# Monitoring soil solution, soil chemistry, and vegetation responses to municipal solid waste leachate applications at the Fenske landfill.

## Report of 2004 Results

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## Introduction

The Michigan Department of Environmental Quality (MDEQ) assumed the responsibility for completing the closure and capping of the Fenske landfill (SE ¼ Section 12, T6N R13W, Ottawa County, Michigan) after the original owner and operator abandoned the property. The final capping was completed in the Fall of 2002, but during active landfill operation, substantial amounts of rainfall had infiltrated and the landfill continues to produce leachate that must be removed to prevent rupture of the landfill cover. To dispose of this leachate, the MDEQ contracted with DLZ Michigan, Inc. to develop a spray irrigation system to apply the leachate on the vegetated landfill cover. Because of the potential for groundwater contamination, soil contamination, and negative effects on vegetation, this type of leachate disposal needs to be carefully monitored both to evaluate its effectiveness and to insure that adverse environmental impacts do not occur (Shrive et al., 1994; Revel et al., 1999; Smith et al., 1999a; 1999b). The MDEQ conducted experimental leachate applications on site during the fall of 2001 and summer of 2002, without any apparent adverse effects on established vegetation. The MDEQ expanded this project in 2003 to an operational level and contracted with Grand Valley State University (GVSU) and the Annis Water Resources Institute (AWRI) to monitor the effects of leachate application on soil chemistry, solute leaching, and plant growth.

Between July and November, 2003, approximately 32 cm of leachate were applied to the irrigation plots. The leachate was high in conductivity, $NH_4$-N, and total organic carbon (TOC), but low in metals and volatile organic compounds (VOCs), similar to many other municipal landfill leachates (Kjeldsen et al., 2002). At the end of the 2003 irrigation season, leachate application had no significant effects on surface or subsurface soil properties, but soil solution conductivity and concentrations of Cl, $NO_3$-N, TOC, Ba, and Cu increased significantly on irrigation plots. Plant biomass on irrigated plots was over three times greater than on control plots as a result of high rates of N and water addition, similar to positive growth effects noted in several other studies (Cureton et al., 1991; Maurice et al., 1999; Revel et al., 1999). High rates of leachate application in 2003 produced elevated leaching losses of both water and solutes, especially Cl and $NO_3$-N. To reduce the potential for leaching losses, we recommended timing leachate applications to match periods of greatest evapotranspirational demand (June-August). Based upon water balance calculations, we recommended that no more than 2.4 cm of leachate should be applied per irrigation date in any location, total leachate applied should not exceed 9.6 cm in any one spray area during an irrigation season, and spray heads should be rotated among several spray areas to distribute the leachate applied.

A major concern noted in 2003 was related to the increase in soil solution electrical conductivity on irrigation plots. At their peak, soil solution conductivities exceeded 4 mmhos/cm, a level at which growth of salt-sensitive vegetation may become inhibited (Munshower, 1993; Stephens et al., 2000; Bowman et al., 2002). While landfill cap vegetation responded positively to leachate application in 2003, it was uncertain whether this positive response would persist if high rates of leachate application continued and soil solution conductivities approached that of the leachate itself (5 to 6 mmhos/cm) during the growing season. Reduced rates of leachate application were recommended to maintain soil solution conductivities at levels that would not inhibit plant growth (e.g., Adarve et al., 1998; Bowman et al., 2002). Reduced rates of leachate application to each spray area also would substantially lower $NH_4$-N deposition, further decreasing the propensity for the high rates of $NO_3$-N losses observed in 2003. In response to these suggestions and concerns, the MDEQ and DLZ Michigan, Inc. established a set of three spray areas for each of the 14 spray heads on the landfill cap, and sequentially rotated weekly leachate applications among these spray areas during the 2004 irrigation season as recommended. This report summarizes the results of the monitoring study for the period January to December, 2004, focusing on the effects of leachate irrigation on soil and soil solution chemistry, solute leaching, and plant responses, and highlights the changes in irrigation effects observed between 2003 and 2004.

## Methods

In 2004, we followed the same experimental and sampling methods used in 2003 with a few minor modifications. We continued the replicated study on the northwest end of the landfill (Phase II) to quantify the effects of the operational leachate applications that commenced in the summer of 2003. Six 20-m diameter plots were monitored: three that were randomly selected to be spray irrigated at operational levels and three that remained as untreated control plots. The irrigated plots each had stand-mounted spray heads that applied leachate to circular areas with average spray radii of 11 m. In 2004, the experimental irrigation plots were included in the rotating irrigation schedule, so the treatment plots were irrigated only once every three weeks between June and September. To monitor leachate chemistry and volumes applied, a composite sample of leachate was collected from three bulk collectors (4-L polyethylene bottles fitted with 17-cm diameter funnels) per plot after each leachate application. On each irrigation date, leachate volumes were recorded for each collector, and all leachate samples were composited by date for analyses. AWRI analyzed these samples for pH, conductivity, Cl, $SO_4$-S, $NO_3$-N, $NH_4$-N, Ca, Mg, soluble reactive phosphorus (SRP-P), total P, and TOC. The MDEQ analytical laboratory analyzed these samples for MI-10 metals (Ag, As, Ba, Cd, Cr, Cu, Hg, Pb, Se, Zn) and VOCs. We installed a standard Universal Recording Rain Gage (series 5-780, Belfort

Instrument Company, Baltimore, MD) on site to record precipitation amounts on a weekly basis from May through November, 2004.

In May, 2003, we installed three 60-cm lysimeters (Soilmoisture, Inc., Santa Barbara, CA) on each plot to collect soil solution at a depth of approximately 50 cm, representing solutions that had passed through the surface soil and primary rooting zone of the vegetated landfill cover. We continued to sample the three lysimeters on each plot weekly between March 11, 2004 and April 29, 2004, approximately every two weeks between April 29, 2004 and November 15, 2004, and weekly between November 15, 2004 and December 13, 2004. Soil solution samples were analyzed at AWRI for pH, conductivity, Cl, $SO_4$-S, $NO_3$-N, $NH_4$-N, Ca, Mg, SRP-P, total P, and TOC. Selected soil solution samples also were analyzed for MI-10 metals and VOCs at the MDEQ analytical laboratory. Potential evapotranspiration was estimated using Thornthwaite's equation and solute fluxes from the landfill cover soils were estimated from volume-weighted mean soil solution concentrations and leaching losses calculated using the water balance method (Mather, 1978). Climatic data for these calculations were obtained from site-specific rain gage measurements and from the National Weather Service station in Grand Rapids, Michigan, which is approximately 15 km southeast of the landfill.

We quantified aboveground biomass on all plots in late September at the peak of biomass production. All vegetation was clipped on nine randomly-located 0.1-$m^2$ quadrats per plot to estimate plot mean biomass. To monitor metal accumulation in plants, red fescue (*Festuca rubra* L.), timothy (*Phleum pratense* L.), red clover (*Trifolium pratense* L.), and white clover (*Trifolium repens* L.) were selectively sampled as indicators, since these four species successfully established on all plots. We dried and weighed plant biomass samples at GVSU and the MDEQ analytical laboratory analyzed the plant tissue samples for MI-10 metals and total Kjeldahl nitrogen.

Bucket augers were used to sample surface (0-25 cm) soils on all plots in October after the end of the irrigation season. Soil samples were taken at nine random locations on each plot, and composited by plot thirds to form three subsamples per plot. We analyzed the post-irrigation soil samples at AWRI for pH and conductivity following standard soil analytical methods (Page et al., 1982). Plot-composite surface soil samples were analyzed for MI-10 metals and surface soils were tested for the presence of VOCs based on one randomly-selected sample per plot by the MDEQ analytical laboratory.

Parametric one-way analyses of variance were used to compare leachate chemistry between years and to compare effects of control and irrigation treatments on soil, soil solution, solute leaching loss, and plant biomass variables. Parametric two-way analyses of variance were used to evaluate treatment and species effects for plant metal concentration data and to evaluate main year effects for soil, soil solution, solute leaching loss, and biomass data. Data were transformed using natural logarithms if required to meet the assumption of homogeneity of variance. Tukey's multiple comparison test was used to judge significant differences between means. Kruskal-Wallis nonparametric one-way analyses of variance were used to test treatment or year effects where data for one treatment or one year had no variance and could not be analyzed using parametric statistics. Significance for all analyses was accepted at $P < 0.05$.

## Results and Discussion

*Leachate Chemistry:* Leachate chemistry in 2004 was very similar to that observed in 2003 (Table 1). The high pH levels observed in both years indicate that the landfill is well into the methanogenic phase of refuse decomposition (Kjeldsen et al., 2002). The leachate had high concentrations of Cl and $NH_4$-N, while concentrations of $NO_3$-N, SRP-P, and total P were lower (Table 1). Metals in the leachate applied in 2004 were present in low concentrations, similar to those observed in 2003, and typical of many methanogenic-phase landfill leachates (Table 1; Kjeldsen et al., 2002). The only statistically significant changes in non-VOC leachate chemistry between 2003 and 2004 were that TOC concentrations in leachate decreased by a factor of three, while Zn concentrations increased by 50 percent (Table 1). Six VOCs were detected in the spray-irrigated leachate in 2004, compared to four detected in 2003. Of these six, only tetrahydrofuran and 2-propanone were observed in 2003, while the four VOCs newly observed in 2004 (benzene, bromodichloromethane, bromoform, and dibromochloromethane) were only sporadically present above detection limits (Table 1). Benzene, tetrahydrofuran, and 2-propanone (acetone) are common organic solvents that are water soluble, volatile, and degradable (Nyer, 1992; Verschueren, 2001). These compounds evaporate rapidly after spray irrigation or are biodegraded in the landfill cap soils. Bromodichloromethane, bromoform, and dibromochloromethane are typically formed as byproducts of water chlorination, and are not commonly found as environmental contaminants (Verschueren, 2001). Since these halogenated materials were only found in 2004 at sporadic, low concentrations, we will watch to see if they reappear in 2005. If not volatilized or biodegraded, all of the VOCs detected to date may leach to groundwater (Verschueren, 2001). None of the VOCs identified in the leachate are considered to be environmentally hazardous because of their low toxicities (Verschueren, 2001).

*Leachate Application and Constituent Deposition Rates:* Leachate application rates varied through the course of the summer, with greatest amounts of leachate applied in June and September, and lower rates applied in July and August (Table 2). A total of 5 cm were applied to experimental plots in 2004, compared to the total of 32 cm applied in 2003 (Table 2).

Rotation of each spray head among three spray areas effectively reduced irrigation rates per spray area in 2004 as planned, but electrical malfunctions further limited the total amount of leachate that could be applied in 2004. Constituent deposition rates, calculated from chemical concentrations and irrigation depths, also were greatly reduced in 2004 as compared to 2003 (Table 3). Deposition of both $NH_4$-N and Cl substantially decreased in 2004, decreasing the risk of N losses to groundwater (Bowman et al., 2002) as well as reducing the potential for adverse effects of Cl on soil solution electrical conductivity and plant growth (Stephens et al. 2000).

*Soil and Soil Solution Chemistry:* Leachate application had no significant effects on soil metal concentrations in 2004, similar to the lack of effects noted in 2003 (Table 4). Soil metal concentrations remained at or below statewide default background levels and well below drinking water protection criteria on both control and irrigation plots, as previously observed in 2003. No VOCs from the applied leachate were detected in surface soils or soil solution samples in either 2003 or 2004 (Table 4, 5, 6), indicating that these chemicals are being volatilized or biodegraded in situ. Surface soil pH was slightly elevated on irrigation plots in 2004, unlike 2003 where there was no difference in soil pH related to irrigation treatments (Table 4). While electrical conductivity remained elevated in surface soils as well as in soil solution on irrigated plots as compared to control plots in 2004 (Table 4, 5, 6), mean soil electrical conductivities on irrigated plots decreased significantly between 2003 and 2004 (Table 4) as a result of the reduction in the amount of leachate applied in 2004.

Soil solution electrical conductivities (Fig. 1) and $NO_3$-N concentrations (Fig. 2) on irrigated plots followed a very pronounced seasonal progression, reaching peaks during irrigation seasons and declining as fall rains diluted the soil solution and spring snowmelt leached solutes from the soil. Leachate application again produced elevated soil solution concentrations of Cl,

$NO_3$-N, and TOC in 2004, but concentrations of these solutes were lower on irrigated plots than in 2003 (Table 5, 6). While concentrations of $NO_3$-N and Cl remained above drinking water criteria on irrigated plots, soil solution concentrations of $NH_4$-N were reduced to below 0.1 mg/L on irrigated plots in both 2003 and 2004 (Table 5, 6), indicative of effective treatment of leachate to reduce $NH_4$-N concentrations (Bowman et al., 2002; Tyrrel et al., 2002). Concentrations of other solutes tended to be elevated in soil solution on irrigated plots in 2004 as in 2003, but effects were not statistically significant, and concentrations generally were lower than those observed in 2003 (Table 5, 6). Concentrations of these solutes remained below drinking water criteria levels on irrigated plots in 2004, as previously reported for 2003.

*Constituent Leaching Losses:* Leachate-irrigated plots had significantly elevated leaching losses of Cl, TOC, $NO_3$-N, $NH_4$-N, SRP-P, total P, As, Ba, Cr, Cu, and Zn in the fall of 2003 (Table 7), but significantly elevated losses of only Cl, TOC, $NO_3$-N, and Cu in 2004 (Table 8). Estimated leaching losses of many solutes from irrigation plots in 2004 (Table 8) exceeded leachate loading rates in 2004 (Table 3), suggesting a continued flux of solutes from the higher loading rates experienced in 2003 (Table 3). Estimated leaching losses of $NO_3$-N in 2004, while still elevated on irrigation plots when compared to controls, tended to be lower than those in 2003. Cl, $SO_4$-S, TOC, $NH_4$-N, SRP-P, total P, and metal leaching losses also began to decline on irrigated plots in 2004 (Table 7, 8). As leachate application continues at lower rates in 2005, leaching losses of most solutes should continue to decline as a result of the reduced loading rates. Elevated leaching losses of $NO_3$-N, however, remain a concern given the potential for off-site movement of $NO_3$-N to environmentally sensitive areas.

*Plant Biomass and Elemental Concentrations:* Leachate irrigation increased plant growth as compared to control plots, with significant differences in biomass apparent in both 2003 and

2004 (Table 9). Increased biomass on irrigated plots also served as a temporary sink for nitrogen, with an estimated 119 kg N $ha^{-1}$ in plant biomass on irrigated plots compared to 62 kg N $ha^{-1}$ in plant biomass on control plots in 2004. Increased plant biomass on leachate-treated areas also serves as an effective erosion control measure, helping to maintain the integrity of the landfill cap soils by protecting the soil surface from raindrop impact, increasing infiltration, slowing runoff, and removing water through evapotranspiration.

Concentrations of Ba and Cu were elevated in vegetation on irrigated plots in both 2003 and 2004, while concentrations of Zn decreased with irrigation (2003) or did not differ between treatments (2004, Table 10, 11). All other metals were below detection limits in vegetation samples from both control and irrigated plots in both years. Plant Zn concentrations were lower in 2004 than in 2003 (Table 10, 11), related to significantly greater plant biomass and dilution of Zn concentrations on both control and irrigation plots in 2004. In both 2003 and 2004, metal concentrations in vegetation were within ranges that should not pose a hazard to humans or wildlife (Williams and Schuman, 1987; Munshower, 1993; Adarve et al., 1998). Total Kjeldahl nitrogen concentrations of both grasses and legumes did not differ significantly between treatments in 2004 (Table 11), similar to observations by Menser et al. (1983) of little or no change in N concentrations of grass species irrigated with landfill leachate.

*Water Balance and Leaching Rates:* On the control plots, soil available water was fully recharged in January, and available water began to be reduced by evapotranspiration in June (Fig. 3). Available water was exhausted in August, with actual evapotranspiration falling below potential evapotranspiration in August and September, creating a seasonal drought typical of this climatic region (Fig.3). As a result of evapotranspirational demands, leaching losses of water from control plots went to zero in June and did not commence again until December after soils were recharged by rainfall (Fig.3). On leachate-irrigated plots, the addition of approximately 5 cm of leachate during June through September supported higher rates of actual evapotranspiration in August and September, but did not prevent a short period of drought during September (Fig. 4). Because of lower rates of leachate application in 2004, total annual leaching losses of water from irrigation plots were identical to those for the control plots (Table 8, Fig. 3, 4). In 2004, elevated leaching losses of solutes from irrigated plots (Table 8) were primarily related to the higher concentrations of these solutes in soil solution (e.g., Fig. 2), and not further driven by excess applications of leachate as observed in the fall of 2003 (Table 7).

## Summary and Conclusions

To reduce the high leaching rates observed in 2003, leachate applications in 2004 were timed to match periods of greatest evapotranspirational demand (June-September), and each of the 14 spray heads on the landfill cap was sequentially rotated among three non-overlapping spray areas to further reduce the potential for surface runoff and elevated leaching losses. This approach was effective in that total annual estimated leaching losses of water did not differ between control and irrigated plots in 2004, and water added from leachate was removed from the soil by evapotranspiration. This approach also substantially reduced the total deposition of leachate constituents on each spray area, greatly reducing the potential long-term impact of leachate application on soils and plants. Leachate applications had no significant effect on metal concentrations in soils in 2004, and soil electrical conductivities on irrigated plots in 2004 were reduced compared to those observed in 2003. While soil solution electrical conductivities and $NO_3$-N concentrations remained significantly elevated on irrigated plots as compared to controls in 2004, these constituents and other solute concentrations began to decline on irrigated plots as compared to 2003. Total leaching losses of $NO_3$-N from irrigated plots again were elevated above those of the controls in 2004, but leaching losses of $NO_3$-N and other solutes declined compared to 2003. Total plant biomass on irrigated plots was significantly greater than on control plots, providing dense vegetation to help protect the landfill cover soil from erosion. Plant metal concentrations on irrigation plots did not differ from those on controls and remained in normal ranges that should not pose ecological or health concerns. The sequential rotation of spray areas instituted in 2004 was effective in greatly reducing the localized impacts of leachate irrigation observed in 2003, while still permitting the efficient disposal of leachate on site. While elevated leaching of $NO_3$-N remains of concern, it is now occurring at a reduced level and the potential for adverse impacts of increased soil electrical conductivities on plant growth has been reduced. The operational application of leachate to the landfill cover at the Fenske Landfill will continue in 2005 using the same sequential rotation of spray heads. We anticipate that the localized effects of high rates of leachate application observed at the end of 2003 will continue to gradually diminish as observed in 2004.

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Table 1. Chemical characteristics of leachate applied at the Fenske Landfill, Section 12, T6N R13W, Ottawa County Michigan, in 2003 and 2004.

| | | 2003 | | 2004 | | |
|---|---|---|---|---|---|---|
| Variable | Units | Mean | SD† | Mean | SD† | $P_{yr}$‡ |
| pH | -log($H^+$) | 8.05 | 0.17 | 8.13 | 0.15 | 0.329 |
| Electrical Conductivity | mmhos/cm | 5.64 | 1.27 | 6.42 | 1.06 | 0.237 |
| Cl | mg/L | 817 | 201 | 908 | 354 | 0.477 |
| $SO_4$-S | mg/L | 8.5 | 3.6 | 7.9 | 3.3 | 0.755 |
| $NO_3$-N | mg/L | 3.4 | 7.3 | 2.6 | 1.8 | *0.406* |
| $NH_4$-N | mg/L | 296 | 123 | 322 | 60 | 0.657 |
| SRP-P§ | mg/L | 0.017 | 0.014 | 0.012 | 0.013 | 0.460 |
| Total P | mg/L | 0.63 | 0.28 | 0.83 | 0.27 | 0.167 |
| Total Organic Carbon | mg/L | **551** | 457 | **190** | 73 | ***0.044*** |
| Ca | mg/L | ND¶ | | 114 | 29 | ND |
| Mg | mg/L | ND | | 220 | 74 | ND |
| As | µg/L | 14.3 | 3.5 | 14.1 | 3.3 | 0.921 |
| Ba | µg/L | 267 | 61 | 236 | 57 | 0.334 |
| Cr | µg/L | 32.6 | 5.1 | 30.2 | 2.6 | 0.326 |
| Cu | µg/L | 22.3 | 19.1 | 32.4 | 13.3 | 0.293 |
| Pb | µg/L | 2.4 | 0.5 | 2.2 | 0.5 | 0.434 |
| Se | µg/L | 2.4 | 1.6 | 2.4 | 1.6 | 0.973 |
| Zn | µg/L | **38.6** | 11.0 | **59.2** | 34.3 | ***0.043*** |
| | | Range | | Range | | |
| Ag | µg/L | <0.5 | | <0.5-1.7 | | 0.094# |
| Cd | µg/L | <0.20-0.24 | | <0.20 | | 0.550# |
| Hg | µg/L | <0.20-0.50 | | <0.20 | | 0.385# |
| 2-Butanone | µg/L | <5.0-13.0 | | <5.0 | | 0.274# |
| 2-Propanone | µg/L | <20-38 | | <20-28 | | 0.884# |
| Benzene | µg/L | <1.0 | | <1.0-1.1 | | **0.015**# |
| Bromodichloromethane | µg/L | <1.0 | | <1.0-1.0 | | 0.094# |
| Bromoform | µg/L | <1.0 | | <1.0-2.0 | | 0.094# |
| Dibromochloromethane | µg/L | <1.0 | | <1.0-3.2 | | **0.015**# |
| Diethyl ether | µg/L | <5.0-7.4 | | <5.0 | | 0.092# |
| Tetrahydrofuran | µg/L | 100-490 | | 120-290 | | 0.430# |

† SD = sample standard deviation, n = 15 in 2003; n = 5 in 2004.

‡ $P_{yr}$ = probability from parametric one-way analysis of variance comparing year effects unless leachate constituent concentration below detection limit during either year (see # below).

§ SRP-P = soluble reactive phosphorus.

¶ ND = not determined; samples were not analyzed for Ca and Mg in 2003.

# Probability from non-parametric Kruskal-Wallis one-way analysis of variance.

Note: P values in italics based on ln-transformed data. **Significant effects (P < 0.05) in bold**.

Table 2. Average leachate application depths and volumes by date on experimental plots, Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, June-September, 2004.

| Application Date | Depth (cm)┼ | Liters╪ | Gallons§ |
|---|---|---|---|
| 6/14/2004 | 1.61 | 5060 | 1341 |
| 7/12/2004 | 0.65 | 2049 | 543 |
| 8/9/2004 | 0.05 | 160 | 42 |
| 8/30/2004 | 1.01 | 3169 | 840 |
| 9/20/2004 | 1.72 | 5389 | 1428 |
| **2004 totals** | **5.04** | **15827** | **4194** |
| **2003 totals**¶ | **32.2** | **101023** | **26771** |

┼ Mean irrigation depths as measured in collectors on plots.
╪ Volume in liters as estimated from irrigation depths and assuming an average effective plot radius of 10 m.
§ Volume in gallons estimated from volume in liters.
¶ Leachate depth and volume estimates for 2003 have been adjusted slightly compared to 2003 report.

Table 3. Estimated mean leachate constituent deposition[┼] rates on experimental plots, Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, in 2003 and 2004.

| Constituent | Units | 2003 | | 2004 | |
|---|---|---|---|---|---|
| | | Mean | SD[╪] | Mean | SD[╪] |
| Ag | g/ha | 0.00 | 0.00 | 0.17 | 0.05 |
| As | g/ha | 46.0 | 5.4 | 7.90 | 1.88 |
| Ba | g/ha | 888 | 112 | 128 | 27 |
| Cd | g/ha | 0.05 | 0.01 | 0.00 | 0.00 |
| Cr | g/ha | 105 | 14 | 15.8 | 3.4 |
| Cu | g/ha | 84.9 | 16.3 | 15.7 | 3.4 |
| Hg | g/ha | 0.32 | 0.09 | 0.00 | 0.00 |
| Pb | g/ha | 8.06 | 1.16 | 1.16 | 0.23 |
| Se | g/ha | 8.72 | 1.61 | 1.14 | 0.39 |
| Zn | g/ha | 134 | 20 | 26.4 | 4.0 |
| SRP-P[§] | g/ha | 52.0 | 5.9 | 8.06 | 2.74 |
| Total P | kg/ha | 2.14 | 0.23 | 0.47 | 0.09 |
| $NO_3$-N | kg/ha | 9.18 | 1.46 | 1.67 | 0.55 |
| $SO_4$-S | kg/ha | 25.6 | 3.2 | 4.04 | 0.97 |
| Ca | kg/ha | ND[¶] | | 51.8 | 9.5 |
| Mg | kg/ha | ND | | 99.4 | 18.8 |
| $NH_4$-N | kg/ha | 961 | 119 | 173 | 39 |
| Total Organic C | kg/ha | 1443 | 204 | 97.0 | 23.9 |
| Cl | kg/ha | 2648 | 298 | 494 | 112 |

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[┼] Deposition calculated from leachate concentrations and depths of irrigation, 2003 estimates have been adjusted slightly compared to 2003 report. Year means are not compared statistically because they largely reflect the differences in amounts of leachate applied (Table 2).

[╪] SD = standard deviation

[§] SRP-P = soluble reactive phosphorus.

[¶] ND = not determined; samples were not analyzed for Ca and Mg in 2003.

Table 4. Effects of leachate irrigation on surface soil properties at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, October, 2003 and 2004.

| Variable | Units | Control Plots<br>Mean | <br>SD┼ | Irrigated Plots<br>Mean | <br>SD┼ | P╪ | |
|---|---|---|---|---|---|---|---|
| | | | 2003 | | | | |
| pH | -log($H^+$) | 7.71 | 0.09 | 7.73 | 0.07 | 0.737 | |
| Conductivity | mmhos/cm | **0.70** | 0.19 | **2.75** | 0.06 | **<0.001** | |
| Ag | mg/kg | 0.0 | 0.0 | 0.0 | 0.0 | ND§ | |
| As | mg/kg | 7.97 | 3.23 | 6.93 | 0.93 | 0.622 | |
| Ba | mg/kg | 67.3 | 17.2 | 67.3 | 13.2 | 1.000 | |
| Cd | mg/kg | 0.0 | 0.0 | 0.0 | 0.0 | ND | |
| Cr | mg/kg | 10.3 | 0.6 | 11.0 | 1.7 | 0.561 | |
| Cu | mg/kg | 10.6 | 1.2 | 11.3 | 1.3 | 0.562 | |
| Hg | mg/kg | 0.02 | 0.03 | 0.0 | 0.0 | 0.317# | |
| Pb | mg/kg | 9.00 | 1.40 | 11.0 | 1.8 | 0.208 | |
| Se | mg/kg | 0.30 | 0.52 | 0.47 | 0.45 | 0.696 | |
| Zn | mg/kg | 35.0 | 2.6 | 37.0 | 5.0 | 0.573 | |
| Volatile organic Compounds (VOCs) | µg/kg | Not detected in any samples | | | | ND | |
| | | | 2004 | | | P╪ | $P_{yr}$¶ |
| pH | -log($H^+$) | **7.87** | 0.06 | **8.09** | 0.07 | **0.013** | **<0.001** |
| Conductivity | mmhos/cm | **0.49** | 0.01 | **1.44** | 0.06 | **<0.001** | **<0.001** |
| Ag | mg/kg | 0.0 | 0.0 | 0.0 | 0.0 | ND | ND |
| As | mg/kg | 7.27 | 2.97 | 8.20 | 0.27 | 0.616 | 0.832 |
| Ba | mg/kg | 69.3 | 14.2 | 79.0 | 3.6 | 0.316 | 0.392 |
| Cd | mg/kg | 0.0 | 0.0 | 0.0 | 0.0 | ND | ND |
| Cr | mg/kg | 10.0 | 0.0 | 11.0 | 1.0 | 0.121# | 0.789 |
| Cu | mg/kg | 11.7 | 0.6 | 12.7 | 0.6 | 0.101 | 0.059 |
| Hg | mg/kg | 0.02 | 0.04 | 0.02 | 0.04 | 1.000 | 0.497 |
| Pb | mg/kg | 9.63 | 1.35 | 8.73 | 2.35 | 0.596 | 0.456 |
| Se | mg/kg | 0.67 | 0.58 | 0.87 | 0.15 | 0.593 | 0.183 |
| Zn | mg/kg | 38.3 | 2.1 | 41.7 | 1.2 | 0.072 | 0.054 |
| VOCs | µg/kg | Not detected in any samples | | | | ND | ND |

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┼ SD = sample standard deviation.

╪ P = probability from parametric one-way analysis of variance comparing treatment effects unless otherwise noted (see # below).

§ ND = not determined; analyte concentrations were below detection limits.

¶ $P_{yr}$ = probability from parametric two-way analysis of variance comparing main year effects, overall 2003 mean compared to overall 2004 mean. # Probability from non-parametric Kruskal-Wallis one-way analysis of variance. Note: **Significant effects (P < 0.05) in bold.**

Table 5. Effects of leachate irrigation on volume-weighted soil solution variables at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, June, 2003-December, 2003.

| Variable | Units | Control Plots<br>Mean | <br>SD┼ | Irrigated Plots<br>Mean | <br>SD┼ | P╪ |
|---|---|---|---|---|---|---|
| pH | $-\log(H^+)$ | 7.79 | 0.15 | 7.44 | 0.11 | 0.053 |
| Conductivity | mmhos/cm | **0.77** | 0.18 | **4.22** | 1.21 | ***0.001*** |
| Cl | mg/L | **15.3** | 3.6 | **1042** | 207 | ***<0.001*** |
| SO$_4$-S | mg/L | 106.4 | 52.6 | 86.0 | 30.4 | 0.609 |
| NO$_3$-N | mg/L | **1.13** | 1.15 | **138.2** | 35.5 | ***0.001*** |
| NH$_4$-N | mg/L | 0.004 | 0.005 | 0.068 | 0.056 | *0.060* |
| Total Organic C | mg/L | **14.7** | 2.1 | **56.4** | 15.2 | ***0.007*** |
| SRP-P§ | mg/L | 0.004 | 0.000 | 0.005 | 0.002 | 0.564# |
| Total P | mg/L | 0.024 | 0.004 | 0.034 | 0.008 | 0.243 |
| Metals¶ | | | | | | |
| As | µg/L | 1.25 | 1.77 | 7.18 | 2.84 | 0.083 |
| Ba | µg/L | **24.0** | 8.8 | **146.7** | 28.5 | **0.011** |
| Cd | µg/L | below detection | | 0.11 | 0.15 | 0.197# |
| Cr | µg/L | 9.15 | 0.93 | 11.13 | 1.13 | 0.136 |
| Cu | µg/L | **3.68** | 0.08 | **14.22** | 3.81 | **0.034** |
| Zn | µg/L | 20.9 | 5.4 | 33.2 | 3.8 | 0.056 |
| Volatile Organic Compounds | µg/L | No VOCs from leachate detected in soil solution | | | | |

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┼ SD = sample standard deviation.

╪ P = probability from parametric one-way analysis of variance comparing treatment effects unless otherwise noted (see # below).

§ SRP-P = soluble reactive phosphorus.

¶ Of the MI-10 metals, only As, Ba, Cd, Cr, Cu, and Zn were above detection limits.

# Probability from non-parametric Kruskal-Wallis one-way analysis of variance.

Note: P values in italics based on ln-transformed data. **Significant effects (P < 0.05) in bold.**

Table 6. Effects of leachate irrigation on volume-weighted soil solution variables at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, March, 2004-December, 2004.

| Variable | Units | Control Plots<br>Mean | <br>SD† | Irrigated Plots<br>Mean | <br>SD† | P‡ | $P_{yr}$§ |
|---|---|---|---|---|---|---|---|
| pH | $-\log(H^+)$ | 7.80 | 0.22 | 7.74 | 0.07 | 0.652 | 0.125 |
| Conductivity | mmhos/cm | **0.66** | 0.14 | **2.97** | 1.70 | ***0.014*** | *0.186* |
| Cl | mg/L | **120.8** | 33.0 | **613.3** | 328.8 | ***0.030*** | ***0.017*** |
| $SO_4$-S | mg/L | 24.9 | 11.3 | 35.6 | 21.8 | 0.579 | **0.016** |
| $NO_3$-N | mg/L | **0.22** | 0.05 | **62.7** | 61.1 | ***0.004*** | *0.075* |
| $NH_4$-N | mg/L | 0.025 | 0.013 | 0.027 | 0.022 | 0.908 | 0.631 |
| Total Organic C | mg/L | **7.59** | 1.46 | **39.3** | 24.1 | ***0.014*** | ***0.043*** |
| SRP-P¶ | mg/L | **0.009** | 0.002 | **0.003** | 0.001 | **0.018** | 0.169 |
| Total P | mg/L | 0.021 | 0.001 | 0.021 | 0.006 | 0.920 | 0.101 |
| Ca | mg/L | 115.3 | 13.1 | 211.2 | 129.9 | 0.396 | ND# |
| Mg | mg/L | 29.4 | 1.0 | 62.7 | 40.5 | *0.270* | ND |
| Metals†† | | | | | | | |
| As | µg/L | below detection | | 5.63 | 6.39 | 0.076‡‡ | 0.617 |
| Ba | µg/L | 30.5 | 10.6 | 77.7 | 55.2 | 0.338 | 0.230 |
| Cd | µg/L | below detection | | 0.07 | 0.12 | 0.414‡‡ | 0.791 |
| Cr | µg/L | 1.15 | 1.63 | 4.80 | 2.17 | 0.140 | **<0.001** |
| Cu | µg/L | 3.40 | 0.28 | 12.60 | 4.80 | 0.083 | 0.692 |
| Zn | µg/L | 5.00 | 7.07 | 25.7 | 9.5 | 0.081 | **0.039** |
| Volatile Organic Compounds | µg/L | No VOCs from leachate detected in soil solution | | | | | |

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† SD = sample standard deviation.
‡ P = probability from parametric one-way analysis of variance comparing treatment effects unless otherwise noted (see ‡‡ below).
§ $P_{yr}$ = probability from parametric two-way analysis of variance comparing main year effects, overall 2003 mean compared to overall 2004 mean; 2003 data in Table 5.
¶ SRP-P = soluble reactive phosphorus. # ND = Ca and Mg not determined in 2003.
†† Of the MI-10 metals, only As, Ba, Cd, Cr, Cu, and Zn were above detection limits.
‡‡ Probability from non-parametric Kruskal-Wallis one-way analysis of variance.
Note: P values in italics based on ln-transformed data. **Significant effects (P < 0.05) in bold.**

Table 7. Estimates of constituent leaching losses at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, September-December, 2003.

| Variable | Units | Control Plots<br>Mean | <br>SD┼ | Irrigated Plots<br>Mean | <br>SD┼ | <br>P╪ |
|---|---|---|---|---|---|---|
| Leaching§ | cm | 8.9 | | 33.6 | | |
| Cl | kg/ha | **13.6** | 3.2 | **3497** | 693 | ***<0.001*** |
| $SO_4$-S | kg/ha | 94.4 | 46.7 | 289 | 102 | *0.057* |
| Total Organic C | kg/ha | **13.0** | 1.9 | **189** | **51** | ***0.001*** |
| $NO_3$-N | kg/ha | **1.0** | 1.0 | **464** | 119 | ***0.001*** |
| $NH_4$-N | g/ha | **3.2** | 4.5 | **228** | 189 | ***0.020*** |
| SRP-P¶ | g/ha | **3.9** | 0.3 | **16.9** | 7.6 | ***0.041*** |
| Total P | g/ha | **21.3** | 3.3 | **112** | 28 | ***0.003*** |
| Metals┼┼ | | | | | | |
| As | g/ha | **1.1** | 1.6 | **24.1** | 9.5 | ***0.016*** |
| Ba | g/ha | **21.3** | 7.8 | **492** | 96 | ***0.001*** |
| Cd | g/ha | below detection | | 0.37 | 0.52 | 0.197# |
| Cr | g/ha | **8.1** | 0.8 | **37.3** | 3.8 | ***<0.001*** |
| Cu | g/ha | **3.3** | 0.1 | **47.7** | 12.8 | ***0.001*** |
| Zn | g/ha | **18.6** | 4.8 | **111** | 13 | ***0.002*** |

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┼ SD = sample standard deviation.
╪ P = probability from parametric one-way analysis of variance comparing treatment effects unless otherwise noted (see ╪╪ below).
§ Site estimate of water leaching losses from Thornthwaite water balance calculations.
¶ SRP-P = soluble reactive phosphorus.
# Probability from non-parametric Kruskal-Wallis one-way analysis of variance.
┼┼ Of the MI-10 metals, only As, Ba, Cd, Cr, Cu, and Zn were above detection limits.
╪╪ Probability from non-parametric Kruskal-Wallis one-way analysis of variance.
Note: P values in italics based on ln-transformed data. **Significant effects ($P < 0.05$) in bold.**

Table 8. Estimates of constituent leaching losses at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, January-December, 2004.

| | | Control Plots | | Irrigated Plots | | | |
|---|---|---|---|---|---|---|---|
| Variable | Units | Mean | SD† | Mean | SD† | P‡ | P$_{yr}$§ |
| Leaching¶ | cm | 32.9 | | 32.9 | | | |
| Cl | kg/ha | **397** | 109 | **2015** | 1080 | ***0.030*** | ***0.001*** |
| SO$_4$-S | kg/ha | 81.8 | 37.1 | 117 | 72 | *0.588* | *0.125* |
| Ca | kg/ha | 379 | 43 | 694 | 427 | *0.335* | ND# |
| Mg | kg/ha | 96.6 | 3.2 | 206 | 133 | *0.270* | ND |
| Total Organic C | kg/ha | **24.9** | 4.8 | **129** | 79 | ***0.014*** | *0.737* |
| NO$_3$-N | kg/ha | **0.7** | 0.2 | **206** | 201 | ***0.002*** | *0.153* |
| NH$_4$-N | g/ha | 81.2 | 43.5 | 87.2 | 71.6 | *0.928* | ***0.046*** |
| SRP-P†† | g/ha | **30.7** | 6.6 | **11.2** | 2.9 | ***0.022*** | ***0.010*** |
| Total P | g/ha | 69.7 | 2.8 | 68.0 | 20.4 | *0.827* | *0.067* |
| Metals‡‡ | | | | | | | |
| As | g/ha | below detection | | 18.5 | 21.0 | 0.076§§ | *0.259* |
| Ba | g/ha | 100 | 35 | 255 | 181 | *0.246* | *0.268* |
| Cd | g/ha | below detection | | 0.23 | 0.40 | 0.414§§ | *0.791* |
| Cr | g/ha | 3.8 | 5.3 | 15.8 | 7.1 | 0.140 | **0.008** |
| Cu | g/ha | **11.2** | 0.9 | **41.4** | 15.8 | ***0.020*** | ***0.019*** |
| Zn | g/ha | 16.4 | 23.2 | 84.3 | 31.1 | 0.081 | 0.335 |

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†SD = sample standard deviation.
‡ P = probability from parametric one-way analysis of variance comparing treatment effects.
§ P$_{yr}$ = probability from parametric two-way analysis of variance comparing main year effects, overall 2003 mean compared to overall 2004 mean; 2003 data in Table 7.
¶ Site estimate of water leaching losses from Thornthwaite water balance calculations.
# ND = Ca and Mg not determined in 2003.
†† SRP-P = soluble reactive phosphorus.
‡‡ Of the MI-10 metals, only As, Ba, Cd, Cr, Cu, and Zn were above detection limits.
§§ Probability from non-parametric Kruskal-Wallis one-way analysis of variance.
Note: P values in italics based on ln-transformed data. **Significant effects ($P < 0.05$) in bold.**

Table 9. Effects of leachate irrigation on plant biomass accumulation at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, September, 2003 and 2004.

| Year | Units | Control Plots<br>Mean | <br>SD[†] | Irrigated Plots<br>Mean | <br>SD[†] | P[‡] | $P_{yr}$[§] |
|---|---|---|---|---|---|---|---|
| 2003 | g/m$^2$ | **141.3** | 11.8 | **466.4** | 49.0 | **<0.001** | **<0.001** |
| 2004 | g/m$^2$ | **385.2** | 99.9 | **638.2** | 45.0 | **0.016** | |

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[†] SD = sample standard deviation, n = 3.
[‡] P = probability from parametric one-way analysis of variance comparing treatment effects.
[§] $P_{yr}$ = probability from parametric two-way analysis of variance comparing main year effects, overall 2003 mean compared to overall 2004 mean. Note: **Significant effects ($P < 0.05$) in bold.**

Table 10. Metal[†] concentrations in plant tissues by species at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, September, 2003.

| Treatment | Red Fescue | Timothy | Red Clover | White Clover | Treatment Mean |
|---|---|---|---|---|---|
| | | | Barium (mg/kg) | | |
| Control | 33.7 | 25.7 | 16.3 | 13.6 | **22.3b**[‡] |
| Irrigated | 44.7 | 39.7 | 21.3 | 21.7 | **31.8a** |
| Species Mean | **39.2x**[‡] | **32.7x** | **18.8y** | **17.6y** | |
| | | | Copper (mg/kg) | | |
| Control | 4.5 | 4.5 | 10.7 | 9.2 | **7.2b** |
| Irrigated | 6.8 | 5.6 | 11.3 | 9.8 | **8.4a** |
| Species Mean | **5.6y** | **5.1y** | **11.0x** | **9.5x** | |
| | | | Zinc (mg/kg) | | |
| Control | 28.7 | 48.0 | 32.0 | 40.0 | **37.2a** |
| Irrigated | 28.7 | 35.0 | 30.3 | 33.3 | **31.8b** |
| Species Mean | **28.7z** | **41.5x** | **31.2yz** | **36.7xy** | |

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[†] Plant tissues analyzed for the following metals: Ag, As, Ba, Cd, Cr, Cu, Hg, Pb, Se, and Zn. Only Ba, Cu, and Zn were present in detectable concentrations.
[‡] Means not followed by the same letter differ significantly at $P < 0.05$ (a, b compare treatment means; x, y, z compare species means).
Note: **Significant effects ($P < 0.05$) in bold.**

Table 11. Metal┼ and nitrogen concentrations in plant tissues by species at the Fenske Landfill, Section 12, T6N R13W, Ottawa County, Michigan, September, 2004.

| Treatment | Red Fescue | Timothy | Red Clover | White Clover | Treatment Mean | |
|---|---|---|---|---|---|---|
| | | | Barium (mg/kg) | | | $P_{yr}$§ |
| Control | 32.3 | 15.3 | 19.7 | 17.3 | **21.2b╪** | 0.160 |
| Irrigated | 40.7 | 26.3 | 27.7 | 23.7 | **29.6a** | |
| Species Mean | **36.5x╪** | **20.8y** | **23.7y** | **20.5y** | | |
| | | | Copper (mg/kg) | | | |
| Control | 3.0 | 2.6 | 11.7 | 10.4 | **6.9b** | 0.503 |
| Irrigated | 6.8 | 5.5 | 12.6 | 8.1 | **8.2a** | |
| Species Mean | **4.9z** | **4.0z** | **12.1x** | **9.2y** | | |
| | | | Zinc (mg/kg) | | | |
| Control | 17.3 | 28.0 | 28.3 | 24.3 | 24.5 | **<0.001** |
| Irrigated | 21.7 | 25.0 | 31.7 | 27.7 | 26.5 | |
| Species Mean | **19.5y** | **26.5x** | **30.0x** | **26.0x** | | |
| | | | Total Kjeldahl Nitrogen (g/kg) | | | |
| Control | 9.7 | 8.5 | 22.3 | 24.3 | 16.2 | ND¶ |
| Irrigated | 20.7 | 13.0 | 20.3 | 20.3 | 18.6 | |
| Species Mean | **15.2xy** | **10.7y** | **21.3x** | **22.3x** | | |

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┼ Plant tissues analyzed for the following metals: Ag, As, Ba, Cd, Cr, Cu, Hg, Pb, Se, and Zn. Only Ba, Cu, and Zn were present in detectable concentrations.

╪ Means not followed by the same letter differ significantly at $P < 0.05$ (a, b compare treatment means; x, y, z compare species means).

§ $P_{yr}$ = probability from parametric two-way analysis of variance comparing main year effects, overall 2003 mean compared to overall 2004 mean; 2003 data in Table 10. .

¶ ND = not determined; plant samples were not analyzed for TKN in 2003.

Note: **Significant effects (P < 0.05) in bold.**

**Figure 1. Soil Solution Conductivity at the Fenske Landfill, June 2003 to December 2004**

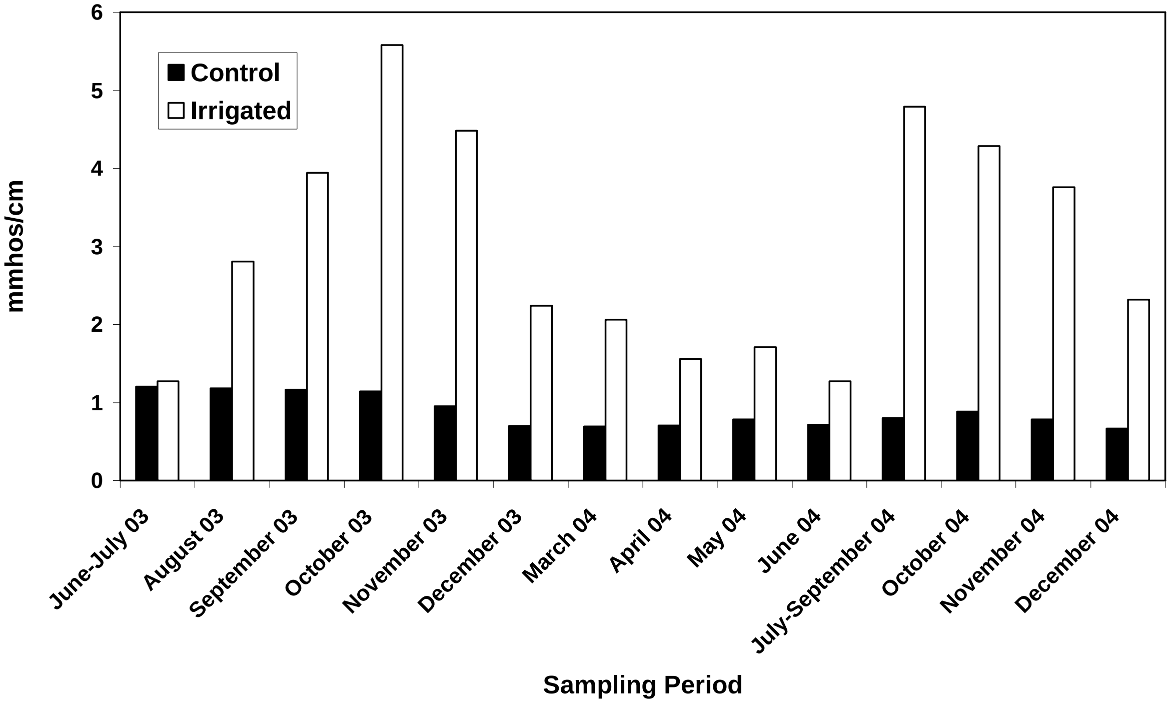

**Figure 2. Soil Solution Nitrate-N Concentrations at the Fenske Landfill, June 2003 to December 2004**

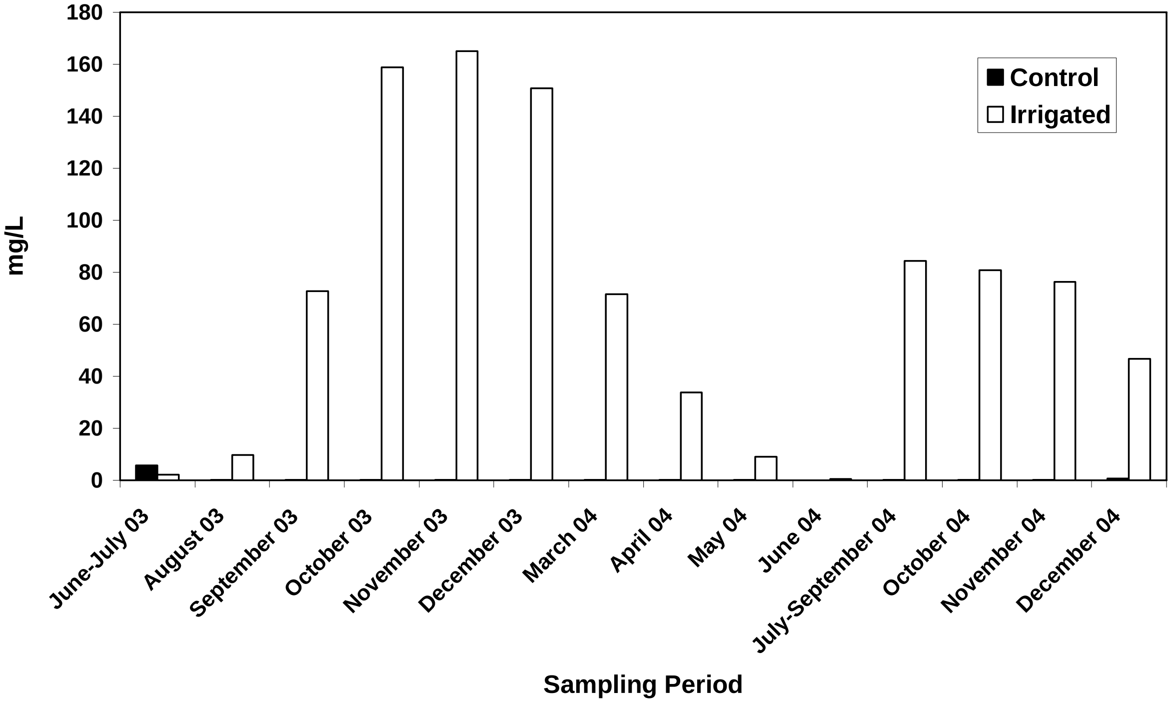

Figure 3. Water balance on control plots at the Fenske Landfill, 2004

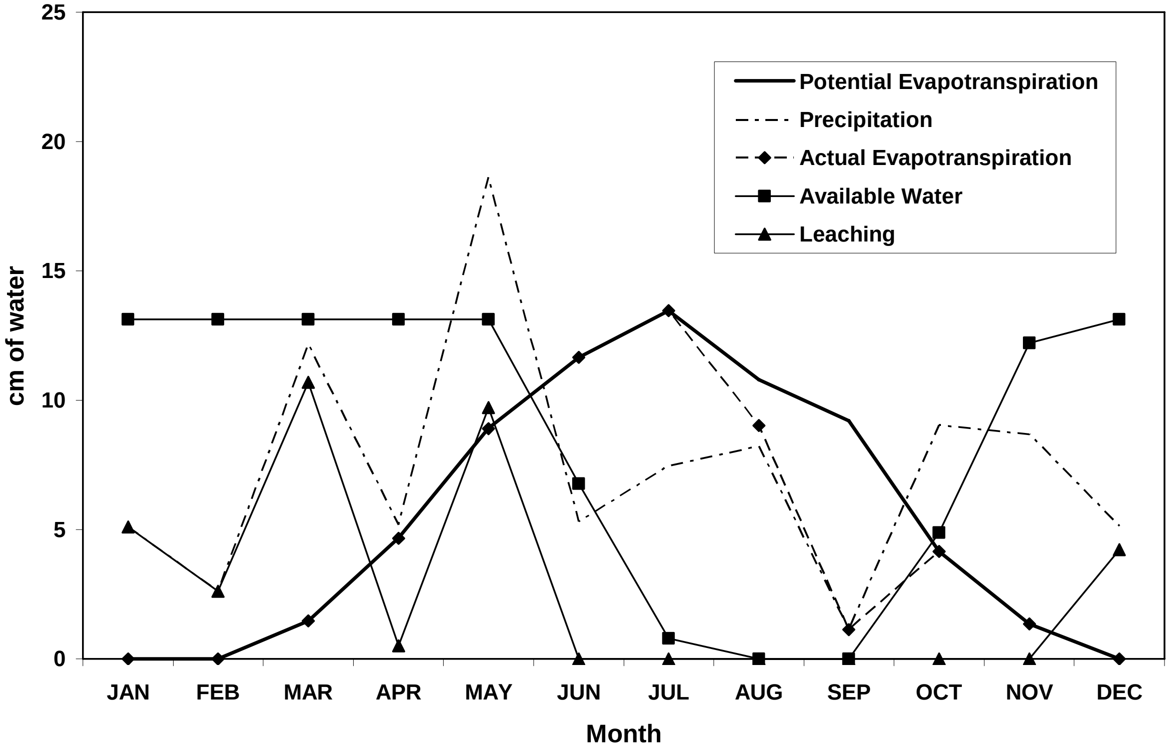

Figure 4. Water balance on leachate-irrigated plots at the Fenske Landfill, 2004