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A Cost Comparison of Pump-and-Treat and In Situ Colloidal Activated Carbon for PFAS Plume Management

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ABSTRACT

This article compares the full installation and operational costs of a hydraulic containment ("pump-and-treat," P&T) system with those of a hypothetical contemporary in situ colloidal activated carbon (CAC) barrier. Worked examples are provided using public domain data from the FT-02 fire-fighting training site on the former Wurtsmith Air Force Base in Oscoda, MI. The projected CAC costs are approximately a third of the P&T costs over projection periods of 15–100 years ($ 7.2 M vs. $ 19 M at 30 years; 38%). Hydraulic containment and CAC remediation systems prevent the spread of per- and polyfluoroalkyl substance (PFAS)-contaminated groundwater. Hydraulic containment works by extracting contaminated groundwater, removing the contamination using activated carbon or other means, and re-injecting the cleaned groundwater. The arrangement of extraction and injection wells and the related groundwater pumping rates create a hydraulic barrier that captures and contains the PFAS plume. In situ CAC barriers work as passive underground filters. Micron-scale particles of activated carbon are injected into contaminated aquifers using drilling equipment or injection wells. Once injected, the carbon particles attach to the soil. An in situ permeable barrier is installed across a contaminant plume through the injection of a number of points at suitable spacings. Groundwater flows through the barrier zone unimpeded while PFAS contamination is captured and contained by the activated carbon. The longevity of the barrier is determined by the quantity of carbon emplaced relative to the contaminant flux. Barriers are typically designed to last for years (decades), after which time, carbon re-applications can be made, if required. Principal differences between the approaches are the scale of operation and maintenance requirements, and, for P&T, the bringing of PFAS-impacted water above ground to treat. This generates a filtration medium that is contaminated with PFAS, and which therefore requires handling as a PFAS waste with attendant liability. Hydraulic containment is also an active technology (requiring external energy input) and requires the operation and maintenance of pumping and filtration equipment. In situ CAC barriers are passive (powered by natural groundwater flow) and have no operation and maintenance requirements. They do not bring PFAS-impacted material above ground and do not generate waste. Performance data of the installed P&T hydraulic containment system were analyzed to estimate the time to remedial completion using the system alone. Data extrapolation supported by statistical analysis indicates clean-up targets will not be reached within 100 years of pumping. It is not realistic for P&T to be regarded as a means of aquifer clean-up as the aquifer will remain contaminated for the realistic future. Comparison is made between P&T and CAC on their common basis as containment approaches. The goal is to reduce the exposure of down-gradient receptors to PFAS.

1 | Introduction

The historical use of military-specified aqueous film-forming foams (AFFF) in firefighting and in training exercises has left a legacy of per- and polyfluoroalkyl substances (PFAS) impacting soil and groundwater at US Department of Defence (DoD) facilities around the world. As many as 3500 current and former US military bases have PFAS soil and groundwater contamination (Salvatore et al. 2022). Recent remediation cost estimates for the legacy DoD PFAS contamination are in the order of US $31 billion (Amarelo 2023).

At the present time, there are two approaches that are commonly used to remediate groundwater impacted with PFAS. These are extraction-based "pump-and-treat" (P&T), in which contaminated groundwater is extracted and treated ex situ, and in situ remediation with colloidal activated carbon (CAC), in which groundwater is cleaned in situ as it passes under natural flow through a zone of activated carbon that has been injected into the aquifer as tiny particles that attach to the aquifer matrix (Interstate Technology & Regulatory Council [ITRC 2023]b; Hall, Wilson, and Birnstingl 2024).

This document provides a comparison of the two approaches focusing on cost, using data from remediation activities conducted under the Comprehensive Environment Response, Compensation and Liability Act (CERCLA) at the former Wurtsmith Air Force base (WAFB) in Oscoda, Michigan.

2 | Site Background

WAFB served as a combat crew bomber training base from 1923 until its formal closure in 1993 (AFAC 2012a). Site FT-02 at the base was used as a fire training area (FTA) from 1958 to 1991 (AFAC 2012a). Fire training exercises involved the use of firefighting foams to extinguish fires of flammable waste oils (AMEC Foster Wheeler 2020). PFAS from the firefighting foams have migrated to water courses in the United States Forest Service (USFS) wildlife recreation area where the Clark's Marsh wetland is located (USAF 2021). The wildlife recreation area includes wetlands, ponds, and creeks that drain south into the Au Sable River (USAF 2021).

PFAS have been detected in tissues of fish taken from the recreation area (AFAC 2012b). A "do not eat fish" advisory for the watercourse was issued by the Michigan Department of Community Health in 2012 (MDHHS 2012, 2019). The contamination issues and related activities are of concern to the public (pfasproject.com 2021).

The distributions of the PFAS species, perfluorooctane sulfonate (PFOS), and perfluorooctanoic acid (PFOA), in the plume at the time the P&T system was designed are shown in Figure 1.

2.1 | PFAS Plume Setting—FT-02/Clark's Marsh

2.1.1 | Geology

The former FTA is in a location described as an "upland" area (Stark, Cummings, and Twenter 1983; USAF 2021). The wildlife recreation area directly south of the former FTA is within a river flood plain.

Unconsolidated glacial deposits overlie sandstone and shale bedrock in the area of the FTA. The glacial deposits include a sand and gravel unit consisting primarily of fine- to coarse-grained sand with occasional gravel to a depth of approximately 65 feet (ft) below ground surface (bgs). The unit grades from fine to coarse sand with increasing depth. It is underlain by clay, which acts as an aquitard (USAF 2021).

2.1.2 | Hydrogeology

Depth to groundwater is approximately 11–15 feet bgs (MWH 2013, 2014). Groundwater flow in the shallow aquifer is generally to the south and southeast. Groundwater flow direction varies near surface-water bodies within the wildlife recreation

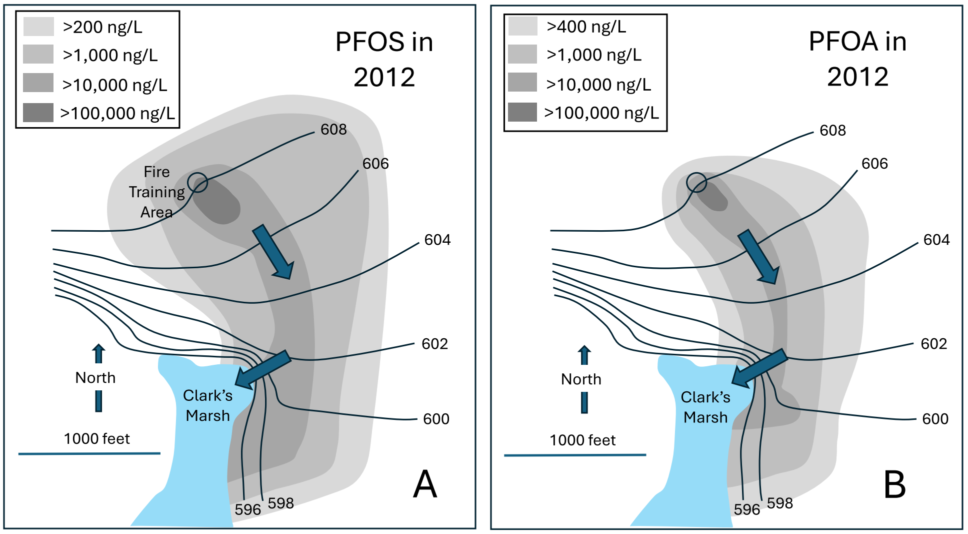

FIGURE 1 | Distribution of PFOS (A) and PFOA (B) in 2012. Distribution redrawn from figures 12 and 13 of MWH (2013). Groundwater contours redrawn from MWH (2014). Groundwater contours in feet above sea level (asl). [Color figure can be viewed at wileyonlinelibrary.com]

area. Groundwater isopleths and inferred flow vectors are shown in Figure 1 (MWH 2014).

Hydraulic conductivity in the unconsolidated aquifer of the FTA ranges from 1.9 to 140 feet per day (ft/day) (0.58–42 m/day). The lower hydraulic conductivity measurements occur at shallow depths where higher amounts of fine-grained sand exist, while the largest hydraulic conductivity measurements occur at depth within more coarse-grained sand and gravel. Groundwater seepage velocity has been calculated to range between 3.5 and 6.4 ft/day (1300–2300 ft/year; 380–710 m/year) in the FT-02 PFAS plume area (MWH 2014).

2.2 | Interim Remediation Measure—Hydraulic Control Migration Barrier

A P&T system was installed in 2014 as a time-critical removal action (USAF 2021). The stated objective of the P&T system was to provide an interim measure "...protective of human health and the environment in the short term ... until a final ROD is signed" (USAF 2021). Protection would be achieved through hydraulic control to capture contamination migrating from the former FTA to Clark's Marsh. Extracted waters would be cleaned using granular activated carbon (GAC) to concentrations below 20 and 40 ng/L for PFOS and PFOA, respectively (ECC 2015; MDEQ 2016), before the water was discharged back into the aquifer through infiltration galleries downgradient of the extraction wells. The remedial strategy recognized that "...this interim remedy will result in pollutants or contaminants remaining on-site above health-based levels" but also that the protection it afforded through containment would be adequate until a final ROD was signed addressing the statutory mandate for a permanent remedy (USAF 2021).

Figure 2 compares the arrangement of the extraction wells and infiltration galleries installed in 2015 to the distribution of PFOS and PFOA in 2012 when the treatment system was designed.

Performance was focused on addressing the PFAS species PFOS and PFOA for which Provisional Health Advisories (PHAs) were in effect at the time of the initial PFAS site investigation in 2012/2013 (USEPA 2009). The PHA values for PFOS and PFOA were 200 and 400 ng/L, respectively. In the first 5 years of operation, the average concentration of PFOS in the influent to the treatment system was 6100 ± 1520 ng/L. The average effluent from the treatment system was 6.4 ± 2.9 ng/L. The average concentration of PFOA in the influent was 1180 ± 250 ng/L, and the average in the effluent was 9.4 ± 4.3 ng/L.

The PHA values for PFOS and PFOA were superseded within 2 years of the P&T system installation by lifetime health advisories (HAs) of 70 ng/L for both PFOS and PFOA alone or in combination (USEPA 2016a, 2016b). The P&T containment system was therefore expanded in 2021/2022 from seven wells to 13 extraction wells to accommodate the wider zone of impacted waters breaching the lower HAs (ECC 2015; Aerostar 2021). The target net groundwater extraction and treatment rate was consequently increased by approximately 185% from 240 to 445 gallons per minute (GPM) (910 L/min to 1720 L/min) (ECC 2015; Aerostar 2021). The original and expanded P&T system arrangements are shown in Figure 3.

2.3 | Treatment of PFAS Using In Situ CAC

Since the time of the 2014 MWH remedial options appraisal, injectable CAC has emerged as a remediation technology for the treatment of contaminated groundwater (Birnstingl et al. 2014; McGregor 2018; Carey et al. 2019; McGregor 2020; McGregor and Zhao 2021; McGregor 2023; Moore 2022a, 2022b; Carey et al. 2022, 2023). Superfine CAC particles measuring less than 2 μm in diameter are injected directly into target units of the aquifer as a liquid suspension of 1%–5% CAC by mass. The CAC locally coats the soil grains with a layer of activated carbon without significantly impacting the movement of water (Regenesis 2018, 2019).

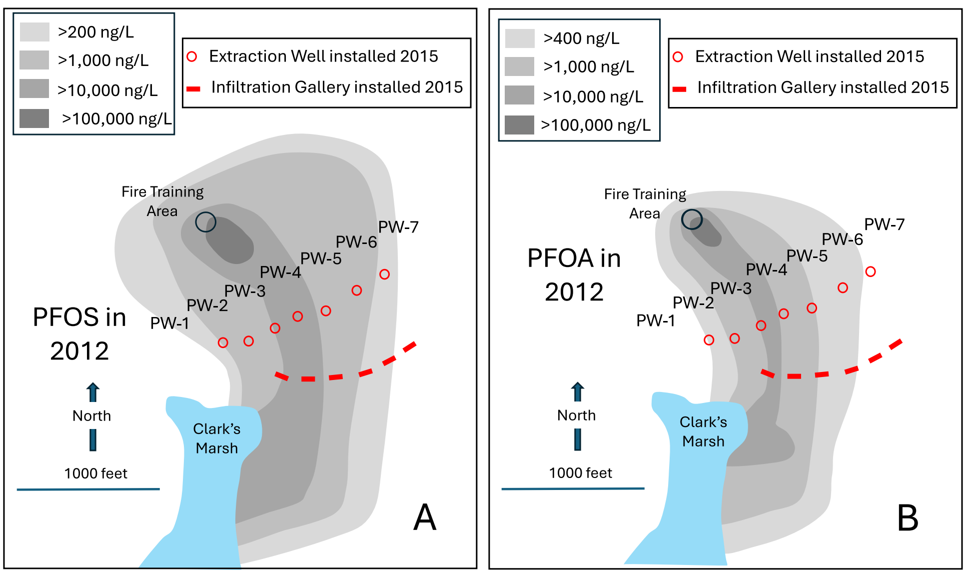

FIGURE 2 | Comparison of the arrangement of the pumping wells and infiltration galleries installed in 2015 to the distribution of PFOS (A) and PFOA (B) in the plume in 2012. Arrangement redrawn from figure 8 of Aerostar (2021). [Color figure can be viewed at wileyonlinelibrary.com]

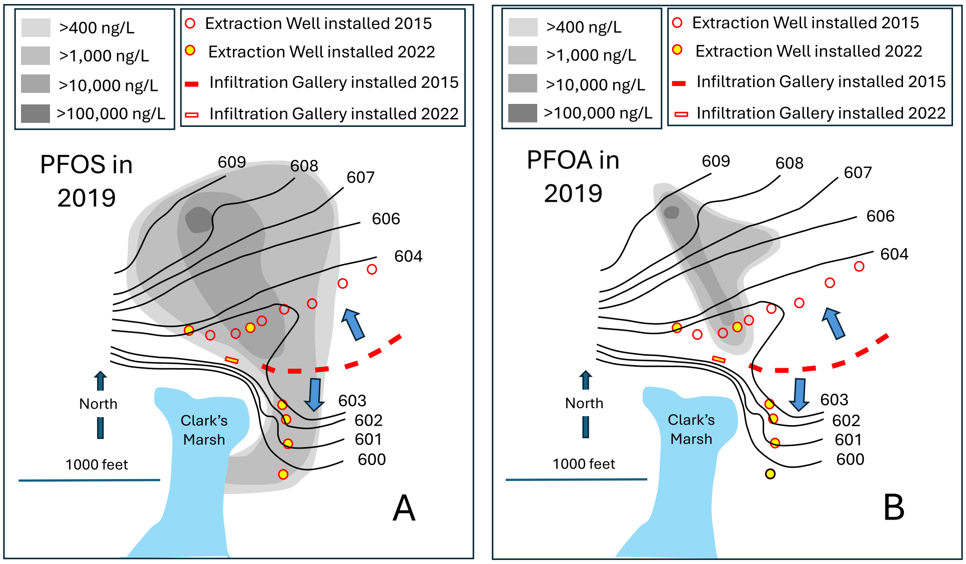

FIGURE 3 | Comparison of the distribution of extraction wells installed in 2022 to the distribution of wells installed in 2015 and to the distribution of PFOS (A) and PFOA (B) in the plume. Distribution PFOS and PFOA redrawn from figures 2–6 and figures 2–7 of Bay West (2022). Groundwater elevations in April 2021 redrawn from figure 6 of USAF (2021). Elevations in feet asl. [Color figure can be viewed at wileyonlinelibrary.com]

Contaminants are sorbed by the CAC from the solution, retarding their movement through the aquifer.

CAC injection offers flexible design options in strategies ranging from source area containment to barrier configurations (www.regenesis.com). In the case of barrier configurations, by injecting the CAC directly into the aquifer in arrays perpendicular to groundwater flow, permeable sorptive barriers are formed. These remove PFAS compounds from the solution while the groundwater migrates under natural flow.

2.4 | PFAS Treatment Cost Comparisons

Published cost comparisons of P&T and CAC remediation of PFAS are rare. At a large petroleum refinery site where CAC was applied to eliminate PFAS from impacting surface water, a comparative cost analysis indicated the CAC application was accomplished for \$3.5 M, while the cost of installing and operating a pumping system was estimated at > \$20 M, representing an estimated cost saving of over 80% (Mora 2023). At a United Kingdom airport, costs of P&T using different treatment alternatives were compared with an in situ CAC approach based on a 15-year operational assessment period (Mallat et al. 2023). The projected cost of the in situ CAC remedy was \$1.57 M compared with P&T at \$4.02 M using GAC or \$4.54 M using foam fractionation for treatment of the extracted water, representing cost savings of 61% and 65%, respectively.

3 | Technology Cost Comparisons

Operational and lifecycle cost comparisons are presented in the following sections for an operational P&T system and a hypothetical CAC barrier applied to the Wurtsmith FT-02 PFAS plume. The P&T costs are the actual costs of the P&T system as installed coupled with projected planned O&M. Costs are adjusted to 2024-dollar values. The CAC costs are those of a hypothetical barrier design based on contemporary practice using available public-domain data related to the Wurtsmith FT-02 PFAS plume.

3.1 | Remedial Alternatives as Compared in 2014

Before the installation of the current P&T system in 2015, a formal feasibility study was conducted that evaluated candidate remediation approaches for the FT-02 PFAS plume that were available at that time (MWH 2014).

The MWH (2014) report provides detailed costings of each approach and screens them for applicability at the subject site. The approaches are summarized in Table 1. Alternative #1, hydraulic containment with ex situ treatment of groundwater, was selected from the assessment for implementation. Injectable CAC was not an available treatment technology at the time of the MWH feasibility study.

3.2 | WAFB FT-02 PFAS Plume—P&T Time to Remedial Completion

The cost of a remedy will comprise its cost of installation and the cost of operation. Cost comparisons of P&T and in situ CAC barriers must therefore consider both. Where costs of operation are ongoing, a timescale for comparison must be specified. This timescale is arbitrary, but time to remedial completion remains an important consideration.

Used alone, it was estimated P&T would achieve the site remedial action objectives (RAOs) in 30 years (Table 1). It was further recognized that "…pollutants or contaminants would remain on-site above health-based levels" throughout that time (USAF 2021). Evaluating the projected time to clean-up the FT-02 PFAS plume using the installed P&T system is therefore a necessary component of the cost comparison of P&T versus in situ CAC for groundwater remediation at the site.

TABLE 1 | Remediation cost comparisons—reproduction of tables 4–1 of MWH (2014).

Technology	Initial capital cost ($)	Annual cost ($)	Total present value ($)	Time to achieve the RAOs (Years)	Likelihood of achieving RAOs
Alternative #1—hydraulic containment	$2,407,972	$204,430	$6,378,093	30 years	Moderately high
Alternative #2—ISCO with hydraulic containment	$12,488,651	$204,430	$13,460,085	5 years	Moderate
Alternative #3—Capping with hydraulic containment	$5,010,299	$214,493	$9,013,315	30 years	Moderately high
Alternative #4—excavation with hydraulic containment	$27,753,683	$204,430	$28,725,118	5 years	High

Note: The above engineer's opinion of probable cost represents an American Association of Cost Engineers (ACEE) Class 5 estimate and has been prepared based on very limited information, and subsequently has a wide accuracy range. The expected accuracy range for the above is from −20% to −50% on the low side and +3% to 100% on the high side, depending on the technological complexity of the alternative. The ranges could exceed those shown in unusual circumstances.
Abbreviations: $, USD (2014 value); ISCO, in-situ chemical oxidation; RAOs, remedial action objectives.

3.2.1 | P&T Performance—Data Extrapolation

The WAFB administrative records and EGLE MiEnviro Portal website provide performance data of the FT-02 P&T system (www.ar.afcec-cloud.ar.mil, www.mienviro.michigan.gov). Bay West (2022) provides concentration data for PFOS and PFOA in the combined flow from the original seven pumping wells to the treatment system for the time interval of April 2015 to December 2019. Samples of the combined flow to the treatment system were collected on a daily to monthly basis (average bi-weekly basis).

Extrapolation of the concentration trends over time in the combined flow to the treatment system can be used to estimate the time required for the concentrations to decline to the performance targets using the present system (Interstate Technology & Regulatory Council ITRC 2013). This estimate is based on the presumption of no supplementary remedial intervention or substantive changes in remedial targets and no other significant external impact.

Trends in concentrations of PFOS and PFOA in the combined flow from the extraction wells are presented in Figures 4 and 5, respectively. Data from August 2022 onward are not included in the analysis of the trend as they include a step-change in the system itself, principally through the substantive change to its catchment. Four of the pumped wells installed in 2022 are located downgradient of the infiltration galleries of the initial system. Within a few months to a few years, the new extraction wells captured water that had already been treated (Figure 3). Additionally, within a few months to years, the infiltration galleries on the east side of the system returned water to the extraction wells installed in 2015.

Linear regression was used to fit trend lines, and confidence intervals on the trend lines, to changes in concentrations of PFOS and PFOA in the combined flow from the extraction wells (Figures 4 and 5). This followed the approach provided in Wilson (2011), in which the natural logarithm of concentrations were regressed on the date of sampling expressed in decimal years. Then the antinatural logarithm was taken of the output of the regression. The uncertainty in the confidence bands were set at $\alpha = 0.20$ or 80% confidence to provide a balance between Type I and Type II errors in the projections (i.e., underestimating and overestimating the projected range, respectively).

The equations for the trend, and the slower and faster confidence intervals on the trend, were solved for the time when $Y = 20$ and 4 ng/L for PFOS and $Y = 40$ and 4 ng/L for PFOA. Results are presented in Table 2.

Two important points may be noted from the data and their analyses:

- The projected time to clean-up is in the order of decades or centuries.
- The projected time to target of PFOS is significantly longer than for PFOA.

3.2.1.1 | 100 Years Will Be Used as the Basis for Comparisons Between P&T and CAC.

Projections of several hundred years based on extrapolation of a 5-year data set have no reasonable predictive value in a numeric sense. They

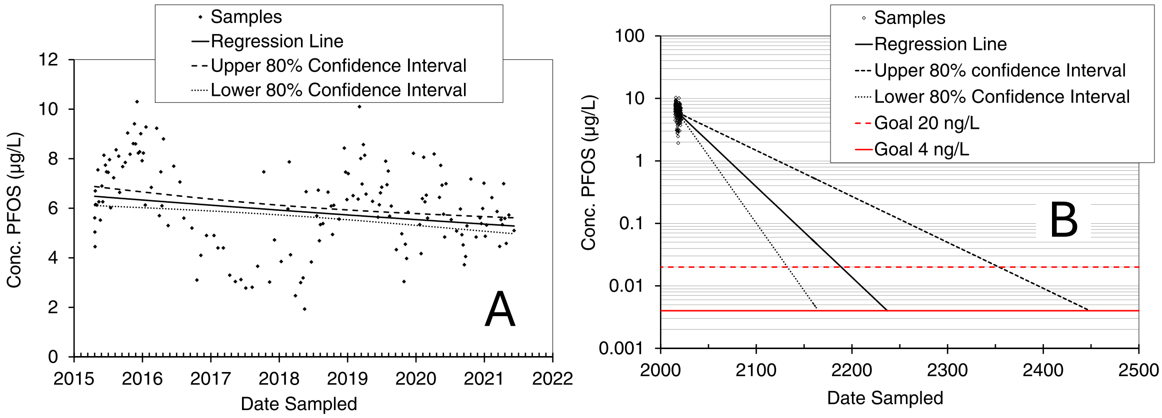

FIGURE 4 | Trends in concentrations of PFOS in the combined flow of the extraction wells (A) and projections of the trend and 80% confidence intervals on the trends to the clean-up goals (B). [Color figure can be viewed at wileyonlinelibrary.com]

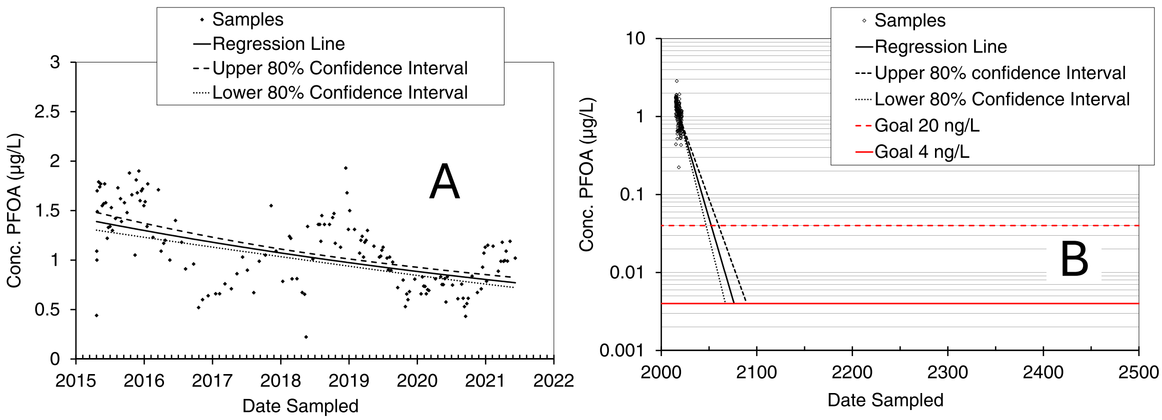

FIGURE 5 | Trends in concentrations of PFOA in the combined flow of the extraction wells (A) and projections of the trend and 80% confidence intervals on the trend to the clean-up goals (B). [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 | Projected time to reach the clean-up goals for PFOS and PFOA. The minimum and maximum times are projections of the 80% confidence band on the regression line (Figures 4 and 5).

Species	Target	Min time to target (years)	Year target reached	Mean time to target (years)	Year target reached	Max time to target (years)	Year target reached
PFOS	20 (ng/L)	119	2134	175	2190	335	2350
PFOA	40 (ng/L)	32	2047	37	2052	52	2067
PFOS	4 (ng/L)	150	2165	222	2237	433	2448
PFOA	4 (ng/L)	52	2067	61	2076	74	2089

Note: There is an 80% probability that the stated clean-up goal will be reached between the maximum and minimum time to target. The probability of the stated clean-up goal being reached in a shorter time than the minimum or a longer time than the maximum will therefore be 10% in either case. The mean time to target represents the best-fit regression.

assume no changes in the hydrology of the system in that period of time. It is unlikely that the assumption will be met. This analysis should be considered in context; rather than being a predictive exercise, the projected times to closure serve to illustrate the point that aquifer clean-up of the WAFB FT-02 PFAS plume will not be secured in a realistic time frame using the present P&T approach alone. Cost projections in Table 1 presumed that the system and monitoring would continue for 30 years (MWH 2014; USAF 2021). This exercise illustrates that the 30-year period would not be expected to secure closure.

The projection exercise illustrates that "centuries" may indeed be required to secure clean-up by the FT-02 P&T system in the absence of supplementary remedial intervention. Similar observations have been made before for P&T (Mackay and Cherry 1989; Travis and Doty 1990). On this basis, and for the purpose of technology comparison in relation to the WAFB FT-02 PFAS plume, it is reasonable to presume that the P&T and in situ CAC containment approaches will be required *for at least 100 years* should either be applied alone. This nominal 100-year period will therefore be used as a basis of the cost comparison in the following sections.

3.3 | Pump & Treat Costs

3.3.1 | Capital and Installation Costs

The MWH (2014) feasibility study provided an estimate of $2,407,972 for capital and installation costs to construct the original P&T system. A community meeting presentation by stakeholders following P&T system construction appeared to confirm that capital and installation costs to construct the original P&T system totaled $2.4 M (AFCEC 2016).

A 2021 Final Interim Record of Decision (ROD) included an estimate of $2,977,432 for capital and installation costs to expand the P&T system (USAF 2021). The construction of the P&T system expansion finished in August 2022, and a 2022 web article indicated that its cost was as high as $4.7 M (Air Force Installation and Mission Support Center AFIMSC 2022), although no breakdown was provided. The present cost comparison exercise uses the lower of these values in the interest of being conservative—that is, the pre-construction estimate of $2,407,972 given in the 2021 ROD.

Estimated capital and installation costs for the original P&T system and P&T expansion are presented in 2024 dollars in Table 3 below. The 2024-dollar values are calculated from the published estimates using the Federal Reserve Bank of Minneapolis Inflation Calculator (FRBM 2024). The calculator uses U.S. Bureau of Labor Statistics-published consumer price index (CPI) values to determine how much a price in Year X would be in Year Y dollars based on the following equation:

$$\text{Year Y Dollars} = \text{Year} \times \text{Price} \times (\text{Year Y CPI} / \text{Year} \times \text{CPI}). \tag{1}$$

3.3.2 | Operation and Maintenance Costs

P&T system operation requirements include routine system checks, data logging and reporting, system process-water sampling and analysis, and compliance reporting. Routine maintenance of the P&T system from 2015 through 2021 has primarily consisted of frequent flow meter cleaning, conveyance-line air scouring/cleaning, extraction well cleaning, submersible pump cleaning due to frequent biofouling, GAC vessel backwashing, and GAC exchanges (Bay West 2020a, 2020b, 2022). GAC vessel backwashing was required one to three times per month, and GAC change-out of the lead vessel averaged about once every 3 months from 2015 through 2020. Nonroutine O&M activities included the replacement of submersible pumps and the replacement of system control equipment due to a lightning strike. The estimated annual electricity usage of the original P&T system was approximately 240,000 kilowatt-hours (kWh).

An annual O&M cost of approximately $204,500 was estimated for the original P&T system in the 2014 Feasibility Study (MWH 2014). This cost included approximately $34,000 for groundwater monitoring network sampling of 12 wells twice per year. Actual annual O&M costs from 2015 through 2020 ranged from $355,000 to $400,000 based on stakeholder presentations in 2016 (AFCEC 2016) and 2020 (AFCEC 2020). Approximately $50,000 of the annual O&M costs are allocated for groundwater monitoring events. These costs are excluded from the present comparison as they are common to both CAC and P&T approaches.

The 2021 ROD estimated a year-one O&M cost of $460,973 for the expanded P&T system and thereafter a $416,790 average annual O&M cost (USAF 2021). Actual operations costs for the expanded P&T system were not available for this evaluation.

The USAF (2021) estimates include the provision of $160,000 for GAC changeouts each year. There is no breakout of PFAS waste disposal costs in these estimates or provision for attendant liabilities (Hall, Wilson, and Birnstingl 2024). It is likely the cost of disposal will have increased following the designation of PFOS and PFOA as hazardous substances in 2024 (USEPA 2024). However, no provision for such an increase or for disposal-related liabilities is included in the present evaluation.

There is similarly no stated provision in the USAF (2021) O&M projections for equipment recapitalization. Engineering hardware will have a finite life. Regular maintenance will extend the life, but periodic replacement will still be required. A well pump, for example, may typically be expected to last 8–15 years (Quality Water Lab 2023). Different expectations may be reasonable for the hardware installed for the FT-02 hydraulic control, but the initial installations would not be expected to last throughout the 100-year evaluation considered in the present assessment (Section 3.2.1.1; Section 3.3.3).

Given the annual O&M estimate for the expanded system is only marginally greater than the stated actual costs for the initial system, and the 7-year period of operation of the initial system would not have required significant equipment recapitalization, the O&M projections of the expanded system would not appear to contain provision for recapitalization.

Engineering estimates of installation longevity and appropriate recapitalization provision will be subjective and will vary.

TABLE 3 | P&T system capital and installation costs.

System ID	Year of estimate	Estimated cost	Consumer price index	Estimated cost in 2024 dollars[a]
Original P&T system	2015	$2,407,972	237	$3,198,422
P&T system expansion	2021	$2,977,432	271	$3,454,261
Capital and installation costs—estimated total				$6,652,682

[a] 2024 CPI = 314.4.

An estimate of 50%–100% of the initial installation costs every 20–30 years would perhaps not be unreasonable. However, given the uncertainty in relation to this, and in the interest of comparison conservatism (Section 4.2), no provision for installation recapitalization is included in the present evaluation.

3.3.3 | Life-Cycle Costs

Based on the above information, a P&T system life cycle cost estimate for the WAFB FT-02 PFAS containment is presented in Table 4. Projections beyond 2024 presume the same remedy, operating at the same capacity, with the same groundwater flow conditions. The extended durations are informed by the time to remedial completion analysis in Section 3.2.1. Forward cost projections beyond 2024 in Table 4 include allowances for inflation and for the value premium of a delayed spend. The 2.5% net discount rate applied combines an annual inflation rate of 2% with a discounted present value (DPV) rate of 4.5%. These are taken from OMB Circular No. A-94, December 2023 (OMB 2024), and use the maximum term of 30 years offered by the document.

TABLE 4 | P&T lifecycle cost estimate.

Year(s) of operation	Estimated O&M cost	Estimated O&M cost adjusted to 2024 Dollars[h]
2015	$230,417[a]	$305,667
2016	$350,000[b]	$458,500
2017	$357,438[c]	$458,500
2018	$366,188[c]	$458,500
2019	$372,896[c]	$458,500
2020	$377,417[c]	$458,500
2021	$395,208[c]	$458,500
2022	$497,885[d]	$534,797
2023	$466,907[e]	$481,771
2024	$ 481,771[e]	$481,771
2025–2045	$10,117,188[f]	$7,797,244[i]
2025–2115	$43,841,150[g]	$17,233,658[i]
Total 30-year O&M cost (2015–2045)		$12,352,250
Total 100-year O&M cost (2015–2115)		$21,306,893
Estimate capital & installation costs (2024 Dollars)		$6,652,682[j]
Total estimated P&T 30-year cost (2024 Dollars)		$19,004,932
Total estimated P&T 100-year cost (2024 Dollars)		$28,441,346

[a]Assumes 8 months of operation at estimated 2016 O&M costs (b).
[b]O&M cost assumed from 2016 AFCEC presentation ($400 K) less an assumed $50 K for GW monitoring costs.
[c]CPI-adjusted from 2016 estimated O&M costs (b) using Equation 1.
[d]First-year operation at 2021 estimated O&M costs from Interim ROD (USAF 2021) CPI-adjusted to 2022.
[e]Operation from 2nd year at 2021 est. O&M costs from Interim ROD (USAF 2021) CPI-adjusted to 2023/2024.
[f]Assumes 2024 O&M costs multiplied by 21—the number of inclusive years from 2025 to 2045.
[g]Assumes 2024 O&M costs multiplied by 91—the number of inclusive years from 2025 to 2115.
[h]Estimated O&M costs from 2015 to 2022 were adjusted to 2024 dollars using Equation 1.
[i]The projected O&M Costs from 2024 onward were determined through present value analysis based on the estimated O&M costs for 2024 (e) and a discount rate of 2.5%. This rate is at the maximum presented duration (30 years) per OMB Circular No. A-94, December 2023 (OMB 2024), and accommodates inflation premiums.
[j]From Table 3.

The shorter- and longer term projections (i.e., to 2045 and to 2115, respectively) provide an interesting comparison. The annual O&M costs are consistent for each, yet the projection to 2115 is four times the duration for only double the cost following DPV adjustment. This is a direct consequence of the DPV consideration, which, for example, accommodates "lost opportunity" value of money spent rather than money available to invest. DPV consideration consequently places a natural emphasis on closer future costs. Many cost projections for capital projects such as P&T installations are therefore for 30 years or less. This should not be taken as an indication that the remedies will be completed within the same period. The required duration may be far longer, as the projections in Section 3.2.1 indicate.

3.4 | In Situ CAC Barrier Costs

3.4.1 | Designing for CAC Versus Designing for Hydraulic Containment

The site characterization information required for a CAC barrier design is not the same as that required for a hydraulic containment system design. Whereas an understanding of the groundwater capture zone is critical for hydraulic containment, the contaminant mass flux and its vertical and horizontal profile are critical for the design of a CAC barrier. The characterization and aquifer testing reports prepared in support of the FT-02 hydraulic containment system at the Wurtsmith AFB are thorough in their scope and content for their express purpose, as are the earlier plume delineation reports prepared in support of risk and liability assessment. However, these reports do not provide the information necessary to determine the contaminant flux profile required for a formal CAC barrier design. This understanding is important as the distribution of contaminant flux determines the quantity and placement of CAC that is required to secure the requisite barrier longevity.

3.4.2 | What Is Contaminant Flux?

Contaminant flux is the mass of contaminant passing through a planar area of aquifer per unit time. Typical units for contaminant flux in groundwater are mg/m^2/day. Contaminant flux may therefore be obtained by multiplying the contaminant concentration by the Darcy velocity (Equation 2).

$$\text{Contaminant concentration (mg/m}^3\text{)} \times \text{Darcy velocity (mg/m}^2\text{/day)} = \text{contaminant flux (mg/m}^2\text{/day)}, \tag{2}$$

where

$$\text{Contaminant concentration } (\text{mg/m}^3) = \text{contaminant concentration } (\mu\text{g/L}),$$

$$\text{Darcy velocity } (\text{m}^3/\text{m}^2/\text{day}) = \text{Darcy velocity } (\text{m/day}).$$

Because of the interplay of Darcy velocity and concentration, high or low contaminant concentrations in groundwater do not necessarily imply high or low contaminant flux as the Darcy velocities may differ. This would occur, for example, in zones of different hydraulic conductivity. Similarly, the zones of highest groundwater velocity are not necessarily the zones of highest contaminant flux. Often, the highest contaminant flux may be observed in zones of moderate concentration and moderate transmissivity.

3.4.3 | Direct Measurement of Contaminant Flux

Contaminant flux and groundwater Darcy velocity may be measured directly using passive flux meters (PFMs) (Annable et al. 2005). These can be placed at multiple positions within an aquifer to provide horizontal and vertical profiles of flux. Data are obtained as averages over their duration of placement, typically 2–3 weeks. From the contaminant flux and Darcy velocity, average contaminant concentration over the placement duration may also be determined by calculation (by dividing the flux by the Darcy velocity–rearrangement of Equation 2).

Direct measurement of flux is the preferred approach for informing CAC barrier designs (Regenesis 2024a). The approach provides an improved resolution of vertical and horizontal flux profiles and avoids the introduction of calculation errors. Such errors may arise, for example, from the requirement to estimate effective porosity in the calculation of seepage velocity or Darcy velocity, in the estimates of these parameters themselves, and in the uniform allocation of such estimates to heterogeneous formations. Estimation errors in excess of 20%–30% would not be unlikely. These would transfer directly to the flux estimate and may therefore materially impact a CAC barrier design.

PFM data were not available for the present study. Instead, data from the P&T system itself were used. The horizontal flux profile (perpendicular to groundwater flow) the hypothetical CAC barrier must intercept was determined from the PFAS capture data from individual extraction wells. The vertical flux profile was estimated from reported vertical groundwater concentration profile data. Details of these approaches are provided in the following sections.

3.4.4 | Vertical Profiling of FT-02 PFAS Flux

Characterization of the Wurtsmith FT-02 PFAS plume area reveals that the principal PFAS detections occur in the shallower aquifer portions (upper half) (Aerostar 2021), with medium and lower depth zones reporting significantly lower or non-detect PFAS concentrations (Wood 2020). Boring logs and engineers' observations meanwhile reveal an overall "fining upward" of the target aquifer unit (USGS 1995; Wood 2020; USAF 2021). Although not quantified or explored directly in the reports, it is likely that the Darcy velocity would therefore be lower in the shallow fine sand zones than the deeper gravel zones owing to lower transmissivities.

These considerations are not important for the determination of capture zones for hydraulic control installations as the transmissivity across the saturated thickness of the aquifer is sufficient for this purpose. The difference is important for CAC barrier designs, however. Calculation of PFAS flux using transmissivity measured across the *whole* formation would invite overestimation when combined with concentration measurements from the shallower zones in which the principal mass of PFAS resides, and contaminant concentrations are higher. Whereas concentration averages are sufficient for a hydraulic containment design, vertical and horizontal profiling are required for a CAC design. Quantitative profiling data are not available from the characterization reports, as these were prepared for risk assessment and P&T design rather than for a CAC barrier design. CAC barrier designs in the present exercise must therefore be undertaken using informed estimates based on data that are available.

3.4.5 | Estimation of Wurtsmith FT-02 PFAS Plume Flux

3.4.5.1 | Method Overview. PFAS flux can be determined from the PFAS mass extraction by the hydraulic containment system and an estimate of the planar CAC barrier dimensions transecting the PFAS plume. The estimated PFAS mass that would enter the barrier over a given period is calculated from the extraction rate of groundwater by the existing hydraulic containment system and the concentrations of PFAS in the extracted water. The values may be normalized to planar area of cross-section perpendicular to groundwater flow to derive flux. This process can be refined to individual wells if their concentrations, extraction-rates, and the areas of their capture-planes are known.

3.4.5.2 | Estimation of Mass Extraction Rates From the Hydraulic Containment System. Table 2 of Bay West (2022) provides the average rate of groundwater extraction by each pumping well in 2015 through 2019. Table 7 of the same report provides the average concentrations of PFOS and PFOA in groundwater extracted by each well over the same period. The mass of contaminant recovered by each well in each year can be estimated by multiplying the pumping rate in each year by the average concentration in each year.

3.4.5.3 | Estimation of Flux Planes. The planar areas for flux-determination require estimation of their respective vertical and horizontal dimensions for the zones described by each well. The horizontal dimensions can be estimated from the relative extraction rates of each well and the overall width of the hydraulic capture zone perpendicular to groundwater flow (Figure 6). The vertical dimension is estimated from the vertical aquifer sampling (VAS) undertaken by Wood (2020), in which PFAS analysis was undertaken from five depths in eight VAS

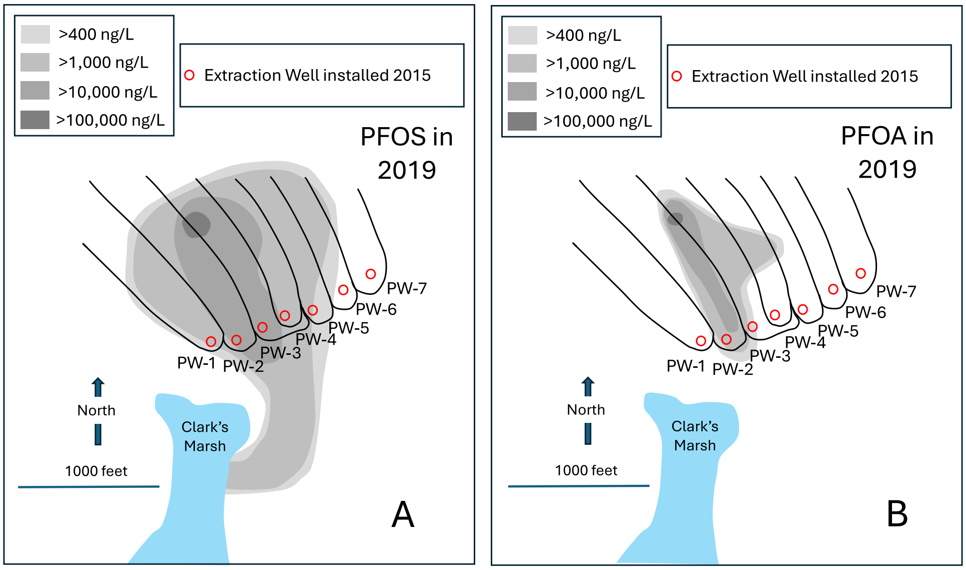

FIGURE 6 | Comparison of the capture zones of individual extraction wells installed in 2015 to the PFOS plume (A) and PFOA plume (B) in 2019. Capture zones redrawn from figures 2–6 of Bay West (2022). [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 5 | Estimate of mass flux of PFOS and PFOA across the capture zone of the seven extraction wells in the P&T system.

	FT02-PW1	FT02-PW2	FT02-PW3	FT02-PW4	FT02-PW5	FT02-PW6	FT02-PW7
				Width of flux plane (feet)			
	279	186	219	186	263	166	202
				Mass flux ($mg{\cdot}m^{-2}{\cdot}day^{-1}$)			
PFOS	1.43	12.2	5.11	1.72	0.54	0.12	0.043
PFOA	0.058	3.01	0.849	0.094	0.064	0.028	0.017

borings in the areas surrounding the FT-02 P&T capture zone. PFAS were detected in the shallower groundwater in all cases. Detections in the deeper groundwater were intermittent and uniformly lower. Health advisory exceedances occurred only in the shallowest or second shallowest vertical intervals with one minor exception.

An average of the extraction rate for each well was calculated for 2016 through 2019. The average rates were summed, and the average for each well was divided by the total flow rate to calculate the proportion of total flow captured by each well.

The combined capture zones of the seven extraction wells extended for 1500 feet (457 m). The width of the flux plane in front of each well was calculated as the fraction of groundwater flow captured by that well multiplied by 1500 feet (Figure 6). The depth of the flux plane was assumed to be one-third of the saturated thickness of the aquifer (ICF 1996a, 1996b; Aerostar 2021) (44 feet/3 = 15 feet; 4.6 m). The mass flux to each well was calculated by dividing the mass collected by each well by the surface area of the flux plane to each well (Equation 3). Results are presented in Table 5.

$$\text{Mass flux to well (mg/m}^2\text{/day)} = \frac{\text{Mass collected by well (mg/day)}}{\text{Surface area of flux plane to well (m}^2)}. \quad (3)$$

Although accurate vertical flux profiling is a critical consideration for a formal CAC barrier design, it is of relatively minor importance in the present cost comparison exercise. This is because the profile impacts the CAC placement but not the required quantity. The CAC quantity is determined by the contaminant flux, which is known from Equation 2, and 3. If the vertical planar dimension is increased or decreased, the normalized mass flux per unit area changes in inverse proportion and therefore the CAC quantity required to address the overall flux does not change. The change in vertical dimension will have some impact on application cost but the overall barrier cost will not be impacted *pro rata*. Without formal vertical profile measurement (Section 3.4.3) the profile used in the calculation will necessarily be an informed estimate. For the present cost comparison exercise, therefore, it is important for the vertical profile estimate to be reasonable, but it is not critical for it to be accurate.

The extraction system became operational in April 2015. At start-up, the pumped wells extracted contaminated groundwater from both upgradient and downgradient of the wells. The treated groundwater was reinjected in infiltration galleries downgradient of the pumped wells. After a period of time, the wells only recruited contaminated water from upgradient of the wells. For this reason, the calculations of mass flux do not include data from 2015, when the system was started up.

The above flux calculations are restricted to PFOS and PFOA and are not extended to other PFAS species known to be present in the captured groundwater. This is consistent with the remediation Substantive Requirement Ordinance (MDEQ 2016) on which the P&T remediation is based, which cites PFOS and PFOA alone. This provides a level basis of comparison of the technologies.

3.4.6 | CAC Barrier Costs

The principal design variables for a CAC barrier are its location within a plume, its dimensions, and the CAC quantity emplaced. To maintain a common basis of comparison between the P&T system and the CAC system, the hypothetical CAC barrier comprises two stages of installation to match those of the P&T system. These are counterparts to the initial 2015 P&T system installation and its extension in 2021/2022. Both the P&T system and the CAC barriers are therefore designed to the same set of conditions, rather than to a more efficient approach determined with the benefit of hindsight.

For the present comparison exercise, the initial CAC barrier is located in the same plume region as the extraction array of the initial P&T system and extends laterally to the limit of the modeled P&T capture zone (Figure 7). It extends vertically though the upper reaches of the aquifer (top third) where the principal flux is understood to occur (Section 3.4.3). The barrier thickness in the direction of flow is a function of the injection point spacing and point arrangement. Barrier dimensions are presented in Table 6.

3.4.6.1 | Use of Modeling in CAC Barrier Design. The principal variable distinguishing sections of the initial CAC barrier perpendicular to groundwater flow is the quantity of CAC emplaced. The quantity of CAC required is determined by the projected sorbate load on the carbon. The target PFOS and PFOA species will represent only a part of this load. Other nontarget PFAS species will also contribute to the burden on the carbon whether or not these are identified in analytical suites. Other contaminants, such as hydrocarbons or VOCs (ECC 2016; Aerostar 2021), must also be accommodated, as must competing natural organics. Given the complexity of these considerations, the PlumeForce modeling software package was used for the design (PlumeForce 5.6.9, REGENESIS, San Clemente, California) (Regenesis 2024b). The retardation of the target contaminant species is computed at a specified CAC dose. From this, the time to breakthrough for each species can be determined. The CAC dose can then be adjusted as necessary to secure the desired performance. The modeling package considers the competition between target and nontarget species and any transformations or degradation that may occur, for example, of competing organics in the case of PFAS. The process is refined as performance data accumulate from one project to the next project through comparison of predicted and actual performance, using data from pilot studies and the growing body of CAC field applications at different sites under different conditions. These serve to calibrate assumptions and inform ongoing model development.

TABLE 6 | First CAC barrier—common parameters.

Soil type	Sand
Effective porosity (EP)	23%
Proportion of EP filled in barrier zone by CAC carrier fluid on injection	70%
Soil density (g/cm^3)	1.65
Barrier thickness (parallel to GW flow) (feet)	13
Barrier length (total) (perpendicular to GW flow) (feet)	1,500
Target treatment zone vertical thickness (feet)	15
Maximum depth (feet below ground surface)	35
Injection point spacing (feet)	5
Injection rows (number)	2

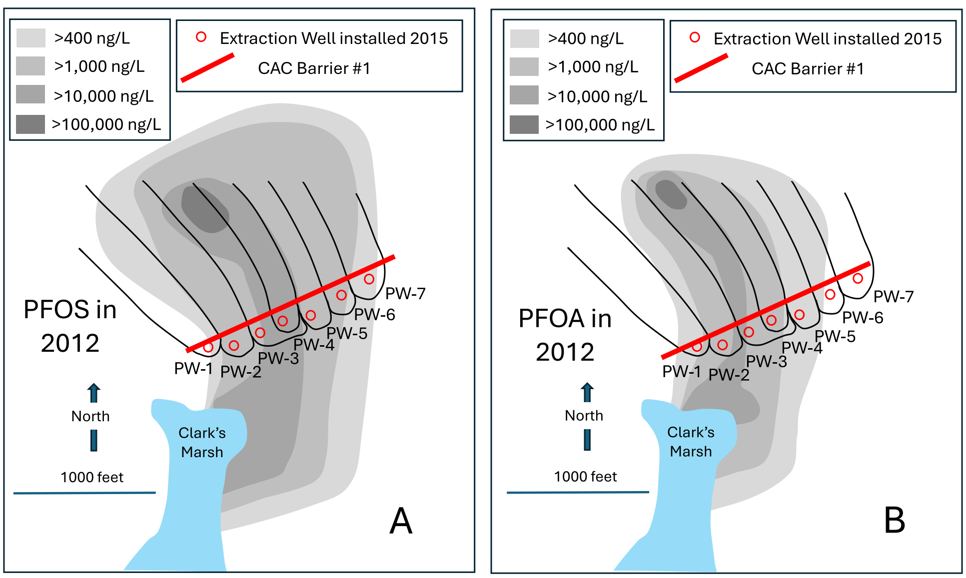

FIGURE 7 | Location of first CAC barrier in relation to PFOS plume (A) and PFOA plume (B) in 2012. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 7 | Well-zone costs—first CAC barrier.

Zone	Raw cost (2024 USD)	Commissioning allowance (20%) (2024 USD)	Total cost (2024 USD)
FT02 PW2	594,891	118,978	713,869
FT02 PW3	560,185	112,037	672,222
FT02 PW4	423,340	84,668	508,008
FT02 PW5	547,722	109,544	657,266
FT02 PW1	576,592	115,318	691,910
FT02 PW6	385,616	77,123	462,739
FT02-PW7	458,053	91,611	549,664
Total	3,546,399	709,280	4,255,679

3.4.6.2 | CAC Barrier Installation Costs—First Barrier Stage. Installation costs for the CAC barrier design, addressing the same objectives as the initial P&T installation in 2015 and broken down by well-catchment zone, are presented in Table 7. A further 20% sum for barrier commissioning is included in each case. This represents an allowance for localized supplementary CAC applications following post-application CAC distribution assessments and performance validation. A cost break-down is presented in Table 8. Differences in costs between well-zones are a function of the required CAC dose and zone dimensions—they arise from the quantity of CAC emplaced and time on site required for its application.

The barriers in the present exercise are designed to last a minimum of 25 years per CAC application. The minimum CAC design emplacement is approximately 0.002 g/g soil (i.e., 0.2% of soil mass within the barrier). At this application rate, the time to PFAS breakthrough in the lower flux zones may be considerably longer than 25 years—greater still if the rate of PFAS entry into the barrier declines over this time. Conversely, the higher flux well-zones may require a greater quantity of CAC to be emplaced to secure the nominal 25 years longevity per application. The minimum longevity is arbitrary. Longer or shorter minimum durations may be selected as performance objectives in any given design.

CAC application rate and projected barrier performance duration are presented for the different well-zones in Table 9. Estimates of flux within each zone are presented in Table 5. Costs for each zone are presented in Table 7.

3.4.6.3 | CAC Barrier Installation Costs—Second Barrier Stage. Installation costs for the CAC barrier second stage design scenarios, addressing the same objectives as those of the expanded P&T installation in 2021/2022, are presented in Table 10. The location of the second barrier relative to the PFOS and PFOA plumes, respectively, is shown in Figure 8.

The incoming PFOS and PFOA flux values used in the extension design are 835 and 79 μg/m^2/day, respectively. The calculation method used for flux determination in the first CAC barrier design was not used, owing to groundwater being drawn into the extension extraction wells from down-gradient (Figure 3) and to the treated water being re-injected up-gradient of the barrier in an extension of the existing 2015 injection array (USAF 2021). These distort the groundwater capture and flow rate from the background conditions the CAC barrier would address. The significance of this is highlighted through the determination of an inferred groundwater velocity of 3000 ft/year calculated from the reported extraction rates (Aerostar 2021) and flux-plane dimensions estimated from section figures (ECC 2014; USAF 2021). This velocity is not consistent with the marsh setting and reported natural gradients (Figure 1) and contrasts sharply with the velocity of 966 ft/year calculated from the initial extraction array using the same method.

TABLE 8 | Application statistics and cost breakdown—first CAC barrier.

Item	2015 Barrier
Zone length (perpendicular to GW flow) (feet)	1500
Injection points (direct push) (number)	600
Injection volume (US gallons) (total)	322,901
Field application time (crew-rig days)	111
Reagent cost (2024 USD)	2,564,179
Fieldwork cost (2024 USD)	982,220
Commissioning allowance (20%) (2024 USD)	709,280
Total cost (2024 USD) (combined, remedy in place)	4,255,679

The flux values for the second barrier design were instead calculated from the maximum concentrations in groundwater in the vicinity of the proposed barrier as reported from the 2019 sampling event (PFOS 4500 ng/L, PFOA 45.8 ng/L FT02-MW9; Bay West 2022). The same seepage velocity as calculated for the upgradient barrier was used (966 ft/year). The horizontal flux-plane dimensions were based on a 450 ft barrier width perpendicular to flow (Figure 8) and a vertical plume thickness of 20 feet based on section figures (ECC 2014; USAF 2021).

The 2019 monitoring event reported by Bay West (2022) provides the last published groundwater data set preceding the 2021/2022 system extension. The reported 2019 PFOA concentrations were close to or below the 4 ng/L target. These concentrations had reduced steadily over preceding annual sampling events (Bay West 2020a, 2020b), presumably due to the influence of the 2015 hydraulic containment system. A declining influent trend to the barrier would make assessments based on these maxima conservative.

TABLE 9 | Well-zone dose, dimensions, and longevity—first CAC barrier.

Well-Zone	CAC-Emplaced (g-CAC/g-soil)	Length (feet)	Longevity (years)
FT02 PW2	0.0038	186	25
FT02 PW3	0.0029	219	25
FT02 PW4	0.0022	186	28
FT02 PW5	0.0022	263	33
FT02 PW1	0.0022	279	30
FT02 PW6	0.0022	166	42
FT02-PW7	0.0022	202	47

Note: Wells ranked in order of descending PFOA flux. PFOA has a lower overall retardation factor than PFOS in most modeled scenarios in the present analysis. The higher the retardation factor, the longer the retention of a species within the barrier. Barrier longevity is the time to break-through of the first contaminant of concern.

TABLE 10 | Second CAC barrier—dose, dimension, cost, and longevity.

FT-02 extension barrier (2021/2022)—Clark's Marsh			
CAC-Emplaced (g-CAC/g-soil)	**Barrier length (feet)**	**Dose longevity (minimum, years)**	**Cost (2024 USD)**
0.0022	450	44	1,149,557
Application contingency (20%) (2024 USD)			229,911
Total cost (2024 USD) (combined, remedy in place)			1,379,469

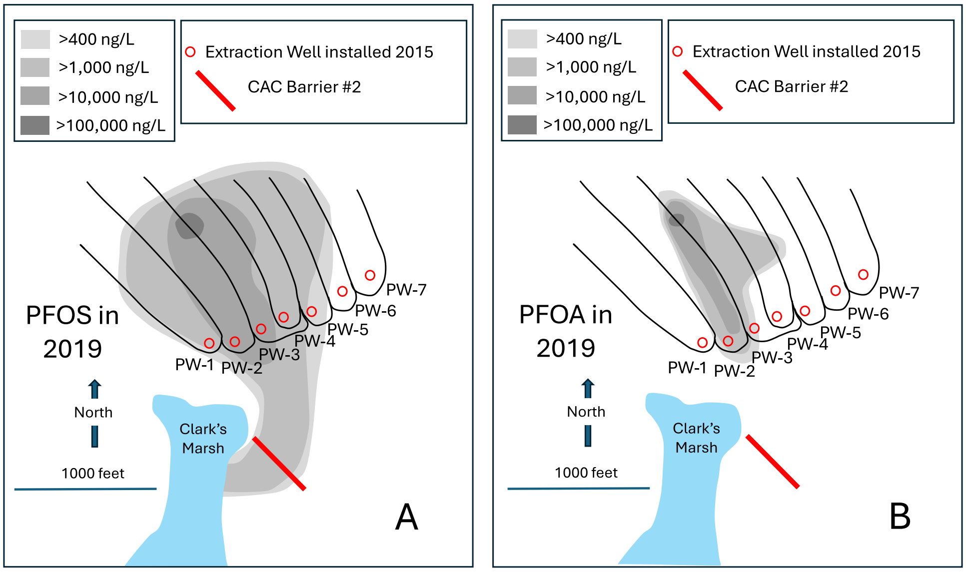

FIGURE 8 | Location of second CAC barrier in relation to PFOS plume (A) and PFOA plume (B) in 2019. [Color figure can be viewed at wileyonlinelibrary.com]

Owing to the low PFAS concentrations, lateral zoning of the extension application based on local flux was not undertaken in the cost analysis. The same CAC application rate is applied to the whole barrier. The incoming PFOA concentrations were already at or approaching compliance in 2018 (Bay West 2020) (Figure 8). The longevity is therefore determined by the PFOS-containment requirement. The minimum projected longevity is 44 years on this basis.

3.4.7 | Estimated Life-Cycle Costs of CAC Barriers

CAC barriers act as in situ contaminant filters. Groundwater passes through them under natural flow. They do not require external energy inputs. Life-cycle costs therefore comprise their installation and periodic CAC reapplications. The frequency of reapplication is dictated by the contaminant sorption characteristics and flux in relation to the CAC quantity emplaced. No further maintenance is required. Groundwater monitoring would be undertaken as for P&T. Its cost is therefore omitted from the present comparison for both P&T and CAC as it would be the same in both cases.

4 | Overall Cost Comparison—P&T and CAC

4.1 | Cost Comparisons

Combined installation and long-term operation and maintenance costs of the WAFB FT-02 P&T system and hypothetical in situ CAC barrier alternative are presented in Table 11. This table provides summary cost data for nominal periods of between 15 and 100 years. The 30-year period represents a common maximum term for extended cost projections (OMB 2024). The 100-year period serves to illustrate the implications of the performance projection in that costs will continue to be accrued beyond the conventional 30-year forecasting horizon. Comparison data are presented graphically in Figures 9 and 10.

TABLE 11 | Comparative P&T and CAC barrier long-term capital and O&M costs.

Costing period	P&T (2024 USD)	CAC (2024 USD)	Cost Ratio (CAC/P&T)
15 years	13,888,174	5,635,147	0.41
20 years	15,791,357	5,635,147	0.36
30 years	19,004,932	7,224,833	0.38
50 years	23,476,524	8,491,644	0.36
100 years	28,441,346	10,454,315	0.37

Note: P&T costs from Table 4. Costing periods run from the 2015 initial barrier application. Costs before 2024 are adjusted to 2024 USD values using Equation 2. CAC cost data are derived from Tables 9 and 10. The projected costs presume reapplication at the original CAC loading for each scenario and at the frequency determined by the stated longevities. Costs include a commissioning allowance of 20% for each application and reapplication. This is applied in the year following each application. Projected costs beyond 2024 are adjusted to 2024 US dollar values using the 20- and 30-year discount rates of 2.5% specified in OMB Circular No. A-94, December 2023 (OMB 2024) except for the 15-year projection which uses the specified 7-year discount rate of 2.2%.

4.2 | Comparison Conservatism

A conservative approach has been adopted in the generation of these cost comparisons. When discretion is required, lower cost positions are taken for P&T and higher positions for in situ CAC.

4.2.1 | P&T Projection May Be Low

P&T maintenance costs from 2022 onward use the annual average rates estimated in the 2021 USAF ROD (USAF 2021). The basis of this estimate is not presented, but it is not stated to contain provision for periodic major replacements that would be anticipated over a projection period longer than 20 years. Such recapitalization costs may be considerable (Section 3.3.2). The P&T projections used do not include longer term provision, which would increase the P&T cost.

Similarly, the P&T projection does not consider cost increases for PFOS and PFOA waste disposal from spent GAC following the designation of these species as hazardous substances. This designation came into effect in July 2024 (USEPA 2024a).

4.2.2 | CAC Projections May Be High

All costings presume constant contaminant input. This affects the CAC projections to a greater extent than the P&T projections. The frequency of CAC reapplication is determined by the contaminant flux. Since CAC has no O&M costs, the frequency of reapplication is the principal factor governing the cost projection.

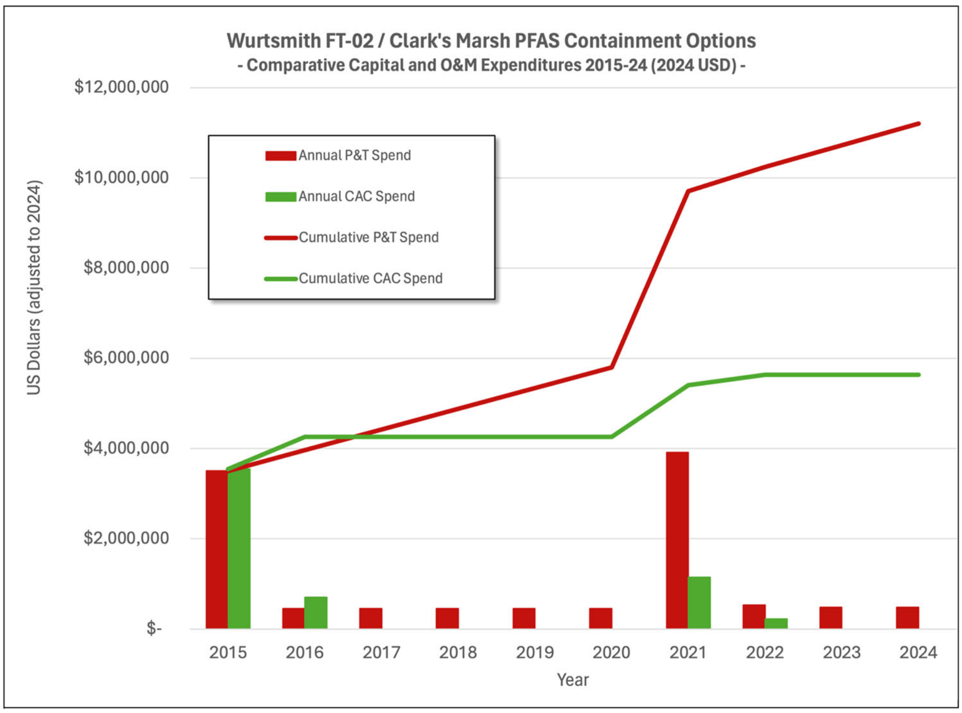

FIGURE 9 | Comparative technology costs (2015–2024). Comparative annual and cumulative costs for the WAFB FT-02/Clark's Marsh P&T system and hypothetical in situ CAC barrier meeting the same design objectives. Installation events for initial and extended systems occur in 2015 and 2021, respectively. CAC barrier commissioning costs fall in the subsequent year to the principal installation for each application event. The CAC barrier has no operational or maintenance costs. [Color figure can be viewed at wileyonlinelibrary.com]

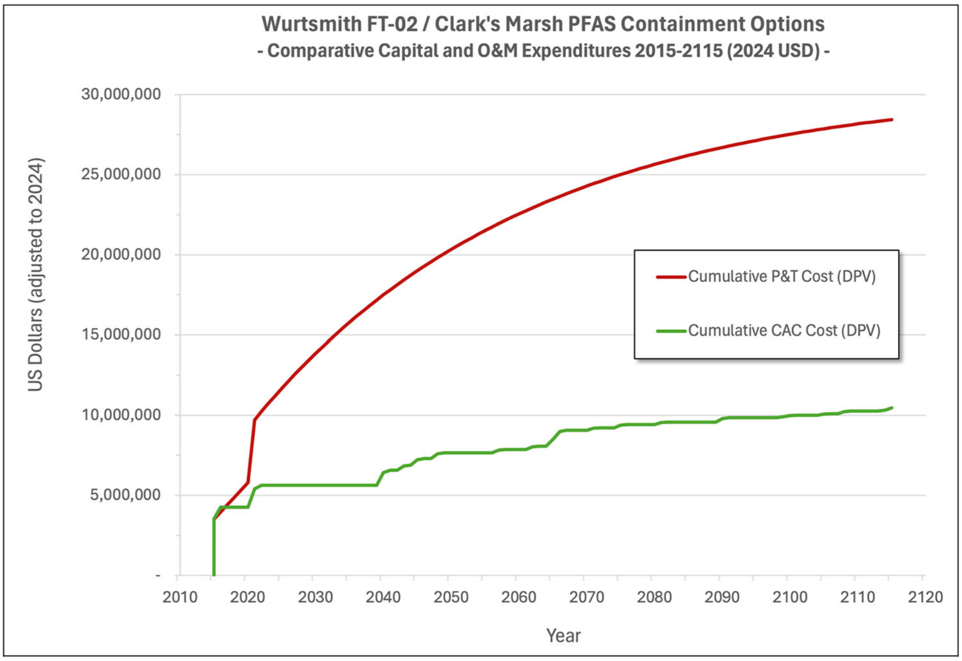

FIGURE 10 | Comparative technology costs (2015–2115). Comparative annual and cumulative costs for the WAFB FT-02/Clark's Marsh P&T system and hypothetical in situ CAC barrier meeting the same design objectives. Installation events for initial and extended systems occur in 2015 and 2021, respectively, with CAC reapplication events at minimum 25-year intervals per Table 9. CAC barrier commissioning costs fall in the subsequent year to the principal installation for each application event. The CAC barrier has no operational or maintenance costs. Costs are adjusted to 2024 USD value. A discount rate of 2.5% is used for projections beyond 2024 using the (maximum) 30-year discount rate of 2.5% specified in OMB Circular No. A-94, December 2023 (OMB 2024). [Color figure can be viewed at wileyonlinelibrary.com]

A declining contaminant flux will therefore extend the time to reapplication and reduce the life-cycle cost.

GAC meanwhile represents approximately 63% of the P&T O&M costs ($129,000 of $204,350 at 2015 USD rates; MWH 2014, and Table 4). The other 37% are power and engineering costs related to pumping and infrastructure. A decline in influent flux—principally PFOA—would therefore lead to a greater proportional reduction in the projected CAC costs relative to the P&T costs.

The projected reduction in PFOA concentrations in Figure 5 is not accommodated in the CAC costing. The future application costs may therefore be high and the applications premature. Accommodation of a declining PFOA influent flux would reduce the projected CAC barrier costs.

5 | Discussion and Conclusion

CAC barrier cost estimates for the remediation of WAFB FT-02 PFAS plume are uniformly lower than those of the installed P&T system (Table 11). Remediation objectives and installation timing for each technology are the same. The greater part of the cost discrepancy arises from O&M—the P&T system has annual O&M costs whereas the CAC barrier has none.

The cost of the system expansion conducted in 2021 is significantly lower for the CAC approach (e.g., Figure 9). The principal reason for this lies at the core of the technology difference—P&T is driven by hydraulic capture requirements whereas CAC is driven by the contaminant flux. For the plume section addressed in the 2021 system expansion, the hydraulic capture demands remain high. The expanded P&T system is therefore broadly equivalent in cost to the original 2015 installation (Table 4, Figure 9). In contrast, the relative cost of the second CAC barrier is a third that of the first. This is because the lower contaminant flux reduces the CAC requirement and extends the barrier longevity, which in turn reduces the installation cost and the necessary reapplication frequency.

This observation illustrates an important point of conservatism in the cost comparison. P&T performance data indicate the PFOS and PFOA influent concentrations to be declining. The rate of PFOS decline is slower than that of PFOA and dictates the projected time to remedial completion. PFOA is retarded by a lesser degree than PFOS in a CAC barrier in most cases and therefore determines the timing of the necessary CAC reapplications. The declining concentrations of PFOA will therefore reduce the required frequency and scale of CAC reapplications and therefore the projected costs. Rather than adjust the projections based on the extrapolation of a relatively small data set, the cost comparison instead presumes these parameters remain constant. Costs for P&T are relatively insensitive to contaminant concentration. If adjustment to the declining PFOA concentrations were to be accommodated, this would reduce the CAC costs more than the P&T costs.

The information informing the P&T design is available through the characterization and work plan reports in the US Air Force Civil Engineering Center (AFCEC) public domain library (https://ar.afcec-cloud.af.mil). The information is focused on the requirements for P&T design and does not contain the flux delineation detail required in a formal CAC barrier design. Flux uncertainty principally influences the longevity of each carbon application. The impact of the uncertainty is reduced in the present assessment by the discount rate, as its cost implication falls in 20-plus years' time.

The examples provide a detailed cost comparison for one site. How typical is the WAFB FT-02 PFAS plume? The answer to this is part-informed by subjective assessment based on the authors' experience. PFAS concentrations in the WAFB FT-02 plume are broadly typical of other CAC sites (Carey et al. 2022) albeit tending moderate to high. The starting concentrations in the plume core are some 1000 times and 500 times the formal 2016 targets for PFOS and PFOA.

Groundwater velocity is fast. The low MWH (2014) estimate of 1300 ft/year is perhaps five times higher than most CAC barrier settings. The estimate of 966 ft/year calculated with the flux estimates used in the CAC designs is itself three to four times higher than commonly encountered. The WAFB worked example therefore represents a high PFAS-flux site. This is more demanding of a CAC barrier as it requires a greater quantity of CAC for a given application longevity and therefore presents a higher cost. The cost comparison in the present exercise may therefore be considered realistic, but conservative.

In the present comparison, the installation and operational cost of an in situ CAC barrier alternative is approximately one-third that of P&T (38% at 30 years' projection). This agrees well with the 35%–39% estimate of Mallat et al. (2023) conducted at a UK airport site in an analogous comparison study (Section 2.4).

Acknowledgments

The authors would like to thank Bay West LLC for technical input in relation to published information on the pump-and-treat system design and operation and site background. The research was supported by Regenesis, San Clemente, California, USA.

Data Availability Statement

The data that support the findings of this study are available from the AFCEC Administrative Record website at https://ar.afcec-cloud.af.mil (Path: BRAC/Wurtsmith AFB/[AR#]). The administrative record numbers (AR#) for the cited documents are included with their citations in the references list of this paper.

Additional data are available at the EGLE MiEnviro Portal website: (https://mienviro.michigan.gov/ncore/external/home) under entry: "USAF-Wurtsmith AFB/Documents." Unless otherwise specified, data used are reported as daily monitoring records (DMR) at: https://mienviro.michigan.gov/nsite/map/results/detail/9124414591157947026/documents

(Path: File/search filter = DMR).

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