Electronic Supplementary Information (ESI)

# Removal of Per- and Polyfluoroalkyl Substances (PFASs) from Contaminated Groundwater using Granular Activated Carbon: A Pilot-Scale Study with Breakthrough Modeling

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**Environmental Science: Water Research and Technology**

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## 1.0 Analytical Sample Prep

All samples were collected in 15 mL pre-weighed polypropylene Falcon (Corning, NY) tubes. The following reagents were added: 63.8% water sample, 3.3% Fisher Scientific Optima LCMS grade water (Hampton, NH) mixed with 0.1% of Optima LCMS grade ammonium hydroxide, 13.6% Optima LCMS grade methanol, 9.6% of Optima LCMS grade isopropanol surrogate mixture, and 9.6% of Optima LCMS grade methanol surrogate mixture. All reagents were prepared in the original sampling vial to mitigate transfer losses. Surrogate concentrations were spiked at 74 pg/mL and 1.35 mL of sample was transferred into a 1.5 mL autosampler vial.

1mL of sample was injected in a SCIEX X500R QTOF System (Framingham, MA). The analytical column used was Phenomenex Gemini C18, 3mm x 100mm x 5µm (Torrance, CA). Prior to the column, a Phenomenex C18 SecurityGuard™ 4mm x 2mm (Torrance, CA) and two Agilent Zorbax 4.6 mm x 12.5 mm x 6 µm DIOL guard columns (Santa Clara, CA) were used. A Phenomenex Luna 5 um C18(2) 100 Ä LC column 30 x 3 mm (Torrance, CA) was used as a delay column to aid in chromatographic separation. The column oven temperature was set to 40C. The eluent mobile phases used were (A) Optima LCMS grade water with 20mM Fisher Scientific HPLC grade ammonium acetate (Hampton, NH) and (B) 100% Optima LCMS grade methanol. The autosampler rinse solution was 100% Optima LCMS grade isopropanol. Eluent flow rate was held at 0.60 mL/min, and composition was ramped from 90% A to 50% A over the first 0.5 minutes, then to 1.0% A at 8 minutes and held until 13 minutes, then ramped to 90% A at 13.5 minutes and held to 20 minutes.

Electrospray ionization in negative mode (ESI-) with SWATH® Data-Independent Acquisition for both TOFMS and MS/MS mode were used. Precursor ion data was collected for m/z 100-1200 for 1283 cycles with a total scan time of 842 ms and accumulation time of 20 ms, with ion spray voltage set at - 4500 V and temperature set to 550 ºC. The ion source, curtain, and collision (CAD) gas were set to 60 psi, 35 psi, and 10 psi, respectively. For QTOF scanning, the collision energy was set to -5 V and the declustering potential to -20 V, both with no spread. Product ion (MS/MS) scanning was conducted for m/z 50-1200 Da. The accumulation time for each SWATH window is 50 ms and collision energy was -35 V with 30 V spread. The instrument was mass calibrated every 5 injections using SCIEX ESI Negative Calibration Solution.

## 2.0 GAC Column Parameters

**Table S1.** GAC column parameters.

| | |
|---|---|
| GAC Height | 45 in |
| Column Diameter | 5.71 in |
| Flowrate/Column | 0.5 gpm |
| Total Bed Volume | 18.88 L |
| Total Run Time | 1841.59 hr |
| Hydraulic Loading Rate | 2.8 gpm/ft$^2$ |
| Empty Bed Contact Time | 10 min |

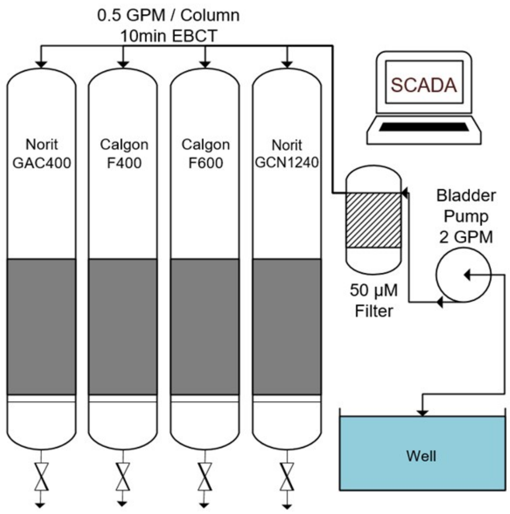

**Figure S1.** Pilot system process diagram.

## 3.0 Modeling Input

**Table S2.** Fixed column model input parameters.

| | F400 | GAC400 | F600 | GCN1240 |
|---|---|---|---|---|
| Column Length (m) | 1.143 | 1.143 | 1.143 | 1.143 |
| Inner Column Radius (m) | 0.073 | 0.073 | 0.073 | 0.073 |
| Total Dry Mass of GAC (kg) | 10.1967 | 9.2525 | 11.7073 | 9.6302 |
| Flow Through Column ($m^3$/s) | 3.15E-05 | 3.15E-05 | 3.15E-05 | 3.15E-05 |
| Dispersion Coefficient ($m^2$/s) | 9.77E-06 | 9.85E-06 | 1.08E-05 | 8.75E-06 |
| Skeletal Density of GAC (kg/$m^3$) | 2200 | 2200 | 2200 | 2200 |
| Radius of GAC (m) | 0.0065 | 0.0065 | 0.0065 | 0.0065 |
| Intraparticle Porosity | 0.59 | 0.63 | 0.53 | 0.61 |

**Table S3.** Compound specific model inputs.

| | Molecular Weight (g/mol) | Avg. Influent Concentration (mM) |
|---|---|---|
| PFPeA | 264.07 | 5.62187E-08 |
| PFHxA | 314.07 | 5.60266E-08 |
| PFHpA | 364.07 | 1.46478E-08 |
| PFOA | 414.07 | 5.08504E-08 |
| PFPrS | 250.13 | 1.25937E-08 |
| PFBS | 300.13 | 7.47829E-09 |
| PFPeS | 350.13 | 2.95955E-08 |
| PFHxS | 400.13 | 1.02123E-07 |
| PFHpS | 450.13 | 2.52849E-09 |
| PFOS | 500.13 | 9.89414E-08 |

## 3.1 Dispersion Coefficient Calculation

The dispersion coefficient was calculated based on the Chung and Wen equation[1, 2]

$$\frac{D_{disp}\rho_w}{\mu_w} = \frac{Re}{0.2 + 0.011Re^{0.48}} \quad \text{(eq 1)}$$

where $D_{disp}$ is the dispersion coefficient ($m^2/s$), $\rho_w$ is the density of water at 14C 999.2 ($kg/m^3$), $\mu_w$ is the viscosity of water at 14 ºC, 0.0010518 (Pa s), and Re is the Reynolds number.

The Reynolds number was defined as

$$Re = \frac{\rho_w v d_p}{\mu_w} \quad \text{(eq 2)}$$

where v is the interstitial velocity (m/s), and $d_p$ is the particle diameter (m).

Interstitial velocity was defined as

$$v = \frac{Q}{\pi {r_p}^2 n} \quad \text{(eq 3)}$$

where Q is the flowrate ($m^3/s$), r is the particle radius (r), and n is particle porosity.

### 3.2 Intraparticle Porosity Calculation

Intraparticle porosity was defined as

$$n = \frac{V_{pores}}{V_{particles}} \quad \text{(eq 4)}$$

where n is the porosity, $V_{pores}$ is the volume of the particle pores, and $V_{particles}$ is the volume of the particles. $V_{particles}$ is the difference between the volume of the bed and the volume of the void. $V_{pores}$ is the difference between the volume of the particle and the volume of the skeletal.

### 3.3 Instantaneous Sorption Equilibrium Model

The column experiments were simulated by considering pollutant transport by advection and dispersion. The pollutant distribution between the mobile column porewater (in between the particles), and the solid matrix of the activated (AC) particles was described by a solid liquid partition coefficient, $K_d$. Parameters were expressed in SI units of moles, seconds, kilograms, and meters (Table S4).

**Table S4.** Independent and dependent column model variables and parameters and their dimensions for the instantaneous sorption equilibrium model.

| | |
|---|---|
| t (s) | Time |
| x (m) | Distance from the column inlet |

| | |
|---|---|
| $C_w$ (moles $nm^{-3}$) | Pollutant concentration in mobile water in between the AC particles |
| $K_d$ ($m^3$ $kg^{-1}$) | Reversible, linear AC solid-water partitioning coefficient for the pollutant |
| $L_C$ (m) | Length of the column |
| $R_C$ (m) | Radius of the column |
| $C_{in}$ (moles $m^{-3}$) | Pollutant concentration in the influent |
| $v_x$ (m $s^{-1}$) | Interstitial velocity of the mobile water in between the AC particles in the x direction |
| $D_{disp}$ ($m^2$ $s^{-1}$) | Dispersion coefficient for pollutants in the water in between the AC particles in the x direction |
| $M_{AC}$ (kg) | Total dry AC mass of particles (of all sizes) in the column |
| $\Theta_{AC,w}$ (-) | Water-filled AC intraparticle porosity |
| $d_{AC}$ (kg $m^{-3}$) | Solid density of the AC skeleton |

### 3.3.1 Calculated Column Properties

The volume fraction of the column filled with AC particles, $\theta_{AC}$, is defined as

$$\theta_{AC} = \frac{M_{AC}}{(1-\theta_{AC,w})d_{AC}L_C\pi R_C^2} \quad \text{(eq 5)}$$

where $M_{AC}$ is the total dry mass of AC particles in the column, $\theta_{AC,w}$ is the water-filled intraparticle AC porosity, $d_{AC}$ is the skeletal solid density of the AC, $L_C$ is the length of the column, and $R_C$ is the radius of the column.

The volume fraction of the space in the column in between the AC particles, which is assumed to be entirely filled with mobile water, θ$_w$, is defined as

$\theta_w = 1 - \theta_{AC}$ (eq 6)

### 3.3.2 Differential Equation

*Pollutant transport in mobile water moving in between the AC particles:*

The following partial differential equation is assumed to govern the pollutant concentration in the mobile water phase moving in between the AC particles

$$\left(\theta_w + \theta_{AC} \cdot \left(\theta_{AC,w} + (1 - \theta_{AC,w}) d_{AC} K_d\right)\right) \cdot {}^{d}/_{dt} C_w = \theta_w D_{disp} {}^{\partial^2}/_{\partial x^2} C_w - \theta_w v_x {}^{\partial}/_{\partial x} C_w$$

(eq 7)

where θ$_w$ is the fraction of the column volume in between the AC particles, which is assumed to be fully water saturated, K$_d$ is the linear AC solid-water partitioning coefficient of the pollutant, D$_{disp}$ is the dispersion coefficient of pollutants in mobile water, and v$_x$ is the interstitial velocity of this water, both in the x direction.

*Boundary conditions for the column*:

The pollutant concentration at the column inlet is equal to the concentration in the column influent, C$_{in}$,

$C_w|_{x=0} = C_{in}$ (eq 8)

And a zero concentration gradient boundary condition is enforced at the column outlet

${}^{\partial}/_{\partial x} C_w \big|_{x=L} = 0$ (eq 9)

### 3.4 Intraparticle Diffusion Model

The column experiments were simulated by considering pollutant transport by advection and dispersion in the mobile water moving in between the AC particles in addition to sorption-retarded intraparticle diffusion into AC particles. The pollutant distribution between water and the solid matrix of the AC particles was described by a linear sorption coefficient $K_d$. Parameters were expressed in SI units of moles, seconds, kilograms, and meters (Table S5).

**Table S5.** Independent and dependent column model variables and parameters and their dimensions for the intraparticle diffusion model.

| | |
|---|---|
| t (s) | Time |
| x (m) | Distance from the column inlet |
| r (m) | Radial distance from the AC particle centre |
| $C_w$ (moles $m^{-3}$) | Pollutant concentration in mobile water in between the AC particles |
| $C_{AC}$ (moles $m^{-3}$) | Pollutant concentration in the AC intraparticle porewater |
| $K_d$ ($m^3\ kg^{-1}$) | Reversible, linear AC solid-water partitioning coefficient for the pollutant |
| $L_C$ (m) | Length of the column |
| $R_C$ (m) | Radius of the column |
| $C_{in}$ (moles $m^{-3}$) | Pollutant concentration in the influent |
| $v_x$ (m $s^{-1}$) | Interstitial velocity of the mobile water in between the AC particles in the x direction |
| $D_{disp}$ ($m^2\ s^{-1}$) | Dispersion coefficient for pollutants in the mobile water in |

| | |
|---|---|
| | between the AC particles in the x direction |
| $M_{AC}$ (kg) | Dry AC mass of particles |
| $R_{AC}$ (m) | AC particle radius |
| $\Theta_{AC,w}$ (-) | Water-filled AC intraparticle porosity |
| $d_{AC}$ (kg $m^{-3}$) | Solid density of the AC skeleton |
| $\tau$ (-) | AC pore network tortuosity factor |
| $D_{aq}$ ($m^2$ $s^{-1}$) | The molecular diffusion coefficient of the pollutant in water |

### 3.4.1 Calculated Column Properties

The volume fraction of the column filled with AC particles $\theta_{AC}$, is defined as

$$\theta_{AC} = \frac{M_{AC}}{(1-\theta_{AC,w})d_{AC}L_C\pi R_C^2} \quad \text{(eq 10)}$$

where $M_{AC}$ is the dry mass of AC particles, $\theta_{AC,w}$ is the water-filled intraparticle AC porosity, $d_{AC}$ is the skeletal solid density of the AC, $L_C$ is the length of the column, and $R_C$ is the radius of the column.

The volume fraction of the column in between the AC particles, which is assumed to be entirely filled with mobile water, $\theta_w$, is defined as

$$\theta_w = 1 - \theta_{AC} \quad \text{(eq 11)}$$

### 3.4.2 Differential Equations

*Pollutant diffusion in intraparticle pore water:*

The following partial differential equation is assumed to govern the pollutant concentration in the AC intraparticle pore water, $C_{AC,ippw}$

$$\left(\theta_{AC,w} + (1 - \theta_{AC,w}) d_{AC} K_d\right) {}^{d}\!/_{dt} C_{AC,ippw} = D_{eff,AC} \frac{1}{r^2} \cdot {}^{\partial}\!/_{\partial r} r^2 \, {}^{\partial}\!/_{\partial r} C_{AC,ippw} \quad \text{(eq 12)}$$

where r is the radial distance from the AC particle center, and t is the time.

The effective diffusion coefficient of the pollutant in the AC pore network is defined as

$$D_{eff,AC} = \frac{\theta_{AC,w} D_{aq}}{\tau} \quad \text{(eq 13)}$$

where $\tau$ is the AC pore network tortuosity factor, and $D_{aq}$ is the molecular diffusion coefficient of the pollutant in water.

*Boundary conditions for the AC particles*:

A no net diffusion flux boundary condition is enforced at r=0 in the AC particle cores

$$ {}^{\partial}\!/_{\partial r} C_{AC,ippw} \Big|_{r = 0} = 0 \quad \text{(eq 14)}$$

The pollutant concentration in AC intraparticle pore water at the mobile water-AC interface is assumed to be equal to the pollutant concentration in the mobile water in between the soil and AC particles (i.e. no external aqueous film mass transfer resistance)

$$C_{AC,ippw} \big|_{r = R_{BC}} = C_w \quad \text{(eq 15)}$$

where $R_{BC}$ is the particle radius.

*Pollutant transport in mobile water in between the AC particles:*

The following partial differential equation is assumed to govern the pollutant concentration in the mobile water phase in between the AC particles:

$$\theta_w \cdot {}^{d}\!/_{dt} C_w = \theta_w D_{disp} \, {}^{\partial^2}\!/_{\partial x^2} C_w - \theta_w v_x \, {}^{\partial}\!/_{\partial x} C_w + r_{\,ippwd,out} \quad \text{(eq 16)}$$

where $\theta_w$ is the fraction of the column volume in between the AC particles, which is assumed to be fully water saturated, $D_{disp}$ is the dispersion coefficient for pollutants in mobile water in the x direction, and $v_x$ is the interstitial velocity also in the x direction.

The AC particles to mobile water mass transfer rate, $r_{ippwd,out}$, is described by

$$r_{ippwd,out} = -\frac{\theta_{AC}}{\frac{4}{3}\pi R_{AC}^{3}} \cdot 4\pi R_{AC}^{2} \cdot D_{eff,AC} \cdot {}^{\partial}\!/_{\partial r} C_{AC,ippw}\Big|_{r=R_{AC}} = -3\frac{\theta_{AC}}{R_{AC}} \cdot D_{eff\_AC} \cdot {}^{\partial}\!/_{\partial r} C_{AC,ippw}\Big|_{r}$$

(eq 17)

*Boundary conditions for the column*:

The pollutant concentration at the column inlet is equal to the concentration in the column influent, $C_{in}$,

$$C_w\big|_{x=0} = C_{in} \quad \text{(eq 18)}$$

And a zero-concentration gradient boundary condition is enforced at the column outlet

$${}^{\partial}\!/_{\partial x} C_w\Big|_{x=L} = 0 \quad \text{(eq 19)}$$

## 3.5 Influent Concentration

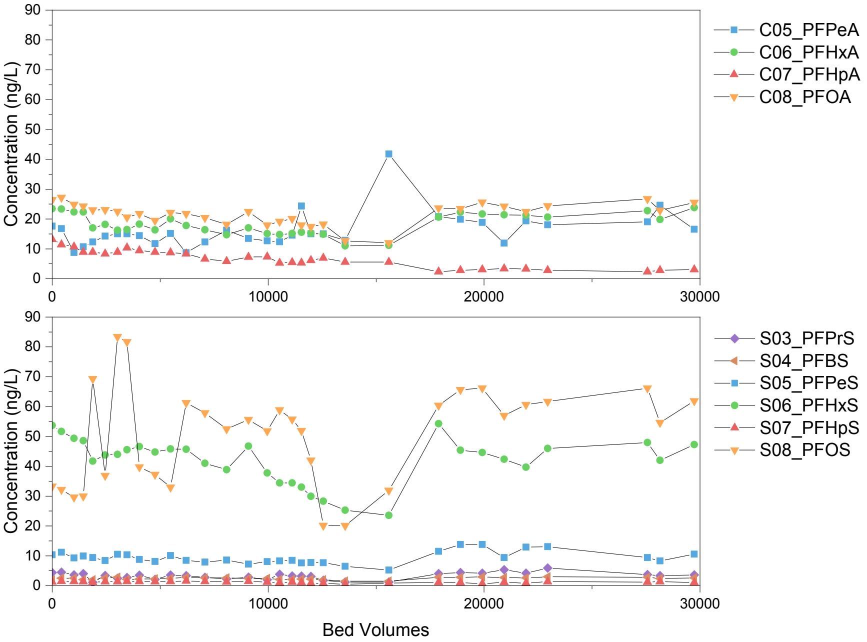

**Figure S2.** Influent concentration over time.

## 3.6 Modeling Output Results

**Table S6.** Equilibrium model derived $K_d$ and SSR values.

| | | PFPeA | PFHxA | PFHpA | PFOA | PFPrS | PFBS | PFPeS | PFHxS | PFHpS | PFOS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F400 | Log Kd (L/kg) | 4.40 | 4.56 | 4.88 | 4.80 | 4.46 | 4.62 | 4.74 | 4.82 | 4.87 | 4.86 |
| | SSR | 0.170 | 0.079 | 0.001 | 0.013 | 0.082 | 0.136 | 0.334 | 0.021 | 0.003 | 0.001 |
| GAC400 | Log Kd (L/kg) | 4.45 | 4.56 | 4.92 | 4.80 | 4.47 | 4.63 | 4.74 | 4.85 | 4.89 | 4.89 |
| | SSR | 0.130 | 0.053 | 0.000 | 0.075 | 0.044 | 0.159 | 0.367 | 0.030 | 0.010 | 0.018 |
| F600 | Log Kd (L/kg) | 4.34 | 4.47 | 4.80 | 4.61 | 4.42 | 4.55 | 4.64 | 4.68 | 4.70 | 4.66 |
| | SSR | 0.248 | 0.253 | 0.007 | 0.387 | 0.241 | 0.397 | 0.402 | 0.241 | 0.066 | 0.245 |
| GCN1240 | Log Kd (L/kg) | 4.41 | 4.45 | 4.86 | 4.59 | 4.43 | 4.49 | 4.54 | 4.64 | 4.76 | 4.70 |
| | SSR | 0.282 | 0.191 | 0.038 | 0.156 | 0.202 | 0.052 | 0.177 | 0.170 | 0.355 | 0.267 |

**Table S7.** Intraparticle diffusion model derived $K_d$ and SSR values at $\tau = 1$.

| | | PFPeA | PFHxA | PFHpA | PFOA | PFPrS | PFBS | PFPeS | PFHxS | PFHpS | PFOS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| F400 | Log Kd (L/kg) | 4.49 | 4.71 | 5.58 | 5.32 | 4.54 | 4.82 | 5.02 | 5.35 | 5.61 | 5.60 |
| | SSR | 1.710 | 1.022 | 0.002 | 0.018 | 1.385 | 0.434 | 0.105 | 0.011 | 0.007 | 0.005 |
| GAC400 | Log Kd (L/kg) | 4.52 | 4.69 | 5.58 | 5.18 | 4.54 | 4.79 | 4.99 | 5.32 | 5.54 | 5.49 |
| | SSR | 1.164 | 1.113 | 0.002 | 0.054 | 1.299 | 0.501 | 0.197 | 0.008 | 0.020 | 0.008 |
| F600 | Log Kd (L/kg) | 4.44 | 4.62 | 5.43 | 4.89 | 4.54 | 4.77 | 4.90 | 5.01 | 5.17 | 5.07 |
| | SSR | 1.735 | 0.652 | 0.001 | 0.167 | 0.607 | 0.265 | 0.076 | 0.055 | 0.084 | 0.139 |
| GCN1240 | Log Kd (L/kg) | 4.47 | 4.52 | 5.36 | 4.77 | 4.50 | 4.59 | 4.68 | 4.85 | 5.09 | 5.02 |
| | SSR | 0.773 | 1.132 | 0.008 | 0.651 | 0.939 | 1.166 | 0.689 | 0.393 | 0.110 | 0.266 |

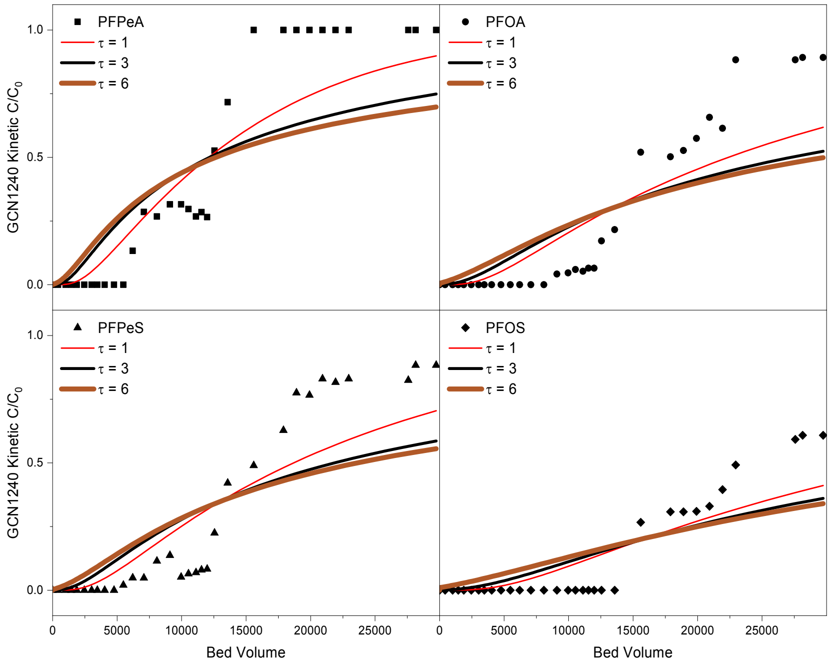

**Figure S3.** Effect of the tortuosity on the best fit $K_d$ for the intraparticle diffusion model using GCN1240 breakthrough results for four different compounds, PFPeA, PFOA, PFPeS, and PFOS.

**Table S8.** SSR at different tortuosity values for selected compounds in GCN1240 pilot data.

| | $\tau = 1$ | $\tau = 3$ | $\tau = 6$ |
|---|---|---|---|
| PFPeA | 0.773 | 1.549 | 1.851 |
| PFOA | 0.651 | 0.976 | 1.113 |
| PFPeS | 0.689 | 1.104 | 1.259 |
| PFOS | 0.266 | 0.370 | 0.460 |

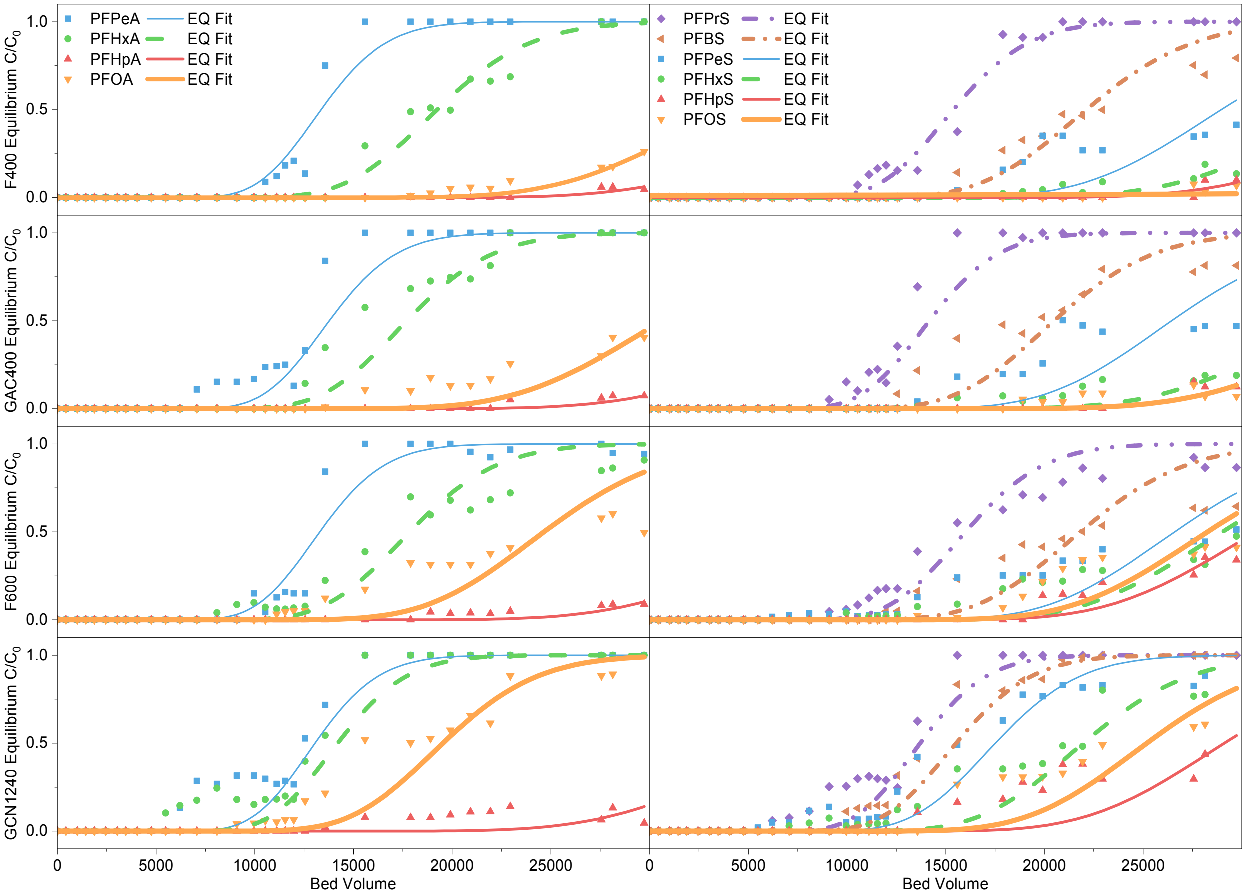

**Figure S4.** Equilibrium model fits to data.

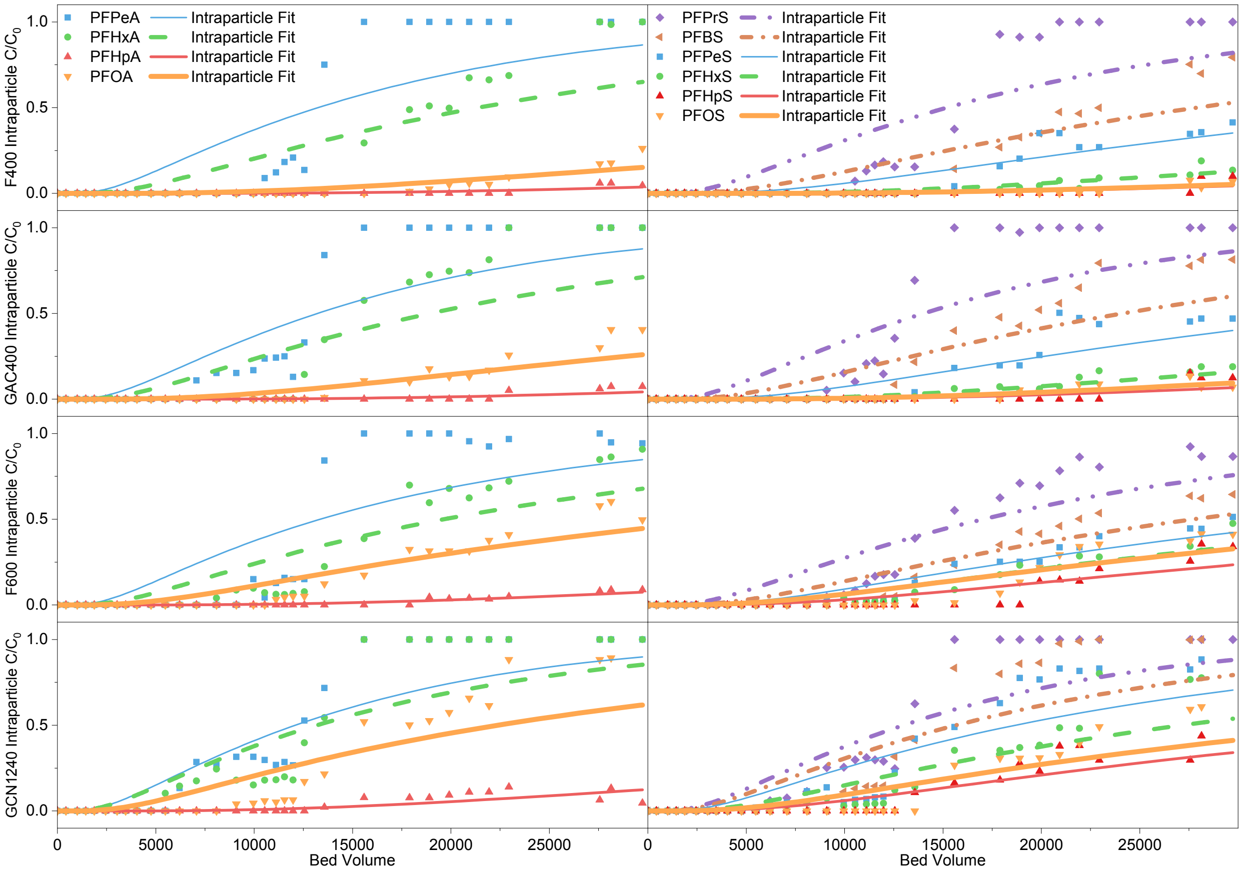

**Figure S5.** Intraparticle diffusion model fits to data.

## 3.7 Linear Regressions from Model Outputs

Table S7 and S8 show linear regression fits from the model output $K_d$ fits. The x variable is PFAS chain length and the y variable is log $K_d$ (L/kg). The intraparticle diffusion model outputs are performed with a tortuosity = 1.

**Table S9.** Equilibrium model linear regression fits.

| | | Equilibrium Model | |
|---|---|---|---|
| | | Carboxylates | Sulfonates |
| F400 | Regression | y = 0.153x + 3.66 | y = 0.081x + 4.28 |
| | R2 | 0.8 | 0.89 |
| GAC400 | Regression | y = 0.139x + 3.78 | y = 0.085x + 4.27 |
| | R2 | 0.72 | 0.89 |
| F600 | Regression | y = 0.114x + 3.81 | y = 0.049x + 4.34 |
| | R2 | 0.55 | 0.74 |
| GCN1240 | Regression | y = 0.094x + 3.97 | y = 0.064x + 4.24 |
| | R2 | 0.35 | 0.89 |

**Table S10.** Intraparticle diffusion model linear regression fits at $\tau = 1$.

| | | Intraparticle Diffusion Model | |
|---|---|---|---|
| | | Carboxylates | Sulfonates |
| F400 | Regression | y = 0.337x + 2.83 | y = 0.228x + 3.90 |
| | R2 | 0.72 | 0.96 |
| GAC400 | Regression | y = 0.286x + 3.13 | y = 0.210x + 3.96 |
| | R2 | 0.59 | 0.94 |
| F600 | Regression | y = 0.216x + 3.44 | y = 0.113x + 4.289 |
| | R2 | 0.42 | 0.86 |
| GCN1240 | Regression | y = 0.176x + 3.64 | y = 0.122x + 4.115 |
| | R2 | 0.31 | 0.93 |

**Table S11.** $K_d$ value comparison between Xiao et al. 2017[3] and EQ model predictions.

| | PFPeA | PFHxA | PFHpA | PFOA | PFPrS | PFBS | PFPeS | PFHxS | PFHpS | PFOS |
|---|---|---|---|---|---|---|---|---|---|---|
| Xiao et al. Batch $K_d$ | 4.29 | 4.18 | 4.49 | 5.25 | 3.83 | 4.69 | 4.64 | 5.28 | 5.79 | 5.95 |
| F400 EQ | 4.40 | 4.56 | 4.88 | 4.80 | 4.46 | 4.62 | 4.74 | 4.82 | 4.87 | 4.86 |
| GAC400 EQ | 4.45 | 4.56 | 4.92 | 4.80 | 4.47 | 4.63 | 4.74 | 4.85 | 4.89 | 4.89 |
| F600 EQ | 4.34 | 4.47 | 4.80 | 4.61 | 4.42 | 4.55 | 4.64 | 4.68 | 4.70 | 4.66 |
| GCN1240 EQ | 4.41 | 4.45 | 4.86 | 4.59 | 4.43 | 4.49 | 4.54 | 4.64 | 4.76 | 4.70 |
| F400 Intraparticle Diffusion | 4.49 | 4.71 | 5.58 | 5.32 | 4.54 | 4.82 | 5.02 | 5.35 | 5.61 | 5.60 |
| GAC400 Intraparticle Diffusion | 4.52 | 4.69 | 5.58 | 5.18 | 4.54 | 4.79 | 4.99 | 5.32 | 5.54 | 5.49 |
| F600 Intraparticle Diffusion | 4.44 | 4.62 | 5.43 | 4.89 | 4.54 | 4.77 | 4.90 | 5.01 | 5.17 | 5.07 |
| GCN1240 Intraparticle Diffusion | 4.47 | 4.52 | 5.36 | 4.77 | 4.50 | 4.59 | 4.68 | 4.85 | 5.09 | 5.02 |

## References

1. S. F. Chung and C. Y. Wen, Longitudinal Dispersion of Liquid Flowing Through Fixed and Fluidized Beds, *AICHE Journal*, 1968, **14**.

2. A. H. Sulaymon and K. W. Ahmed, Competitive adsorption of furfural and phenolic compounds onto activated carbon in fixed bed column, *Environ. Sci. Technol.*, 2008, **42**, 392-397.

3. X. Xiao, B. A. Ulrich, B. Chen and C. P. Higgins, Sorption of Poly- and Perfluoroalkyl Substances (PFASs) Relevant to Aqueous Film-Forming Foam (AFFF)-Impacted Groundwater by Biochars and Activated Carbon, *Environ Sci Technol*, 2017, **51**, 6342-6351.