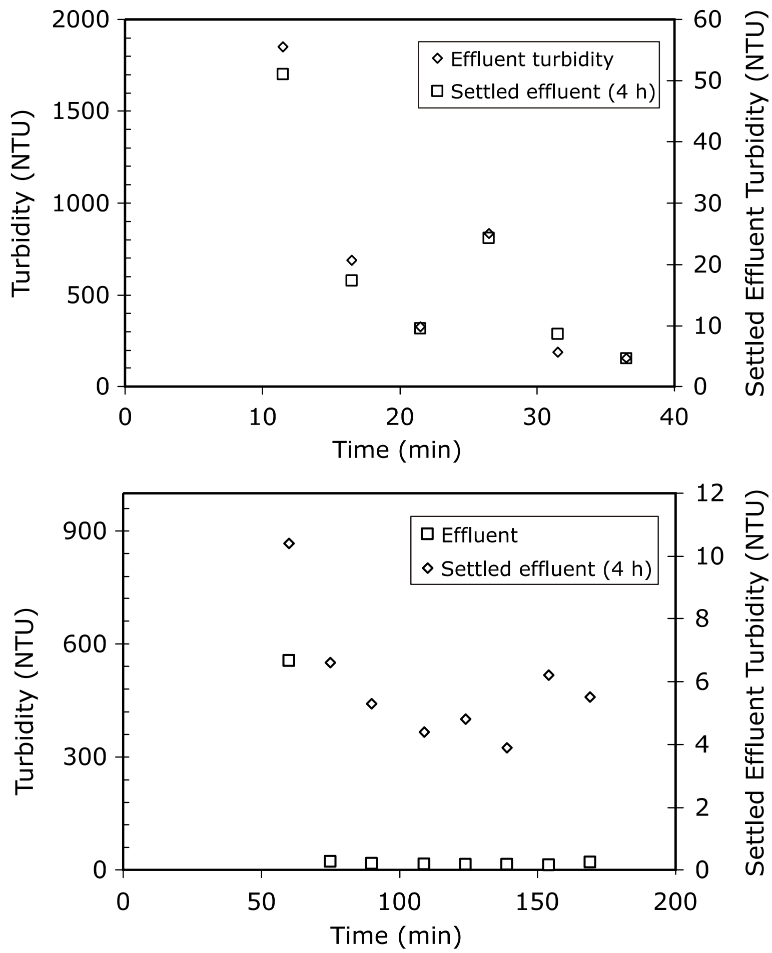

Figure 7. Comparison of Turbidity Values for Effluent Samples at Time of Collection and After 4 Hours of Settling for Hydraulic Retention Time (HRT) = 31.8 min *(top)* and HRT = 132 min *(bottom)*

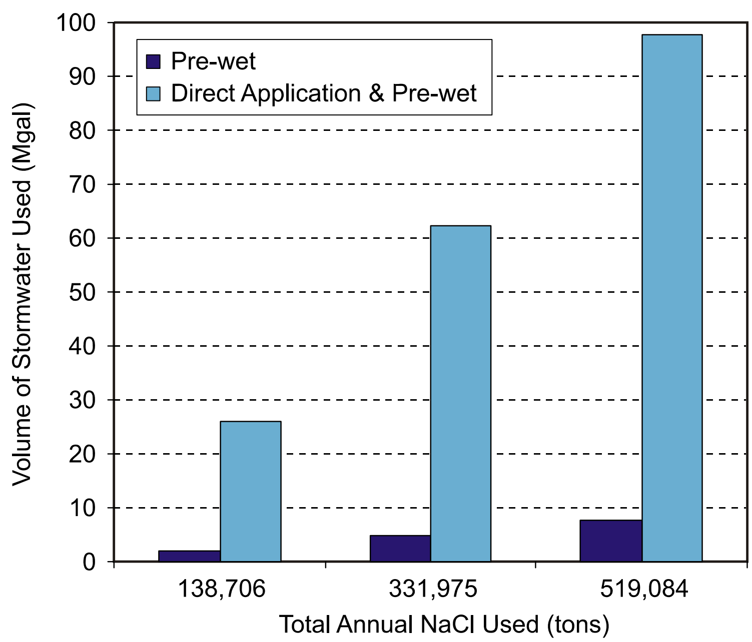

Figure 8. Estimated Annual Stormwater Usage for Pre-wetting and Direct Application and Pre-wetting Based on Low, Average, and High 5-Year Total NaCl Application

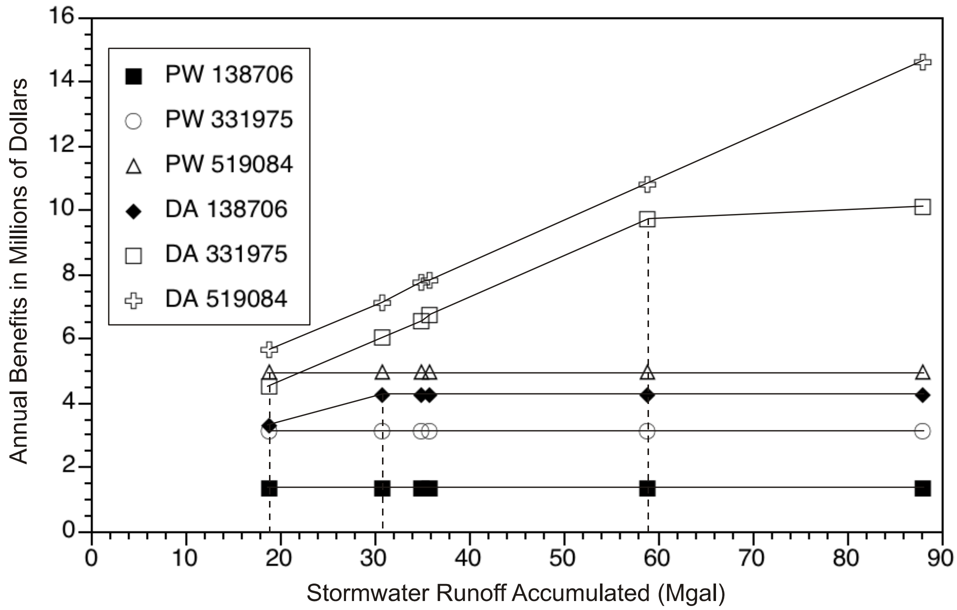

Figure 9. Annual Benefits Obtained by Use of Pre-Wetting (PW) or Direct Application (DA) Strategies as Function of Volume of Stormwater Runoff Accumulated and Amount of Road Salt Purchased. ***Vertical dashed lines*** **indicate stormwater volumes at which maximum benefits were accrued for three quantities of road salt used: 138,706; 331,975; and 519,084 tons, respectively.**

CONCLUSIONS

- *Low HRTs and high temperatures are the optimum conditions for brine generation in terms of time of operation and percentage of NaCl used.* Lower HRTs will require more frequent additions of road salt to the brine generation reactor.

- *The lower water temperatures likely to result from the use of water from stormwater ponds during the late fall and winter will reduce the efficiency of the brine generation equipment compared to the use of water at a higher temperature coming from a groundwater source.* The efficiency of brine generation when stormwater is used should be similar to that when a municipal drinking water source is used since the temperature of the water from these two sources is comparable.

- *TSS levels of approximately 20 mg/L, as found in VDOT's captured stormwater, do not reduce the efficiency of the brine generation process.* The values for TSS in the stormwater were relatively small compared to those for the source of granular NaCl.

- *With minimal filtering, stormwater from runoff storage ponds can be recycled for brine production without harm to brine generation or distribution equipment.*

Table 5. Number of Years Required to Recover Capital Investment for (1) Pre-Wetting and (2) Direct Application and Pre-Wetting as Function of Stormwater Runoff Accumulated and Amount of Road Salt Purchased

Application Method	Amount of Salt Purchased (tons)	Stormwater Runoff Accumulated (million gallons)	NPV 1 Payoff with Disposal = $0.13/gal (years)	NPV 2 Payoff with Disposal = $0.55/gal (years)
Pre-wetting	138,706	19	3.6	2.0
		31	3.6	2.0
		35	3.6	2.0
		36	3.6	2.0
		59	3.6	2.0
		88	3.6	2.0
	331,975	19	1.4	0.8
		31	1.4	0.8
		35	1.4	0.8
		36	1.4	0.8
		59	1.4	0.8
		88	1.4	0.8
	519,084	19	0.9	0.5
		31	0.9	0.5
		35	0.9	0.5
		36	0.9	0.5
		59	0.9	0.5
		88	0.9	0.5
Direct application and pre-wetting	138,706	19	2.7	0.7
		31	2.0	0.5
		35	2.0	0.5
		36	2.0	0.5
		59	2.0	0.5
		88	2.0	0.5
	331,975	19	1.9	0.7
		31	1.4	0.4
		35	1.3	0.4
		36	1.3	0.4
		59	0.9	0.2
		88	0.8	0.2
	519,084	19	1.5	0.6
		31	1.2	0.4
		35	1.1	0.4
		36	1.1	0.4
		59	0.8	0.2
		88	0.6	0.2

NPV = net present value. NPV 1 is based on a salt water disposal cost of $0.13/gal; NPV 2 is based on a salt water disposal cost of $0.55/gal.

- *Based on the total annual stormwater collection estimate of 60 million gallons, VDOT captures sufficient water for all pre-wetting conditions and for the low and average direct application conditions requiring approximately 25 and 60 million gallons, respectively*.

- *The implementation of a VDOT recycling program using stormwater runoff for brine generation appears economically feasible*. There will be large variations in the benefits accrued by VDOT depending on the volumes of stormwater runoff accumulated during the year, the total volume of NaCl applied, and local disposal costs.

- *Between the two brine application alternatives examined, for most scenarios investigated, the combination of direct application and pre-wetting results in a faster positive return on VDOT's initial investment (see Table 5).*

- *Assuming average total NaCl application volumes, the maximum benefits derived from stormwater reuse are obtained when capturing less than 60 MG of stormwater statewide*. More water would be needed only during years with extremely high chemical application.

RECOMMENDATIONS

1. *VDOT's Richmond District should participate in a pilot study using stormwater for brine generation.* This study would be conducted by VTRC in conjunction with the Prince George AHQ maintenance facility and would document the volumes of water collected and used for brine generation, the resulting cost savings, and any other consequences of stormwater reuse. The outcome of this pilot would speed up implementation of stormwater reuse by demonstrating significant cost savings.

2. *VDOT's Asset Management Division should institute the use of NaCl brine generated from stormwater for the pre-wetting of granular NaCl.* This would require that additional maintenance facilities purchase and operate brine generation units but would result in decreased volumes of stormwater requiring disposal and decreased purchases of $MgCl_2$ and $CaCl_2$.

3. *Following the completion of the pilot study and the purchase of brine generation equipment, VDOT's Asset Management Division should begin to integrate the use of direct brine application*. This would require additional application equipment but would increase the volume of stormwater reused (thereby decreasing the volume requiring disposal).

4. *VDOT's Asset Management Division should continue to implement the recommendations previously stipulated in Fitch et al. (2004, 2006) to reduce the size of the loading pads and to install diversion valves.* The implementation of these two practices would provide VDOT significantly greater control over the quantity of stormwater that is captured at its facilities.

COSTS AND BENEFITS ASSESSMENT

Depending on the method of brine application (pre-wetting or direct brine application) employed by VDOT, significant cost savings could be accrued. Disregarding the cost savings touted in several recent anti-icing studies (Alleman et al., 2004; Ketcham et al. 2006; O'Keefe and Shi, 2005; Wisconsin DOT, 2005) resulting from a reduction in total chemicals needed and an increased level of service, for VDOT, the savings would result from the reuse of stormwater that would otherwise require disposal. Based on calculations using the most conservative chemical application, brine use, and total stormwater capture estimates, VDOT would save nearly $1.5 million each year by pre-wetting with NaCl brine generated from its salt-laden stormwater. The equipment required to implement this practice statewide would have an estimated cost of approximately $4 million.

When assuming average chemical application volumes and stormwater collection, if brine is applied directly in addition to being used to pre-wet granular NaCl, VDOT's savings could be as high as $6.5 million a year with estimated capital costs of nearly $8 million. Given the same scenario, the calculations showed that it would take approximately 1.3 years for the forgone disposal and chemical additive costs to offset the brine generation and application capital investment costs when assuming a stormwater disposal cost of $0.13/gal. Assuming a disposal cost of $0.55/gal for stormwater, capital investment costs would be offset in 0.4 year.

REFERENCES

Alleman, J.E., Partridge, B.K., and Yeung, L. *Innovative Environmental Management of Winter Salt Runoff Problems at INDOT Yards*. FHWA/IN/JTRP-2001/27. Purdue University Joint Transportation Research Project, West Lafayette, IN, 2004.

Blackburn, R.R., Bauer, K.M, Amsler, Sr., D.E., Boselly, S.E., and McElroy, A.D. *Snow and Ice Control: Guidelines for Materials and Methods.* NCHRP Report 526. Transportation Research Board, Washington, DC, 2004.

Code of Federal Regulations. Title 40: Protection of Environment. Washington, DC, 2002.

Fitch, G.M., Smith, J.A., and Bartelt-Hunt, S.L. *Characterization and Environmental Management of Stormwater Runoff from Road-Salt Storage Facilities.* VTRC 05-R15. Virginia Transportation Research Council, Charlottesville, 2004.

Fitch, G.M., Bartelt-Hunt, S.L., and Smith, J.A. Characterization and Environmental Management of Stormwater Runoff from Road Salt Storage Facilities. In *Transportation Research Record No. 1911.* Transportation Research Board, Washington, DC, 2005, pp. 125-132.

Fitch, G.M., Craver, V.O., and Smith, J.A. *Potential Use of Reverse Osmosis in Managing Salt-Water Waste Collected at Road-Salt Storage Facilities*. VTRC 06-R26. Virginia Transportation Research Council, Charlottesville, 2006.

Ketcham, S.A., Minsk, L.D., Blackburn, R.R., and Fleege, E.J. *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel*. FHWA-RD-95-202. Federal Highway Administration, Turner-Fairbank Highway Research Center, Office of Engineering Research & Development, McLean, VA, 1996.

Landers, J. California Drainage Project to Rely on Local Disposal. *Civil Engineering,* Vol. 73, 2003, pp. 24-27.

O'Keefe, K., and Shi, X. *Synthesis of Information on Anti-icing and Pre-wetting for Winter Highway Maintenance Practices in North America.* Western Transportation Institute, Montana State University, Bozeman, 2005.

Roosevelt, D.S. *A Survey of Anti-Icing Practice in Virginia*. VTRC 98-R19. Virginia Transportation Research Council, Charlottesville, 1997.

Southeast Regional Climate Center. *Historical Climate Summaries and Normals for the Southeast*. Columbia, SC, 2004.

Virginia State Climatology Office. *Regional Evaporation Rates from 1971-2000*. Charlottesville, 2001.

Wisconsin Department of Transportation, Bureau of Highway Operations. Anti-icing Technique, Guideline 32.35. *State Highway Maintenance Manual.* Madison, 2005.