Fate of pfas in dune-infiltration systems

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At the coast, PFAS – also known as 'forever chemicals' – are carried ashore in significant amounts via sea spray. Small droplets of seawater are released into the air by breaking waves, thereby reaching the coast. In the Netherlands, pre-treated river water is infiltrated into coastal dunes as a purification step in the production of drinking water. The fate of PFAS during this process is not yet fully understood.

PFAS, or per- and polyfluoroalkyl substances, are a group of persistent chemicals that pose a risk to human health and the environment. To date, little research has been conducted on PFAS in dune infiltration systems. There is limited knowledge about sources of contamination, occurrence, transport, accumulation, and leaching into groundwater.

Atmospheric deposition is a major source of contamination for coastal dunes, occurring not only through rain and other forms of precipitation, but also via sea spray aerosols (SSA). Research has shown that SSA can contain high levels of PFAS [1,2]. To better understand the fate of PFAS during dune infiltration and the potential impact of SSA deposition, we investigated PFAS concentrations in infiltrated water, extracted water, and in soil and sediment within a dune infiltration system near Wijk aan Zee.

PFAS in soil and sediment

We collected sediment and soil samples at three locations: an infiltration pond (location 1), between an infiltration pond and its associated abstraction well (infiltration dune, location 2), and a dune outside the infiltration system (outer dune, location 3 – see diagram). At each location, the top layer (~0–0.02 m), middle layer (~2 m), and bottom layer (2.5–4 m) were sampled.

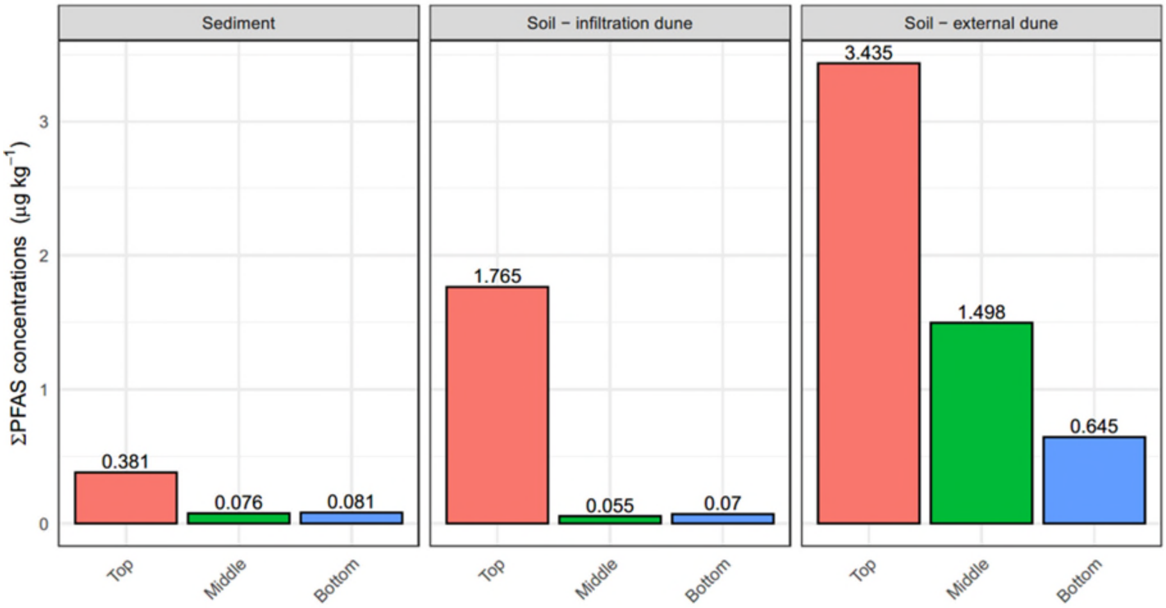

Figure 1. Total PFAS in sediment (location 1) and soil (locations 2 and 3) (n = 1).

Soils and sediment at all three locations were found to contain PFAS (Figure 1), with higher concentrations in the top layer compared to the middle and bottom layers. Unlike the other two locations, PFAS concentrations in the outer dune decreased gradually with depth, indicating atmospheric deposition and downward leaching from the surface toward the groundwater.

The middle layer of the outer dune (location 3) contained significantly more PFAS than the same layer in the infiltration dune (location 2). In the infiltration dune, this layer lies within the saturated zone influenced by infiltrated surface water, whereas in the outer dune, the same depth is unsaturated and influenced only by atmospheric deposition. The elevated PFAS concentration in the unsaturated zone of the outer dune can likely be attributed to:

- Accumulation of PFAS from atmospheric deposition, followed by slow leaching through the unsaturated zone toward the groundwater;
- A higher content of PFAS-binding soil components, which may have been partly depleted in the infiltration dune due to long-term infiltration of surface water;
- PFAS sorption at the air–water interface in the soil of the outer dune, a binding mechanism that increases concentrations in the unsaturated zone but not in the saturated zone.

PFAS concentrations in the bottom layer of location 2 (infiltration dune) were similar to those in the middle layer. The concentrations were relatively low and consisted largely of PFOS (the orange peaks in Figure 2). Based on the measured PFOS levels and literature values for the soil–water partition coefficient of PFOS in sandy soils with low organic matter content [3], groundwater concentrations of up to 15 nanograms per liter can be expected. This is higher than the concentration in the infiltrated surface water and suggests that PFOS release from saturated soil at location 2 could contribute to elevated PFOS levels in the extracted water.

In the sediment of the infiltration pond (location 1), the highest PFAS levels were measured in the top layer (Figure 1, left). This could be due the presence of organic carbon and mineral particles, which can adsorb PFAS [4]. PFAS concentrations in the middle and bottom layers were lower and comparable to those in the same layers of the infiltration dune (location 2).

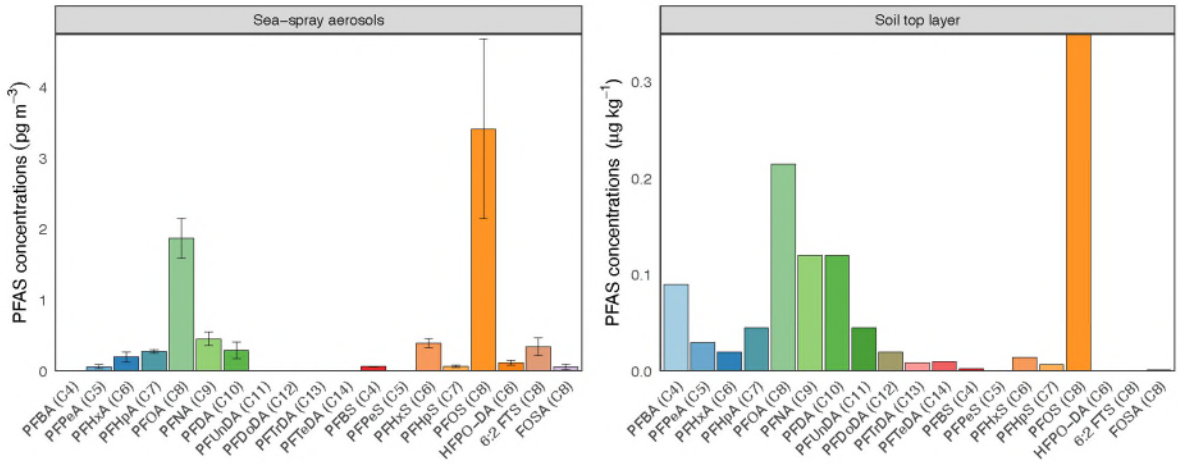

Figure 2. PFAS concentrations in sea spray aerosols (mean ± SD, n = 8) and in the top soil layers (average of locations 2 and 3, n = 2). The peaks represent PFOA (green) and PFOS (orange). The average PFOS concentration in the topsoil layer is 1.85 µg kg^{-1}.

Influence of SSA deposition

In Figure 2, PFAS with a carboxylic acid group are shown on the left (PFCA – blue and green), and PFAS with a sulfonic acid group on the right (PFSA – red and orange). The PFCA concentrations in the topsoil layer and in sea spray aerosols (SSA) display a similar pattern, with a peak for PFOA (C8). The same applies to the PFSA concentrations, which show a peak for PFOS. This suggests that deposition from sea spray could be an important source of PFAS in the unsaturated dune soil. An exception is PFBA (far left in Figure 2), which was not detected in sea spray but was present in the soil. This could indicate:

- other atmospheric sources of PFBA besides SSA;
- formation of PFBA from known precursors such as 6:2 FTS, HFPO-DA, and FOSA, which were detected in the aerosol samples (far right, next to the PFOS peak) [5].

Fate of PFAS during dune infiltration

Total PFAS concentrations (ΣPFAS) increased from 25.5–36.3 nanograms per liter in infiltrated water (Inf-A and Inf-B, Figure 3) to 35.2–57.5 nanograms per liter in abstracted groundwater (Abs-A and Abs-B). Figure 3 shows that PFHxS and PFOA contributed the most to this increase. There was no clear difference in ΣPFAS between the extraction wells located in the center of the infiltration area (Abs-A), which are mainly fed by infiltrated water, and those at the edge of the infiltration area (Abs-B), which also receive inflow of natural groundwater from the outer dune. Likewise, the increase in ΣPFAS compared to the infiltrated surface water (Inf-A and Inf-B) did not differ significantly between these wells.

This suggests that the flow of natural groundwater to the extraction wells does not currently contribute significantly to the increase in PFAS concentration. This is supported by the relatively low PFAS concentrations in the groundwater wells (GW1 and GW2, Figure 3). However, since this study only analyzed deep groundwater (approximately 15 to 40 meters depth), the potential contribution of shallow groundwater should be further investigated. Remobilization of PFAS adsorbed to saturated soil particles or leaching from the unsaturated soil above the shallow groundwater are the most likely causes of the increase observed between infiltration and extraction.

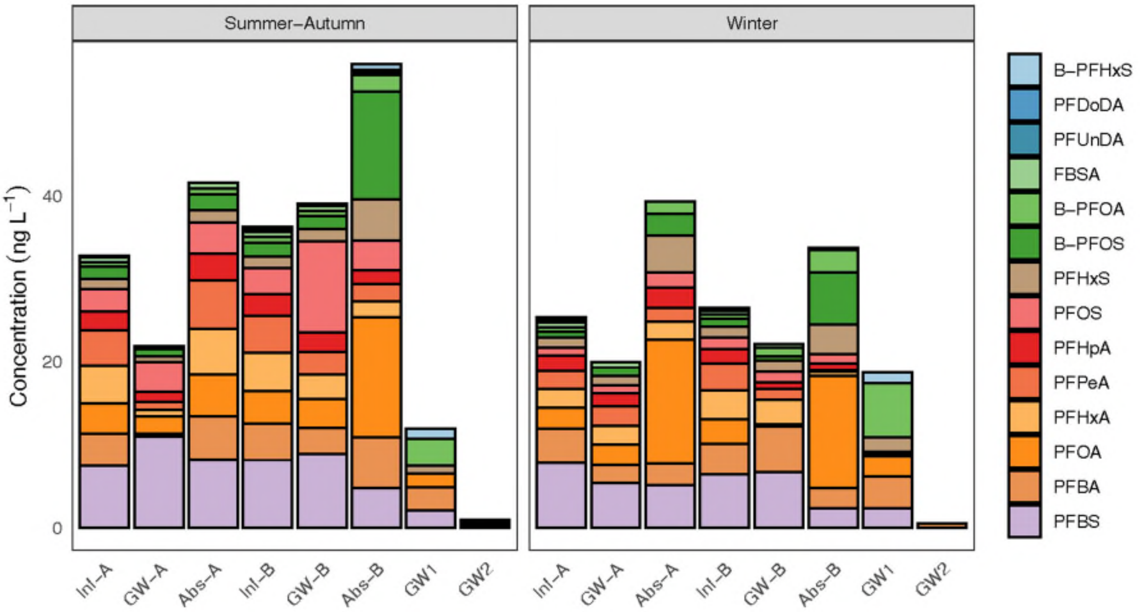

Figure 3. PFAS concentrations in the infiltration ponds (Inf-A and Inf-B), groundwater between infiltration and abstraction wells (GW-A, Abs-A, GW-B, Abs-B), and deeper groundwater in the outer dune (GW1 and GW2) collected in summer–autumn and winter (n = 1–3). B-PFHxS, B-PFOA, and B-PFOS are branched molecules; all others are linear.

Conclusions

This study showed that PFAS concentrations in water extracted after passage through the dune soil were clearly higher than in the pretreated river water that was infiltrated. The cause is still unclear but could be attributed to three main processes:

- Release of 'legacy' PFAS originating from decades of infiltration of river water containing higher PFAS levels. These compounds became bound to soil particles over time and are now being released through desorption. The low PFAS concentrations in the current, cleaner infiltrated water enhance this remobilization;
- Contributions from atmospheric deposition, including sea spray;
- Transformation of precursors into stable PFAS (e.g., the aforementioned potential precursors of PFBA).

Understanding the sources and behavior of PFAS in dune infiltration systems helps explain the increase of PFAS during infiltration. Further research is needed to more accurately quantify these contributions in order to better assess their long-term effects on the extracted water. Based on this knowledge, drinking water companies can implement measures, such as (temporary) additional treatment steps or reducing the inflow of contaminated groundwater to the abstraction wells through improved management of the infiltration area.

SUMMARY

Drinking water sources are highly vulnerable to PFAS contamination, even in protected areas such as dune infiltration zones. PFAS concentrations in the abstracted groundwater are higher than in the infiltrated surface water. The cause of this increase is not yet clear. However, it is evident that PFAS in the topsoil layers originate from sea spray and precipitation. Another source is the remobilization of PFAS that was adsorbed onto dune sand during the period when the infiltrated river water contained higher PFAS levels.

SOURCES

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