VERIFICATION DOCUMENT FOR HWIR99 PSEUDO -THREE DIMENSIONAL AQUIFER MODULE

Work Assignment Manager and Technical Directions:

Dr. Zubair A. Saleem
U.S. Environmental Protection Agency
Office of Solid Waste
Washington, DC 20460

Prepared by

HydroGeoLogic, Inc.
1155 Herndon Parkway, Suite 900
Herndon, VA 20170
Under Contract No. 68-W7-0035

U.S. Environmental Protection Agency
Office of Solid Waste
Washington, DC 20460

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Acknowledgments

A number of individuals have been involved with the verification of the aquifer module. Dr. Zubair A. Saleem of the U.S. EPA, Office of Solid Waste, provided overall technical coordination and review throughout this work. Dr. Varut Guvanasen of HydroGeoLogic, Inc. developed the approach for verification of the module. Mr. Theodore P. Lillys of HydroGeoLogic, Inc. implemented the analytical solution and conducted the verification, and the report was prepared by Mr. Lillys, Dr. Guvanasen, and Mr. Patrick Sullivan, also of HydroGeoLogic, Inc.

1.0 BACKGROUND

The HWIR99 computational saturated zone simulation module (referred to herein as the Aquifer module) has been developed, tested, documented (US EPA, 1998), and externally reviewed by the Dynamac Corporation (Dynamac, 1998). The Aquifer module comprises the following sub-modules:

- Steady-state saturated flow; and

- Advective and dispersive transport of soluble constituents.

The two sub-modules are described in detail in the HWIR99 Background document for the Vadose and Aquifer modules (US EPA, 1998). The primary assumptions are steady saturated flow within a homogeneous porous media and linear transport.

The steady state saturated flow sub-module is an implementation of an analytical solution to the vertically integrated, one-dimensional flow equation subject to boundary conditions as described in the background document (US EPA, 1998). The contaminant transport sub-module is a hybrid analytical-numerical model specifically designed for large scale Monte Carlo simulations where computational efficiency is desirable. The origin of both sub-modules are rooted in the EPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) (U.S. EPA, 1996a,b,c).

Inputs to the saturated flow sub-module consist of

- Infiltration and recharge provided by the Vadose and Watershed modules, respectively;
- Hydrogeologic parameters (*eg.*, regional hydraulic gradient, saturated thickness, saturated hydraulic conductivity); and
- Site-specific parameters (*eg.*, source area, regional groundwater flow direction);

The primary output of the saturated flow sub-module is an average groundwater specific flow rate.

The transport sub-module expects

- Water table concentrations from the Vadose zone module;
- Average groundwater specific flow rate from the saturated flow sub-module;
- Chemical specific parameters; and
- Site specific transport parameters.

The primary output of the transport sub-module are concentrations at receptor wells and mass fluxes to an assumed fully-penetrating surface water body.

2.0 VERIFICATION PLAN

The verification of the Aquifer module was conducted in stages, described below:

1. Verification of the average groundwater specific flow rate determined by the saturated flow sub-module using Darcy's Law and regional hydrogeologic parameters. Average groundwater specific flow rate is a primary input into the transport sub-module.

2. Verification of the numerical component of the contaminant transport sub-module using an analytical solution. Mass fluxes to the surface water body are derived from this component of the transport solution. Also, receptor well concentrations are based upon the numerical component of the solution

3. Verification of the combined analytical-numerical contaminant transport sub-module using verification results of Stage 2 subject to the analytical portion of the Aquifer transport sub-module. Receptor well concentrations are the product of this stage.

The verification approach and results described herein are based on the assumption that initial testing and verification of the Aquifer module has been conducted. The emphasis of the current verification is on the consistency of the output of the Aquifer module.

3.0 SOFTWARE VERIFIED AND DATA USED

The Aquifer module is written in Fortran 77 and utilizes features of Fortran 90 for memory management, computational efficiency, and source code readability. The compiler is Digital Visual Fortran V 5.0.

The verification plan was executed using the site simulation files (SSF) and global result files (GRF) generated by the HWIR99 Software System User Interface (SUI) for a non-degrading Benzene release from a land application unit (LAU) at site identifier "1632106". The concentration in waste level (CW) was set to "3". A complete description of input and output file formats used in HWIR99 is given in Section 4.0 of "The Vadose and Saturated Zone Module Extracted from EPACMTP for HWIR99" (U.S. EPA, 1998).

4.0 VERIFICATION DESCRIPTION

4.1 Stage 1 - Verification of the Average Groundwater Specific Flow Rate

The saturated flow sub-module computes the analytic specific flow rate at each node in the computational grid. Print statements were added to the Aquifer module to output these velocities to a file. The contents of that file are in Appendix A. The average flow rate calculated from those results is 732.05 m/y. A regional groundwater specific flow rate, q, can be determined using Darcy's Law

$$q = -K \frac{dh}{dl} \qquad \textbf{(1)}$$

where *dh/dl* is the hydraulic gradient, and *K* is the saturated hydraulic conductivity. The regional values of gradient and conductivity are given in the site layout SSF, slLA1632106.ssf, as

AquGrad	0.013
AquSatK	56341 m/y

Using the above values, Equation 1 gives q = 732.43 m/y, a difference of less than 0.1% from the average calculated by the flow sub-module.

4.2 Stage 2 - Verification of the Numerical Component of the Contaminant Transport Sub-Module

The Aquifer module simulates the transport of a dissolved contaminant using a hybrid analytical-numerical formulation designed specifically for large scale Monte Carlo simulations. The numerical component of the transport sub-module is a transient, one dimensional numerical solution of the advection dispersion equation aligned with the primary flow direction (U.S. EPA, 1996a,b,c). This approach is verified with an analytical solution by Ogata (1970) and is presented by Freeze and Cherry (1979). The solution is in the form

$$C(x, t, C_o, U, D_x) = \frac{1}{2} C_o \left[erfc\left(\frac{x - Ut}{2\sqrt{D_x t}}\right) + \exp\left(\frac{Ux}{D_x}\right) erfc\left(\frac{x + Ut}{2\sqrt{D_x t}}\right) \right] \quad \textbf{(2)}$$

where

$$U = \frac{q_x}{\phi R} \quad \textbf{(3a)}$$

$$D_x = \frac{\alpha_L q_x}{\phi R} \quad \textbf{(3b)}$$

$$R = 1 + \frac{\rho_B K_{OC} f_{OC}}{\phi} \quad \textbf{(3c)}$$

and

q_x = the average linear groundwater specific flow rate [L/T]
α_L = the longitudinal dispersivity [L]
x = the independent space variable [L]
t = the independent time variable [T]
R = the retardation factor
ρ_B = the bulk density of the saturated porous media [M/L^3]
K_{OC} = the normalized distribution coefficient for organic carbon
f_{oc} = the fraction of organic carbon content of the porous media
ϕ = the effective porosity
C_o = the source concentration [M/L^3]

Equation 2 is subject to the following boundary conditions:

$$C(x,0) = 0, x \geq 0, \quad \textbf{(4a)}$$

$$C(0,t) = C_o, t > 0, \quad \textbf{(4b)}$$

$$C(\infty,t) = 0, t \geq 0 \quad \textbf{(4c)}$$

Taken together, Equations 4a-c, define an initially contaminant free semi-infinite domain with a constant source at one end having concentration C_0.

The boundary condition stated in Equation 4b is inconsistent with the delivery of contaminant mass to the water table from the vadose zone module. Contaminant mass is assumed to arrive at the water table as an arbitrary function of time. The transport sub-module approximates the arbitrary source function with a series of finite step functions. A similar approach may be taken when using Equation 2. Exploiting the linearity of the transport equation, the method of superposition may be employed. For example, let the source concentration, C_0, be defined as follows:

$$C_o\left(t < t^I_{BEG}\right) = 0, \quad \textbf{(5a)}$$

$$C_o\left(t^I_{BEG} \leq t \leq t^I_{END}\right) = C^I_o, \quad \textbf{(5b)}$$

$$C_o\left(t > t^I_{END}\right) = 0. \quad \textbf{(5c)}$$

Where C^I_o is the Ith constant concentration pulse applied at the water table over the time interval $t^I_{BEG} \leq t \leq t^I_{END}$. Equations 5 a-c describe a finite, constant concentration or square pulse source that may be used in conjunction with equation (2) to give:

$$C_s(x,t) = \sum_{I=1}^{N_P}\left[C(x, t - t^I_{BEG}, C_o{}^I, U, D_x) - C(x, t - t^I_{END}, C_o{}^I, U, D_x)\right] \quad \textbf{(6)}$$

where:

C_s = Concentration based on superposition at location *x* and time *t* [M/L^3].
N_P = Number of finite source function pulses used to approximate the arbitrary source function.

The constant inputs to the verification model, summarized in Table 1, are taken directly from the site layout SSF (slLA1632106.ssf) and the aquifer SSF (aq01.ssf) (see Appendix B). The vadose zone GRF (vzLA1632106.grf) contains the point estimates of concentrations at the water table (parameter CWT) over time (TWT). These data require pre-processing for use in the verification model. There are NTS concentration-arrival time pairs in the vadose GRF which must be converted into N_P average concentrations over N_P time intervals, where N_P = NTS -1 The pre-processed water table concentrations are presented in Appendix C.

Table 1. Constant inputs to the verification model.

Source	Parameter	Value	Units	Description
cpaq.ssf	ChemKoc	48.3	mL/g	Normalized distribution coef. for organic carbon
slLA1632106	AquGrad	0.013		Regional gradient in saturated zone
slLA1632106	AquSATK	56341	m/y	Saturated hydraulic conductivity
aq01.ssf	AL	67.696	m	Longitudinal dispersivity
aq01.ssf	BDENS	1.3663	g/cm3	Bulk density
aq01.ssf	FOC	0.0003	fraction	Fraction organic carbon
aq01.ssf	POR	0.2228		Effective porosity

The site coordinate system used in HWIR99 places the origin at the center of the waste management unit (WMU) and aligns the X and Y axes with true East and North, respectively. The aquifer module transforms the *global* site coordinates into a *local* coordinate system whose X axis is aligned with the regional groundwater flow direction and originates at the center of the down gradient edge of the WMU. Receptor locations are also transformed to the local system (see U.S.EPA, 1998).

The pseudo-three dimensional aquifer module requires a single discretized space dimension (*i.e.*, the X direction) for numerical simulation. The numerical grid is designed to include a node corresponding to each receptor's local X coordinate resulting in a unique node for each receptor. A logical flag in the aquifer module source code controls the output of the numerical solution for debugging purposes. This flag was turned on so that the aquifer module would report to a file the concentrations over time at each node in the numerical grid. Five receptor wells were selected from the aquifer GRF that are evenly distributed along the direction of flow. The receptor well numbers used for verification are given in Table 2 with site and model coordinates. In addition, the surface water body connection location is included in Table 2. The selection of a surface water body connection location is detailed in "The Vadose and Saturated Zone Modules Extracted from EPACMTP for HWIR99" document (US EPA, 1998). In this instance the connection location is located along the down gradient edge of the WMU.

Table 2. Receptor Well and Surface Water Body Locations used in Verification.

Receptor Well Number	Site Coordinates [m]			Model Coordinates [m]		
	X	Y	Z	X	Y	Z
58	-213.8	-478	0.4896	257.87	308.49	2.9863
81	-289.3	-746.1	0.0321	504.31	438.13	0.196
93	-270.3	-1203	0.6136	955.06	514.44	3.7432
103	920.73	-1469	0.8547	1462.6	595.29	5.2138
115	-17.54	-2179	0.7731	1962.4	470.17	4.7156
Surface Water Body Water Body Network 2, Reach 3, Node 8	400.31	0.25	na	0	0	na

4.3 Stage 3 - Verification of the Combined Analytical-Numerical Contaminant Transport Sub-Module

The Aquifer module computes transient receptor well concentrations using a hybrid analytical numerical simulator. The verification of the numerical component was described in the previous section. The analytical component extrapolates the one-dimensional numerical results to receptor well locations (see the The Vadose and Saturated Zone Modules document for details). A select number of well concentrations reported in aqu01.grf file are verified by applying the analytical extrapolation to the one-dimensional verification solution used in section 4.2. Verification is based on the assumption that the initial dimensions of the vertical representation of the source boundary conditions are correct.

The selected receptor well locations are given in Table 3. A spread sheet was constructed to compute the analytical extrapolation terms for each of the five receptor well locations. The verification results for each receptor well location are presented in figures 7 - 11. The module results are in good agreement with the analytical results.

5.0 SUMMARY OF VERIFICATION RESULTS

The HWIR99 Aquifer Module developed and document by HydroGeoLogic has been successfully verified. The major components of the Aquifer Module are the steady-state saturated flow sub module and contaminant transport sub-module. The average groundwater specific flow rate flow computed by the flow sub-module is in excellent agreement with the regional flow rate predicted by Darcy's Law. Receptor well concentrations and surface water body mass fluxes are in good agreement with the analytical verification model. A summary of each verification stage is provided below.

1. The saturated groundwater flow sub-module has been verified. Agreement between the sub-module generated average groundwater specific flow rate and the hand-calculated flow rate is excellent.
2. The numerical component of the transport sub-module has been verified. The one-dimensional numerical results are in good agreement with the one-dimensional analytical verification model, as described in section 4.2.

3. The combined analytical-numerical transport sub-module has been verified. Agreement between select receptor well concentrations in the aquifer GRF file and the extrapolated one-dimensional analytical verification model is good.

6.0 REFERENCES

Dynamac Corporation, Technical Memo to U.S. EPA OSW. Independent Testing of Groundwater Modules (Interm Comments), 1998.

Freeze, R. Allan, Cherry, J. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey, p. 391, 1979.

Ogata, Akio. Theory of Dispersion in a Granular Medium. U.S. Geol. Surv. Prof. Paper, 411-I, p. 134, 1970.

U.S.EPA. The Vadose and Saturated Zone Modules Extracted from EPACMTP for HWIR99, Office of Solid Waste, U.S.EPA, 1988.

U.S.EPA, EPA's Composite Model for Leachate Migration with Transformation Products, EPACMTP. Background Document, Office of Solid Waste, U.S. EPA, 1997.

Appendix A

The table below lists the velocities determined along the one-dimensional numerical described in Section 4.2.

Specific Flow Rates from Analytic Solution at all Computational Grid Nodes.

Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]
1	716.14	49	722.24	97	731.58	145	737.04
2	716.27	50	722.36	98	731.71	146	737.17
3	716.40	51	722.49	99	731.84	147	737.31
4	716.53	52	722.62	100	731.97	148	737.45
5	716.65	53	722.74	101	732.10	149	737.58
6	716.78	54	722.87	102	732.14	150	737.72
7	716.91	55	723.00	103	732.15	151	737.86
8	717.03	56	723.12	104	732.28	152	737.90
9	717.16	57	723.25	105	732.37	153	737.96
10	717.29	58	723.38	106	732.47	154	738.09
11	717.41	59	723.50	107	732.60	155	738.19
12	717.54	60	723.63	108	732.73	156	738.33
13	717.67	61	723.76	109	732.74	157	738.47
14	717.79	62	723.89	110	732.87	158	738.61
15	717.92	63	724.01	111	733.00	159	738.75
16	718.05	64	724.14	112	733.13	160	738.89
17	718.18	65	724.27	113	733.26	161	739.03
18	718.30	66	724.39	114	733.33	162	739.18
19	718.43	67	724.52	115	733.46	163	739.32
20	718.56	68	724.65	116	733.59	164	739.46
21	718.68	69	724.77	117	733.72	165	739.60
22	718.81	70	725.06	118	733.76	166	739.74
23	718.94	71	725.39	119	733.90	167	739.88
24	719.06	72	725.72	120	734.03	168	740.02
25	719.19	73	726.05	121	734.16	169	740.10
26	719.32	74	726.38	122	734.29	170	740.24
27	719.44	75	726.70	123	734.42	171	740.38
28	719.57	76	727.03	124	734.56	172	740.52
29	719.70	77	727.36	125	734.69	173	740.66
30	719.82	78	727.69	126	734.82	174	740.80
31	719.95	79	728.02	127	734.95	175	740.94
32	720.08	80	728.34	128	735.08	176	741.08
33	720.21	81	728.67	129	735.22	177	741.23
34	720.33	82	729.00	130	735.35	178	741.35
35	720.46	83	729.10	131	735.43	179	741.43
36	720.59	84	729.42	132	735.56	180	741.58
37	720.71	85	729.75	133	735.70	181	741.60
38	720.84	86	730.08	134	735.83	182	741.75

Specific Flow Rates from Analytic Solution at all Computational Grid Nodes (continued)..

Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]	Node Number	Velocity [m/yr]
39	720.97	87	730.40	135	735.96	183	741.77
40	721.09	88	730.45	136	736.10	184	741.85
41	721.22	89	730.57	137	736.23	185	742.00
42	721.35	90	730.70	138	736.24	186	742.16
43	721.47	91	730.83	139	736.38	187	742.31
44	721.60	92	730.96	140	736.41	188	742.46
45	721.73	93	731.08	141	736.55	189	742.61
46	721.86	94	731.20	142	736.68	190	742.70
47	721.98	95	731.33	143	736.76	191	742.85
48	722.11	96	731.46	144	736.90	192	743.01

Appendix B

Site layout SSF for LAU at location 1632106 (Abbreviated Version)

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Appendix C

Pre-processed Water Table Concentrations

Time	vz.grf	Pulse Time On	Pulse Time Off	Approximate Square Pulse Concentration
1	22.369	1	1.23463	30.685
1.2346	39.001	1.23463	1.46925	43.023
1.4693	47.045	1.46925	1.70388	47.811
1.7039	48.578	1.70388	1.9385	45.768
1.9385	42.958	1.9385	2.17313	39.098
2.1731	35.238	2.17313	2.40775	33.056
2.4078	30.874	2.40775	2.64238	30.041
2.6424	29.208	2.64238	2.87701	28.424
2.877	27.641	2.87701	3.11163	26.619
3.1116	25.597	3.11163	3.34626	24.944
3.3463	24.292	3.34626	3.58088	24.040
3.5809	23.789	3.58088	3.81551	23.745
3.8155	23.702	3.81551	4.05013	23.757
4.0501	23.812	4.05013	4.28476	23.867
4.2848	23.922	4.28476	4.51939	23.947
4.5194	23.972	4.51939	4.75401	23.988
4.754	24.004	4.75401	4.98864	24.038
4.9886	24.073	4.98864	5.22326	24.106
5.2233	24.14	5.22326	5.45789	24.157
5.4579	24.175	5.45789	5.69251	24.258
5.6925	24.341	5.69251	5.92714	24.836
5.9271	25.332	5.92714	6.16177	25.984
6.1618	26.636	6.16177	6.39639	27.011
6.3964	27.386	6.39639	6.63102	27.618
6.631	27.849	6.63102	6.86564	29.046
6.8656	30.242	6.86564	7.10027	32.350
7.1003	34.458	7.10027	7.33489	35.892
7.3349	37.326	7.33489	7.56952	37.862
7.5695	38.398	7.56952	7.80415	37.620
7.8041	36.841	7.80415	8.03877	34.389
8.0388	31.936	8.03877	8.2734	29.868
8.2734	27.799	8.2734	8.50802	26.873
8.508	25.947	8.50802	8.74265	25.768
8.7426	25.59	8.74265	8.97727	25.975
8.9773	26.361	8.97727	9.2119	26.828
9.2119	27.296	9.2119	9.44653	27.538
9.4465	27.781	9.44653	9.68115	27.797
9.6812	27.813	9.68115	9.91578	27.366
9.9158	26.919	9.91578	10.1504	26.272
10.15	25.626	10.1504	10.385	25.241
10.385	24.855	10.385	10.6197	24.795

Pre-processed Water Table Concentrations (continued)

Time	vz.grf	Pulse Time On	Pulse Time Off	Approximate Square Pulse Concentration
10.62	24.734	10.6197	10.8543	25.800
10.854	26.866	10.8543	11.0889	28.993
11.089	31.12	11.0889	11.3235	32.628
11.324	34.135	11.3235	11.5582	34.729
11.558	35.323	11.5582	11.7928	34.813
11.793	34.303	11.7928	12.0274	32.382
12.027	30.461	12.0274	12.262	28.766
12.262	27.07	12.262	12.4967	26.294
12.497	25.518	12.4967	12.7313	25.347
12.731	25.175	12.7313	12.9659	25.463
12.966	25.751	12.9659	13.2005	26.120
13.201	26.489	13.2005	13.4352	26.691
13.435	26.894	13.4352	13.6698	27.097
13.67	27.301	13.6698	13.9044	28.387
13.904	29.472	13.9044	14.139	31.060
14.139	32.647	14.139	14.3737	33.606
14.374	34.566	14.3737	14.6083	34.905
14.608	35.245	14.6083	14.8429	34.976
14.843	34.706	14.8429	15.0775	33.954
15.078	33.202	15.0775	15.3122	32.656
15.312	32.11	15.3122	15.5468	31.881
15.547	31.653	15.5468	15.7814	32.425
15.781	33.198	15.7814	16.016	35.727
16.016	38.257	16.016	16.2507	40.557
16.251	42.856	16.2507	16.4853	43.951
16.485	45.046	16.4853	16.7199	44.819
16.72	44.591	16.7199	16.9545	42.016
16.955	39.44	16.9545	17.1892	36.294
17.189	33.147	17.1892	17.4238	31.485
17.424	29.823	17.4238	17.6584	29.268
17.658	28.712	17.6584	17.8931	28.892
17.893	29.072	17.8931	18.1277	29.532
18.128	29.992	18.1277	18.3623	30.339
18.362	30.687	18.3623	18.5969	30.776
18.597	30.864	18.5969	18.8316	30.998
18.832	31.131	18.8316	19.0662	31.317
19.066	31.504	19.0662	19.3008	31.598
19.301	31.692	19.3008	19.5354	31.786
19.535	31.88	19.5354	19.7701	31.650
19.77	31.42	19.7701	20.0047	30.669
20.005	29.919	20.0047	20.2393	29.298
20.239	28.677	20.2393	20.4739	28.241
20.474	27.804	20.4739	20.7086	28.413
20.709	29.022	20.7086	20.9432	32.311

Pre-processed Water Table Concentrations (continued)

Time	vz.grf	Pulse Time On	Pulse Time Off	Approximate Square Pulse Concentration
20.943	35.601	20.9432	21.1778	39.681
21.178	43.761	21.1778	21.4124	46.144
21.412	48.528	21.4124	21.6471	48.948
21.647	49.368	21.6471	21.8817	47.226
21.882	45.084	21.8817	22.1163	41.015
22.116	36.946	22.1163	22.3509	34.217
22.351	31.488	22.3509	22.5856	30.569
22.586	29.651	22.5856	22.8202	28.827
22.82	28.003	22.8202	23.0548	27.033
23.055	26.063	23.0548	23.2894	25.307
23.289	24.551	23.2894	23.5241	24.164
23.524	23.778	23.5241	23.7587	23.767
23.759	23.756	23.7587	23.9933	23.750
23.993	23.744	23.9933	24.2279	23.794
24.228	23.844	24.2279	24.4626	23.946
24.463	24.048	24.4626	24.6972	23.996
24.697	23.944	24.6972	24.9318	23.992
24.932	24.039	24.9318	25.1664	24.121
25.166	24.203	25.1664	25.4011	24.150
25.401	24.097	25.4011	25.6357	24.154
25.636	24.211	25.6357	25.8703	24.664
25.87	25.116	25.8703	26.1049	25.724
26.105	26.332	26.1049	26.3396	26.743
26.34	27.154	26.3396	26.5742	27.430
26.574	27.707	26.5742	26.8088	28.628
26.809	29.548	26.8088	27.0435	31.379
27.043	33.209	27.0435	27.2781	35.048
27.278	36.887	27.2781	27.5127	37.718
27.513	38.55	27.5127	27.7473	37.894
27.747	37.237	27.7473	27.982	35.302
27.982	33.366	27.982	28.2166	31.064
28.217	28.762	28.2166	28.4512	27.365
28.451	25.968	28.4512	28.6858	25.786
28.686	25.604	28.6858	28.9205	25.894
28.92	26.184	28.9205	29.1551	26.603
29.155	27.022	29.1551	29.3897	27.325
29.39	27.628	29.3897	29.6243	27.754
29.624	27.88	29.6243	29.859	27.612
29.859	27.344	29.859	30.0936	26.659
30.094	25.975	30.0936	30.3282	25.351
30.328	24.727	30.3282	30.5628	24.757
30.563	24.787	30.5628	30.7975	25.537
30.797	26.287	30.7975	31.0321	27.995
31.032	29.704	31.0321	31.2667	31.718

Pre-processed Water Table Concentrations (continued)

Time	vz.grf	Pulse Time On	Pulse Time Off	Approximate Square Pulse Concentration
31.267	33.732	31.2667	31.5013	34.607
31.501	35.482	31.5013	31.736	35.027
31.736	34.573	31.736	31.9706	33.040
31.971	31.507	31.9706	32.2052	29.712
32.205	27.917	32.2052	32.4398	26.751
32.44	25.586	32.4398	32.6745	25.305
32.674	25.023	32.6745	32.9091	25.373
32.909	25.723	32.9091	33.1437	26.167
33.144	26.611	33.1437	33.3783	26.558
33.378	26.506	33.3783	33.613	26.796
33.613	27.085	33.613	33.8476	28.106
33.848	29.127	33.8476	34.0822	30.465
34.082	31.803	34.0822	34.3168	32.937
34.317	34.072	34.3168	34.5515	34.657
34.551	35.242	34.5515	34.7861	35.089
34.786	34.936	34.7861	35.0207	34.286
35.021	33.637	35.0207	35.2554	32.942
35.255	32.246	35.2554	35.49	31.925
35.49	31.603	35.49	35.7246	32.273
35.725	32.942	35.7246	35.9592	34.738
35.959	36.535	35.9592	36.1939	39.063
36.194	41.591	36.1939	36.4285	43.513
36.428	45.435	36.4285	36.6631	45.192
36.663	44.95	36.6631	36.8977	42.717
36.898	40.483	36.8977	37.1324	37.740
37.132	34.997	37.1324	37.367	32.658
37.367	30.319	37.367	37.6016	29.459
37.602	28.598	37.6016	37.8362	28.852
37.836	29.106	37.8362	38.0709	29.646
38.071	30.185	38.0709	38.3055	30.231
38.305	30.276	38.3055	38.5401	30.373
38.54	30.471	38.5401	38.7747	30.739
38.775	31.007	38.7747	39.0094	31.417
39.009	31.828	39.0094	39.244	31.772
39.244	31.717	39.244	39.4786	31.661
39.479	31.605	39.4786	39.7132	31.261
39.713	30.917	39.7132	39.9479	30.627
39.948	30.337	39.9479	40.1825	30.015
40.182	29.693	40.1825	40.4171	29.194
40.417	28.696	40.4171	40.6517	27.322
40.652	25.948	40.6517	40.8864	22.798
40.886	19.649	40.8864	41.121	15.539
41.121	11.429	41.121	41.3556	7.892
41.356	4.3558			

FIGURES

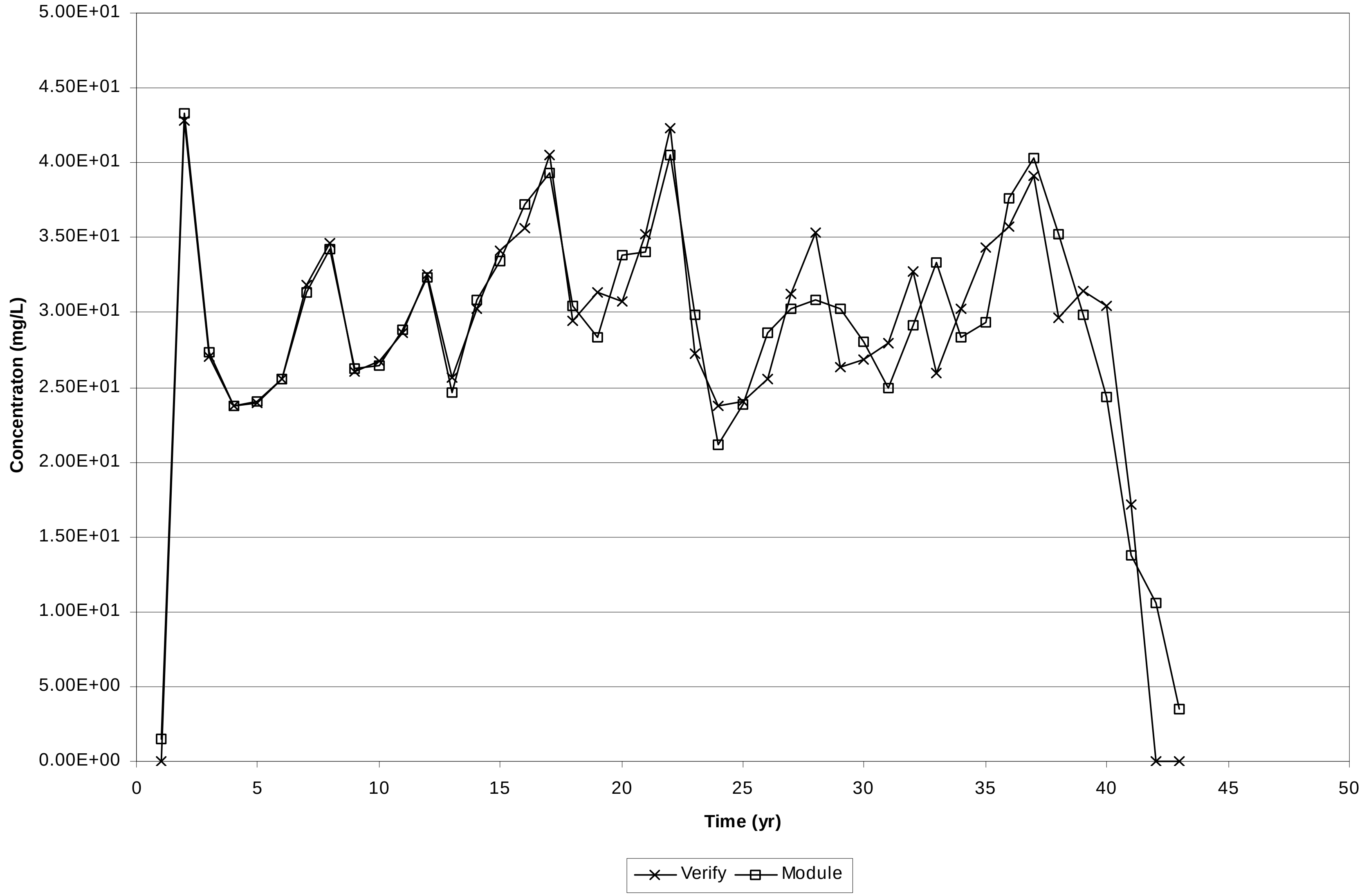

Figure 1. Centerline Breakthrough Curve for HWIR99 And Verification Modules, X = 257, for Well 58.

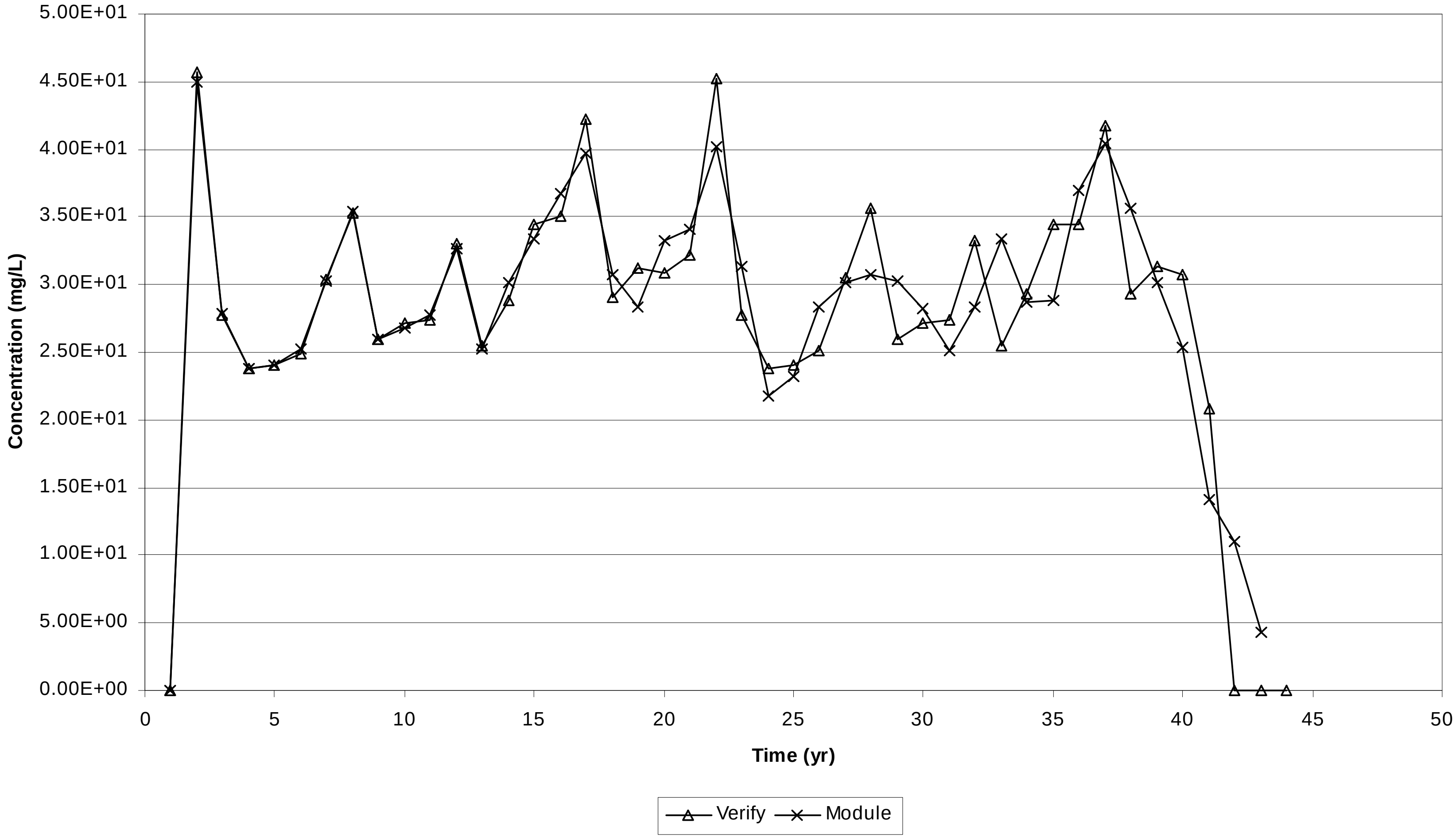

Figure 2. Centerline Breakthrough Curve for HWIR99 And Verification Modules, X = 504, for Well 81.

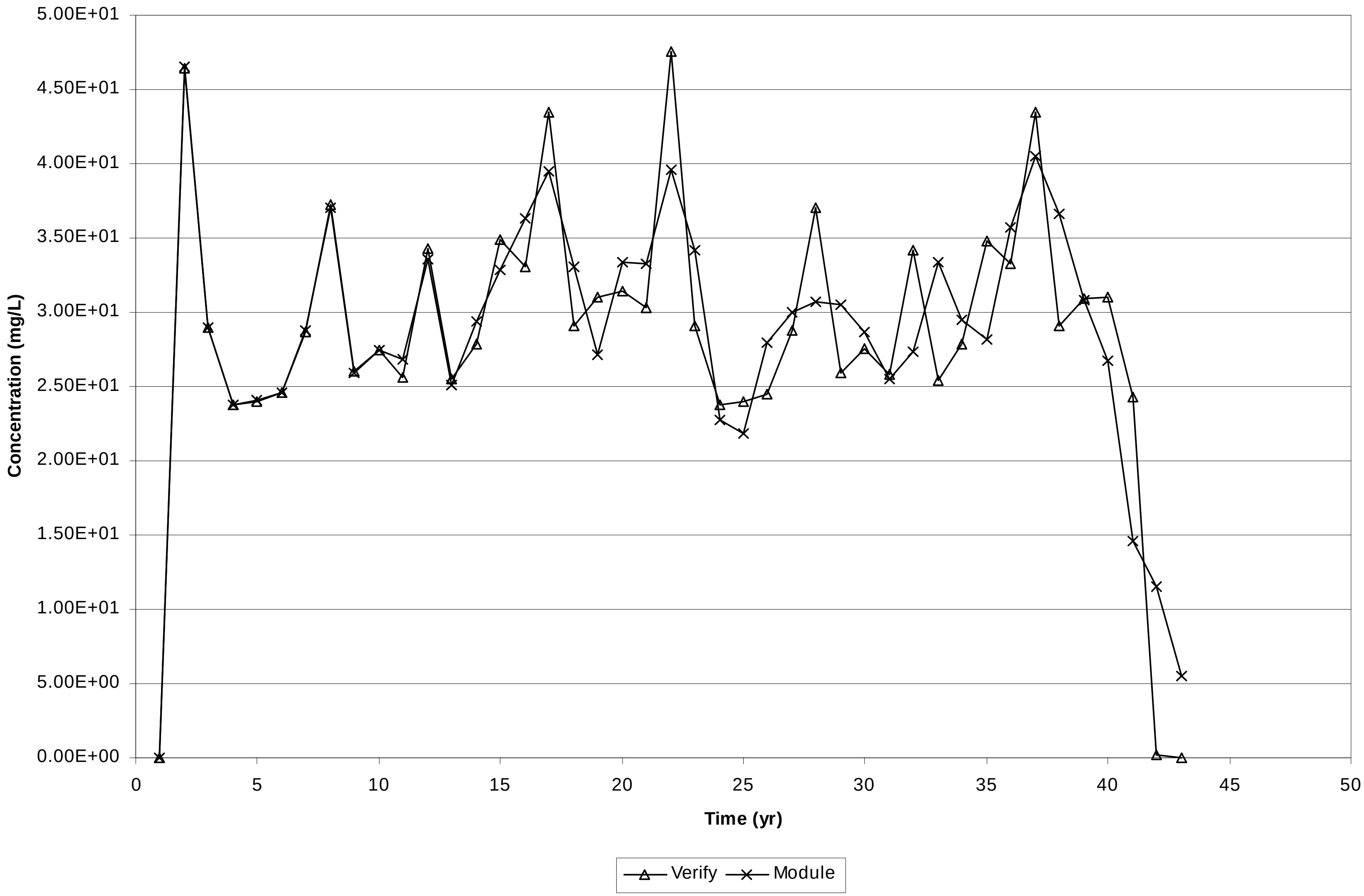

Figure 3. Centerline Breakthrough Curve for HWIR99 And Verification Modules, X = 955, for Well 93.

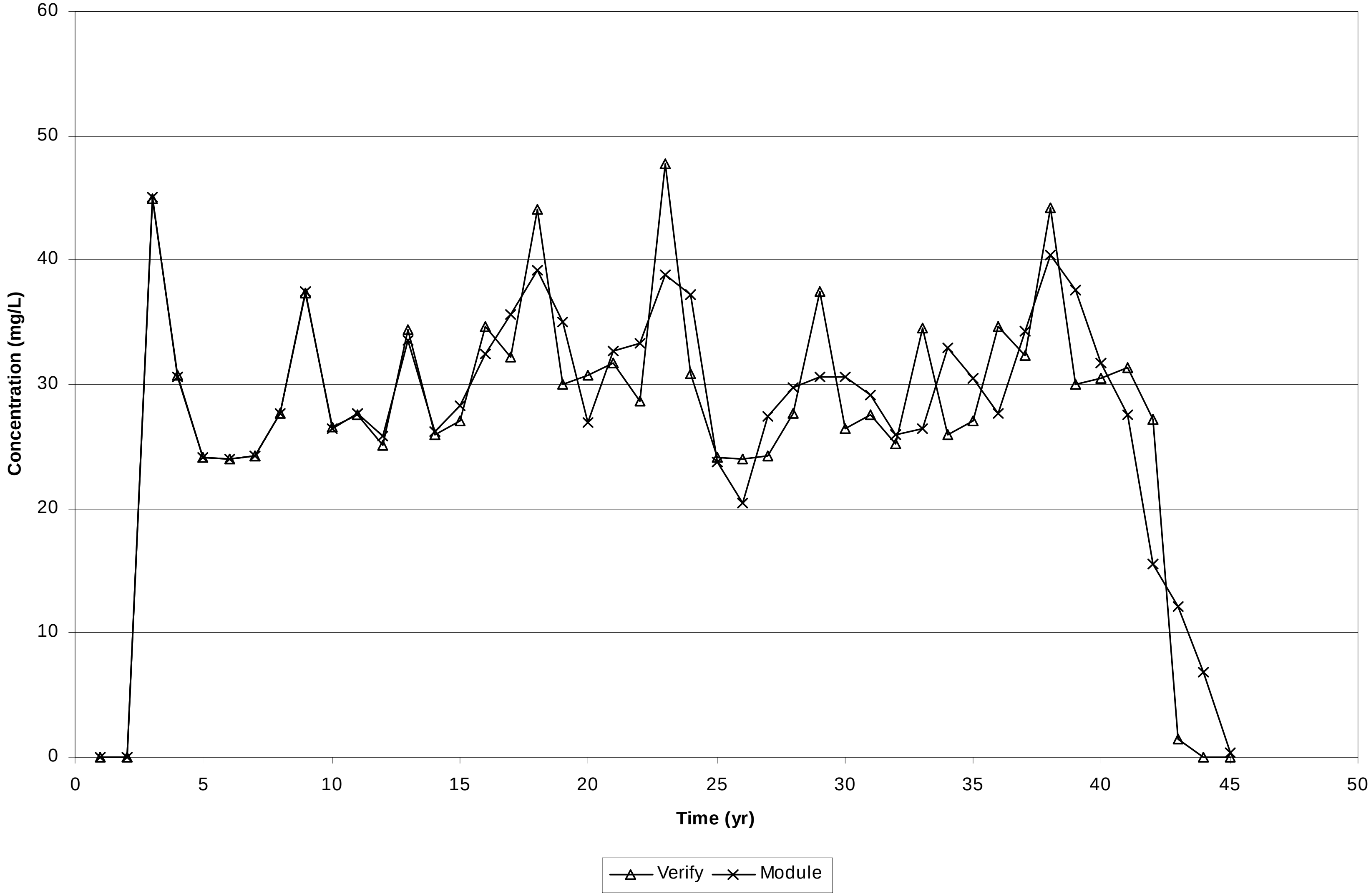

Figure 4. Centerline Breakthrough Curve for HWIR99 And Verification Modules, X = 1462, for Well 103.

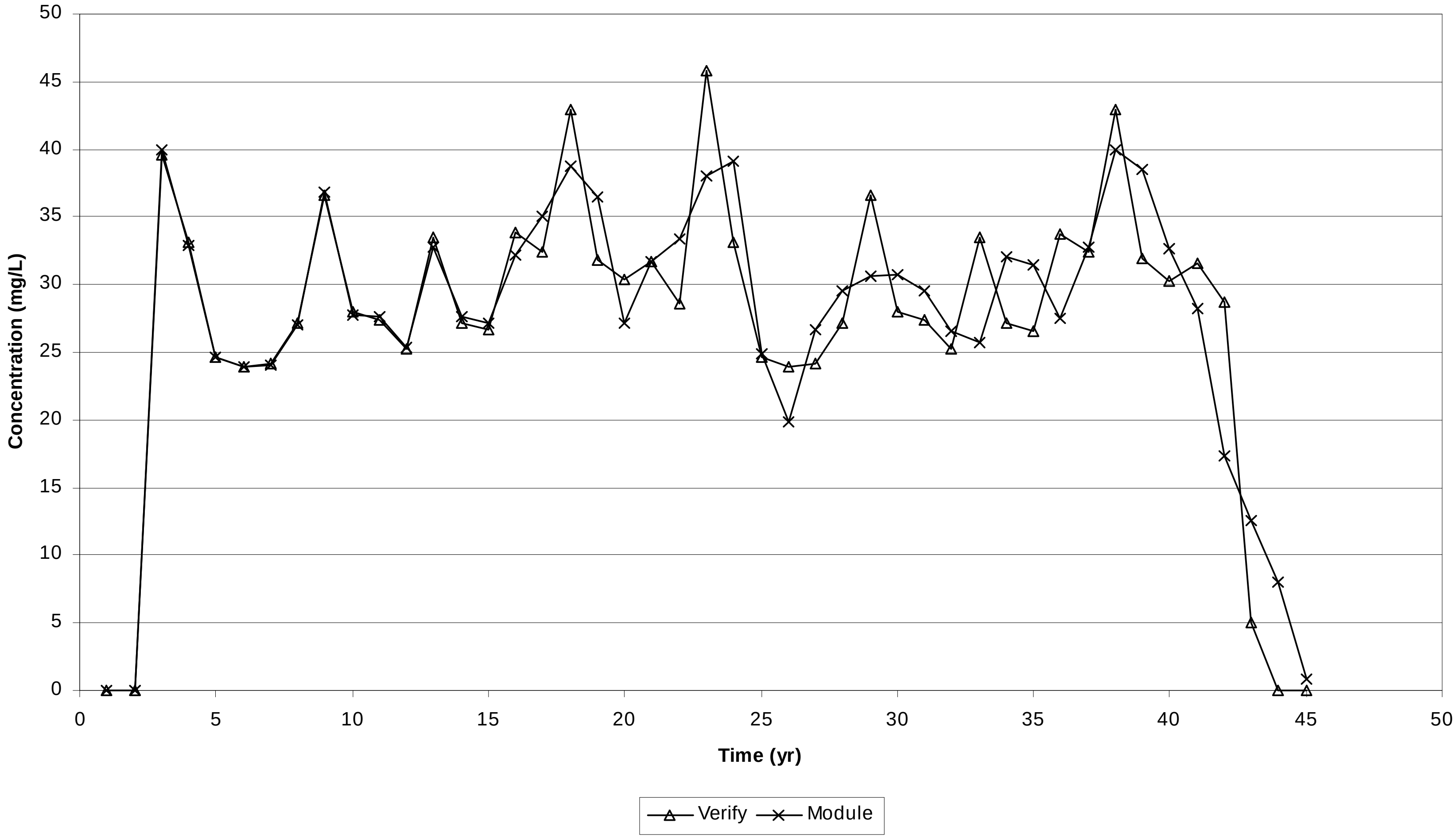

Figure 5. Centerline Breakthrough Curve for HWIR99 And Verification Modules, X = 1962, for Well 115.

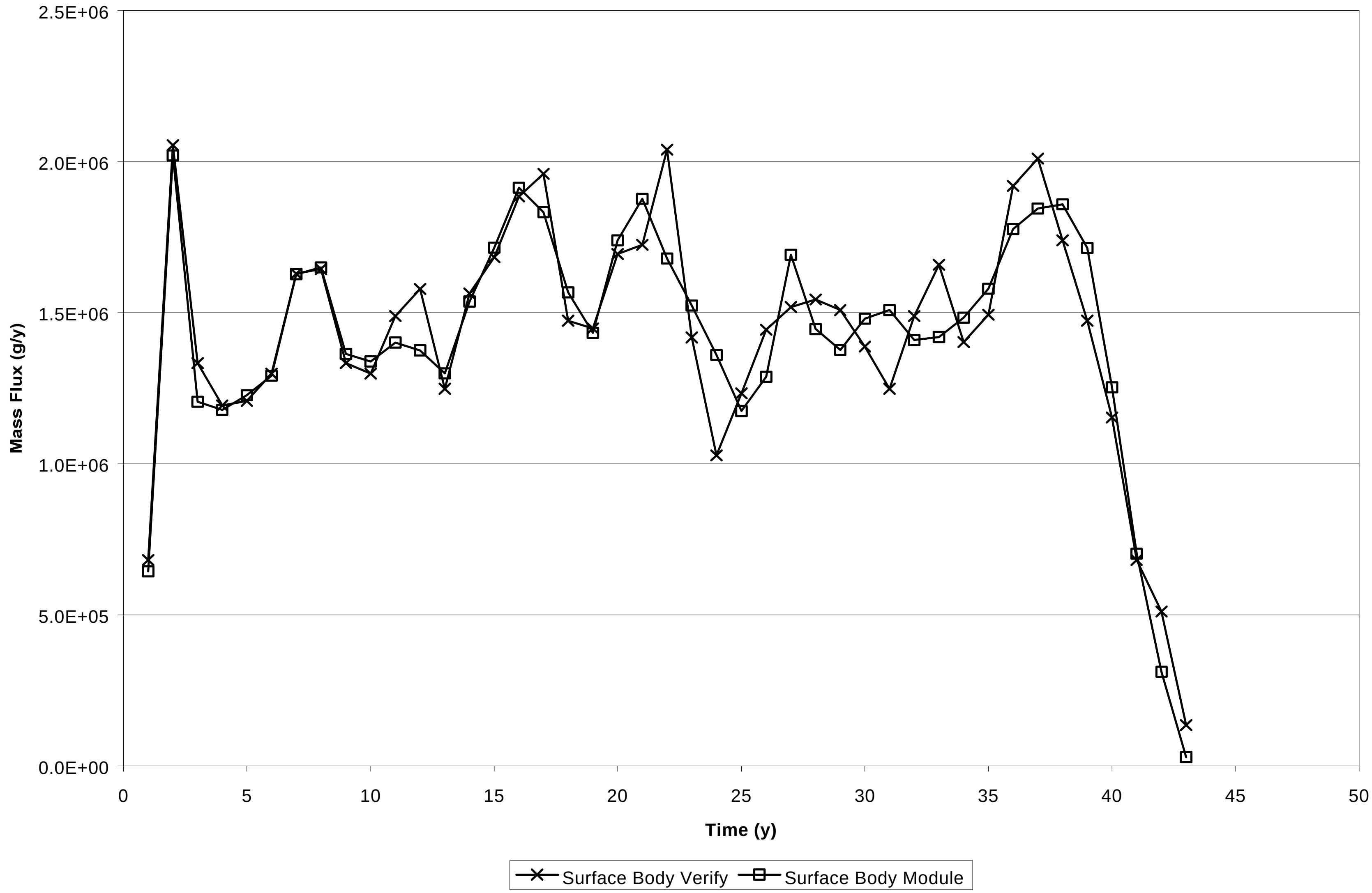

Figure 6. Surface Water Body Verification

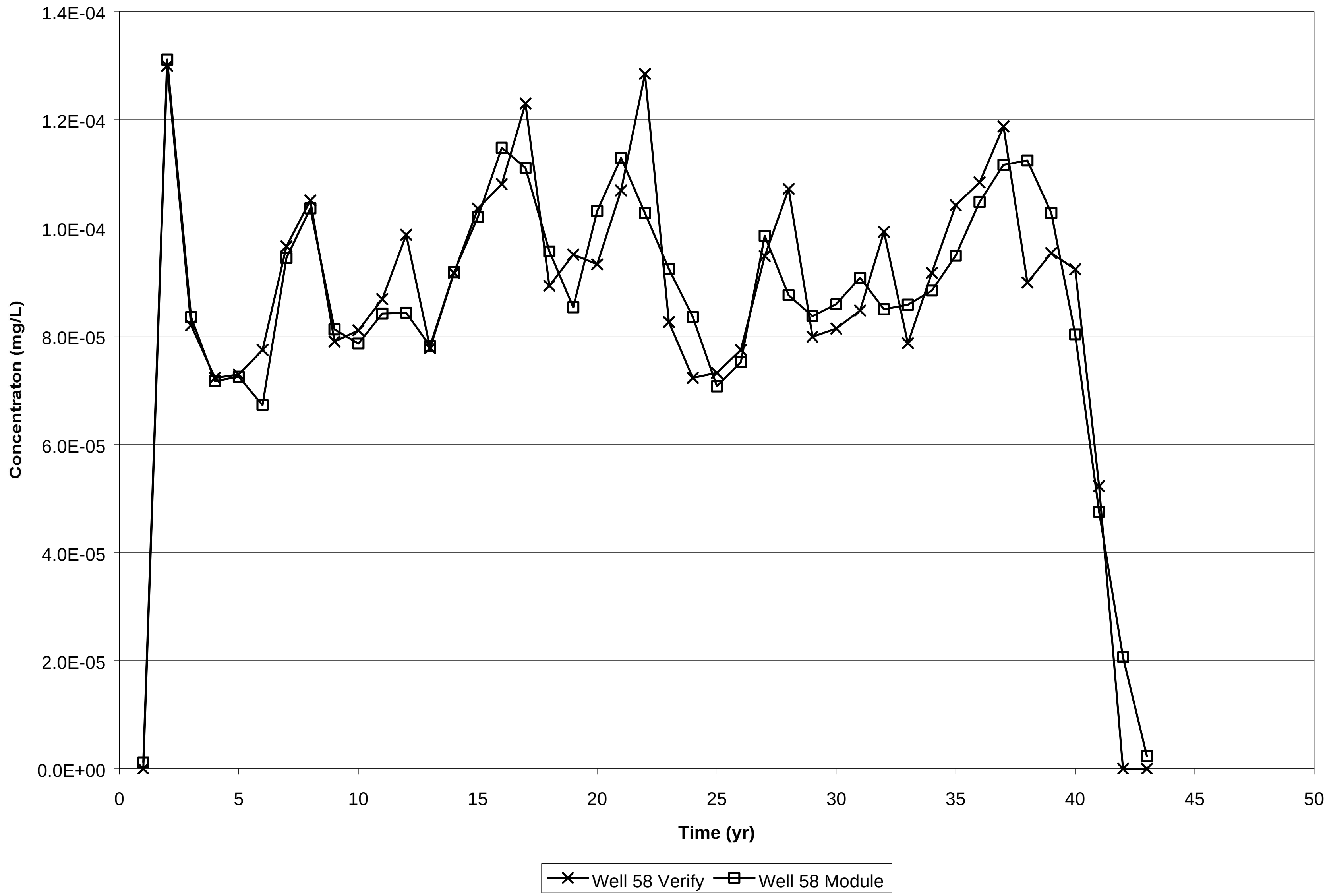

Figure 7 Breakthrough Curves for HWIR99 and Verification Modules at Well 58.

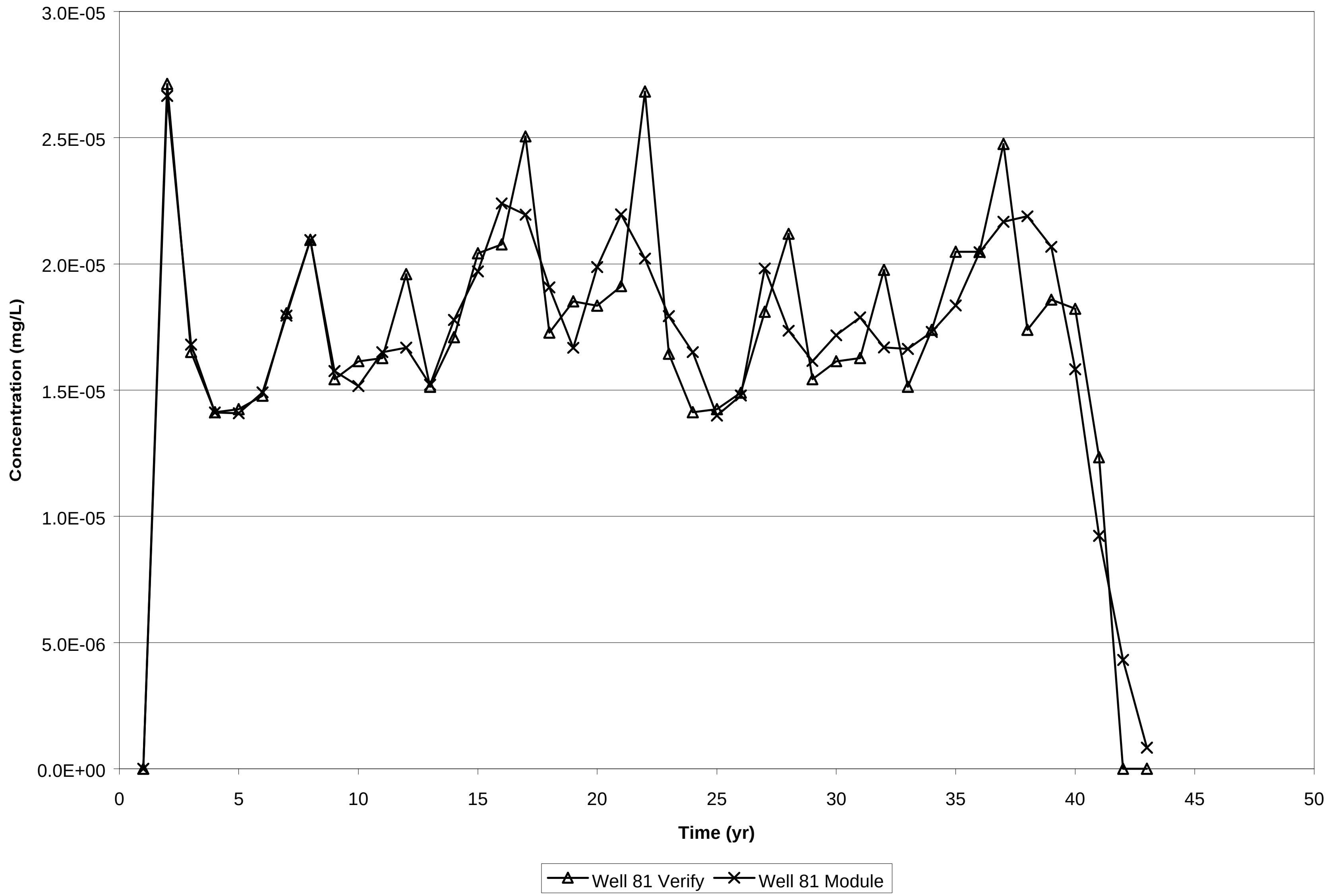

Figure 8 Breakthrough Curves for HWIR99 and Verification Modules at Well 81.

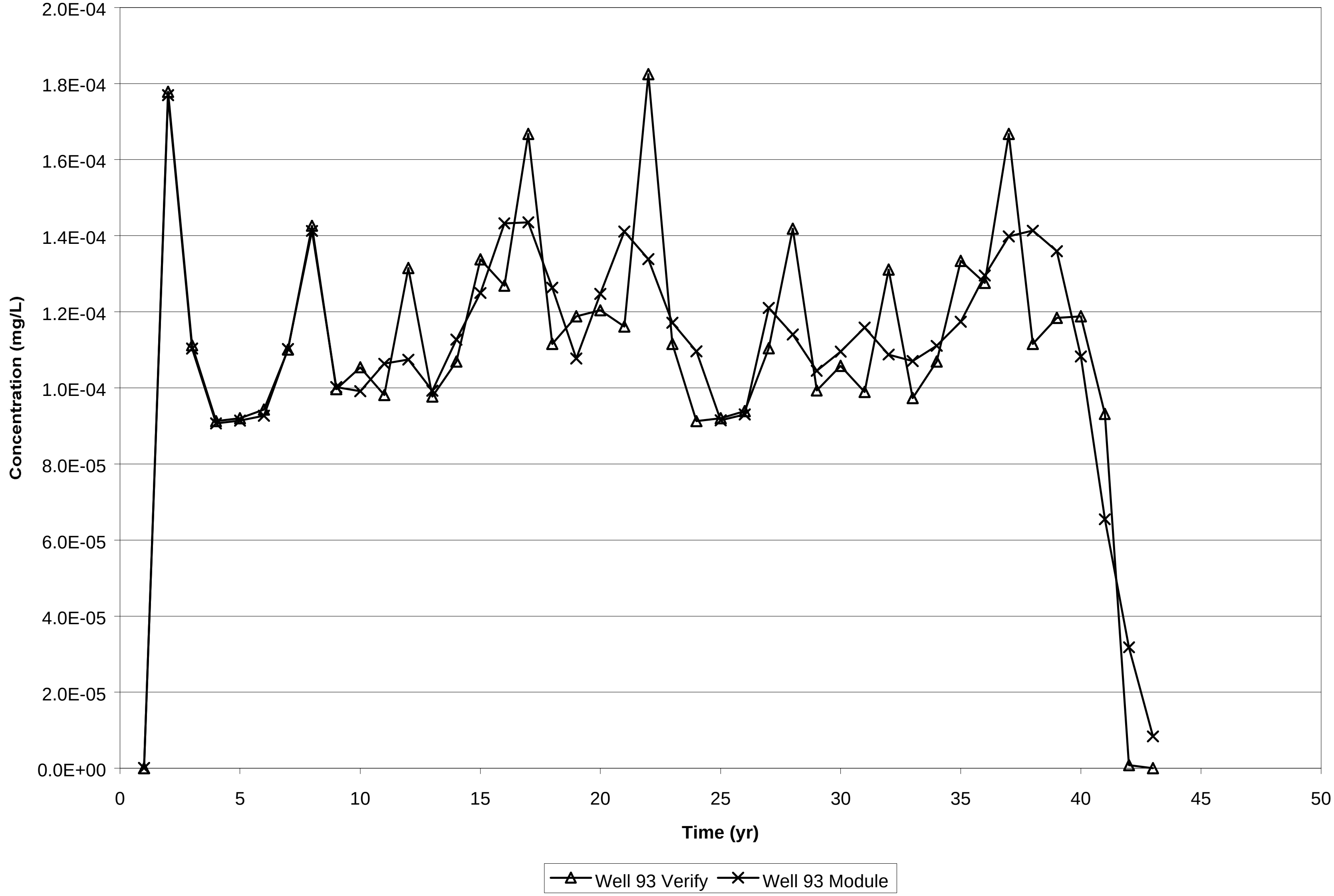

Figure 9 Breakthrough Curves for HWIR99 and Verification Modules at Well 91.

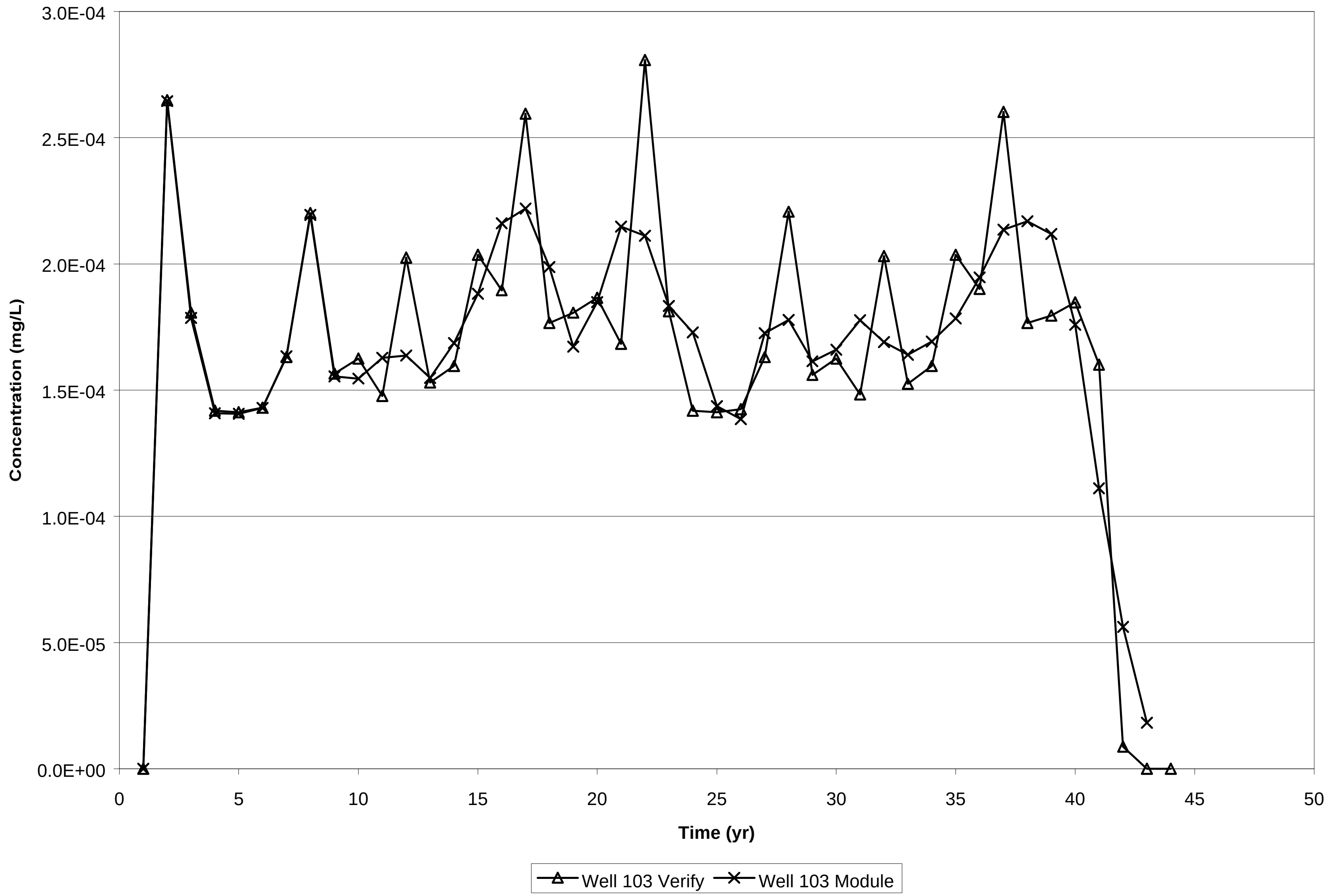

Figure 10 Breakthrough Curves for HWIR99 and Verification Modules at Well 103.

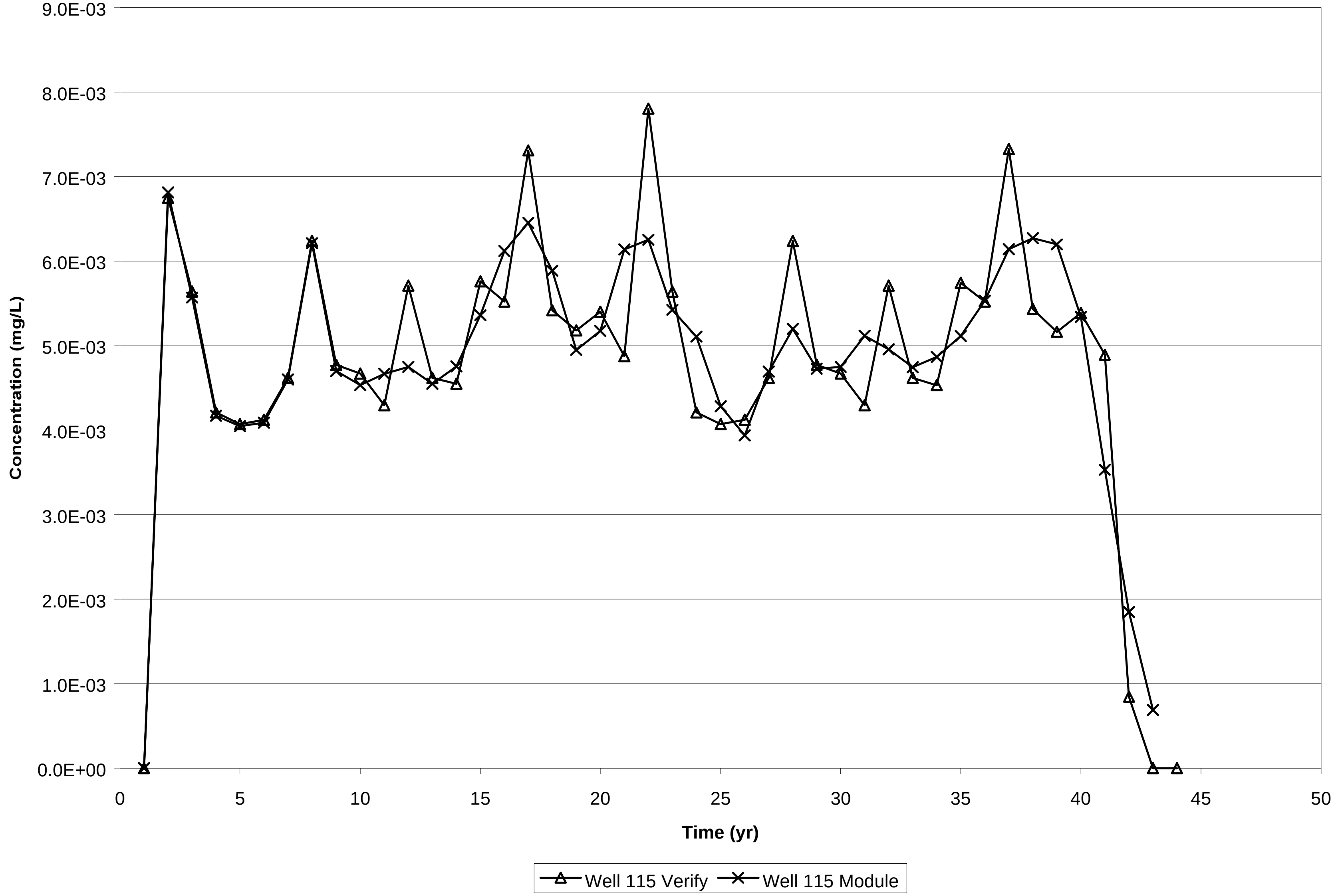

Figure 11 Breakthrough Curves for HWIR99 and Verification Modules at Well 115.