# Statewide Study on the Occurrence and Distribution of PFAS in Groundwater at Minnesota Landfills

*Minnesota Landfill Coalition PFAS Group*

Prepared for
Minnesota Landfill Coalition PFAS Group

Prepared by
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June 2025

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# Certification

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the laws of the state of Minnesota.

| | |
|---|---|
| Jim Eidem | June 24, 2025 |
| PG #: 44064 | Date |

# Errata Sheet

**Document Title:** Statewide Study on the Occurrence and Distribution of PFAS in Groundwater at Minnesota Landfills

**Date:** June 2025

| No. | Date | Reference | Error | Correction |
|---|---|---|---|---|
| 1 | 7/29/25 | Pg. 17, Bullet #1 | The original report stated that 14% of participating landfills had one or more regulated PFAS above an HRL. | The percentage value was inadvertently transposed (from 41.8%) and has been corrected to 42%. |

# Statewide Study on the Occurrence and Distribution of PFAS in Groundwater at Minnesota Landfills

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## Abbreviations

| | |
|---|---|
| 11Cl-PF3OUdS | 11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid |
| 4:2 FTS | 1H,1H, 2H, 2H-Perfluorohexane sulfonic acid |
| 8:2 FTS | 1H,1H, 2H, 2H-Perfluorodecane sulfonic acid |
| 9Cl-PF3ONS | 9-Chlorohexadecafluoro-3-oxanone-1-sulfonic acid |
| ADONA | 4,8-dioxa-3H-perfluorononanoic acid |
| AFFF | aqueous firefighting foam |
| C&D | construction and demolition debris |
| HBV | Health Based Values |
| HRL | Health Risk Limit |
| IL | Intervention Limit |
| IQR | interquartile range |
| ITRC | Interstate Technology & Regulatory Council |
| MCL | Maximum Contaminant Level |
| MDH | Minnesota Department of Health |
| MPCA | Minnesota Pollution Control Agency |
| MSW | municipal solid waste |
| N-MeFOSE | 2-(N-methylperfluoro-1-octanesulfonamido)-ethanol |
| Pace | Pace Analytical Services |
| ppt | Parts per trillion |
| PFAS | per- and polyfluoroalkyl substances |
| PFBA | perfluorobutanoic acid |
| PFBS | perfluorobutanesulfonic acid |
| PFDOS | perfluorododecanesulfonic acid |
| PFHpA | perfluoroheptanoic acid |
| PFHxA | perfluorohexanoic acid |
| PFHxS | perfluorohexanoic sulfonic acid |
| PFNS | perfluorononanesulfonic acid |
| PFOA | perfluorooctanoic acid |
| PFOS | perfluorooctane sulfonate |
| PFPeA | perfluoropentanoic acid |
| QA/QC | Quality Assurance/Quality Control |
| RAA | Risk Assessment Advice |
| RCRA | Resource Conservation and Recovery Act |
| RPD | Relative Percent Difference |
| SAP | sampling and analysis plan |
| SoR | Sum of Ratios |
| SOP | standard operating procedure |
| USEPA | United States Environmental Protection Agency |
| VOC | volatile organic compound |

# Abstract

It is well established that landfills are passive receivers of end-of-life materials that contain per- and polyfluoroalkyl substances (PFAS). This study, conducted by the Minnesota Landfill Coalition PFAS Group, investigates the occurrence and distribution of state-regulated PFAS in groundwater at Minnesota landfills. Groundwater samples were collected from 282 monitoring wells at 48 permitted landfills across the state. The wells were categorized based on hydraulic positioning relative to landfilled waste, waste type, and landfill bottom liner presence. PFAS concentrations met promulgated groundwater standards (Health Risk Limits or HRLs) in all groundwater samples collected downgradient of lined municipal solid waste (MSW) landfills constructed with Resource Conservation and Recovery Act (RCRA) Subtitle D liners and lined construction and demolition debris (C&D) landfills, and downgradient of approximately half of the legacy closed (unlined) MSW and unlined C&D landfills. One or more regulated PFAS were detected in groundwater upgradient of 76% of the landfills. Upgradient PFAS in groundwater were most prevalent in areas of industrial and agricultural land use. A key finding of this study was that regulated PFAS concentrations in downgradient groundwater correspond more with liner status than waste type, underscoring that landfill liner systems effectively prevent PFAS impacts to groundwater. Due in part to their presence in background groundwater, the inclusion of PFAS in routine monitoring programs does not universally translate into improvements in landfill release detection over that afforded by traditional monitoring parameters such as boron, chloride, and volatile organic compounds. However, this study indicated that inclusion of PFAS as part of an assessment groundwater monitoring strategy may make sense at some solid waste facilities.

# 1 Introduction

PFAS are a family of fluorinated chemicals that have been used across numerous industries and incorporated into countless products and building materials for the last 70 years (ITRC, 2020). Common household products and building materials that contain PFAS include non-stick cookware, food packaging, cleaning products, personal care products, adhesives, sealants, and other coatings. As long as PFAS-containing products and building materials remain in use and are ultimately disposed of in landfills, landfills will continue to passively receive inputs of PFAS-containing waste (Stoiber et al., 2020).

The presence of PFAS in various waste streams entering the waste management system has been extensively documented. Studies have reported detectable levels of PFAS in landfill waste materials and the widespread detection of PFAS in municipal landfill leachate across the United States and elsewhere (VDEC, 2020; Wei et al., 2019; Lang et al., 2017; Zang et al., 2022; Tang et al., 2024). Studies of PFAS in the waste management system have largely focused on MSW landfills, wastewater treatment plants, and land application of biosolids, largely due to the data availability for those media. Tolaymet et al. (2023) compiled PFAS loading data from various landfill types, including MSW, MSW ash, C&D, and hazardous waste landfills, and provided a landfill PFAS mass balance framework to account for PFAS storage in waste and removal from leachate and landfill gas collection. Although studies continue, there has not been a universal correlation between landfill types and PFAS compounds/concentrations in leachate due to various factors (Sanborn Head, 2019; Zang et al., 2022; Coffin et al., 2023) and the study of PFAS in groundwater downgradient of specific landfill types has not been a primary focus.

Many of the unique chemical properties that contributed to the widespread use of PFAS also contribute to the persistence, solubility, and overall mobility of PFAS in the environment (ITRC, 2023). Advances in analytical measurement techniques over the last 10+ years have allowed for the detection and measurement of PFAS concentrations at increasingly lower levels. This has resulted in an increased awareness of the widespread presence of PFAS on a global level and a continuing evaluation of the potential effects of PFAS on human health and the environment (Cousins et al., 2022; ITRC, 2023). Locally, the Minnesota Pollution Control Agency (MPCA) has documented the presence and “ambient background” concentrations of certain PFAS in groundwater in remote areas of Minnesota that have been introduced by general anthropogenic activity in addition to widespread and variable presence of PFAS concentrations in urban areas across the state (MPCA, 2024a and 2024b).

In late 2022, members of the Minnesota Landfill Coalition, a group of Minnesota landfill owners, operators, and stakeholders, developed this voluntary PFAS groundwater study to obtain reliable and consistent data. The objective of the study was to advance the understanding of the relationship between landfills and the occurrence of PFAS in groundwater. Forty-eight landfills located throughout Minnesota elected to participate in the study.

# 2 Minnesota Landfills and PFAS Groundwater Monitoring

There are approximately 153 permitted landfills in Minnesota[1] (MPCA, 2023). The configuration and construction of each of these landfills are unique due to facility age, the type of disposed waste, and site-specific conditions. The landfills that participated in this study manage one or more of the following types of disposed waste:

- MSW, which is generated by the disposal of residential, commercial, and community activities;
- C&D, which is generated by the construction, remodeling, and demolition of buildings and other infrastructure;
- Industrial waste, which is generated from industrial processes or service and commercial establishments; and
- MSW combustor ash (ash), which is produced during the incineration of MSW in solid waste combustion facilities.

Prior to the early 1980s, most landfills in Minnesota accepted co-mingled wastes and did not have, and were not required to have, what are now known as modern engineering controls and environmental monitoring systems. MPCA established citing and design standards, including liner and leachate collection requirements, for new landfills in the State in the late 1980s. The RCRA Subtitle D regulations became effective in 1991 and, together with Minnesota statutes, resulted in provisions that required modern landfills in Minnesota to meet location, design, construction, closure, and waste acceptance requirements. As a result, landfills either ceased operations and closed or continued to operate under compliance with the modern landfill requirements as permitted by the state. The unlined portions of the older landfills were closed, and new areas (or cells) that were designed to contain MSW, industrial, and ash were constructed with bottom liners to protect the environment by collecting and removing leachate. C&D landfills were subject to other requirements but were not required to be lined as demolition debris was considered relatively inert material (MPCA, 1988).

Groundwater monitoring at Minnesota landfills is required per Minnesota Rules as reflected in site-specific solid waste permits issued by the MPCA. These permits include monitoring parameters that are intended to identify releases from the waste materials managed at each respective facility, and the monitoring frequency can vary based on the site-specific hydrogeologic conditions. Each landfill is surrounded by monitoring wells that are constructed generally within 200 feet of the landfill waste to allow for the collection of depth-to-water measurements to determine groundwater flow direction and the collection of groundwater quality samples. Monitoring well networks typically include one or more wells that are located hydraulically upgradient of each landfill to monitor the quality of groundwater flowing toward/ beneath the landfill, and multiple wells are located hydraulically downgradient of each landfill to monitor for potential landfill-leachate releases from the waste to groundwater (**Figure 2-1**). These monitoring wells typically target saturated geologic units that constitute preferential groundwater flow pathways, including water table wells and wells screened in deeper glacial outwash or bedrock units, but may also be completed in less conductive geologic units (e.g., glacial diamicton).

[1] Count includes municipal solid waste, industrial, and demolition debris land disposal facilities, and excludes 319 permitted by rule demolition debris landfills, seven waste to energy facilities, and four waste processing facilities (MPCA, 2023).

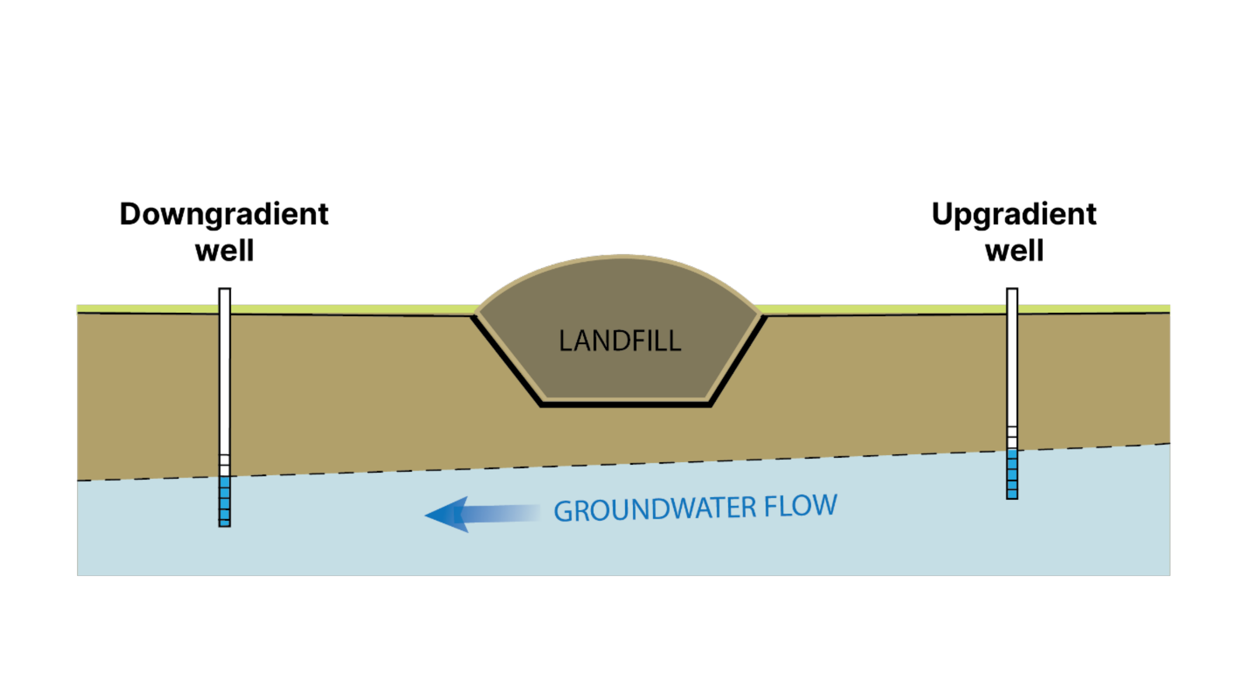



**Figure 2-1 Upgradient and downgradient monitoring well positioning**

Groundwater samples are collected upgradient and downgradient of active landfills, generally up to three times per year, using standard collection methods according to protocols included in site-specific sampling and analysis plans. The groundwater samples are submitted for chemical analysis to an analytical laboratory that is certified by the Minnesota Department of Health (MDH). The groundwater quality monitoring data are included in laboratory reports issued to each respective landfill, and an electronic copy of the data is also sent to the MPCA.

Per Minnesota rules, groundwater quality monitoring data are compared to Health Risk Limits (HRLs). HRLs are promulgated human health risk-based standards derived by the MDH to represent the concentration of a chemical in drinking water that poses little or no health risk to humans, including vulnerable subpopulations such as fetuses, infants, children, pregnant women, and others, based on the current level of scientific understanding (MDH, 2023 and 2024). HRLs were developed and/or updated between 2009 and 2023 for six individual PFAS. **Table 2-1** lists the six "regulated PFAS" and their respective HRLs in nanograms per liter (ng/l).[2]

**Table 2-1 PFAS with promulgated Health Risk Limits**

| Regulated PFAS | HRL (ng/l) | Year Promulgated |
|---|---|---|
| PFBA (perfluorobutanoic acid) | 7000 | 2018 |
| PFHxA (perfluorohexanoic acid) | 200 | 2023 |
| PFBS (perfluorobutanesulfonic acid) | 100 | 2023 |
| PFOA (perfluorooctanoate acid) | 35 | 2018 |
| PFHxS (perfluorohexanoic sulfonic acid) | 47 | 2023 |
| PFOS (perfluorooctane sulfonate) | 300 | 2009 |

[2] One nanogram per liter is equivalent to one part per trillion (ppt).

This study involved the collection of groundwater samples from shallow monitoring wells (typically <100 feet deep)[3] that are located at the participating landfills. Although not drinking water, the groundwater PFAS data collected as part of the study are compared to HRLs for the purpose of this report. The MDH has developed unpromulgated guidance for some PFAS and several non-PFAS parameters in groundwater in the form of Health Based Values (HBVs) and Risk Assessment Advice (RAAs). In addition to HRLs, some Minnesota landfills may screen groundwater using these unpromulgated guidance values. Finally, groundwater at Minnesota landfills is also screened against Intervention Limits (ILs), which are typically equal to one-quarter of HRLs, HBVs, RAAs or, in some cases, Maximum Contaminant Levels[4] (MCLs), per Minnesota rules and site-specific solid waste permits.

[3] Total well depths range from 13 to 195 feet deep with an average total well depth of 53 feet (n=274 reported depths).
[4] MCLs are federally promulgated criteria that are the maximum level allowed of a contaminant in water which is delivered to any user of a public water system.

# 3 Study Overview

The study was set up to provide flexibility for the participating landfills by allowing each to select the sampling schedule, PFAS monitoring network, and sampling methods within a framework consistent with PFAS sampling, analysis, and data review as described below.

## 3.1 Planning and Coordination

A Sampling and Analysis Plan (SAP) was prepared to describe the design, data collection, and data review elements of the study. The SAP included details regarding the PFAS analytical method, procedures, reporting and control limits used by the laboratory, the PFAS data review and assessment process (i.e., Quality Assurance/Quality Control [QA/QC] procedures), and other supporting details.

Each landfill developed a site-specific sampling plan that identified the PFAS monitoring schedule, the monitoring wells selected for PFAS testing, planned QA/QC samples, and sample container shipping information.

## 3.2 Sample Collection

Groundwater sample collection activities were led by each of the participating landfills. The groundwater samples were collected by field staff (either employed or contracted by each participating landfill) who were experienced in collecting environmental groundwater samples, familiar with PFAS sampling considerations, and knowledgeable of the conditions at their respective facility. The PFAS samples were collected from monitoring wells generally located within 200 feet upgradient and downgradient of the landfills during two routine groundwater compliance monitoring events conducted between April 2023 and May 2024. No drinking water wells were sampled as part of the study.

The sampling methods and field procedures used for the study were consistent with those used by the landfills under their respective compliance groundwater monitoring programs. In addition, the PFAS sampling best practices in MPCA's Guidance for Per- and Polyfluoroalkyl Substances (PFAS): Analytical (MPCA, 2022b) were reviewed and followed. Care was taken by each sampling crew to minimize sample exposure to human, atmospheric, and other potential sources of PFAS cross-contamination. QA/QC samples, including field duplicates, field (atmospheric) blanks, equipment blanks, and trip blanks, were also collected as determined by the landfills to help assess the validity of the reported PFAS data.

Two groundwater samples were collected for PFAS analysis from nearly all (97%) of the monitoring wells included in the study. The samples were submitted under chain-of-custody procedures to the laboratory, Pace Analytical Services, located in Minneapolis, Minnesota (Pace), for PFAS analysis. The samples were received and logged in at the laboratory, and if follow-up was required, Pace contacted Barr's quality assurance specialist for support.

## 3.3 PFAS Sample Analysis and Data Review

The groundwater samples were analyzed using United States Environmental Protection Agency (USEPA) Method 537.1 (modified). The PFAS analyte list was consistent with the thirty-three PFAS listed in MPCA's Guidance for Per- and Polyfluoroalkyl Substances (PFAS): Analytical, and the standard method reporting limits met the MPCA's method reporting limit goals (MPCA, 2022c).

Barr reviewed each lab report to assess the validity of the PFAS analytical data. The review was conducted in accordance with Barr's SOP for Routine Level PFAS Data Evaluation, which is based on *The National Functional Guidelines for Organic and Inorganic Data Review* (USEPA, 2020a and 2020b). The review examined laboratory analytical procedures associated with the sampling events; field sampling procedures where QA/QC samples were collected to monitor potential impacts from sampling equipment, sample collection, transport, or storage; laboratory procedures utilizing technical holding times, preservation, method blank samples, accuracy data, precision data; and data package completeness. The PFAS analytical data were deemed acceptable for the purposes of the study, with the qualification assigned during the data evaluation process.

## 3.4 Non-PFAS Analytical Data and Site-specific Information

Each landfill was asked to provide non-PFAS analytical data (non-PFAS data) from the groundwater monitoring samples that were collected contemporaneously with the groundwater samples collected for PFAS analysis. The non-PFAS data were submitted to Barr in an electronic format and considered in the study as provided by the facilities after a cursory consistency check against hard-copy analytical reports (if provided).

Information surveys were developed by Barr to collect site-specific information regarding each landfill, each monitoring well sampled for PFAS, and each groundwater sampling event conducted as part of the study. The surveys were completed by the landfills (or their consultants) and provided to Barr electronically.

The non-PFAS data and information survey responses were used to evaluate the PFAS data. The PFAS data, non-PFAS data (if provided), and the categorization of each monitoring well relative to the respective landfill based on the survey responses were tabulated and provided to a representative for each landfill for verification before data evaluation began.

## 3.5 Study Data Set

The 48 landfills that participated in the study are located throughout Minnesota (**Figure 3-1**).

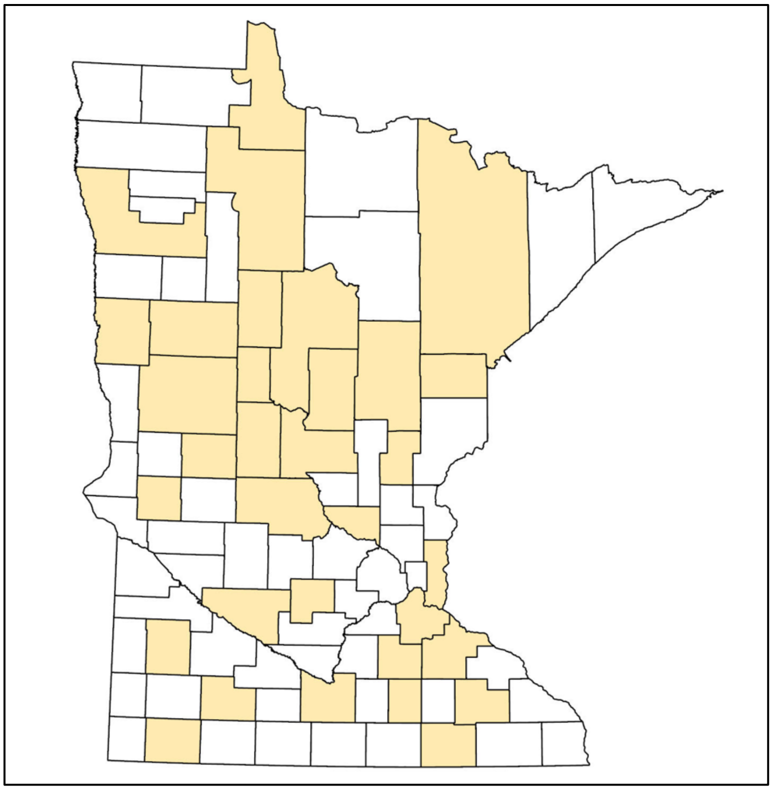


**Figure 3-1 General distribution of the landfills (shaded) participating in the study**

A total of 555 samples were collected from 282 monitoring wells and analyzed for PFAS as part of the study. The number of sampled monitoring wells equates to approximately 40% of the total number of monitoring wells at the participating landfills. The hydraulic position of each monitoring well involved in the study was categorized as upgradient, downgradient, or side gradient by the landfills (**Table 3-1**).

**Table 3-1 Total number of groundwater monitoring wells and PFAS samples analyzed, sorted by hydraulic position relative to the participating landfills**

| Hydraulic Position | Number of Wells Sampled for PFAS | Number of PFAS Samples Analyzed |
|---|---|---|
| Upgradient | 90 | 176 |
| Downgradient | 174 | 343 |
| Side Gradient | 18 | 36 |
| **Total** | **282** | **555** |

Two rounds of PFAS groundwater samples were collected from 97% of the monitoring wells included in the study. The PFAS data from individual samples are presented in the study, rather than reducing the concentrations to a central tendency value for each monitoring well. To assess the variability of concentrations in different samples collected from the same wells, the relative percent differences (RPDs) for the regulated PFAS were calculated. RPDs were only calculated for concentrations above 10 ng/l (i.e., ~5x the reporting limit) due to the magnification of RPD values of concentrations near the reporting limit. The RPD values for the regulated PFAS ranged from less than 1 to approximately 110 (median = 17±4; n = 528), with a median of 117 days between the sample collection dates. The RPDs show reasonable variability, considering values were calculated with independent samples from individual wells at different times (rather than duplicate samples).

Non-PFAS data were provided for 39% of the PFAS samples collected, and nearly all (98%) requested informational surveys were completed by the landfills. The non-PFAS data primarily included volatile organic compounds (VOCs), dissolved metals, and general water quality parameter analytical data, which were used to evaluate correlations with regulated PFAS concentration data (as discussed later in this report). The study data set, including PFAS data, non-PFAS data, and selected survey responses, is reported under blinded identification numbers (for confidentiality purposes) in **Appendix A**.

## 3.6 Data Comparisons

Box-and-whisker plots are used throughout this report to compare the regulated PFAS concentrations of different categories of wells. As shown on **Figure 3-2**, box-and-whisker plots consist of a central box, with the lower limit of the box indicating the first quartile (25th percentile of the data) and the upper limit of the box indicating the third quartile (75th percentile of the data). The height of the box (the difference between the first and third quartiles) is called the interquartile range (IQR).

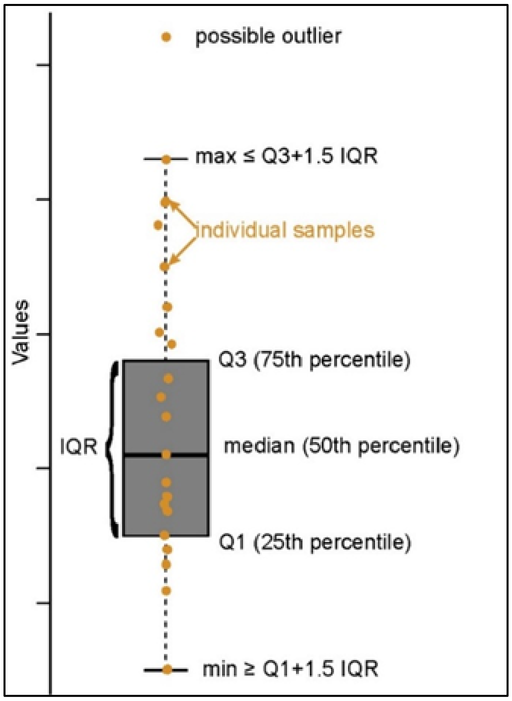



**Figure 3-2 Box and whisker plot key**

A heavy line within the box indicates the median (50th percentile of the data). Extending in each direction from the box are “whiskers,” which show values within one and a half times the IQR from each end of the box. Individual sample results are plotted as points, and the points plotting outside of the whiskers are considered possible statistical outliers that may indicate either a high groundwater concentration from a release to the environment or an anomalous result from other factors.

Individual sample results are plotted without box-and-whiskers for groups of samples with detection frequencies less than 50%. Results below the laboratory reporting limits (i.e., ~2 ng/l) were plotted at one-half of their method detection limits with different symbology and are labeled as “non-detect.”

## 3.7 PFAS and Non-PFAS Parameter Correlations

The PFAS and non-PFAS groundwater data were reviewed for correlations by comparing PFAS sum of ratios[5] (SoR) values to the informational survey responses, and by comparing paired PFAS data and non-PFAS concentration data using a Kendall's tau correlation.

SoR values were calculated to assess the additive PFAS concentrations of individual groundwater samples with a single value that is weighted by regulatory standards in this section. PFAS SoR values were calculated for each groundwater sample using the concentrations of the six regulated PFAS weighted by their corresponding HRL value with the following formula:

$$SoR = \frac{C_{PFBA}}{HRL_{PFBA}} + \frac{C_{PFBS}}{HRL_{PFBS}} + \frac{C_{PFHxA}}{HRL_{PFHxA}} + \frac{C_{PFHxS}}{HRL_{PFHxS}} + \frac{C_{PFOA}}{HRL_{PFOA}} + \frac{C_{PFOS}}{HRL_{PFOS}}$$

Where: $C_{PXXX}\ is\ the\ concentration\ of\ PFAS_{PXXX};\ HRL_{PXXX}\ is\ the\ HRL\ for\ PFAS_{PXXX}$

A SoR value greater than 1.0 indicates a possible exceedance of one or more PFAS HRLs for the corresponding groundwater sample.

To account for regulated PFAS concentrations in groundwater upgradient of each facility, PFAS SoR values for groundwater samples collected from downgradient monitoring wells were adjusted by subtracting the median PFAS SoR value that was calculated using upgradient PFAS data collected during the study for each landfill.[6] The median upgradient PFAS SoR value was used (rather than the maximum) as it was considered a more conservative adjustment.

The informational survey responses regarding groundwater release identification at monitoring wells included in the study were reviewed to determine if adjusted PFAS SoR values greater than 1.0 occurred in samples with or without an indication of a potential groundwater release. The indication of potential groundwater releases included non-PFAS data above HRLs, ILs, non-promulgated groundwater criteria (i.e., RAAs, HBVs), or MCLs in samples collected contemporaneously with the PFAS samples and/or survey responses indicating the presence of a previously identified release to groundwater at a particular well.

Kendall's tau correlation is a non-parametric correlation method that is appropriately applied when there is no assumption of data distribution. A Kendall's tau correlation coefficient is calculated and used to evaluate the degree of correlation. A coefficient value of 0 indicates the data are perfectly uncorrelated, and values of 1 and -1 indicate the data are perfectly positively and negatively correlated, respectively. A Kendall's tau correlation coefficient around 0.5/-0.5 shows a low/moderate correlation, and values at or above 0.75/-0.75 show a strong correlation. A total of 216 groundwater samples with PFAS and non-PFAS data were joined and used for the Kendall Tau's correlation analysis. Non-detect values were dropped from the analysis.

[5] Also referred to as sum of fractions, Hazard Index, or Health Risk Index (USEPA, 2024; MPCA, 2024c).

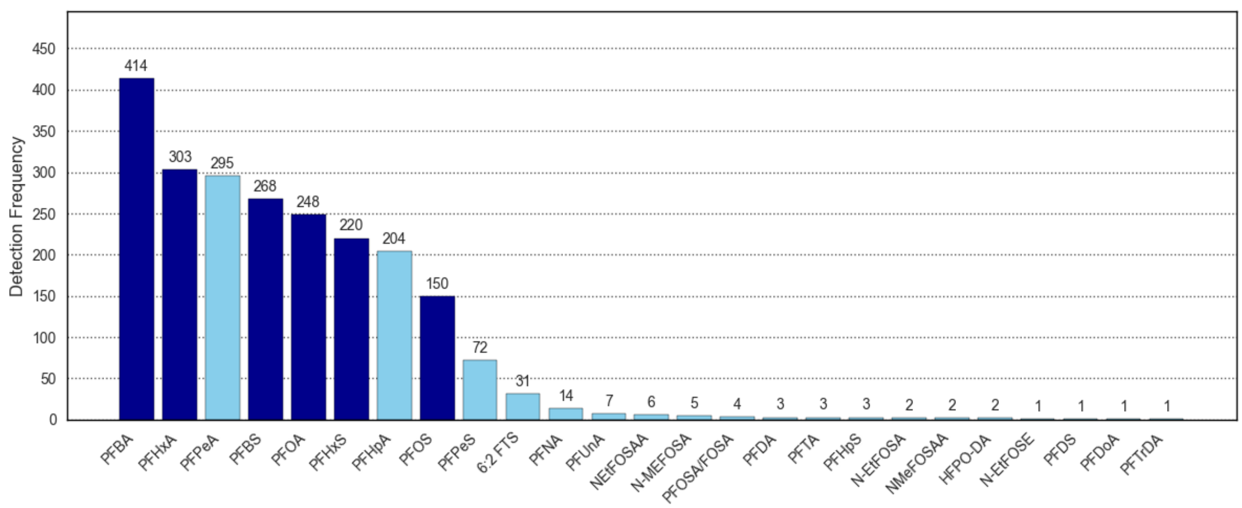
[6] Downgradient PFAS SoR values were not adjusted if regulated PFAS were not detected in upgradient groundwater samples. The downgradient PFAS SoR values were adjusted by subtracting the single upgradient PFAS SoR value for three facilities where only one upgradient PFAS sample was collected.

# 4 Results

This section presents a comprehensive overview of the study results regarding the occurrence and distribution of PFAS in groundwater at Minnesota landfills, including study-wide PFAS detection frequencies, upgradient regulated PFAS concentrations categorized by predominant upgradient land use, downgradient regulated PFAS concentrations in groundwater categorized by upgradient landfill waste type and liner status, an assessment of adjusted PFAS SoR values relative to HRLs, and a correlation analysis between PFAS and non-PFAS analyte concentrations.

## 4.1 PFAS Detection Frequencies

The laboratory analysis provided concentration data for 33 individual PFAS for each study sample; however, eight of those PFAS were not detected in a single sample.[7] The eight most frequently detected PFAS include the six regulated PFAS, plus perfluoropentanoic acid (PFPeA) and perfluoroheptanoic acid (PFHpA; **Figure 4-1**). These eight PFAS were detected in more than 25% of the groundwater samples analyzed as part of the study. PFBA, the most commonly detected PFAS in the study, was detected in approximately 75% of the groundwater samples.




*Plot includes PFAS detections in groundwater samples collected from monitoring wells located upgradient, downgradient, and side gradient of the landfills (n = 555). Dark blue shading identifies the six PFAS for which an HRL has been derived (i.e., regulated PFAS).*

**Figure 4-1 PFAS detection frequency**

The regulated PFAS, shown in dark blue shading on **Figure 4-1**, are amongst the most frequently detected PFAS in the study and other statewide groundwater studies in the upper Midwest (MPCA, 2024b; Silver et al., 2023). The regulated PFAS can be released directly to the environment or formed via transformation/degradation of other PFAS and are considered “terminal PFAS,” meaning they are not

[7] The eight PFAS that were not detected in any of the groundwater samples included: 4,8-dioxa-3H-perfluorononanoic acid (ADONA); 2-(N-methylperfluoro-1-octanesulfonamido)-ethanol (N-MeFOSE); Perfluorononanesulfonic acid (PFNS); Perfluorododecanesulfonic acid (PFDOS); 11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid (11Cl-PF3OUdS); 9-Chlorohexadecafluoro-3-oxanone-1-sulfonic acid (9Cl-PF3ONS); 1H,1H, 2H, 2H-Perfluorodecane sulfonic acid (8:2 FTS); 1H,1H, 2H, 2H-Perfluorohexane sulfonic acid (4:2 FTS).

known transform (or degrade) into other PFAS (ITRC, 2023). The remainder of this report focuses on the presence and concentrations of the six regulated PFAS based on their detection frequencies and HRLs.

## 4.2 PFAS in Upgradient Groundwater

Regulated PFAS were detected in upgradient groundwater at 75% of the 45 landfills that collected upgradient groundwater samples. One or more regulated PFAS was detected in 64% of the upgradient groundwater samples (n=163),[8] and all six regulated PFAS were detected in 10% of the upgradient groundwater samples.

The primary upgradient land use for 85% of the evaluated upgradient monitoring wells was reported in the informational surveys. Each upgradient monitoring well was assigned to one of the following upgradient land use categories based on the survey responses: agricultural, industrial/solid waste (which includes separate solid waste facilities), or residential/undeveloped.[9] **Figure 4-2** includes concentration plots of the regulated PFAS categorized by upgradient land use. The following observations of individual regulated PFAS concentrations in upgradient monitoring wells are drawn from Figure 4-2:

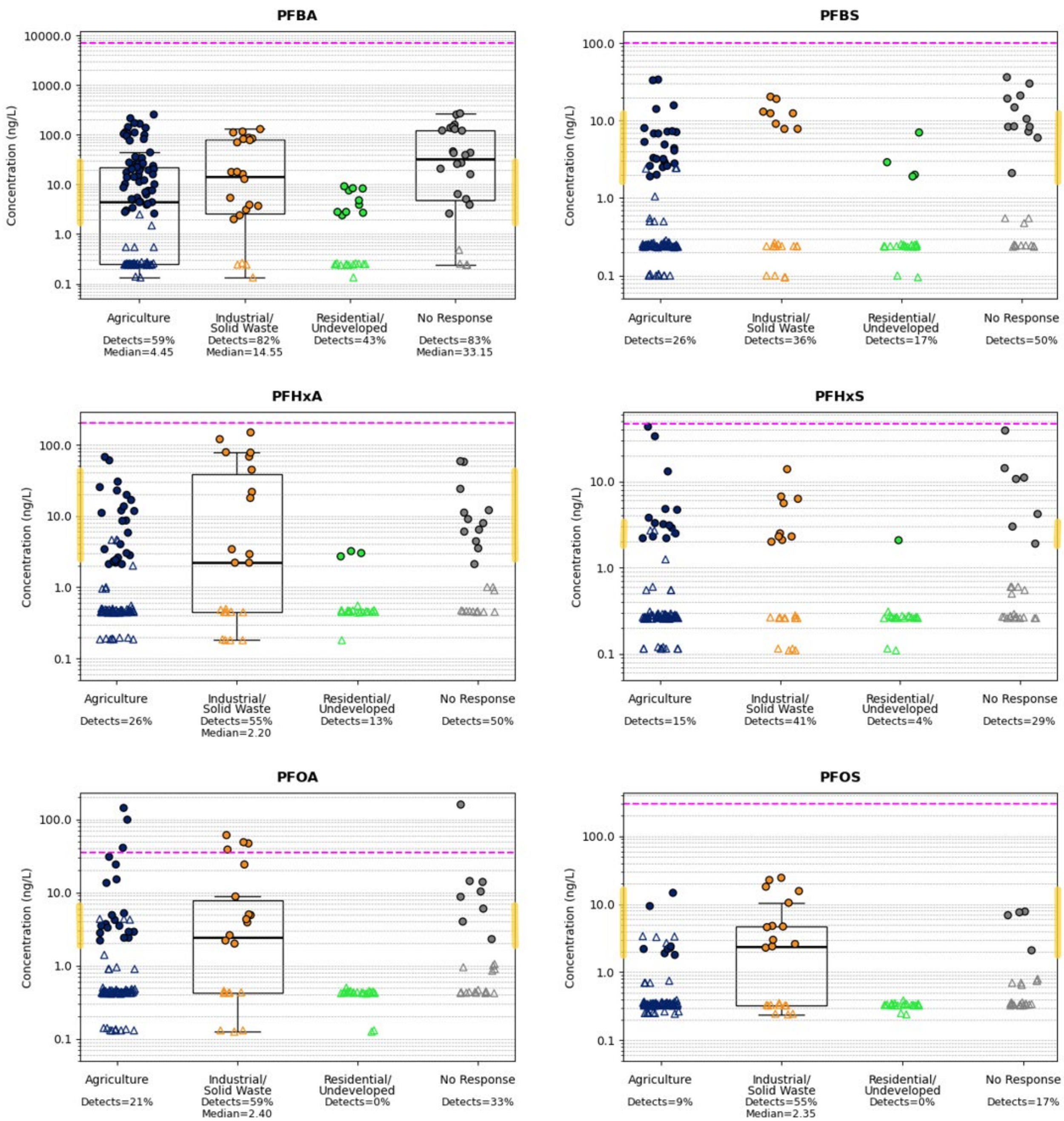
- PFOA was detected in 25% of the upgradient groundwater samples collected during the study, and the highest detected concentration was 159 ng/l. PFOA was not detected in any wells with upgradient residential/undeveloped land use. Upgradient PFOA concentrations were detected above the HRL (35 ng/l) in groundwater samples from five upgradient monitoring wells, including two with upgradient agricultural land uses and two with upgradient industrial/solid waste land uses, and one with no response. No other PFAS were detected at concentrations above HRLs in upgradient groundwater samples.

- PFBA was the most commonly detected PFAS in upgradient groundwater (detected in 63% of the samples) and at the highest concentration (269 ng/l). The median PFBA concentration was slightly higher in upgradient groundwater samples at landfills with upgradient industrial/solid waste land use (14.6 ng/l) than the median concentration from samples at landfills with upgradient agricultural uses (4.5 ng/l). PFBA was less frequently detected in samples collected from wells with upgradient residential/undeveloped land use, and detected concentrations were below 10 ng/l.

- PFBS was detected in 29% of the upgradient groundwater samples collected, and the highest detected concentration was 36.2 ng/l. PFBS detection rates were highest in the upgradient industrial/solid waste land use category (36%) and lowest in the residential/undeveloped land use category (17%).

- PFHxA was detected in 31% of the upgradient groundwater samples collected, and the highest detected concentration was 148 ng/l. Detected frequency and concentrations were higher in the industrial/solid waste upgradient land use category than in the agriculture category. PFHxA was detected at concentrations below 5 ng/l in two wells with upgradient residential/undeveloped land use.

[8] Samples collected from upgradient wells at the four unlined MSW landfills with leachate spray fields were excluded from the analysis due to potential PFAS inputs related to leachate application.
[9] Non-agricultural




*Detected results are shown with circles. Non-detect results are shown with colorized triangle symbols. HRLs are shown as pink dashed lines. The approximate concentration ranges of regulated PFAS in upgradient groundwater samples from landfills that land-apply leachate (n=17) are shown with shaded bands on the Y-axes of each plot.*

**Figure 4-2 Log distribution of regulated PFAS concentrations in groundwater samples from upgradient monitoring wells, sorted by primary upgradient land use**

- PFHxS was detected in 19% of the upgradient groundwater samples collected, and the highest detected concentration was 43.3 ng/l, which is slightly lower than the HRL (47 ng/l). PFHxS was detected in one of 23 samples collected from wells with upgradient residential/undeveloped land use.

- PFOS was the least commonly detected PFAS in upgradient groundwater (detected in 15% of the upgradient groundwater samples), and the highest detected concentration was 24.5 ng/l. PFOS was not detected in any wells with upgradient residential/undeveloped land use. Upper-end detected concentrations in the upgradient industrial/solid waste and agricultural land use categories are comparable (~10 - 30 ng/l).

Four of the landfills included in the study land-apply leachate by spray irrigation. Three of the leachate application areas are located upgradient of the landfills, and one is located side gradient. The upgradient PFAS concentration data for the three landfills that land-apply leachate upgradient of their facilities are not plotted on **Figure 4-2**; however, the range of PFAS concentrations from the upgradient groundwater samples from these three landfills are shown with shading on the Y-axes for reference. PFAS concentrations in the upgradient groundwater samples collected at landfills with leachate spray fields were below HRLs. The data set is too limited to draw conclusions, but it is noted that the range of upgradient PFAS concentrations at the landfills with upgradient leachate spray fields are within the range of concentrations detected upgradient of landfills with reported upgradient agricultural and industrial/solid waste land uses.

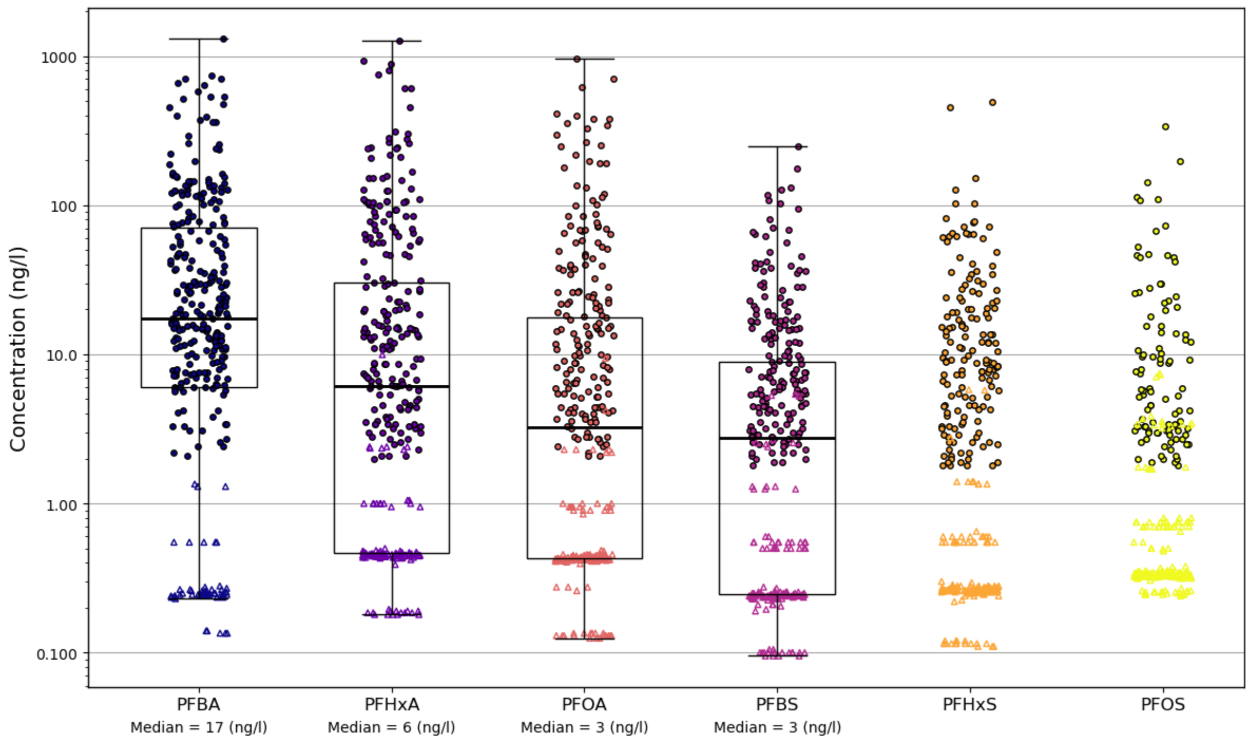
The sources of PFOA and other PFAS in upgradient groundwater samples collected as part of this study have not been determined. However, in industrial/solid waste settings, PFOA and other PFAS may be released from unlined wastes, industrial effluents, or air emissions (NHDES, 2021; MPCA, 2020a). In agricultural settings, potential sources of PFOA and PFAS include the application of biosolids (as fertilizer) or from the leaching of coatings on fluorinated plastic agrichemical containers (USEPA, 2023). In certain residential settings, septic systems provide a conduit to transfer dissolved PFAS to subsurface soils and groundwater (Penrose et al., 2025).

## 4.3 PFAS in Downgradient Groundwater

One or more regulated PFAS was detected in 89% of the downgradient groundwater samples (n=314),[10] and all six regulated PFAS were detected in 21% of the downgradient groundwater samples. The detection frequency of individual regulated PFAS detections in downgradient groundwater samples ranged from 83% (PFBA) to 32% (PFOS). On average, regulated PFAS were detected at a 24% higher rate in downgradient groundwater samples compared to upgradient samples.

The concentrations for individual regulated PFAS detected in groundwater downgradient of the participating landfills ranged from the laboratory reporting limits (~2 ng/l) to greater than 1,000 ng/l for PFBA, PFHxA, PFPeA, and PFOA (**Figure 4-3**).

[10] Samples collected at the three unlined MSW landfills with upgradient leachate spray fields are excluded from the analysis due to potential PFAS inputs uniquely related to leachate application. Samples collected downgradient of the single unlined ash landfill that participated in the study are excluded due to the limited data set. The evaluation of the downgradient data sets presented in this section does not account for the presence or concentration of the PFAS in groundwater upgradient of the facilities. Upgradient PFAS concentrations are factored into the evaluation in Section 4.4 of this report.




*Detected results are shown with circles. Non-detect results are assigned to one-half the method detection limit and shown with colorized triangles for differentiation. (n = 314)*

**Figure 4-3 Log distribution of the regulated PFAS concentrations in downgradient groundwater samples**

The observed downgradient concentration ranges for the six regulated PFAS and the detection frequencies for PFBA and PFHxA are generally consistent with recently published results (MPCA, 2024b), but the detection frequencies of PFOA, PFBS, PFHxS, and PFOS are slightly lower (by ~10 to 20%). The difference is slight and may be related to the inclusion of groundwater samples collected downgradient of lined landfill cells in this study.

The type of waste and landfill liner status located upgradient of each downgradient monitoring well were reported in the information surveys. The survey results were used to assign each of the downgradient monitoring wells to one of the following waste type/landfill liner categories:

- Legacy Closed (unlined) waste, which includes closed (i.e., capped and covered) landfill cells, were constructed either without an engineered bottom liner and leachate removal system in accordance with regulations at that time or liner and leachate systems that complied with State rules at the time (i.e., prior to the promulgation of RCRA Subtitle D regulations). Landfilled waste in these cells is not well documented (because they were filled prior to waste segregation requirements) and typically includes MSW and other waste types, such as C&D, industrial waste, and potentially others. These facilities are differentiated from unlined C&D facilities because a significant portion of the landfilled waste presumably has higher organics content associated with MSW (compared to C&D) and are typically much older.

- Lined MSW, which includes landfill cells that were constructed with an engineered bottom liner and leachate removal system and contain MSW, approved industrial wastes, and/or ash. The majority (but not all) of the lined MSW cells included in this study have composite liner systems that meet RCRA Subtitle D regulations.

- Unlined C&D, which includes landfill cells containing C&D placed without an engineered bottom liner and leachate removal system to collect and remove leachate.

- Lined C&D, which includes landfill cells containing C&D and approved industrial wastes that were constructed with an engineered bottom liner and leachate removal system. Bottom liner and leachate removal systems are not required for C&D landfills federally (or in Minnesota) because C&D debris is generally considered more inert and poses a lower risk of contamination than MSW. As a result, bottom liner and leachate collection systems that are voluntarily installed at these landfills are generally less robust than those required for MSW landfills by RCRA Subtitle D regulations and can vary between landfills and between lined C&D cells at the same facility.

The categorization of the monitoring wells located downgradient of multiple landfill cells with different waste types/liner status was assigned using a hierarchal approach that weighted liner status (primary: unlined cells over lined cells) and waste type (secondary: MSW/ash over C&D/industrial) to attribute each downgradient monitoring well to one upgradient waste type/liner status category identified by representatives of the participating facilities to be the most likely to affect groundwater quality at that particular well. The following examples are provided for illustration purposes:

- Example 1: a monitoring well located downgradient of a lined C&D cell, a lined MSW cell, and an unlined C&D cell was assigned to the unlined C&D category.

- Example 2: a monitoring well located downgradient of a legacy closed (unlined) waste cell and unlined C&D cell was assigned to the legacy closed (unlined) waste category.

The number of landfills, downgradient monitoring wells, and downgradient groundwater samples assigned to the four identified categories is provided in **Table 4-1**. Legacy closed (unlined) waste and unlined C&D landfills outnumber the number of lined MSW and C&D landfills by approximate factors of two and four, respectively. The number of monitoring wells and groundwater samples collected downgradient of unlined facilities also outnumber those collected downgradient of lined facilities by slightly more than a factor of two and a half for the MSW landfills and nearly two for C&D landfills. The difference in the number of MSW and C&D facilities reflects the greater number of C&D landfills in Minnesota compared to MSW landfills.[11] Although the count disparities temper conclusions drawn between categories, the inclusion of lined facilities differentiates this study from others that have focused on PFAS in groundwater downgradient of unlined landfills (MPCA, 2024b).

[11] Landfills managed by the MPCA's Closed Landfill Program are not included in the study.

**Table 4-1 Number of facilities, downgradient monitoring wells sampled, and downgradient groundwater samples, categorized by upgradient waste type and liner status**

| Liner Status of upgradient landfill cells to which groundwater quality is attributed | Number of Facilities Reporting Downgradient Data | | | Number of Downgradient Wells | | | Number of Downgradient Samples | | |
|---|---|---|---|---|---|---|---|---|---|
| | MSW | Legacy Closed Waste | C&D | MSW | Legacy Closed Waste | C&D | MSW | Legacy Closed Waste | C&D |
| Lined | 7 | -- | 6 | 19 | -- | 31 | 38 | -- | 61 |
| Unlined | -- | 13 | 24 | -- | 52 | 57 | -- | 103 | 112 |

*Excludes samples collected downgradient from three legacy closed (unlined) waste landfills with leachate spray fields, one unlined ash landfill, and monitoring wells located upgradient and side gradient to waste. Some facilities appropriately reported downgradient data for multiple waste type/liner status categories due to the proximity of wells relative to differing upgradient landfill cell construction and contained waste type at large landfills.*

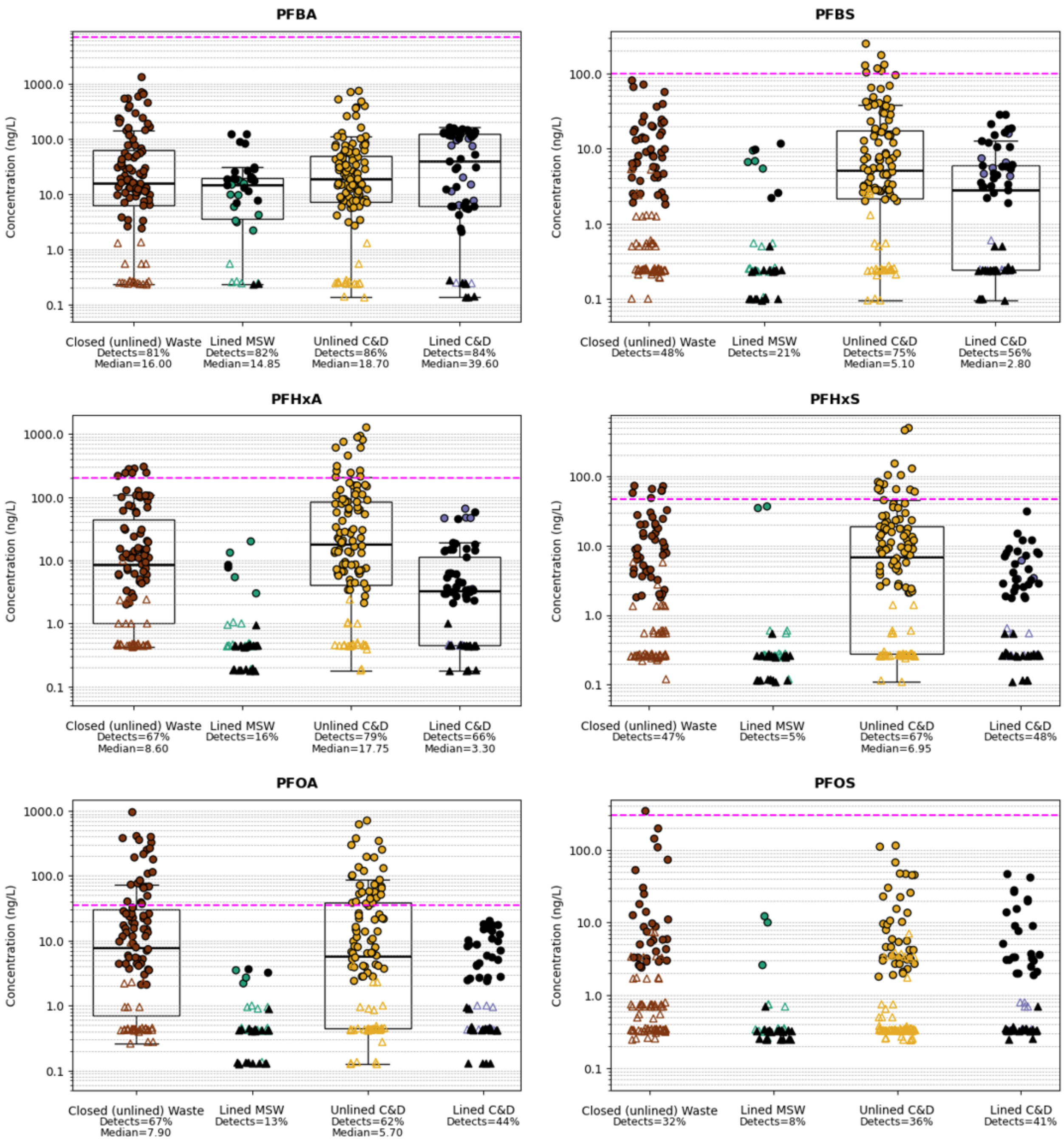
The frequency and concentrations of regulated PFAS in downgradient groundwater samples vary between waste type/liner status categories (**Figure 4-4**). Most notably, all regulated PFAS concentrations in groundwater downgradient of lined MSW and lined C&D cells are below HRLs. These data indicate that the landfill bottom liners and leachate removal systems are effectively managing PFAS in lined landfilled waste at the facilities that participated in the study.

The majority of regulated PFAS concentrations in groundwater downgradient of legacy closed (unlined) waste and unlined C&D cells are also below HRLs, but certain regulated PFAS demonstrate broader concentration ranges, with some data above HRLs. The following bullets provide a summary of the regulated PFAS occurrence and concentrations.

- One or more regulated PFAS were detected in groundwater at concentrations above an HRL at 42% of the participating landfills (n=43) where downgradient groundwater quality was evaluated. On a waste type/liner status category basis, 46% of the legacy closed (unlined) landfills (n=13) and 50% of the unlined C&D landfills (n=24) had one or more wells with at least one regulated PFAS HRL exceedance. No regulated PFAS were detected above HRLs downgradient of lined MSW or lined C&D landfills.

- In terms of monitoring wells, one or more regulated PFAS was detected at concentrations above an HRL in a sample(s) from nine percent (9%) of the downgradient monitoring wells where data were evaluated in the study (n=159). On a waste type/liner status category basis, 29% of the monitoring wells located downgradient of legacy closed (unlined) waste (n=52) and 35% of the monitoring wells located downgradient of unlined C&D (n=57) had one or more regulated PFAS HRL exceedances.

- In total, 20% of the downgradient groundwater samples evaluated in the study (n= 314) had one or more detections of PFBS, PFHxA, PFHxS, PFOA, or PFOS at a concentration above an HRL. On a waste type/liner status category basis, 25% of the groundwater samples collected downgradient of legacy closed (unlined) waste (n=103) and 32% of the groundwater samples collected downgradient of unlined C&D (n=112) had one or more regulated PFAS HRL exceedances. As indicated above, no regulated PFAS were detected at concentrations above an HRL in the groundwater samples collected downgradient of lined MSW (n=38) or lined C&D (n=61).




*Detected results are shown with circle symbols. Black circles show PFAS concentrations from fully lined facilities; colorized symbols represent regulated PFAS concentrations from unlined or partially unlined facilities. Non-detect results are shown with triangle symbols. HRLs are shown as pink dashed lines.*

**Figure 4-4 Log distribution of regulated PFAS concentrations in groundwater samples collected from downgradient monitoring wells, sorted by upgradient landfilled waste and liner types**

The following observations of individual regulated PFAS concentrations downgradient of the four waste type/liner status categories are drawn from **Figure 4-4**:

- **PFBA** was the only regulated PFAS detected in greater than 50% of the samples collected downgradient of each of the four waste type/liner status categories. All PFBA concentrations were below the HRL (7,000 ng/l). Although the PFBA concentration ranges are broadest for the legacy closed (unlined) waste and unlined C&D categories (by approximately an order of magnitude), the median values are comparable across all four categories and are approximately two or more orders of magnitude below the HRL. The PFBA outlier concentrations in the lined MSW category are attributed to upgradient groundwater at one facility and are unrelated to the subject facility. PFBA is a short-chain, terminal PFAS and is one of the most ubiquitous PFAS in the environment (Li et al., 2020).

- **PFBS** was detected in greater than 50% of the samples collected downgradient of unlined C&D and lined C&D, and slightly less than 50% for the legacy closed (unlined) waste category. PFBS concentrations above the HRL (100 ng/l) were detected in seven samples collected from a total of four downgradient monitoring wells located at three unlined C&D facilities. Median PFBS concentrations in both C&D categories are more than an order of magnitude below the HRL. PFBS was detected at concentrations below 12 ng/l in samples downgradient of lined MSW at two facilities,[12] one of which is constructed with a pre-RCRA Subtitle D landfill bottom liner (clay only), and the other has higher PFBS concentrations in samples collected from an upgradient monitoring well (i.e., this is the same facility noted for PFBA above).

- **PFHxA** was detected in greater than 50% of the samples collected downgradient of legacy closed (unlined) waste, lined C&D, and unlined C&D and was detected at a much lower rate (16% of the samples) in the lined MSW category. PFHxA concentrations above the HRL (200 ng/l) were detected in 14 samples collected from a total of eight downgradient monitoring wells located at five unlined C&D facilities and seven samples collected from four wells located at two legacy closed (unlined) waste facilities. Median PFHxA concentrations for the legacy closed (unlined) waste, lined C&D, and unlined C&D categories are approximately an order of magnitude or more below the HRL. The outlier PFHxA concentrations in the lined C&D category (which are below the HRL) are from two facilities: one with a separate but adjacent and closed unlined C&D landfill and the other with a previously identified and isolated bottom liner issue that affects water quality at the subject wells.

- **PFHxS** was detected in greater than 50% of the samples collected downgradient of unlined C&D. PFHxS concentrations above the HRL (47 ng/l) were detected in 14 samples collected from eight downgradient monitoring wells located at six unlined C&D landfills, and in seven samples from four downgradient monitoring wells located at two legacy closed (unlined) waste landfills. The median PFHxS concentration from the unlined C&D category is approximately 10% of the HRL.

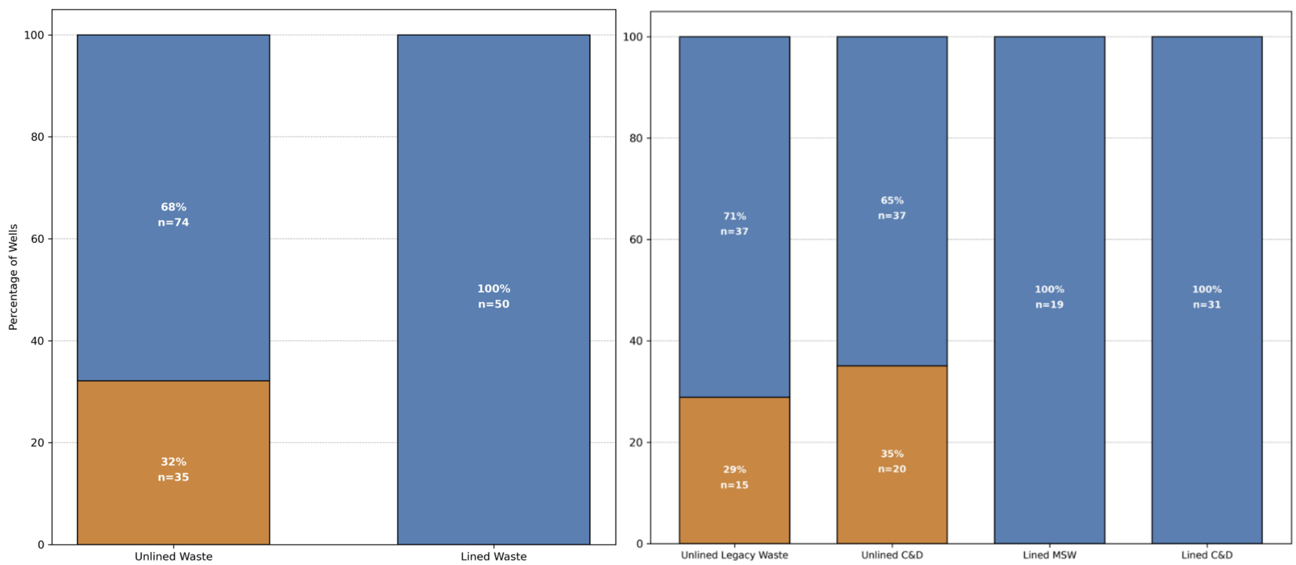
- **PFOA** was detected in greater than 50% of the samples collected downgradient of unlined C&D and legacy closed (unlined) waste and was the regulated PFAS with the highest detection frequency above the HRL. PFOA has the lowest HRL of the regulated PFAS (35 ng/l). PFOA concentrations above the HRL were detected at the highest frequency, including in 30 samples collected from 18 downgradient wells located at 11 unlined C&D facilities and in 25 samples from 15 downgradient wells located at six legacy closed (unlined) waste facilities. The median PFOA

[12] These two facilities account for most of the elevated concentrations of PFBA, PFHxA, PFHxS, PFOA, and PFOS in the lined MSW category and are not specifically discussed further in this section of the report.

concentrations from the unlined C&D and legacy closed (unlined) waste categories are approximately 25% of the HRL. Nine of the ten PFOA detections above 10 ng/l in the lined C&D category are from one landfill with a history of significantly elevated PFOA (and other PFAS) concentrations in upgradient groundwater (and are unrelated to the lined C&D waste).

- **PFOS** was detected in less than 50% of the samples collected downgradient of all waste type/liner status categories. PFOS concentrations were below the HRL (300 ng/l) in all but one downgradient groundwater sample. The single PFOS detection above the HRL occurred in a monitoring well located downgradient of a legacy closed (unlined) landfill. The PFOS concentration in the second sample from this well was approximately one-third of the initial concentration (and HRL).

Data show that PFAS presence and concentration of the above HRLs in downgradient groundwater (that are not attributed to upgradient sources) correspond more with bottom liner status than the landfill waste type (**Figure 4-5**).




*The percentage of wells with one or more PFAS detected above an HRL is shown in orange. The percentage of wells with no PFAS detected above HRL is shown in blue. (n=159)*

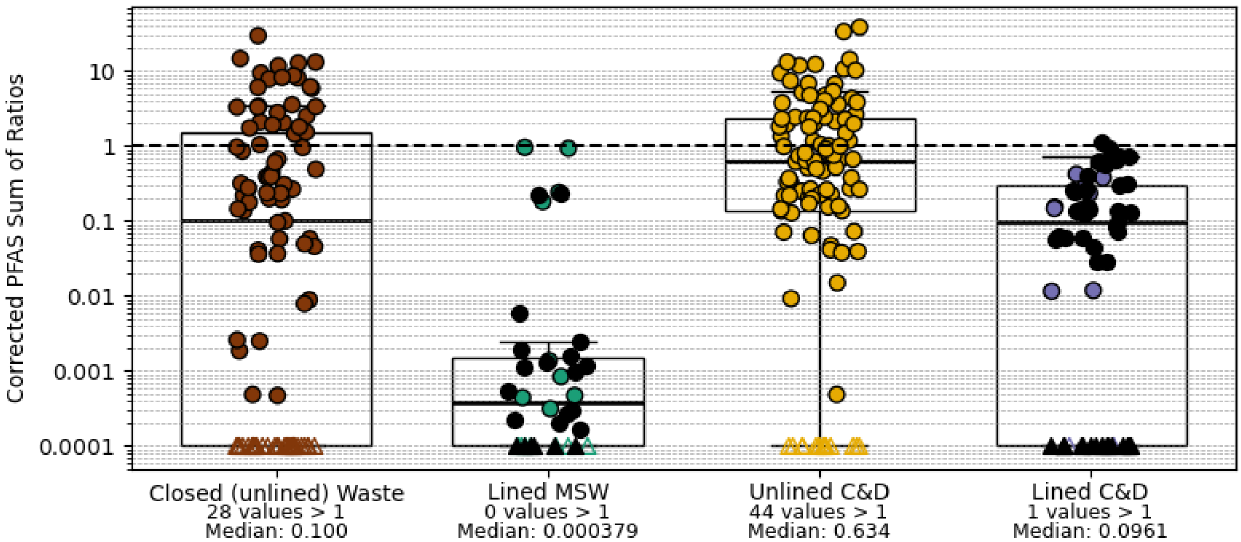
**Figure 4-5 Percentages of downgradient monitoring wells with and without PFAS detections above HRLs by liner status (left) and by waste type (right).**

The regulated PFAS concentrations in the downgradient groundwater samples included in the study are generally consistent with concentrations reported downgradient from active and closed MSW and C&D landfills in Minnesota reported by others (MPCA, 2024a) and are orders of magnitude lower than some concentrations reported at PFAS sites in the east metro area of the Twin Cities (MPCA, 2020) and aqueous firefighting foam (AFFF) sites (Brewer, 2020).

## 4.4 PFAS Sum of Ratios in Downgradient Groundwater

Twenty-three percent (23%) of the adjusted PFAS SoR values from downgradient groundwater samples were above 1.0 (n=314). Samples collected downgradient of unlined C&D and legacy closed (unlined) waste accounted for all but one of the adjusted PFAS SoR values greater than 1.0. The single adjusted PFAS SoR value greater than 1.0 from the lined C&D category was from a facility with historical (i.e., prestudy) upgradient PFAS concentrations above HRLs, and no single PFAS was detected above an HRL in the sample.

The range of adjusted PFAS SoR values is largely consistent between the legacy closed (unlined) waste and unlined C&D categories and between the lined MSW and lined C&D categories (**Figure 4-6**). The highest adjusted PFAS SoR values for the unlined C&D and legacy closed (unlined) waste are 38 and 30, respectively. Adjusted PFAS SoR values greater than 1.0 were detected in 44 samples collected from 24 downgradient monitoring wells located at 13 unlined C&D landfills and in 28 samples collected from 16 downgradient monitoring wells located at seven legacy closed (unlined) waste landfills. The highest adjusted PFAS SoR values for the lined MSW and lined C&D are 1.0 and 1.1, respectively; however, neither sample had a single PFAS concentration above an HRL. The two highest adjusted PFAS SoR values in the lined MSW category are associated with a landfill that was constructed with a pre-RCRA Subtitle D landfill bottom liner. The majority of adjusted PFAS SoR values near 1.0 in the lined C&D landfill category are from samples collected at the previously mentioned landfill with a history of regulated PFAS concentrations in upgradient groundwater.




*Black circles show adjusted PFAS SoR values from fully lined facilities. Colorized circles show adjusted PFAS SoR values from unlined or partially unlined facilities. Adjusted PFAS SoR values shown with triangle symbols represent samples that had higher upgradient regulated PFAS concentrations than downgradient regulated PFAS concentrations or non-detect concentrations.*

**Figure 4-6 Log distribution of adjusted PFAS SoR values in groundwater samples collected from downgradient monitoring wells, sorted by upgradient waste and landfill liner types.**

PFOA, which has the lowest HRL of the regulated PFAS (35 ng/l), is the driver for 84% of the adjusted PFAS SoR values greater than 1.0 (n=73). The other regulated PFAS that are drivers for the adjusted PFAS SoR values greater than 1.0 include PFHxA (11%; HRL = 200) and PFHxS (5%; HRL = 47).

The adjusted PFAS SoR evaluation is a conservative approach that puts cumulative regulated PFAS results for each groundwater sample in context to the HRLs. The results of the adjusted PFAS SoR evaluation are consistent with the evaluation of individual regulated PFAS presented earlier in this report.

## 4.5 PFAS Correlations

The study results show non-PFAS landfill monitoring parameters are, in some cases, more effective than PFAS in identifying impacted groundwater at the participating landfills. Non-PFAS data were reported for 85% of the groundwater samples (n=72) that had adjusted PFAS SoR values greater than 1.0. For each sample with an adjusted PFAS SoR value greater than 1.0, one or more non-PFAS groundwater parameter(s) were either detected above an HRL, IL, non-promulgated groundwater screening criteria (i.e., RAAs, HBV) or MCLs, or a previously identified release to groundwater was identified in the informational survey response for that subject monitoring well. In some cases, non-PFAS data above groundwater screening criteria were detected in contemporaneous samples and/or reported in the informational surveys for samples with adjusted PFAS SoR values below 1.0, which suggests traditional monitoring parameters are more conservative/effective than PFAS at identifying potential releases at some landfills. The non-PFAS analytes that were above groundwater screening criteria or noted in the informational survey as a previously identified release included (in general order of prevalence) manganese, boron, VOCs, arsenic, nitrate, iron, and cadmium.[13]

The non-PFAS analyte concentrations were not found to strongly correlate with concentrations for any of the regulated PFAS or to be a reasonable proxy for all of the regulated PFAS (**Figure 4-7**).This finding, coupled with the upgradient groundwater quality findings discussed earlier, may suggest a reduced reliability of PFAS as detection monitoring parameters.

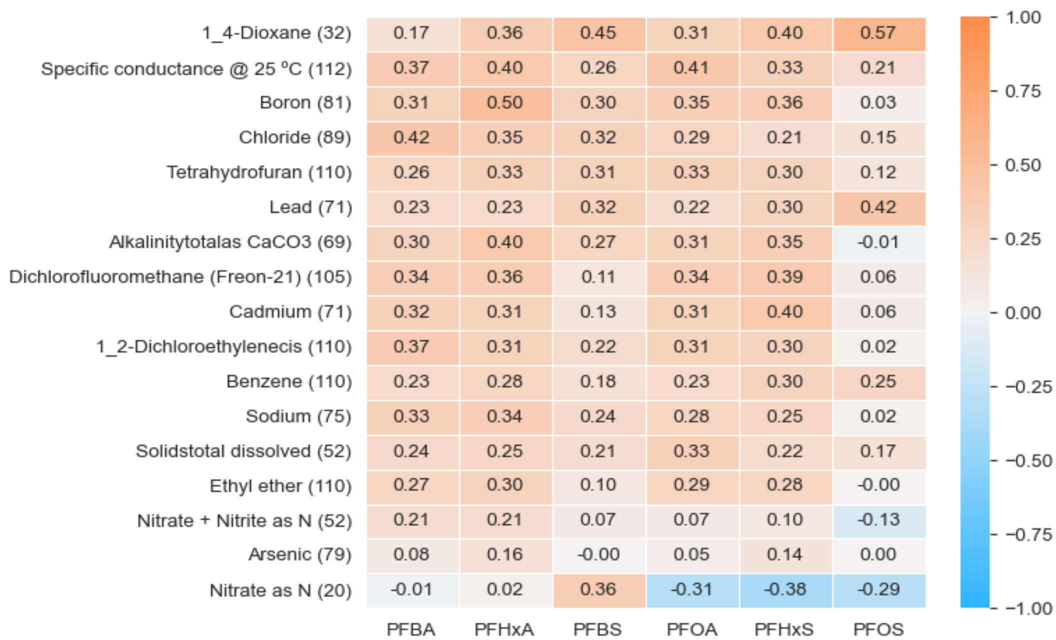



**Figure 4-7 Kendall's tau correlation coefficients for concentrations of regulated PFAS and non-PFAS analytes demonstrating the highest correlations in the study**

A standard approach for optimizing groundwater monitoring constituents for release detection monitoring includes analyzing parameters that are found in leachate at the highest concentration in contrast to ambient/background concentrations (ASTM International, 2017). Inclusion of PFAS in routine detection monitoring programs may not improve detection capabilities, given the ubiquitous presence of PFAS in

[13] An unconfirmed detection of mercury at a concentration above groundwater criteria was also reported for one groundwater sample.

the environment, the lack of strong correlation between regulated PFAS and non-PFAS analyte concentrations, and the effectiveness of traditional monitoring parameters (such as boron, VOCs, and chloride; Ranjan et al., 2022) in identifying landfill releases to groundwater as described above. However, the inclusion of PFAS in documenting baseline groundwater quality conditions and/or assessment monitoring programs may be appropriate in circumstances where traditional monitoring parameters are detected above HRLs, ILs, non-promulgated groundwater screening criteria (i.e., RAAs, HBVs), or MCLs.

# 5 Limitations

The data used in this study were collected by experienced sampling personnel that followed state-approved sampling methods under site-specific sampling plans with considerations for PFAS sampling. The groundwater samples were analyzed by one laboratory (Pace), which was certified for the groundwater sample analysis by the MDH and used a consistent analytical method that was approved by the MPCA. Each sample result was reviewed by a Barr quality assurance specialist using standard methods to assess the validity of the PFAS analytical data and, if necessary, assign data qualifiers accordingly. Sample results above method reporting limits were used for the evaluation. Barr staff reviewed informational survey responses, followed up with the participating facilities, and verified data completeness and the self-reported hydraulic positioning, upgradient water type, and upgradient liner status for each monitoring well included in the study.

Study limitations relate to site-specific histories that may not be readily known by participating facility administrators or staff, environmental professionals who provide consulting services to the participating facilities, or Barr. Examples of potential limitations include the unknown nature and content of landfill waste at older legacy closed (unlined) landfills and older unlined C&D landfills, past groundwater remedial actions that could affect the groundwater quality at certain landfills, or if waste fires have occurred at the participating facilities and were extinguished with an AFFF.[14]

[14] Responses to informational survey questions regarding past fires and use of AFFF were not deemed sufficient to utilize in this evaluation due to the high rate of non-responses or unknown.

# 6 Summary and Discussion

The results of this study show that landfill bottom liners effectively manage solid waste containing PFAS and that the PFAS presence and concentration above HRLs in downgradient groundwater correspond more with landfill bottom liner status than the landfill waste type. There was no evidence of significant regulated PFAS releases in groundwater samples attributed to lined MSW landfills constructed with RCRA Subtitle D liners. PFAS concentrations in groundwater downgradient of lined C&D landfills also met HRLs.

The PFAS concentrations in groundwater downgradient of legacy closed (unlined) MSW and unlined C&D landfills were more variable. PFAS concentrations in downgradient groundwater at approximately half of the legacy closed (unlined) landfills and unlined C&D landfills met HRLs. At the unlined facilities that had PFAS exceedances in downgradient groundwater, PFOA was the most frequently detected above standards (18% of the samples), followed by PFHxA and PFHxS (both at 7%), PFBS (2%), and PFOS (<1%). PFBA was not detected above its HRL.

One or more regulated PFAS were detected in groundwater upgradient of 76% of the landfills that collected upgradient groundwater samples. PFBA was the most frequently detected regulated PFAS in upgradient groundwater (64% of the samples), followed by PFHxA (31%), PFBS (29%), PFOA (25%), PFHxS (19%), and PFOS (15%). Regulated PFAS detections were more prevalent upgradient of landfills with industrial or agricultural land uses than those with upgradient residential/undeveloped land use. PFOA was detected above HRLs in 6% of the upgradient monitoring wells. A number of regulated PFAS concentrations detected in upgradient groundwater samples were higher than ambient background concentrations in shallow groundwater (MPCA, 2024a) and in regional atmospheric inputs in Minnesota and Wisconsin (Silver et al., 2023).

The detection of regulated PFAS in upgradient groundwater samples highlights the environmental ubiquity of these substances, particularly in areas with industrial or agricultural land uses. The combination of the widespread presence of PFAS in the environment, their weak correlation with non-PFAS analytes, and the proven efficacy of traditional monitoring parameters (e.g., boron, VOCs, and chloride) to detect landfill releases to groundwater indicates that the inclusion of PFAS in routine monitoring programs does not consistently enhance the detection of landfill releases compared to traditional monitoring parameters. Inclusion of PFAS monitoring as part of baseline and/or source assessment monitoring at landfills where a traditional monitoring parameter is detected above a HRLs, ILs, non-promulgated groundwater criteria (i.e., RAAs, HBVs), or MCLs is consistent with monitoring approaches utilized in Minnesota and elsewhere in the United States.

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# Appendix A

## PFAS and Non-PFAS Analytical Data

(available by request)