Induced Recharge Tracer Test in Aare River Using Solute and Particle Tracers

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Introduction

This report provides a brief outline of the procedures and results of a tracer test carried out in the Aare River (the Aare)to investigate the vulnerability of wells located in a downstream riparian zone to solute and particle contamination present in the river water. The test involved adding artificial solute and particle tracers to the Aare from the bridge over the river at Belp, BE , approximately five Km upstream on two well fields. Monitoring for both tracers in both water supply well fields and in the adjacent stretch of river provided important information concerning transport of contaminants contained in recharge waters flowing to the wells from the river. Overall the results of this project provide a preliminary indication of the vulnerability of water supply wells located riparian zones to contamination associated with induced recharge.

This project is a joint collaboration between the Office of Hydraulic and Energy Economics of the Canton of Berne (WEA) who retained Kellerhals and Haefeli AG (K&H) as consultants, and the Centre d'hydrogéologie of the University of Neuchâtel (CHYN). The joint test was carried out over a four day between 24 January 2002 and 28 January 2002. Note that the K&H final report for this test provides a more comprehensive treatment of background details.

Site Setting

Both well fields are located along the banks of the Aare approximately 10 Km south of the City of Berne (BE). All wells are set in highly permeable unconsolidated quaternary alluvial deposits and constitute important municipal water sources. Two water supply wells each located approximately 50 metres from the eastern bank of the Aare River at Muri (W1 and W 2) provide water to the commune of Muri. The two public supply wells located approximately 100m west of the river, north west of Berne Airport (K1 and K3) supply the city of Berne and the adjacent commune of Kehrsatz. K&H recently instaled an additional well, P1, approximately 50m west of the river. All five points were monitored for tracers during the tracer test, along with river water monitoring points on the eastern and western sides of the Aare.

Materials and Methods

Selection of the artifical tracers Sodium Fluorescein (Fluorescein) and the H40/1 bacteriophage allowed the migration of solutes and particles from the Aare in the deposits adjacent to the river to be investigated. Comparitive responses provide an indication of the differing behaviour of the different particle types.

Fluorescein is a highly soluble, widely used fluorescent solute that can be easily detected in low concentrations (<1 ug/l) in water. In the absence of organic matter, fluorescein undergoes little to no interaction with aquifer materials, thereby approximating conservative solute behaviour. Nonetheless Fluorescein displays strong photosensitivity. Despite fluroesceins very low detection limits, the high flow rate in the Aare indicated that large quantities of the tracer would be necessary if the tracer were to be deteced downstream.

On-line fluoresence measurement in the two water supply wells on the eastern bank of the Aare (W1 and W2) and in the adjacent stretch of the Aare, using fluorometers provided by the

Geomagnetism Group of the Université de Neuchâtel (GGUN), allowed fluorescein concentrations as low as 0.1 ppb to be measured. Moreover, laboratory analyses at the WEA laboratory, of samples collected manually by K&H from all five wells and on both sides of the Aare, allowed the fluorometer concentrations to be verified. Both data sets provided the necessary data to allow solute breakthrough curves to be generated.

H40/1 acted as the particle tracer during this experiment. The particle is a non pathogenic host specific bacteriophage, which only infects one species of marine bacterium. Consequently H40/1 is naturally absent in freshwaters and thus allowing detections at very low concentrations. The Microbiology Laboratory of the University of Neuchâtel (LAMUN) has carried out much research on bacteriophage cultivation, concentration and analyses during the past ten years. Moreover, collaborative efforts between the CHYN and LAMUN have allowed the migration characteristics of various phages to be investigated, and the most suitable phages for particular studies to be selected. The CHYN/LAMUN team selected H40/1 for this study since it is both capable of migrating significant distances in unconsolidated aquifers and can be easily concentrated / analysed. H40/1s transport properties allow it to travel further in aquifers than many conventional pathogenic microbes such as polio. Consequently, the response of H40/1 can be regarded as being more conservative than numerous conventional pathogenic viruses.

Using newly developed techniques, LAMUN provided approximately 6×10^{15} pfu of H40/1in three litres for the experiment (the stock). This stock was mixed with the fluorescein tracer and injected simultaneously during the tracer experiment. Consequently, any differences in tracer responses are a result of differing transport and attenuation processes, rather than differing injection signals.

Conventional bacteriophage concentration analysis involves a two step procedure in which the presence of the phage is determined by counting the number of plaque forming units (pfu) formed in a layer of the host bacteria. If concentrations exceed 10 pfu/ml, a second step involving a more comprehensive titration, permits a more detailed quantification. Using this technique, concentrations of 0.5 pfu/mL can be measured. Coupled with the conventional approach outlined above, LAMUN has recently developed an alterrnative technique which allows phages to be detected at up to 0.1 pfu/mL. These techniques and materials allow the migration of solutes and viruses in the Aare River and the deposits adacent to the five wells downstream to be investigated with a high degree of resolution.

Monitoring Methodology.

K&H and CHYN developed monitoring programs for solute and particle tracers prior to the experiment in order to optimise detection and analysis procedures. Approximately one hour prior to injection of the tracer mixture, CHYN and K&H collaborators mixed 750mL of bacteriophage stock in each of the four drums containing 40 litres of 10% fluorescein. Source samples were subsequently collected for bacteriophage analyses on calibration of the GGUN fluorometers. Immediately prior to injection K&H placed the four drums at approximately equal spacings on the Bridge over the Aare at Belp. CHYN collaborators collected additional source samples immediately prior to injection to ascertain whether the concentrations of phages in the mixture had declined in the mixture. Injection into the river took place between 17:12 and 17 :36 (24 January 2002) using the siphon method to draw the tracer from the four drums and inject it into the Aare. This injection technique and mixing along the five Km stretch of river maximized the chances for complete tracer homogenisation from each of the four injection points before the tracers reached the downstream monitoring points.

Manual collection of Aare river-water samples for fluorescein and bacteriophage analyses commenced approximatly 10 minutes after the end of injection and continued for three minute intervals on both banks for the following 2.5hrs to 3hrs. In addition, a GGUN fluorometer measured fluorescein concentrations at ten second intervals at a point in the eastern part of the Aare from approximately one hour before injection until seven hours thereafter.

Monitoring for both tracers in wells W1 and W2 started approximately two hours prior to injection and continued for the following four days. A downhole fluorometer measured fluorescein concentrations in well W1 at four minute intervals. CHYN/K&H collaborators used a stainless steel bailer to collect well water for bacteriophage analyses a predefined intervals. In a similar manner, a GGUN flurometer measured on line concentrations of the discharge water pumped from W2 at 4 minute intervals. An automatic sampler collected water samples for bacteriophage analysis at 15 minute intervals for the first 14 hours after injection. K&H collaborators manually collected additional water samples from both wells for bacteriophage and fluorescein analyses after this period until the end of the joint test four days later. Furthermore, K&H collaborators manually collected the samples of water pumped from wells K1, K3 and P1 to the west of the Aare for bacteriophage and fluorescein analyses over similar time intervals.

All water samples collected for fluorescein measurement were stored away from bright light to minimise photodegradation. Similarly, water samples collected for bacteriophage analyses were refridgerated upon collection to eliminated the possibility of bacteriophage deactivation due to elevated temperatures.

Results :

Figure 1 shows a composite plot of on-line fluorescein concentrations and bacteriophage concentrations in the Aare River with time. Figures two and three display similar plots for wells W1 and W2. Note that in all cases the concentrations of Fluorescein were determined using calibrations curves developed using samples collected from the sample drums prior to injection (assumed to be at 4 Kg in 40.75 litres).

Moreover, although no phages are noted in W2 using conventional techniques, the recently developed detection method used for very low phage concentrations detected phages in this well, although exact concentrations were as yet not available at the time of writing (3 Feb. 2002). Analyses of samples from K1, K3 and P1 failed to detect bacteriophages. Table 1 : Summarises test results for the Aare River and Wells W1 &W2. Results of Bacteriophage analyses are contained in Appendix I.

Table 1 : Summary of Breakthrough Characteristics for Fluorescein and H40/1 in the Aare River, Well W1 and Well W2.

Location	Fluorsecene First Detection Time (Hrs)	Fluorsecene Peak Conc. Time (Hrs)	Fluorsecene $C_{max}/(C_{maxRiver})$	H40/1 First Detection (Hours)	H40/1 Peak Conc. Time (Hours)	H40/1 $C_{max}/(C_{maxRiver})$
Aare River	**1.24**	**1.6**	**1**	**1.24**	**1.59**	**1**
Well W1	**10.58**	**25**	**0.58/53.9 $=1x10^{-2}$**	**2.21**	**3.71**	**4/100800 $= 4 x 10^{-5}$**
Well W2	**9.6**	**30**	**0.69/53.9 $=1.3 x 10^{-2}$**	**PNQ***	**PNQ***	**PNQ***

* Present but not quantified at time of writing (3 Feb 2002)

Figure 1: Plot of Sodium Fluorescene and H40/1 Bacteriophage Concentrations, Aare River. Muri. 24-25 January 2002.

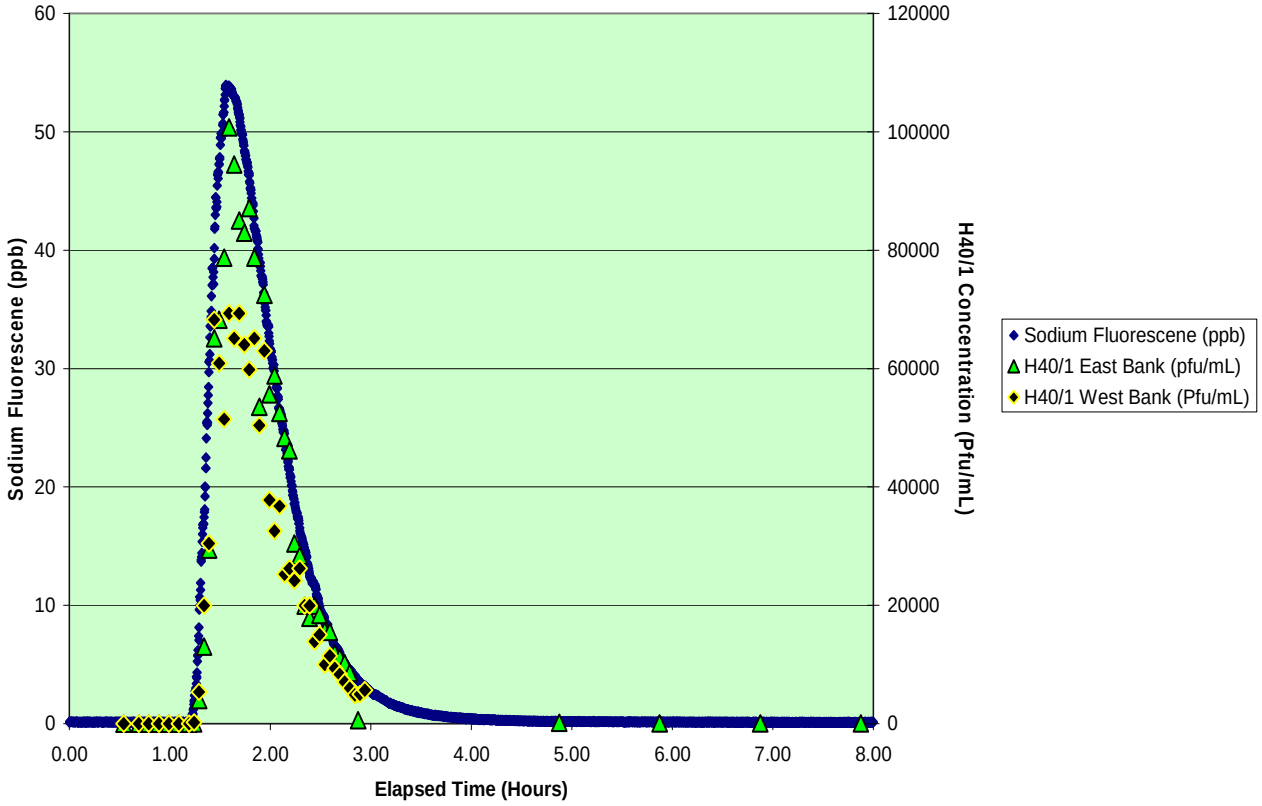


Figure 2: Plot of Fluorescein and H40/1 Concentrations in Water Supply Well W1. Muri, BE. Jan 24-27 2002

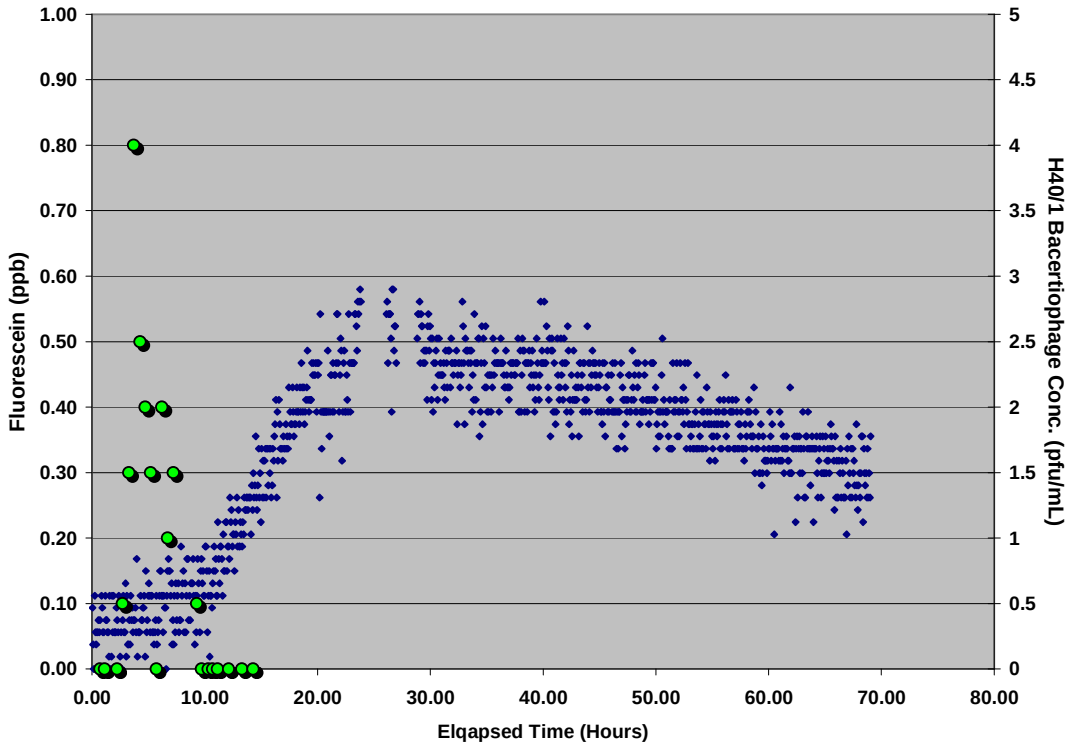
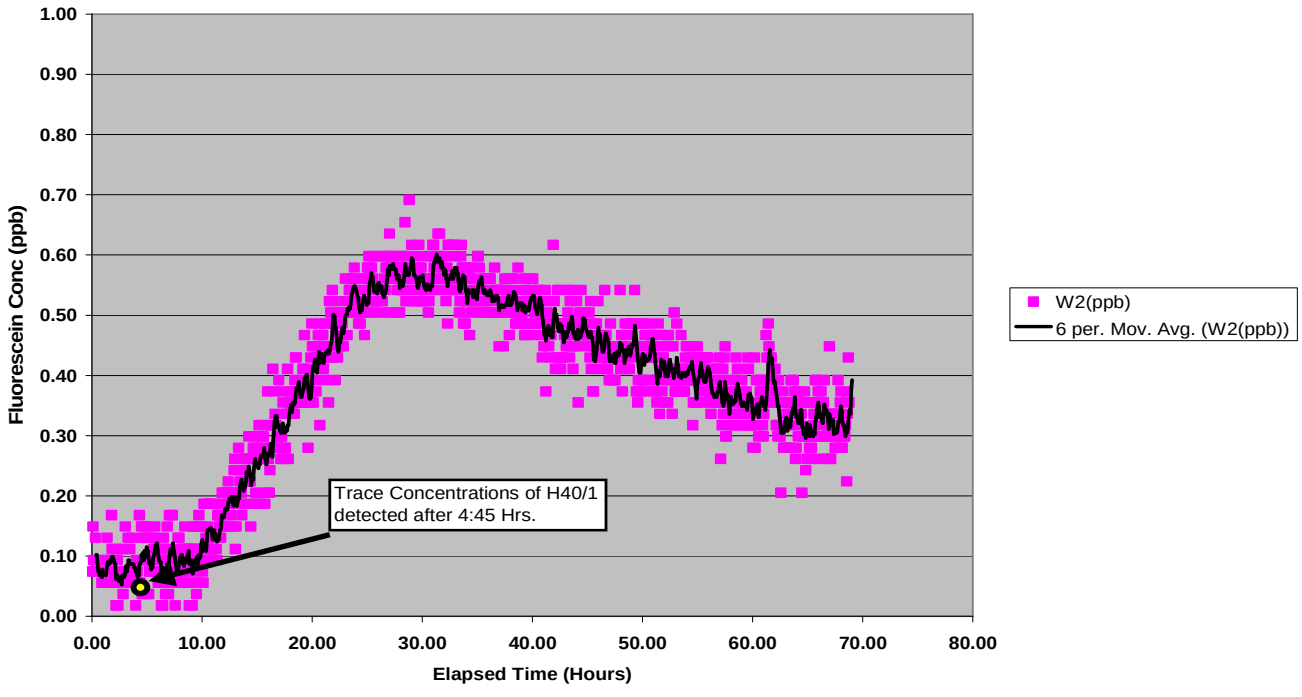


Figure 3: Plot of Fluorescein Concentration in Water Supply Well W2, Muri. Jan 24-27 2002.



Despite the results provided above, independent fluorescein analyses reported concentrations of fluorescein in W1 below levels detectable with the GGUN fluorometer. This material is suspected to be cross contamination from source material. Approximate concentrations have been reported at around 0.01ppb, and do not significantly influence the solute breakthrough curve observed in the well. Nonetheless, WEA has expressed concern that the bacteriophage concentrations observed in the well may also be a result of contamination.

CHYN believes this to be improbable for the following reasons:

1. Independent analyses report fluorescein contamination to be present in samples collected at 0.71hrs, 1.13hr and 2.21hrs immediately after injection. However, bacteriophages are absent in all these samples.

2. Bacteriophages have unequivocally been detected in well W2 where no contamination has been reported.

3. The bacteriophage breakthrough curve behaves in a manner typical for viral breakthrough curves where there is strong attenuation, namely earlier first arrivals than solutes and earlier peak times. (These phenomena are further discussed). Figure 1 in Appendix II illustrates this process using tracer test data collected at the Kappelen test sit, Kappelen, BE. Using an attenuation factor of 10^{-5} instead on 10^{-3} as used in Kappelen, the breakthrough curve observed at Muri can be adequately reproduced. This is demonstrated in Figure 2 in Appendix 2. The difference in these attenuation factors are a result of different textural conditions present in the fluvioglacial deposits at Kappelen and the alluvial deposits at Muri.

The following discussion assumes the above to be the case.

Discussion

Tracer test results illustrate that viruses contained in Aare riverwater may migrate to Muri water supply wells. Table 1 shows that phage the first arrival times are considerably less than those of the solute. Moreover the time of the peak phage concentration is also substantially shorter than that of the solute. This information does not mean that the phages travel faster than the solute. It is, in fact, a result of significantly lower analytical detection limits for the phages compared to those of the solute, i.e. the solute is also present in the well but at levels below the detection limit. The reason why the arrival times are much shorter to the phages relates to the pore size distribution and attenuation properties of the aquifer materials separating the Aare from the water supply wells. A comparison of the relative maximum concentrations of fluorescein and H40/1 shows that the phages are significantly attenuated relative to the solute. In fact the phages can only travel along a very limited number of flow paths, namely those with the highest velocity. Following other flow paths results in phage adsorbtion/deactivation which prevents the viruses from reaching the wells.

In contrast to H40/1, fluorescein can reach the well via a much larger number of flow paths, although the overall flow velocities along these routes are lower. This explains both the higher relative concentrations of the solute and the later arrival times.

Significantly, the Fluorescein breakthrough curves for W1 and W2 are very similar, whereas the responses for the phages in both wells show that attenuation is significantly higher in W2. This is believed to be a reflection of aquifer heterogeneity. The attenuation of bacteriophages in an aquifer may be due to variations in aquifer grain size, mineralogy or hydrochemistry. The available data do not permit an identification of the appropriate process. Nonetheless the results indicate the risks associated with choosing a solute tracer to simulate particle transport and visa-versa.

Based on these conclusions, the importance of site heterogeneity and choice of appropriate tracer must be emphasised in studying the effects of contaminant transport reaching water supply wells from adjacent rivers.

From a public health perspective, the test results illustrate that the aquifer materials separating the water supply wells from the Aare have a significant attenuation capacity. Nonethless the presence of viruses in wells W1 and W2 effectively demonstrates that microbes can reach the wells and thus, despite the low relative concentrations, potentially pose a health risk. The absence of phages in the wells to the west of the Aare indicates that these wells are better protected from microbial contamination, possibly due to their location at greater distances from the river.

Appendix I-

Results of H40/1 Bacteriophage Analyses for W1, W2 and Aare River.

H40/1 Results East Bank Aare River

Start Sampling 1/24/02 17:45
Injection Time 1/24/02 17:12

Sample	Time	Elapsed Time	H40/1 (Pfu/mL)Aare East Bank
1	1/24/02 17:45	0.54	0
3	1/24/02 17:54	0.69	0
5	1/24/02 18:00	0.79	0
7	1/24/02 18:06	0.89	0
9	1/24/02 18:12	0.99	0
11	1/24/02 18:18	1.09	0
13	1/24/02 18:24	1.19	0
14	1/24/02 18:27	1.24	52.5
15	1/24/02 18:30	1.29	3990
16	1/24/02 18:33	1.34	13020
17	1/24/02 18:36	1.39	29400
18	1/24/02 18:39	1.44	65100
19	1/24/02 18:42	1.49	68250
20	1/24/02 18:45	1.54	78750
21	1/24/02 18:48	1.59	100800
22	1/24/02 18:51	1.64	94500
23	1/24/02 18:54	1.69	85050
24	1/24/02 18:57	1.74	82950
25	1/24/02 19:00	1.79	87150
26	1/24/02 19:03	1.84	78750
27	1/24/02 19:06	1.89	53550
28	1/24/02 19:09	1.94	72450
29	1/24/02 19:12	1.99	55650
30	1/24/02 19:15	2.04	58800
31	1/24/02 19:18	2.09	52500
32	1/24/02 19:21	2.14	48300
33	1/24/02 19:24	2.19	46200
34	1/24/02 19:27	2.24	30450
35	1/24/02 19:30	2.29	28350
36	1/24/02 19:33	2.34	19950
37	1/24/02 19:36	2.39	17850
38	1/24/02 19:39	2.44	19950
39	1/24/02 19:42	2.49	18375
40	1/24/02 19:45	2.54	15645
41	1/24/02 19:48	2.59	15540
42	1/24/02 19:51	2.64	11865
43	1/24/02 19:54	2.69	11130
44	1/24/02 19:57	2.74	10185
45	1/24/02 20:00	2.79	8610
	1/24/02 20:05	2.87	546
	1/24/02 22:05	4.88	136.5
	1/24/02 23:05	5.87	56.7
	1/25/02 0:05	6.87	23.1
	1/25/02 1:05	7.88	30.45

H40/1 Results West Bank Aare River

Start Sampling 1/24/02 17:45
Injection Time 1/24/02 17:12

Sample	Time	Elapsed Time	Count	C/Co
1	1/24/02 17:45	0.54	0	
3	1/24/02 17:54	0.69	0	
5	1/24/02 18:00	0.79	0	
7	1/24/02 18:06	0.89	0	
9	1/24/02 18:12	0.99	0	
11	1/24/02 18:18	1.09	0	
13	1/24/02 18:24	1.19	0	
14	1/24/02 18:27	1.24	168	
15	1/24/02 18:30	1.29	5355	
16	1/24/02 18:33	1.34	19950	
17	1/24/02 18:36	1.39	30450	
18	1/24/02 18:39	1.44	68250	
19	1/24/02 18:42	1.49	60900	
20	1/24/02 18:45	1.54	51450	
21	1/24/02 18:48	1.59	69300	
22	1/24/02 18:51	1.64	65100	
23	1/24/02 18:54	1.69	69300	
24	1/24/02 18:57	1.74	64050	
25	1/24/02 19:00	1.79	59850	
26	1/24/02 19:03	1.84	65100	
27	1/24/02 19:06	1.89	50400	
28	1/24/02 19:09	1.94	63000	
29	1/24/02 19:12	1.99	37800	
30	1/24/02 19:15	2.04	32550	
31	1/24/02 19:18	2.09	36750	
32	1/24/02 19:21	2.14	25200	
33	1/24/02 19:24	2.19	26250	
34	1/24/02 19:27	2.24	24150	
35	1/24/02 19:30	2.29	26250	
36	1/24/02 19:33	2.34	19950	
37	1/24/02 19:36	2.39	19950	
38	1/24/02 19:39	2.44	13860	
39	1/24/02 19:42	2.49	15015	
40	1/24/02 19:45	2.54	9975	
41	1/24/02 19:48	2.59	11445	
42	1/24/02 19:51	2.64	9345	
43	1/24/02 19:54	2.69	8295	
44	1/24/02 19:57	2.74	7035	
45	1/24/02 20:00	2.79	5985	
46	1/24/02 20:03	2.84	4830	
47	1/24/02 20:06	2.89	4935	
48	1/24/02 20:09	2.94	5670	

H40/1 Results W1 Supply Well

Start Sampling	1/24/02 17:45
Injection Time	1/24/02 17:12

Elapsed Time	H40/1 (Pfu/mL) W1 Supply Well
0.71	0
1.13	0
2.21	0
2.71	0.5
3.26	1.5
3.71	4
4.26	2.5
4.71	2
5.21	1.5
5.71	0
6.21	2
6.71	1
7.21	1.5
9.29	0.5
9.71	0
10.29	0
10.69	0
11.12	0
12.12	0
13.29	0
14.29	0

H40/1 Results W2 Supply Well

Start Sampling	1/24/02 17:45
Injection Time	1/24/02 17:12

17:21	0.15	0
17:36	0.40	0
17:51	0.65	0
18:06	0.90	0
18:21	1.15	0
18:36	1.40	0
18:51	1.65	0
19:06	1.90	0
19:21	2.15	0
19:36	2.40	0
19:51	2.65	0
20:06	2.90	0
20:21	3.15	0
20:36	3.40	0
20:51	3.65	0
21:06	3.90	0
21:21	4.15	0
21:36	4.40	Trace
21:51	4.65	0
22:06	4.90	0
22:21	5.15	0
22:36	5.40	0
22:51	5.65	0
23:06	5.90	0
23:21	6.15	0
23:36	6.40	0
23:51	6.65	0

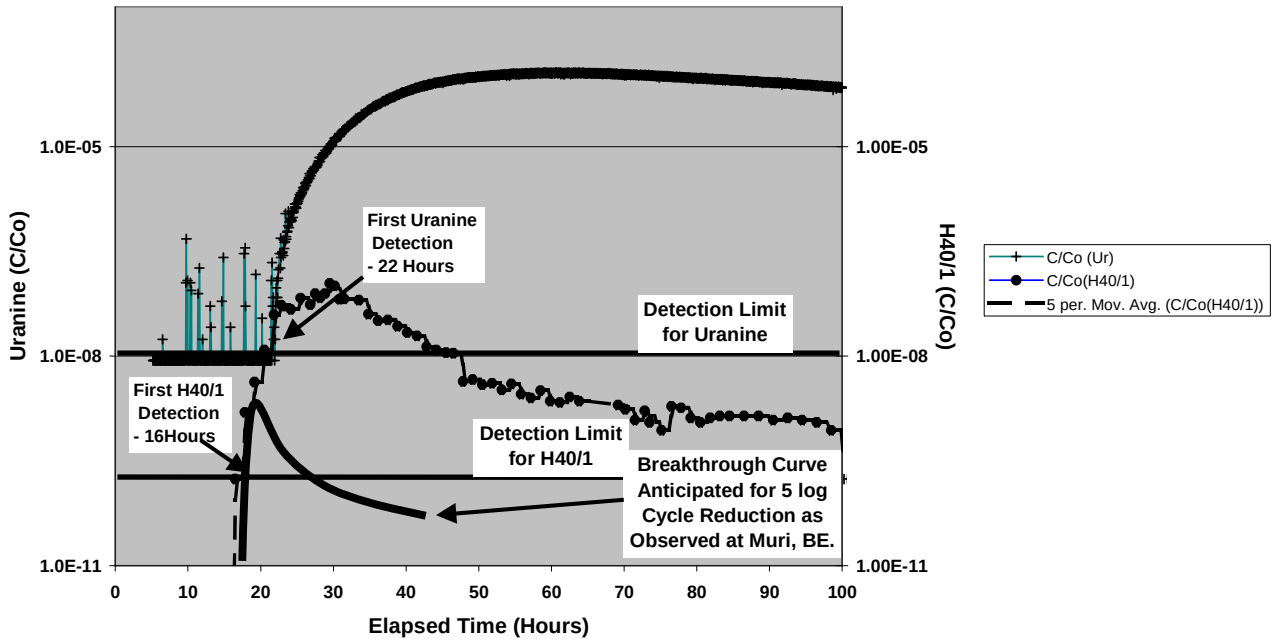
Note : Results for wells on west bank of Aare contained in original Laboratory analyses report sheets (Appendix III).

Appendix II-

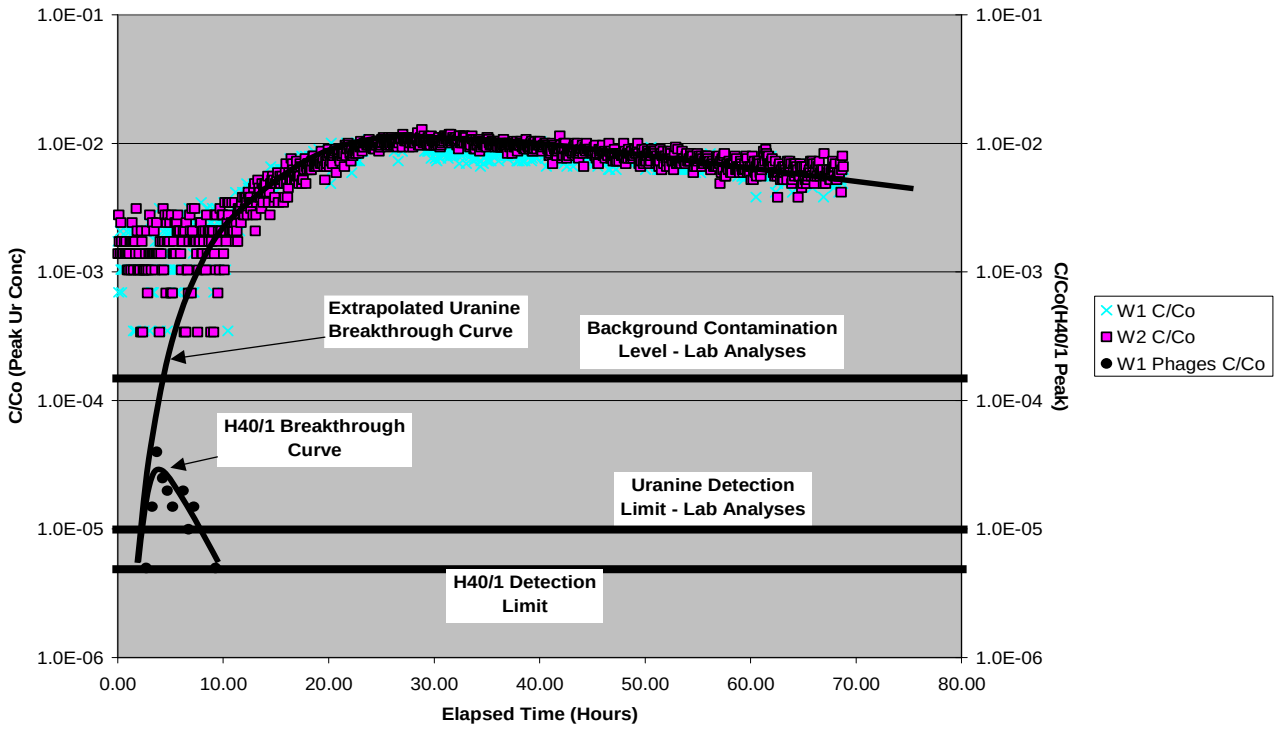
Standard and Simulated Bacteriophage

Breakthrough Curves.

Figure 1: Plot of Uranine and H40/1 Bacteriophage Signals for K3-2 Deep Zone



Plot of Uranine and H40/1 Bacteriophage Breakthrough Curves for Well W1, Muri, BE.



Appendix III-

Original Laboratory Report Sheets

For H40/1 Analyses.