

Water and contaminant flux estimation from multi-layer passive flux meter measurements

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Abstract

The passive flux meter (PFM) enables the measurement of cumulative water and contaminant mass fluxes in porous aquifers. It consists of a sorbent material, which is installed in a monitoring well to intercept groundwater flow. Tracer losses and contaminant retention on the sorbent are used to estimate water and contaminant mass fluxes through the device. In the multi-layer PFM different (sorbent) materials are used in an annulus (layer-type) configuration. This allows leached tracers inside the PFM (no tracer release into aquifer) to be retained and facilitates simultaneous deployment of different sorbent types in a single device. In order to estimate undisturbed ambient fluxes in the aquifer, measurements need to be corrected for flow convergence or divergence induced by the well and PFM components. We make use of an analytical solution to the potential flow



problem of uniform flow disturbed by a system of concentric rings of contrasting hydraulic conductivities. A flow convergence factor is defined as a function of PFM ring conductivities and radii, where tracer elution and contaminant sorption may occur in arbitrary layers. The results are used for calibration of convergence factors of a multi-layer PFM to laboratory sand box experiments.

Keywords: aquifer, groundwater, plume, flow convergence, sand box.

1 Introduction

Groundwater contamination is recognized as a dangerous threat to ecosystems and human drinking water supplies. Besides contaminant concentrations (mass per volume), contaminant mass fluxes (mass per cross sectional area per time) have been used more recently as relevant measures for contaminant source identification, risk assessment, decision making and remediation performance control (ITRC [1]). Currently, three fundamental approaches are available for measuring contaminant fluxes: (1) Multi-level sampling (MLS; Einarson and Mackay [2]), which is based on separate measurements of contaminant concentrations and water fluxes for subsequent multiplication to obtain contaminant fluxes. (2) Integral pump tests (IPT; Bockelmann *et al.* [3]), which extract contaminated groundwater from the aquifer through pumping from a well and monitor contaminant concentrations at the well head over time. (3) Passive flux meter measurements (PFM; Hatfield *et al.* [4], Annable *et al.* [5]) based on the installation of sorbent materials in observation wells, where the sorbents initially contain known amounts of resident tracers. From detected tracer losses from a sorbent and contaminant masses sorbed onto a sorbent through laboratory analyses, cumulative (i.e., time integrated or averaged over the period of installation) water and contaminant fluxes may be obtained simultaneously as depth profiles along the well.

PFMs have typically been deployed in observation wells as self-contained units consisting of a single sorbent material, which acts as both a leaching tracer reservoir and a contaminant trap. As a consequence, it has to be assured that (1) the sorption properties of the sorbent material are appropriate for both tracer(s) and target contaminants, and (2) that the chemical properties of the tracer(s) are such that tracer release (even though minimal) into the aquifer does not cause legal or environmental problems. In an effort to circumvent these two issues (e.g., for measuring water and contaminant fluxes at Rifle, CO, USA) a multi-layer PFM has been developed and tested, which consists of multiple concentric rings (layers) of different materials (which may be sorbents or not).

Figure 1 compares the two different PFM configurations, where figure 1a shows a single sorbent installed inside a well screen, while figure 1b illustrates the annular composition of a multi-layer PFM installed in a screened well. From the periphery towards the center k_i [L/T] and r_i [L] denote the hydraulic conductivities and outer radii of the different rings. k_0 corresponds to the aquifer, k_1 is the well screen, k_2 an outer sorbent layer for contaminant sorption (e.g., Lewatit resin for uranium), k_3 an intermediate sorbent layer (e.g., granular activated carbon (GAC) for alcoholic tracers) to retain tracers eluded from an

inner sorbent layer of k_5 (e.g., also consisting of GAC for alcoholic tracers). Between the two GAC layers, there is a thin perforated stainless steel pipe of conductivity k_4 , which serves to separate the inner GAC from the outer one for installation and laboratory analysis. The center circle of radius r_6 is an impermeable pipe for physical stabilization and water evacuation during PFM

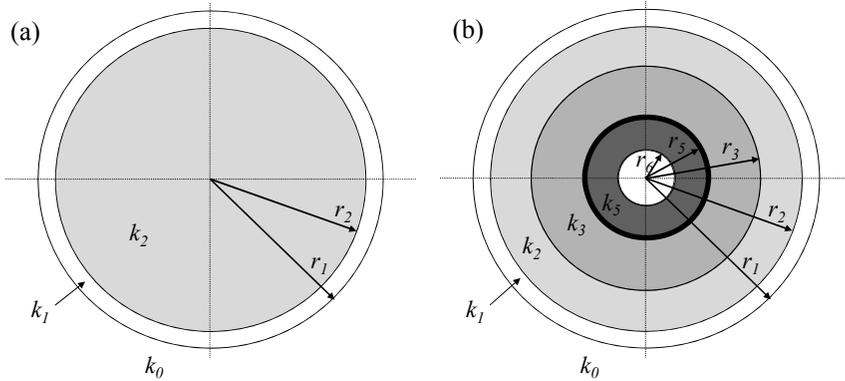


Figure 1: Horizontal cross sections of well screens and (a) a PFM consisting of a single sorbent and (b) a multi-layer PFM as used in laboratory testing. Bold black circle is of outer radius r_4 and conductivity k_4 .

Table 1: Summary of multi-layer PFM properties as depicted in figure 1b with k_1 and k_4 to be determined from laboratory box experiments.

Ring n ^o . i [-]	Conductivity k_i [m/day]	Outer radius r_i [cm]	Material / purpose
0	33	infinite	Aquifer (sand)
1	k_1	5.7	Well screen (slotted PVC pipe)
2	250	5.1	Lewatit resin for uranium sorption
3	350	3.8	GAC for tracer retention
4	k_4	2	Perforated pipe for separation
5	350	1.9	GAC for tracer elution
6	0	0.8	Impermeable center pipe

installation and removal. Table 1 summarizes the properties of the multi-layer PFM configuration used in laboratory sand box experiments for determination of k_1 and k_4 and subsequent deployment for measuring water and uranium fluxes at the uranium field site in Rifle.

Similar to the simple PFM, the multi-layer PFM provides data in terms of tracer losses from sorbent ring 5 and contaminant masses retained from sorbent ring 2. Following the method of Hatfield *et al.* [4] the apparent flux $q_{PFM,i}$ [L/T] through the i -th ring of a PFM may be found as

$$q_{PFM,i} = \frac{(1 - m_{r_i})(r_i^2 - r_{i+1}^2)\pi\theta_i R_i}{2r_i t} \quad (1)$$

where m_{r_i} [-] is the relative mass of a tracer remaining (with respect to the initial mass of that tracer) after time of exposure t [T] in the i -th ring of relative water content θ_i [-] and retardation factor R_i [-]. The attribute “apparent” indicates that flow is generally not uniform inside a multi-layer PFM and $q_{PFM,i}$ is to be understood as a discharge per unit transect area of the i -th ring perpendicular to incident flow direction. In analogy, an apparent contaminant mass flux $J_{PFM,i}$ [M/(TL²)] through the i -th ring may be obtained from

$$J_{PFM,i} = \frac{M_{si}}{2r_i b t} \quad (2)$$

where M_{si} [M] is the mass of contaminant sorbed in the i -th layer over a PFM interval of length b [L]. Eqn (1) is valid as long as none of the stream tubes through the i -th layer are completely cleared (empty) of tracer, while eqn (2) is valid as long as none of the contaminant previously sorbed onto the i -th layer is again released from it. As a consequence, within their ranges of validity eqns (1) and (2) do not depend on the properties (e.g., non-uniformity) of the flow field in the respective rings. Note that for $r_{i+1} = 0$ (i.e., the i -th layer is the center circle) eqn (1) reduces to eqn (18) of Hatfield *et al.* [4], whose coefficient of 1.67 appears as $\pi/2 \approx 1.57$ here. This is a consequence of the range of validity stipulated (an analogous observation applies to eqn (2)).

However, due to the more complex configuration of the multi-layer PFM and flow refraction between layers of different conductivities, an assessment of undisturbed ambient water and contaminant fluxes in the aquifer is not straightforward. Klammler *et al.* [6] present an analytical solution to the potential flow problem through the multi-layer PFM and they develop flow convergence factors for estimation of undisturbed (uniform) ambient fluxes. These factors, however, are with respect to the inner-most ring (center circle) only and are not applicable to other rings. The present work generalizes the convergence factors of Klammler *et al.* [6] to arbitrary layers in a multi-layered PFM configuration and uses the result for calibration of unknown parameters (well screen and perforated pipe conductivities k_l and k_d) through a laboratory sand box experiment, such that they may be applied to the multi-layer PFM deployment at Rifle for measuring water and uranium fluxes.

2 General flow field solution

The solution of Klammler *et al.* [6] is based on potential flow through porous media (Strack [7]). It makes use of a flow field analogy between uniform flow



disturbed by a cylindrical inhomogeneity in hydraulic conductivity and uniform flow disturbed by an impermeable or infinitely permeable cylinder. Its application is best illustrated by a numerical example, for which we use the flow domain of figure 1b (table 1) with values of $k_l = 2.3$ m/d and $k_d = 3.2$ m/d. This leads to the flow field (stream lines) of figure 2 with the stream function Ψ_i [L^3/T] in the i -th ring given by

$$\Psi_i = q_i r b \left(1 - \frac{a_i^2}{r^2} \right) \sin \gamma \quad (3)$$

where r [L] and γ [-] are the radial and angular coordinates, respectively, b [L] is the thickness of the flow domain (length of PFM interval in eqn (2)) and the parameters a_i [L] and q_i [L/T] are given in table 2 and obtained as follows: Starting with an initial value of $a_6 = 0$ in table 2, the columns of k_{ia} [L/T] and a_i are populated from bottom up by alternately applying eqns (4) and (5). Subsequently, the column of q_i is populated from top down by consecutive use of eqn (6). Most parameters in table 2 are auxiliary variables without direct physical equivalences (some of them complex/ imaginary). Exceptions are q_0 (undisturbed flux in the aquifer; assumed uniform), k_{6a} (equal to conductivity k_6 of inner ring), k_{0a} (equal to aquifer conductivity k_0) and q_6 (specific discharge in inner ring). Since $k_6 = 0$, it is further seen that a_5 is equal to the center pipe radius r_6 . Following this example, the step-wise solution scheme of eqns (3) through (6) is generally applicable to an arbitrary number of layers.

$$k_{ia} = k_i \frac{1 - \left(\frac{a_i}{r_i} \right)^2}{1 + \left(\frac{a_i}{r_i} \right)^2} \quad (4)$$

$$a_{i-1} = r_i \sqrt{\frac{1 - \frac{k_{ia}}{k_{i-1}}}{1 + \frac{k_{ia}}{k_{i-1}}}} \quad (5)$$

$$q_i = q_{i-1} \frac{1 + \frac{k_i}{k_{ia}}}{1 + \frac{k_{i-1}}{k_{ia}}} \quad (6)$$

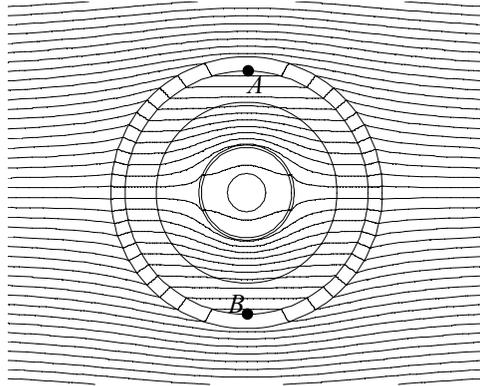


Figure 2: Flow field solution depicted as stream lines (lines of constant Ψ_i) for flow domain of figure 1b (table 1).

Table 2: Summary of flow field parameters and convergence factors for multi-layer PFM of figure 1b for $k_l = 2.3$ m/d and $k_d = 3.2$ m/d. $j = \sqrt{-1}$ is the imaginary unit.

Ring n ^o . i [-]	a_i [cm]	k_{ia} [m/day]	q_i/q_0 [-]	α_i [-]
0	2.94	33	$q_0/q_0 = \mathbf{1}$	1
1	5.05j	19.12	0.41	0.73
2	0.79	238.38	0.83	0.81
3	1.73	229.46	1.01	0.80
4	1.88j	49.78	0.13	0.25
5	0.80	244.59	0.32	0.26
6	$a_6 = \mathbf{0}$	0	0	0

3 Flow convergence factors for arbitrary layers

Using the solution of Ψ_i from eqn (3) for an arbitrary number of layers, the apparent flux $q_{PFM,i}$ [L/T] through the i -th ring of eqn (1) may be found. It is equal to the difference of the stream function between the lateral-most points (e.g., for $i = 2$ points A and B in figure 2) of the ring divided by the cross sectional area perpendicular to flow.

$$q_{PFM,i} = \frac{\Psi_i(r_i, \frac{\pi}{2}) - \Psi_i(r_i, -\frac{\pi}{2})}{2r_i b} = \frac{\Psi_i(r_i, \frac{\pi}{2})}{r_i b} = q_i \left(1 - \frac{a_i^2}{r_i^2} \right) \tag{7}$$

In the undisturbed aquifer the flow is assumed to be of uniform flux q_0 , such that a flow convergence (or divergence) factor α_i [-] for the i -th ring may be defined by

$$\alpha_i = \frac{q_{PFM,i}}{q_0} = \frac{q_i}{q_0} \left(1 - \frac{a_i^2}{r_i^2} \right) \tag{8}$$

In other words, the flow convergence factor expresses how much flow crosses the i -th ring of a multi-layer PFM with respect to the ambient flow through a ring of the same size, if the aquifer was not disturbed by the well and PFM components. A value of α_i larger than one may be viewed as a situation of flow convergence, while a value smaller than one reflects a condition of flow divergence. For a single layer PFM, flow convergence occurs when the PFM sorbent is more permeable than the aquifer and flow divergence occurs when the contrary is true. For multi-layer PFMs, however, $\alpha_i \geq 1$ and $\alpha_i \leq 1$ may occur simultaneously in different layers of a single device depending on the sequence of k_i . Returning to the example of figure 1b and using values of r_i from table 1 with values of q_i/q_0 and a_i from table 2, the values of α_i as given in the last column of table 2 are directly obtained from eqn (8) (note hereby that some values of a_i are imaginary).

The flow convergence factor α_i from eqn (8) is a generalization over that of Klammler *et al.* [6], because it is applicable to any layer. If i is equal to the total number of layers present, such that α_i applies to the center circle of the flow domain as shown in figure 1, for example, then eqn (8) becomes equal to α_i from Klammler *et al.* [6]. Moreover, for $i = 1, 2$ and 3 (and an arbitrary total number of layers), eqns (3), (12) and (13) of Klammler *et al.* [6] may be written in a generalized form by using k_{1a}, k_{2a} and k_{3a} from eqn (4) instead of k_1, k_2 , and k_3 resulting in

$$\alpha_1 = \frac{2}{1 + \frac{k_0}{k_{1a}}} \tag{9}$$

$$\alpha_2 = \frac{4}{\left(1 + \frac{k_0}{k_1} \right) \left(1 + \frac{k_1}{k_{2a}} \right) + \left(1 - \frac{k_0}{k_1} \right) \left(1 - \frac{k_1}{k_{2a}} \right) \left(\frac{r_2}{r_1} \right)^2} \tag{10}$$

$$\alpha_3 = \frac{8}{\left(1 + \frac{k_0}{k_1} \right) \left(1 + \frac{k_1}{k_2} \right) \left(1 + \frac{k_2}{k_{3a}} \right) + \left(1 - \frac{k_0}{k_1} \right) \left(1 - \frac{k_1}{k_2} \right) \left(1 + \frac{k_2}{k_{3a}} \right) \left(\frac{r_2}{r_1} \right)^2 + \left(1 + \frac{k_0}{k_1} \right) \left(1 - \frac{k_1}{k_2} \right) \left(1 - \frac{k_2}{k_{3a}} \right) \left(\frac{r_2}{r_1} \right)^2 + \left(1 - \frac{k_0}{k_1} \right) \left(1 + \frac{k_1}{k_2} \right) \left(1 - \frac{k_2}{k_{3a}} \right) \left(\frac{r_2}{r_1} \right)^2} \tag{11}$$

For $i = 4$, the result of Appendix B in Klammler *et al.* [6] is incomplete and after substituting k_4 by k_{4a} it should be

$$\alpha_4 = \frac{16}{A + B + C + D + E + F + G + H} \tag{12}$$



with

$$\begin{aligned}
 A &= \left(1 + \frac{k_0}{k_1}\right) \cdot \left(1 + \frac{k_1}{k_2}\right) \cdot \left(1 + \frac{k_2}{k_3}\right) \cdot \left(1 + \frac{k_3}{k_{4a}}\right) \\
 B &= \left(1 - \frac{k_0}{k_1}\right) \cdot \left(1 - \frac{k_1}{k_2}\right) \cdot \left(1 + \frac{k_2}{k_3}\right) \cdot \left(1 + \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_2}{r_1}\right)^2 \\
 C &= \left(1 + \frac{k_0}{k_1}\right) \cdot \left(1 - \frac{k_1}{k_2}\right) \cdot \left(1 - \frac{k_2}{k_3}\right) \cdot \left(1 + \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_3}{r_2}\right)^2 \\
 D &= \left(1 - \frac{k_0}{k_1}\right) \cdot \left(1 + \frac{k_1}{k_2}\right) \cdot \left(1 - \frac{k_2}{k_3}\right) \cdot \left(1 + \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_3}{r_1}\right)^2 \\
 E &= \left(1 + \frac{k_0}{k_1}\right) \cdot \left(1 + \frac{k_1}{k_2}\right) \cdot \left(1 - \frac{k_2}{k_3}\right) \cdot \left(1 - \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_4}{r_3}\right)^2 \\
 F &= \left(1 + \frac{k_0}{k_1}\right) \cdot \left(1 - \frac{k_1}{k_2}\right) \cdot \left(1 + \frac{k_2}{k_3}\right) \cdot \left(1 - \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_4}{r_2}\right)^2 \\
 G &= \left(1 - \frac{k_0}{k_1}\right) \cdot \left(1 + \frac{k_1}{k_2}\right) \cdot \left(1 + \frac{k_2}{k_3}\right) \cdot \left(1 - \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_4}{r_1}\right)^2 \\
 H &= \left(1 - \frac{k_0}{k_1}\right) \cdot \left(1 - \frac{k_1}{k_2}\right) \cdot \left(1 - \frac{k_2}{k_3}\right) \cdot \left(1 - \frac{k_3}{k_{4a}}\right) \cdot \left(\frac{r_2 r_4}{r_1 r_3}\right)^2
 \end{aligned} \tag{13}$$

Note that eqns (9) through (13) are equivalent formulations to the step-wise procedure of eqns (4) through (6). While closed form expressions of α_i for $i > 4$ may be derived, they become increasingly lengthy and computational implementation of eqns (4) through (6) (e.g., in a spreadsheet) may be more convenient.

Not immediately obvious from eqns (9) through (13) and more easily verifiable using eqns (5), (6) and (8) is that the ratio α_i/α_{i-1} is only a function of k_m and r_m , where $m \geq i - 1$. More intuitively, this means that flow refraction between two adjacent layers does not depend on the radii and conductivities of any outside layers or the aquifer. This may be convenient for comparing flux estimates from different layers independent of the perhaps uncertain aquifer conductivity k_0 and will be explored for estimating k_1 and k_4 below. However, it also precludes the possibility of estimating an unknown k_0 from two flux estimates in different layers (as may be attempted in analogy to the method presented in Klammler *et al.* [6]).

Assuming that contaminant transport is dominated by advection (i.e., contaminant particles travel along the same stream tubes as water particles and effects of diffusion and dispersion are neglected), $q_{PFM,i}$ and q_0 in the first equality of eqn (8) may be substituted by $J_{PFM,i}$ from eqn (2) and the undisturbed ambient contaminant mass flux J_0 [M/(L²T)], respectively. It is recalled that m_{r_i} for estimation of $q_{PFM,i}$ and M_{s_i} for estimation of $J_{PFM,i}$ do not have to stem from the same PFM layer (i.e., index i in eqns (1) and (2) generally takes different

values). However, if m_{ri} and M_{si} are obtained from the same layer, then the same flow convergence factor α_i applies.

4 Laboratory experiments and calibration

For application of the multi-layer PFM configuration of figure 1b at the uranium site in Rifle and determination of unknown conductivities k_l and k_d , laboratory sand box experiments are performed. Box size is 39 x 30.5 x 17.9 cm (length L x width W x height H) and table 1 contains the sand conductivity as well as well screen and PFM parameters. ‘‘Ambient’’ water fluxes q_0 and uranium fluxes J_0 through the box are obtained from

$$q_0 = \frac{Q_0}{WH} \tag{14}$$

$$J_0 = q_0 C_u \tag{15}$$

where Q_0 [L³/T] is the independently measured water discharge through the box and C_u [M/L³] is the uranium concentration in the influent water. Eleven tests of different durations were run for water flux obtaining estimates $q_{PFM,5}$ from eqn (1) for comparison to q_0 of eqn (14). In five of these tests uranium was added at $C_u \approx 200$ $\mu\text{g/l}$ for comparison of $J_{PFM,2}$ from eqn (2) with J_0 of eqn (15).

Table 3: Summary of results from sand box experiments.

t [days]	q_0 [cm/day]	$q_{PFM,5}$ [cm/day]	α_5 [-]	J_0 [$\mu\text{g}/(\text{cm}^2\text{day})$]	$J_{PFM,2}$ [$\mu\text{g}/(\text{cm}^2\text{day})$]	α_2 [-]	
3.00	15.95	4.12	0.26	N/A			
2.87	16.85	4.03	0.24				
2.92	16.85	3.44	0.20				
2.99	18.48	4.13	0.22				
4.24	17.03	3.84	0.23				
4.05	19.44	4.09	0.21				
5.92	7.87	2.40	0.30	1.68	1.86	1.11	
3.94	11.52	3.64	0.32	2.38	1.80	0.76	
1.95	25.02	6.17	0.25	5.05	2.16	0.43	
1.51	31.78	7.93	0.25	6.15	2.96	0.48	
12.00	3.87	1.68	0.43	0.80	1.05	1.30	
Average $\alpha_5 =$			0.26	Average $\alpha_2 =$			0.81

Table 3 summarizes the results of the sand box experiments and indicates average values of $\alpha_2 = J_{PFM,2}/J_0 = 0.81$ and $\alpha_5 = q_{PFM,5}/q_0 = 0.26$. At this point we return to table 2 and revert the previous assumption that the conductivities k_l and k_d of the well screen and the perforated pipe are known. Instead, the experimental values of α_2 and α_5 are used to determine effective values of k_l and k_d to be used in the interpretation of field deployments. For this purpose,



advantage is taken of the previous conclusion that the ratio $\alpha_5/\alpha_2 = 0.32$ is not affected by k_1 . Thus, k_4 may be directly found, which is most conveniently achieved by systematically varying k_4 for an arbitrary value of k_1 and observing the results in terms of α_5/α_2 . Figure 3 shows the outcome of this process and leads to two possible values of $k_4 = 3.2$ and 18851 m/day. For each of the values found for k_4 , the same process is repeated with k_1 to reach the required value of $\alpha_2 = 0.81$ (or equally $\alpha_5 = 0.26$). This is illustrated in figure 4 and shows that again two values of k_1 may be combined with each value of k_4 , thus resulting in the four solutions given in the first two rows of table 4.

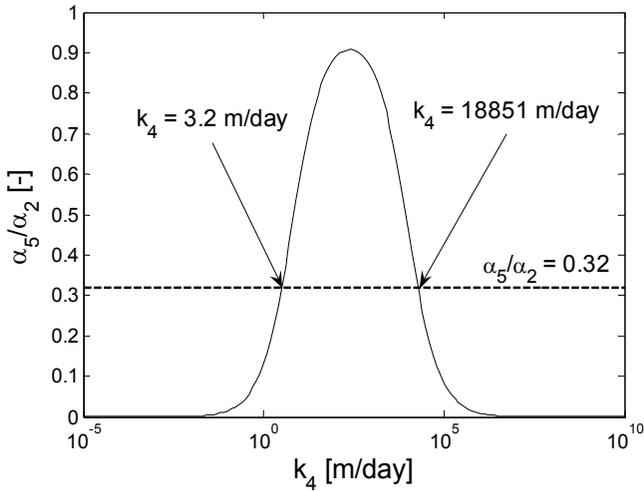


Figure 3: α_5/α_2 as a function of k_4 for arbitrary k_1 to achieve target value $\alpha_5/\alpha_2 = 0.32$.

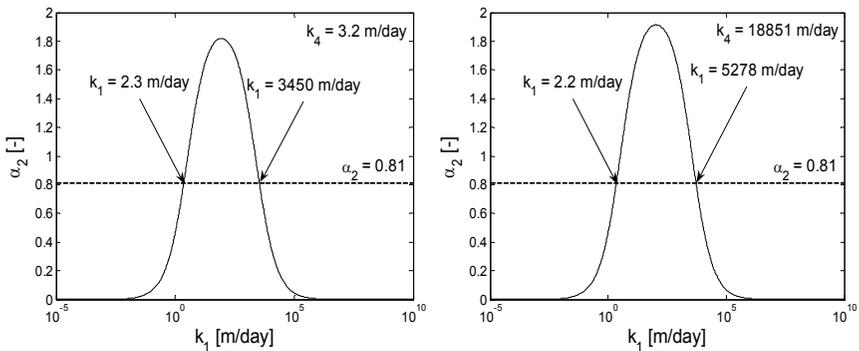


Figure 4: α_2 as a function of k_1 for $k_4 = 3.2$ and 18851 m/day to achieve target value $\alpha_2 = 0.81$.



Table 4: Possible combinations of k_I and k_d in m/day to achieve $\alpha_2 = 0.81$ and $\alpha_5 = 0.26$ from box experiments and resulting α_q and α_J for the Rifle deployment.

k_I	2.3	3450	2.2	5278
k_d	3.2		18851	
α_q	0.20	0.36	0.20	0.37
α_J	0.61	1.13	0.61	1.16

For each of the four solutions pairs, a flow convergence factor α_q for water flux and a flow convergence factor α_J for uranium may be computed for the deployment conditions at the Rifle site. These conditions are identical to those of figure 1b, except for the presence of a filter pack of radius 10.2 cm and conductivity 160 m/day around the well screen and inside an aquifer of conductivity of approximately 2.5 m/d. Considering these modifications, results for α_q and α_J from application of eqns 4, 5, 6 and 8 are given in the last two rows of table 4. It may be seen that $\alpha_q/\alpha_J = \alpha_5/\alpha_2 = 0.32$ remains constant and, more interestingly, that the solutions are pair wise identical (up to chart reading and rounding errors). It appears that this is not a coincidence as the same behaviour may be observed for other hypothetical values of aquifer and filter pack conductivities and radii. From the remaining two solution, $\alpha_q = 0.20$ and $\alpha_J = 0.61$ are proposed for use at the Rifle site, since they are associated with a low value of $k_I = 2.3$ (and either value of k_d). This choice is justified by two related arguments: (1) From an independent borehole dilution test (no PFM installed) in the sand box a value of $k_I = 87$ m/day is estimated. This may be regarded as an upper bound for k_I as flow in the vicinity of an open borehole is radial. Flow components in the tangential direction through the well screen are hindered by the fact that screen slots are not continuous along the circumference of a PVC screen. (2) As illustrated by the flow field in figure 2, low k_I and k_d cause flow in the respective rings to be essentially radial, which is in agreement with the geometric properties of the screen slots and the pipe perforations acting as water conduits. Large values of k_I and k_d , in turn, would lead to a certain degree of flow short circuiting along these rings, which is considered less plausible, particularly since the sorbents are granular and tend to settle into the well and close possible voids along the pipe or screen surfaces.

5 Summary

Based on an existing solution to the potential flow problem of uniform flow disturbed by an arbitrary number of concentric rings of contrasting conductivities, flow convergence (or divergence) factors are developed for interpretation of multi-layer PFM measurements. Flow convergence factors convert water and contaminant fluxes measured in an arbitrary layer of the PFM into estimates of respective undisturbed ambient fluxes (i.e., unaffected by the



presence of well and PFM). Using the results in combination with laboratory sand box experiments, effective conductivities of a well screen and another separation screen between layers are determined. With these conductivities, flow convergence factors for measuring water and uranium fluxes at a site in Rifle, CO, USA, are proposed.

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