Remediation of Groundwater in combination with ATES

Degradation of chlorinated ethenes by means of UV photolysis in aquifer thermal energy storage systems

TOPSECTOR
WATER

PHILIPS

Hydreco
waar water energie brengt

ARCADIS Design & Consultancy
for natural and
built assets

brabant Water

KWR Watercycle
Research
Institute

Remediation of Groundwater in combination with ATES

Degradation of chlorinated ethenes by means of UV photolysis in aquifer thermal energy storage systems

KWR 2016.059 | September 2016

Project number
400547

Project manager
Jan Willem Kooiman

Client
TKI Watertechnologie

Quality Assurance
Niels Hartog

Author(s)

Roberta Hofman-Caris, Danny Harmsen, Niels Hartog

Sent to
Frits Melgert (Philips), Erone Breur (Philips), Thomas Keijzer (Philips), Tom Nicolaes (Arcadis), Marion de Heus (Arcadis), Arjan de Vries (Brabant Water), John Ottevanger (Hydreco), Léon Janssen (Best UV)

KWR 2016.059 | September 2016 © KWR

Samenvatting

Combinatie WKO/UV-systeem is een stabiel proces met beperkte toepasbaarheid

In een WKO-systeem wordt energie gewonnen uit grondwater, dat in een gesloten systeem wordt rondgepompt. Soms bevat dat grondwater echter verontreinigingen. Fotolyse van dergelijke verontreinigingen door middel van UV-straling is een elegante manier deze stoffen af te breken. Er hoeven geen chemicaliën te worden toegevoegd, en er worden geen afvalstromen gegenereerd, zoals bij veel andere saneringstechnieken wel vaak het geval is. Door een UV-reactor te combineren met een WKO-systeem kan grondwatersanering plaatsvinden in een gesloten systeem, terwijl tegelijkertijd op een duurzame en efficiënte manier thermische energie kan worden opgeslagen en gebruikt.

In dit project zijn de mogelijkheden om UV-fotolyse toe te passen voor de sanering van met chloorethenen verontreinigd anaeroob grondwater bestudeerd. Hiervoor zijn twee systemen getest:

- Een UV-reactor ingebouwd in een bestaand WKO-systeem (in Strijp-S)
- Een mobiele UV-reactor, die werd gevoed met verontreinigd water uit verschillende peilbuizen.

Het bleek dat de operationele stabiliteit van een dergelijk systeem goed is: de grondwaterkwaliteit (UV-transmissie en turbiditeit) was goed voor toepassing van een UV-reactor, en deze heeft inhet WKI-systeem gedurende de testperiode van ruim anderhalf jaar stabiel gefunctioneerd.

Wel bleek tijdens de experimenten dat niet alle typen verontreinigingen even goed kunnen worden afgebroken door middel van fotolyse. Zo bleek het proces wel goed te werken voor per- en trichloortheen, maar werden dichlooretheen en vinylchloride veel minder goed afgebroken.

Het onderzoek heeft geleid tot de conclusie dat een WKO/UV-systeem een betrouwbaar, operationeel stabiel proces is. Ook voor grondwatersanering is fotolyse met behulp van een UV-reactor wellicht een optie. In de praktijk is het echter afhankelijk is van het type verontreiniging en de watermatrix of het systeem economisch rendabel is.

Summary

Photolysis of pollutants by means of UV irradiation is a very elegant way to remove these pollutants from e.g. groundwater. No chemicals have to be dosed, and no concentrate is obtained, which are disadvantages of many common remediation techniques like (advanced) oxidation or membrane filtration. Besides, in aquifer thermal energy storage systems groundwater already is pumped to the surface in a closed system. So, by adding a UV reactor to this system, groundwater remediation may be achieved in this closed system, while simultaneously sustainable and efficient seasonal storage of thermal energy is realized.

In this project the possibilities to apply UV photolysis for the remediation of groundwater polluted with chlorinated ethenes were studied in two different systems:

1.   A combination of a UV reactor and a full scale aquifer thermal energy storage system at Strijp-S
2.   A mobile UV-reactor to treat polluted groundwater from monitoring wells.

A literature study was carried out, which shows that such UV treatment of the groundwater is not expected to negatively affect the microbial population of the groundwater system. It may affect or kill microorganisms in the aqueous phase, but as the majority of the microorganisms are sediment-attached, this will hardly affect the total population.

Another literature search showed that there is little experience with the UV-photolysis of chlorinated ethenes. It cannot be excluded that some toxic transformation products are formed, although the chances for this are larger in the presence of oxygen, which is not the case in the systems studied within the framework of this project.

Experiments carried out in the combined energy storage/UV system showed that the groundwater tested complied with the boundary conditions for a possibly successful UV application: a UV-T of about 76% and a very low turbidity. The UV reactor also appeared to run very stably.

It was found that UV photolysis is an effective degradation method for the more highly chlorinated ethenes, tetra- and trichloroethene (PCE and TCE, respectively), but that it is less efficient for the removal of dichloro ethene (DCE) and vinylchloride (VC). Although some conversion could be observed, also of other compounds, both DCE and VC show only about 5% removal at a UV dose of 500-800 mJ/cm^2.

For the mobile UV-reactor, which was tested with three different monitoring wells at Strijp, it was also found that PCE and TCE were degraded more than small DCE and VC. In addition, it was observed that the concentrations in the abstracted groundwater may vary with the depth of the well, with the flow rate, and on a daily base.

In all cases it was shown that photolysis of chloroethenes may result in the formation of trans-1,2-dichloroethene, whereas in contaminated groundwater the cis variety typically occurs. As the groundwaters in this study were variably contaminated with PCE, TCE, DCE and VC, the accumulation of trans-DCE was the most direct indication of the conversion of chlorinated ethenes by the UV photolysis treatment.

Contents

1 Introduction

Worldwide the inner city groundwater has been polluted at many sites, often caused by (previous) industrial activities. Remediation of this water can be necessary because of legislation and/or new application of these areas. Furthermore, aquifer thermal energy storage (ATES) is applied more and more, and often in areas with polluted groundwater. For some types of pollutants photolysis by means of UV radiation may be an effective degradation method. By combining an ATES installation with a UV reactor the polluted groundwater can be treated, whereas simultaneously efficient energy use can be promoted. It should be noted that the water flow through the ATES system shows seasonal variations, which may affect the photolysis efficiency.

In principle a UV reactor can also be applied in other situations. Examples are pump-and-treat systems, in which contaminated groundwater is pumped.

For both applications it is important to understand the mechanism of degradation of the compounds involved. Although in principle mineralization of pollutants (conversion into CO_2 and H_2O) is possible, in general this level will be not be reached within one irradiation cycle, as this would require a disproportional amount of energy. By repeated treatment of groundwater still a high level of degradation may be obtained, and it is possible that the transformation products formed are better biodegradable, as a result of which additional removal of the pollutants will be obtained. However, It cannot be excluded that possibly harmful transformation products may be formed. Therefore, knowledge about the degradation processes and the transformation products involved is required for a save application of the technology.

The project builds on a previous investigation (Hofman-Caris et al., 2014). An important issue in the full scale application of the technology is how different parameters, like the concentrations and types of pollutants, pH etc. affect the process efficiency. Insight in this influence is required in order to optimize the groundwater remediation and energy production, while simultaneously minimizing the energy demand of the process itself.

Within this project the issues mentioned above are addressed. The project contains four different subjects:

1. The disinfection capacity of UV is well known, so it is to be expected that also microorganisms in the treated groundwater will be inactivated. A literature search was carried out on the effect of groundwater treatment by means of UV irradiation on microorganisms in the water, and the effect this will have on the biodegradation processes that occur in the groundwater system.
2. Incomplete conversion of pollutants may result in the formation of possibly toxic transformation products. A literature search was carried out to identify the risks, and to determine what type of transformation products may be formed.
3. At Strijp a UV reactor was built into a full scale ATES system, and the process was run for almost one year. In the meantime experiments were carried out in order to determine the process efficiency.
4. A mobile UV reactor was used for groundwater remediation using three different monitoring wells in Strijp, with different levels of contaminants.

2 Materials and methods

2.1 The WKO/UV installation at Strijp

2.1.1 WKO/UV-installation

At Strijp-S in the 'Klokgebouw' a UV reactor was built into a full scale ATES system. The process was run for almost one year. In the meantime experiments were carried out in order to determine the process efficiency. A process flow diagram of the combined aquifer thermal energy storage /UV system is depicted in Figure 2-1.
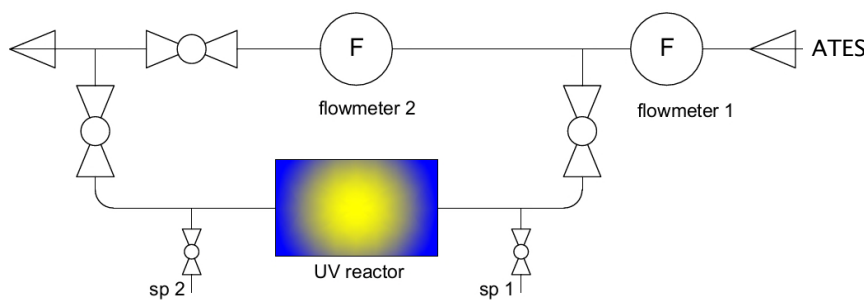
FIGURE 2-1 PROCESS FLOW DIAGRAM COMBINED ATES/UV SYSTEM

The UV reactor with 24 Low Pressure (LP) UV lamps (type E130) was provided by BestUV B.V. (Best, The Netherlands). Further technical details can be found in Appendix I.

The UV reactor was placed in a by-pass stream of scale ATES system (see Figure 2-1. The flow from the ATES system was measured with flowmeter 1(see also Appendix I). The flow through the UV-reactor was regulated by butterfly valves. The flow of the headstream before the butterfly valve was measured with flowmeter 2 (Clamp-on flowmeter; Endress + Hauser 39PA1-11AB0AACAAAB, 1-10 m/s). The flow through the UV-reactor was calculated by subtracting the flow of flowmeter 2 from the flow through flowmeter 1. Samples were taken before (sp1) and after (sp2) the UV-reactor. Turbidity was measured on-line with a turbiditymeter (Aqascat P from Sigrist; 0-100 FTU) which was connected to sp1.

2.1.2 Experimental set-up

2.1.2.1 January and February 2015

A first set of experiments was carried out in January 2015. Various UV doses were tested. In order to apply these doses the flow through the reactor was adjusted. Experiments were carried out at 3 different flows through the reactor. The flow was respectively (i) full stream, (ii) 25 m^3/h and (iii) 6 m^3/h. Every flow was tested twice. Samples were taken before and after UV after at least 5 times the hydraulic retention time.

The UV-Transmission at 254nm (UV-T) and turbidity of the influent stream were measured on-site with a UV-T meter (see Appendix I) and turbidity meter (Aqascat P from Sigrist; 0-100 FTU). All samples were analyzed for dichloro methane, trichloro methane, Tetrachloro methane, trichloro ethane, tetrachloro ethane, 1,1-dichloro ethane, 1,2-dichloro ethane , 1,1,1-trichloro ethane, 1,1,2-trichloro ethane, 1,2- cis- and trans-dichloro ethane, vinylchloride, methane, ethane and ethane.

Furthermore one influent sample (before UV) was analyzed for pH, Dissolved Organic Carbon (DOC), conductivity and nitrate.

All samples during this study were analyzed by Eurofins Analytico BV (Barneveld, The Netherlands) according to standard methods.

The experiments of January were repeated in February. The turbidity was measured on-line with a turbidity meter (Aqascat P from Sigrist; 0-100 FTU).

2.1.2.2 March 2015

The experiments in March were carried out at the lowest applied flow through the UV reactor (6 m³/h) in previous experiments in order to have the highest possible UV-dose through the system. The experiments were carried out in triplo. In addition to the analyzes in previous experiments it was decided to analyze the samples of 2 experiments for a complete set of parameters, in order to obtain information on all compounds that are present in the water. This was a so called "Terrascan". The terrascan was also analyzed by Eurofins Analytico BV according to standard methods (see section 5.4).

2.1.2.3 June 2015

Previous results showed that the flow in Strijp-S can vary during an experiment, which may cause significant variations in the water composition. Besides, another aspect had to be checked. It was suggested that organic halogens, because of their high volatility, may leave the water phase, when the water goes from deep underground to ground level. This might result in decreasing concentrations measured. Therefore, in comparison with previous experiments three changes to the experimental set-up were made:
1. Experiments were carried out at a fixed flow (flowmeter 1) through the total system.
2. Two types of samples were taken. Apart from the direct samples, that were also taken during previous experiments, mixed samples were taken. Here a relatively large volume of water was collected, in order to average any differences that may occur during sample taking.
3. A dosing set-up was developed that enables us to check the possible degassing of samples.

A schematic overview of the set-up used is shown in Figure 2-2. The "small" (5 liter) glass bottle will catch any gases formed in case degassing would occur. The PP bottle (10 liter) is the sample bottle.
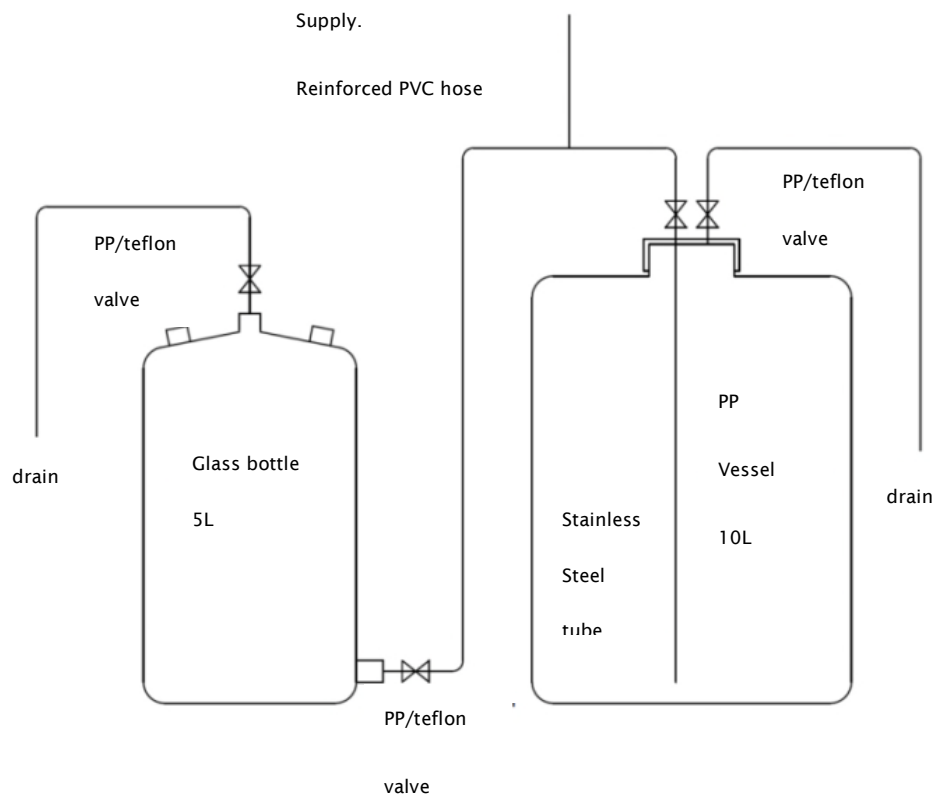
FIGURE 2-2: SCHEMATIC OVERVIEW OF THE SET-UP FOR MIXED SAMPLES, AND TO CHECK DEGASSING

Before the start of the experiments the flow through the thermal energy storage system was fixed. After that the flow through the UV reactor was set to 6 m³/h. Samples were taken before UV and analyzed for pH, Dissolved Organic Carbon (DOC), conductivity and nitrate. As during previous experiments UV-T and turbidity were measured directly. During the experiments samples were taken in duplo before and after UV and analyzed for dichloro methane, trichloro methane, Tetrachloro methane, trichloro ethene tetrachloro ethane, 1,1-dichloro ethane, 1,2-dichloro ethane , 1,1,1-trichloro ethane, 1,1,2-trichloro ethane, 1,2- cis- and trans-dichloro ethane, vinylchloride, methane, ethane and ethane.

First samples were taken direct at the tap of the sample point. This was the same sample procedure as during previous experiments. After that, mixed samples (10 liter) were taken, in duplo, using the set-up which is depicted in Figure 2-2. During the sample taking of the mixed samples the possible degassing of samples was also checked.

The sampling procedure of the mixed samples was as follows. A set-up was connected direct at the sample point before and after UV. The sample bottles were simultaneously filled at a flow of 2 L/min (1 L/min per bottle). During the filling of the bottles gas formation was visually checked and pictures were taken. Sample taking took place after 30 minutes. It was expected that after 30 minutes a homogeneous samples could be taken. After 30 minutes the sample bottle was closed and disconnected from the set-up and analyzed.
It was found that in the initial period of sampling no degassing (bubbles) could be detected. As sampling of a large mixed sample took 30 minutes (at a flow of 2L/hour) at the end of this period in the long run some gas bubbles were detected Figure 2-3, but their volume was negligible in comparison with the water value. This is in accordance with the results from the UV reactor, which showed no changes in output (this would have been expected if bubbles

would occur inside the reactor). Due to these tiny bubbles some evaporation of ethenes may have occurred, which may have affected the calculated results. However, as the bubble volumes were so very small, it is expected that the difference in results caused by this effect will be very small or even negligible. This is in accordance with a theoretical evaluation of the system.
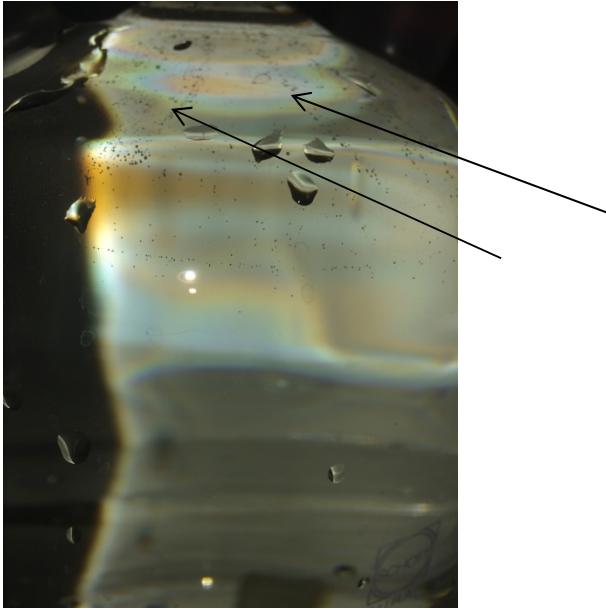
FIGURE 2-3: FORMATION OF TINY GLASS BUBBLES IN THE GLASS BOTTLE.

2.2   The mobile UV reactor at Strijp

For this set-up a UV-reactor (with one UV-lamp) of BestUV was used. The specifications can be found in Appendix III. The specifications of the UV-T meter are given in Appendix I.

First experiments were carried out with two observation pipes in the same area in Strijp, later also another pipe (nr. 4) at the other side of the road was used. Details can be found in

TABLE 2-1: OBSERVATION PIPES USED WITH MOBILE UV-REACTOR

Date	Observation pipe	Depth (m)
03/09/2015	11	60
04/-09/2015 – 08/09/2015	9	30
18/02/2015	4	10

Details on the water composition of these pipes can be found in Appendix IV.

The UV reactor appeared to be sensitive towards fouling, and therefore water was only flown through the reactor when UV-experiments were carried out (it has not been operating continuously).

3 Effect of UV irradiation of groundwater on the biodegradation capacity of the groundwater system

3.1 Introduction

In this chapter the subsurface mobility of bacteria, with focus on the Dehalococcoides species is reported. The literature study was performed within the TKI-project WKO-UV. The relevance of studying the mobility of bacteria in the context of this study, stems from the aim of the project to investigate the removal of contaminants from groundwater through the use UV treatment in ATES systems. UV-treatment is known for its sterilizing capacity by destruction of bacterial cells. The sterilization of bacteria present in the groundwater pumped through an ATES system equipped with an UV-treatment could however have a negative impact on the bacterial population present in the groundwater system. This would be the case if the majority of bacteria present in the groundwater system would be present in the groundwater, rather than attached to the sediment matrix. Particularly, as the primary goal of the project is to target chlorinated solvents, the natural bacteriological capacity present in the contaminated aquifer for dehalogenation by Dehalococcoides species could then be negatively impacted. Therefore, through this literature review it was assessed whether the majority of bacterial cells, with particular focus on the Dehalococcoides species, present in an aquifer would have to be considered sediment-bound or mobile with groundwater. During the literature study two helpful perspectives were recognized and further explored to address this research question. Firstly, scientific studies that focused on the naturally established distribution of bacteria in either contaminated or uncontaminated groundwater systems and secondly the scientific studies that focused on enhancing the natural dechlorination by introducing Dehaloccoides species to a contaminated aquifer by injection. The results of the exploration of literature of both these perspectives are summarized below.

3.2 Natural microbial distribution

Anaerobic biological degradation processes, such as dehalogenation of chlorinated ethenes require both the presence of suitable bacteria as well as supply of electron donor, such as organic substrate. The study of (Bürgmann, Kleikemper et al. 2008) focused on the presence of *Dehalococcoides* bacteria in the plume of a chlorinated ethene-contaminated aquifer undergoing natural attenuation. The partitioning of *Dehalococcoides* between sediment and groundwater was quantified. In contrast to studies on biostimulated or bioaugmented aquifers, lower cell densities and activities were expected for this site, which had a relatively low level of contamination, similar to the Strijp-S location. Multiple lines of evidence indicated that reductive dechlorination (and likely dehalorespiration) was an active process in the investigated aquifer, and both PCR-based quantification methods used indicated that low numbers of mostly sediment-bound *Dehalococcoides* were present in the contaminated zone of the aquifer. Estimates based on the quantitative PCR methods ranged from 2.1×10^7 to 1.5×10^8 sediment-bound *Dehalococcoides* 16S rRNA gene copies per liter of aquifer volume. In contrast, the liquid phase only contained between 8 and 80 copies per liter aquifer volume, indicating that the sediment hosted over 500,000 times more bacteria than groundwater.

This much higher abundance of *Dehalococcoides*-related bacteria in the sediment rather than the well water samples indicated that the preferred habitat is on the surface of sediment particles. The associated low mobility is positive with respect to the research question on the effect of UV-treatment.

Noteworthy, the authors also point out that the assessment of the *Dehalococcoides* population at sites undergoing natural attenuation solely on water samples are likely biased. As sediment sampling is considerably more labor intensive and costly than well sampling, they conclude that new sampling procedures for attached bacteria in aquifers should accordingly be investigated, e.g., approaches to dislodge and remove bacteria with suitable solutions injected into the aquifer. Moreover, (Field, Stams et al. 1995) showed that the *Dehalococcoides* bacteria primarily bound to sediment in biofilms attached to particles facilitate the maintenance of anoxic microniches in aquifers and therefore the functioning of the anaerobic dehalogonation processes, which may allow the occurrence of anaerobic dehalogenation processes even in partially aerobic systems.

The importance of the sediment-association of bacteria is, for example, emphasized by the study by (Himmelheber, Pennell et al. 2007). In PCE-contaminated groundwater they found a diverse microbial community. Here multiple *Dehalococcoides* strains as indicated by the amplification of the reductive dehalogenases *tceA*, *vcrA*, and *bvcA* by PCR were present. The activity of *Dehalococcoides* only achieved complete dechlorination when the microorganisms present in the sediment were continuously provided electron donor from the sediment. Similarly, bacterial processes in uncontaminated aquifers seem to predominantly occur in close sediment-association. Although some studies have found bacteria present in groundwater but not in the associated sediments, this seems to be due to sediment matrix effects and the relatively small sediment volumes used that yield below-detection results (Lehman 2007). In the pristine Mahomet aquifer, (Flynn 2011) found a diverse ecosystem of bacteria and archaea that were examined in 18 wells across the aquifer by filtering cells suspended in groundwater and trapping sediment bound populations on sterile samplers incubated in the wells themselves. They showed that over the two-year timescale of the study, the bacterial community in the aquifer did not necessarily reflect its geochemical environment. Rather, a community retains the imprint of the forces that drove its initial formation and composition long after local conditions have changed.
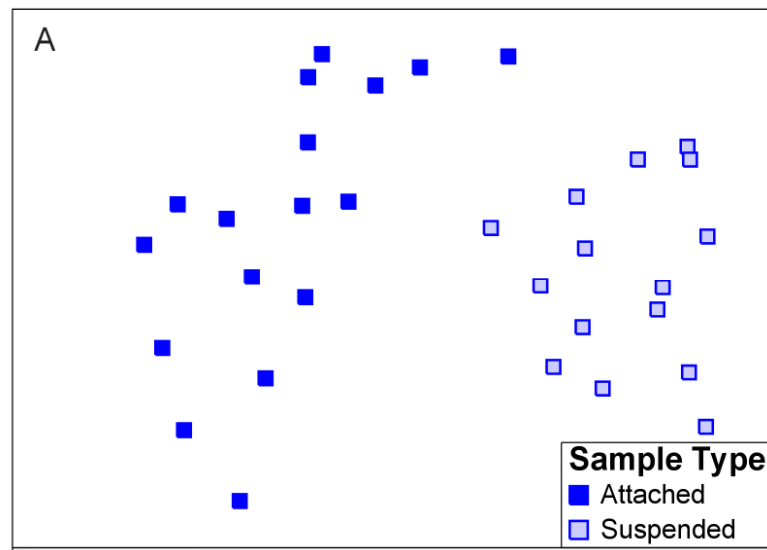
FIGURE 3-1: PCR-COMPONENT PLOT REFLECTING THE COMPOSITION DIFFERENCES BETWEEN SEDIMENT-ATTACHED AND GROUNDWATER-SUSPENDED MICROBIAL COMPOSITION WITHIN A SINGLE AQUIFER FLYNN (2011)

Although most studies of microbial ecosystems in aquifers, solely focus on cells filtered from pumped groundwater, this at least partially ignores the populations that attach to sediment particles, even though sediment-attached populations constitute the majority of cells in the subsurface (Flynn 2011)and physiological differences between sediment-attached and suspended microbial communities in a contaminated aquifer occur (Flynn, Sanford et al. 2008). (Flynn, Sanford et al. 2008) Moreover, the diversity of microbial communities in sediment can be expected more diverse than in the associated groundwater (Ugolini, Henneberger et al. 2013). Also (Lima, Parker et al. 2012) concluded that monitoring wells did not efficiently sample the *Dehalococcoides* organisms in an aquifer. Rather than relying solely on groundwater samples, they suggest that if *Dehalococcoides* DNA is detected at a density of 1×10^7 *Dehalococcoides* cells per liter of ground water at conventional plumes this should be used as an indication for further site characterization into the occurrence of sediment-associated natural attenuation through natural biological reductive dechlorination.

3.3   Enhanced Natural Attenuation
To stimulate the natural dechlorination that occurs by *Dehalococcoides*, the injection of a solution containing this species has been applied at many sites and has been reported in many studies. For this application, to efficiently bioaugmentate a contaminated site, the introduced microorganisms have to be distributed in the subsurface and come into close contact with the contaminant(s). However, in these studies, sufficient transport of the injected *Dehalococcoides* is a key concern. Many factors contribute to hampering the transport of bacteria, as was summarized in the following table by Stroo, Major et al. (2010).

TABLE 3-1: FACTOR IMPACTING MICROBIAL TRANSPORT AND GROWTH (STROO, MAJOR ET AL. 2010).

430   H.F. Stroo et al.

Table 13.2. Factors Impacting Microbial Transport and Growth

Impact on Microbial Growth and Survival	Impact on Microbial Transport	References
pH		
Must remain within tolerance range for specific microorganisms	Ionization of mineral grains and coatings can enhance transport at high pH.	Scholl and Harvey, 1992
Ionic Strength		
Minimal within typical range of ionic strength for groundwater	Increased ionic strength reduces electrostatic repulsion and can inhibit transport by increasing adhesion.	Scholl et al., 1990
Grain-size Distribution		
Soil particles provide sites for biofilm growth	Enhanced migration in coarse soil. Surface charge effects of clay fraction may retard particle migration. Size exclusion may enhance transport.	Harvey et al., 1989; Mayotte et al., 1996
Soil Mineralogy		
Some minerals can provide limiting nutrients (e.g., iron, phosphorus)	Metal oxyhydroxide coatings may retard transport due to charge interactions.	Rogers, 2002; Scholl et al., 1990
Nutrient Availability		
Bioavailable dissolved organic substrates may be utilized metabolically for cell growth and division	Nutrient addition increases aqueous-phase bacteria and enhances transport by promoting growth.	Murphy et al., 1997
Groundwater Velocity		
Minimal	Increasing groundwater velocity can increase cell detachment rates; higher velocity also can decrease attachment of non-motile cells.	Camesano and Logan, 1998; McCaulou et al., 1995; Marlow et al., 1991
Bacterial Cell Surface		
Multiple effects depending on the cell surface characteristic, the geochemistry and mineralogy of the subsurface	Key features include surface charge, surface polymers and proteins, hydrophobicity and the presence of flagella or pili. These affect adhesion and therefore transport.	Sharma et al., 1995; Camesano and Logan, 2000; DeFlaun et al., 1990; Ginn et al., 2002
Bacterial Motility		
Motile bacteria can move to favorable environments, enhancing growth and survival	Motile bacteria exhibit chemotaxis and have the ability to enhance their transport.	Barton and Ford, 1997; Jenneman et al., 1985; Reynolds et al., 1989
Inoculum Cell Density		
Higher cell densities provide more opportunity for added microorganisms to colonize favorable environmental niches	Higher inoculum densities may reduce transport if cell-to-cell interactions are more favorable than cell surface. Otherwise, higher cell densities may enhance transport by blocking attachment sites.	Camesano and Logan, 1998; Ginn et al., 2002; Warren et al., 1992

Another example comes from the experimental lab study by (Schaefer, Condee et al. 2009), in which they concluded that the injected inoculum only migrated a very short distance (<2 cm) into the column before becoming immobilized. It was concluded that only through the subsequent growth of the immobilized DHC a fraction of this new growth detached and migrated (without subsequent re-attachment) through the column. Also (Hage 2004) concluded that the transport of cells in the subsurface is often limited because injected cells are filtered by soil. Cells attach to soil grains and, as a result, the concentration of suspended bacteria can decrease by several orders-of-magnitude within a short distance (e.g. 0.1 to 1 m) from the injection well. And although the use of solutions of low ionic strength and surfactants can enhance bacterial transport, the effects are limited for field applications, when cells have to be transported over distances >1 m.

3.4 Conclusions of literature study on the effect of UV irradiation of groundwater on subsurface bacteria.

Based on the reviewed literature, natural bacteria consortia are predominantly (>500,000 times more) associated with the sediment phase. For a given groundwater system, the numbers of bacteria suspended in groundwater are negligible compared to the numbers associated with the sediment. The Dehalococcoides species appears to be no exception. Moreover, the activity of sediment-associated bacteria is higher through the availability of biofilms, micro-niches and access to electron donor, such as organic substrate. Also, with the injection of microbial suspensions for the purpose of enhanced natural attenuation, the

mobility of the injected bacteria is typically limited and most microbial mass quickly immobilizes on the sedimentary phases present in the aquifer.

Based on these outcomes from the literature study, it is concluded that integration of UV treatment in ATES systems will have negligible effects on the microbial population of a groundwater system, even when accounting for the accumulation of sterilization effects on groundwater through multiple ATES cycles during the lifetime of the ATES system.

4 Degradation pathways of organic halogens by means of oxidation and UV photolysis

4.1 Introduction

Although in literature much attention is paid to the conversion of organic halogens, and especially organic halogens in water, relatively little is known about the reaction mechanisms involved. However, it is known that the presence or absence of (traces of) oxygen is of crucial importance.

4.2 Biodegradation

The most well known and investigated degradaton method is biodegradation by various bacteria. In anaerobic groundwater bacteria are able to convert organic halogens into compounds containing less chlorine, or even without any chlorine groups (Aulenta, Verdini et al. 2013). For the complete degradation of tetrachloro ethane or trichloro ethane, however, specific microorganisms (so called dehalococcoides) are required, which not always are present in the water or in the sediment. Besides, this degradation process often occurs at a rather low reaction rate. In the presence of oxygen conversion of cis-1,2-dichloro ethane and vinylchloride into CO_2, HCl and water occurs at a higher rate, katalysed by the important enzyme mono oxygenase. Under "anaerobic" conditions, however, often traces of oxygen (at concentrations < 0.02 mg/L) appear to play an important role. The degradation of cis-dichloro-etheen in most cases starts by the formation of an epoxide.

4.3 Degradation caused by UV radiation

The bond between a carbon atom and a halogen like chlorine or fluor may be broken by UV radiation. Chlorinated compounds are more sensitive towards UV irradiation than fluorine compounds, as the binding strength of fluorides is higher. It is possible to increase the degradation efficiency by means of advanced oxidation or advanced reduction, based on UV. For advanced oxidation (AOP) UV radiation can be combined with addition of H_2O_2. By means of UV photolysis of the H_2O_2 hydroxylradicals (•OH) are formed, which can react non-selectively with a broad range of organic compounds. However, organic halogens in fact can be considered as already oxidized compounds, as a result of which oxidation often will not be very effective in degradation of such compounds. In advanced reduction processes (ARP) UV irradiation is combined with a reductor like potassium jodide (KJ), dithionite ($S_2O_4^{2-}$), sulfite (SO_3^{2-}) of sulfide. For such compounds ARP probably will be more effective than AOP. In both cases, however, the process starts with absorption of UV radiation, which brings molecules into an excited state, from which they can further react.

4.3.1 Photolysis and advanced oxidation of organic halogens

Sedykh et al. developed a mathematical model to describe the photolysis of molecules (Sedykh, Saiakhov et al. 2001). This model contains a library with numerous reactions that may occur. A bond, which can easily be broken by means of photolysis, is a C-H bond. By breaking this bond a radical is generated, which will immediately react with oxygen, in case oxygen is present. Another reaction that often occurs upon UV irradiation of organic halogens is dehalogenation. This results in the formation of an alkyl radical, which can either react with oxygen, or withdraw a proton from another molecule. When photolysis of a C-O

bond in an ether occurs, two radicals will be formed, which can trigger a broad range or reactions, resulting in a large number of products. Alkoxy radicals can withdraw a proton from another molecule, thus forming an alcohol, but formaldehyde or aldehydes also can be formed. Alkyl radicals can adopt a proton, form a double bond, or react with oxygen, forming an alcohol or a carbonyl group. During photolysis of an alcohol also an O-H, C-O of C-H bond can be broken, resulting in the formation of alkoxy or alkyl radicals.

Research by (Gürtler, Möller et al. 1994) showed that mono- and dichlororethene can hardly absorb UV radiation with a wavelength of 254 nm. Vinyl chloride cannot be converted by this wavelength, and conversion of 1,2-dichloroethene requires a long period of irradiation. Tri- and tetrachloro ethane are quickly converted at 254 nm, resulting in the formation of chlorine radicals.

Although the photolysis of vinlyl chloride occurs to a limited extend, the mechanism is as follows:

$$CH_2=CHCL + 185\ nm \rightarrow CH_2=CH\cdot + Cl\cdot\ en\ HC\equiv CH + HCl \qquad (1)$$

$$CH_2=CHCl + Cl\cdot \rightarrow CH_2Cl\text{-}CHCl\cdot \qquad (2)$$
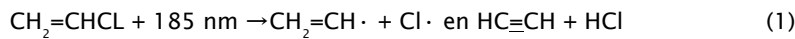
In the presence of oxygen subsequently CO_2, CO, HCl, chloro-acetaldehyde ($HCOCH_2Cl$) and phosgene ($COCl_2$) can be formed.

The photolysis of 1,2-dichloro-ethene occurs at a higher rate than that of vinylchloride:

$$CHCl=CHCl + 185\ nm \rightarrow \cdot CH=CHCl + Cl\cdot \qquad (3)$$

$$CHCl=CHCl + Cl\cdot \rightarrow CHCl_2\text{-}CHCl\cdot \qquad (4)$$
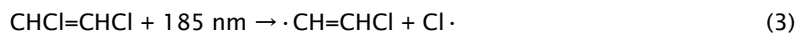
Here too the presence of oxygen will finally result in the formation of chloro-acetaldehyde and phosgene. The same will happen during the photolysis of 1,1-dichloroethene, trichloro-ethene, and tetrachloro-ethene in the presence of oxygen (Gürtler, Möller et al. 1994).

(Shirayama, Tohezo et al. 2001) studied the photolysis of chlorinated hydrocarbons (C_2Cl_4, C_2HCl_3, $C_2H_4Cl_2$, 1,1,1-$C_2H_3Cl_3$, 1,1,2-$C_2H_3Cl_3$, $CHCl_3$ en CCl_4) under both aerobic and anaerobic circumstances, at a wavelength of 185 nm and of 254 nm. They concluded that tetrachloro-ethene had the highest degradation rate, independent of the dissolved oxygen content of the water. However, the degradation of chloromethane and chloro-ethane occurred at a higher rate under anaerobic conditions. Probably this can be attributed to the UV absorption of UV by oxygen, which competes with absorption by organic compounds. During anaerobic photolysis the breaking of a C-Cl bond results in the formation of organic radicals, whereas under aerobic circumstances mainly ozone and hydroxyl radicals will be formed. In all cases this will result in a decrease in pH (in the presence of oxygen from about 5 to about 3, in the absence of oxygen from 9 to 8). It appeared to be more difficult to convert double bonds in the absence of oxygen. An overview is shown in Figure 4-1.

Anaerobic VUV irradiation of water results in the formation of hydroxyl radicals, which in turn cause all kinds of subsequent reactions. However, at 254 nm the hydrolysis of water can be neglected. UV irradiation of organic halogens results in the following reactions:

$$CCl_4 + h\nu \rightarrow CCl_3 + Cl \qquad (5)$$

$$CCl_3 + h\nu \rightarrow CHCl_2 + Cl \tag{6}$$

For a bromo compound at 193 nm the following reactions were observed:

$$C_2H_3Br + h\nu \rightarrow C_2H_3 + Br \tag{7}$$

$$C_2H_3Br + h\nu \rightarrow C_2H_2 + HBr \tag{8}$$

At this wavelength (193 nm) also the following processes can take place:

$$1,1\text{-}C_2H_2XCl_2 + h\nu \rightarrow C_2HCl + HCl \tag{9}$$

$$1,1\text{-}C_2H_2XCl_2 + h\nu \rightarrow C_2H_2 + 2Cl \ (of \ Cl_2) \tag{10}$$

$$1,1\text{-}C_2H_2XCl_2 + h\nu \rightarrow CH_2CCl + Cl \tag{11}$$

$$C_2Cl_4 + h\nu \rightarrow C_2Cl_2 + 2Cl \ (of \ Cl_2) \tag{12}$$

$$C_2Cl_4 + h\nu \rightarrow C_2Cl_3 + Cl \tag{13}$$
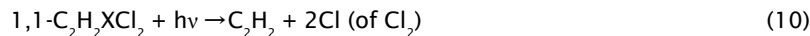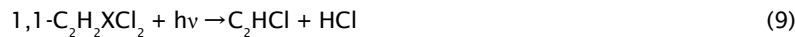
Such reactions appear to be more effective at a lower wavelength, but also occur at 254 nm. In the absence of dissolved oxygen this will result in the formation of radicals like •CCl_3, •$CHCl_2$, •C_2HCl_2 en •C_2Cl_3, etc.
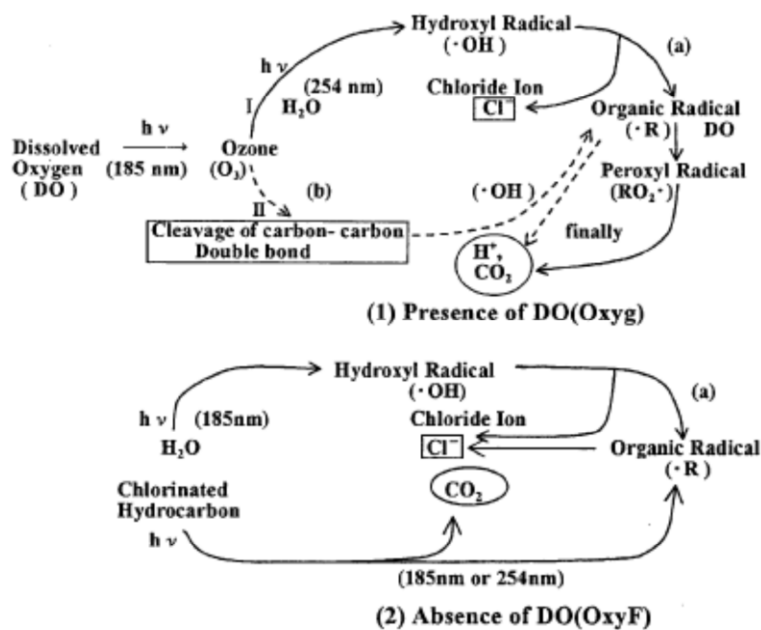
FIGURE 4-1: CONVERSION OF ORGANIC HALOGENS BY MEANS OF UV IRRADIATION IN THE PRESENCE OF DISSOLVED OXYGEN (DO) (OXYG) OR ABSENCE OF DO (OXYGEN FREE:OXYF). (A) CONVERSION OF CHLORINATED HYDROCARBON; (B) CONVERSON OF CHLORO-ETHENE (SHIRAYAMA, TOHEZO ET AL. 2001).

Research into the conversion of 1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane (DDT) (Foght, April et al. 2001) indeed showed that photolysis causes dehycrochorination, resulting in the formation of 1,1-dichloro-2,2-bis-(4-chlorophenyl)ethylene (DDE) (Figure 4-2).
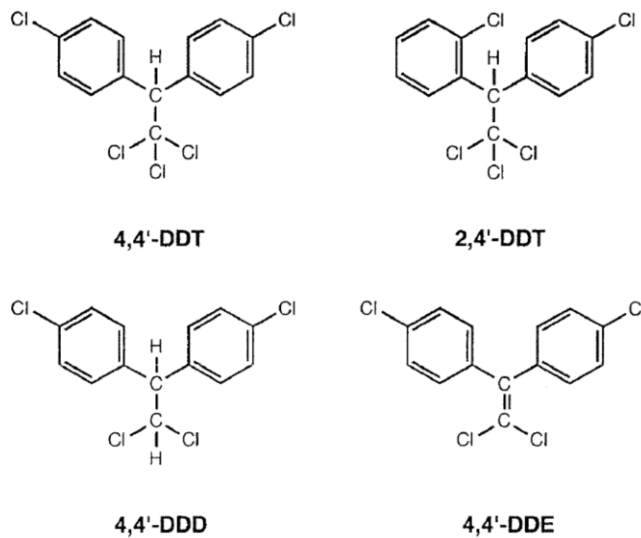
FIGURE 4-2: POSSIBLE FORMATION OF BYPRODUCTS OF THE PHOTOLYSIS OF DDT (FOGHT, APRIL ET AL. 2001)

The conversion of chlorobenzene in water by means of UV based advanced oxidation processes was studied by (Dilmeghani and Zahir 2001). They compared UV (254 nm) processes with UV/H_2O_2 and $UV/H_2O_2/O_3$ processes both under aerobic and anaerobic conditions. Here too it was found that degradation in the presence of oxygen occurs at a significantly higher rate: the pseudo first order reaction rate constant of chloro-benzene varies from $1,8*10^{-4}$ s^{-1} under aerobic circumstances, to $6,4*10^{-4}$ s^{-1} in aqueous solutions, saturated with oxygen. Furthermore it was observed that the reaction rate constant increases by one order upon addition of hydrogen peroxide or ozone.

Photolysis products of chlorobenzene include phenol, biphenyl-, and chlorobiphenyl isomers, and benzaldehyde, according to the following reaction scheme (Figure 4-3):

$$ClBz + hv \rightarrow * ClBz \tag{14}$$

$$* ClBz \rightarrow ClBz + warmte \tag{15}$$

$$* ClBz \rightarrow I_{UV} \tag{16}$$

$$I_{UV} + hv \rightarrow * I_{UV} \rightarrow producten \tag{17}$$

ClBz represents chlorobenzene, IUV are the formed intermediates, and * indicates excited state molecules. The excited chlorobenzene molecule can either return to its ground state, emitting energy, or react with intermediates. During the reactions HCl can be formed, resulting in a decrease in the pH value during the reactions.
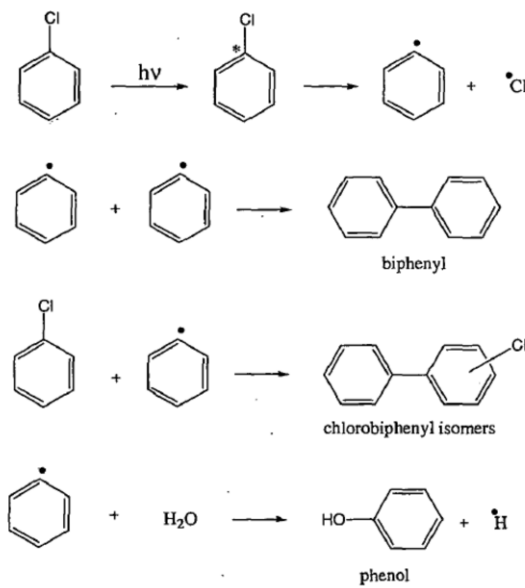
FIGURE 4-3: UV PHOTOLYSIS OF CHLOROBENZENE ((DILMEGHANI AND ZAHIR 2001)

In cases (traces of) oxygen are present, the following reactions will occur:

$$I_{UV} \text{ of } * I_{UV} + {}^{3}O_2 \rightarrow \text{producten} \tag{18}$$

$$* ClBz + {}^{3}O_2 \rightarrow ClBz + {}^{1}O_2 \tag{19}$$

$$ClBz + {}^{1}O_2 \rightarrow \text{intermediate} \tag{20}$$

The conversion of chlorobenzene in the presence of oxygen appears to occur at a three to four times higher rate than under anaerobic circumstances

During these experiments also the formation of benzaldehyde was observed. It is not yet clear how this compound could have been formed. Probably reaction with another photolysis product of chlorobenzene was involved.

The reaction rates and the distribution of the formed products under anaerobic circumstances appeared to differ from those obtained under aerobic circumstances. According to the authors products like biphenyl and chlorobiphenyl under anaerobic circumstances quickly react further, as a result of which the concentrations of intermediates don't increase. However, in the presence of oxygen intermediates are formed which may mutually compete for the absorption of UV radiation, resulting in accumulation of intermediates.

(Trautwein and Kümmerer 2012) concluded that the chemical conversion of chloropromazine under the influence of sunlight and oxygen resulted in the formation of at least twelve reaction products. Under anaerobic circumstances, however, polymers were formed. Irradiation at 270 nm caused photo-ionisation, whereas at higher wavelengths (320-400 nm) radicals were formed. In Figure 4-4 the molecular structures of chloropromazine and its three most important photolysis products are shown:
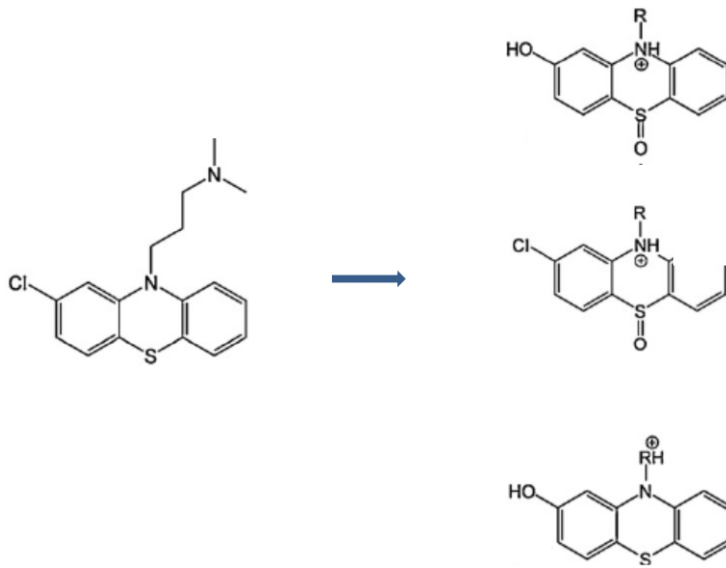
FIGURE 4-4: CHLOROPROMAZINE AND ITS THREE MOST IMPORTANT PHOTOLYSIS PRODUCTS (UV/VIS, XENON LAMP) (TRAUTWEIN AND KÜMMERER 2012).

The conversion of furosemide by means of a MP UV lamp (200-300 nm) follows the reaction path shown in Figure 4-5 (Vargas, Volkmar et al. 1998):
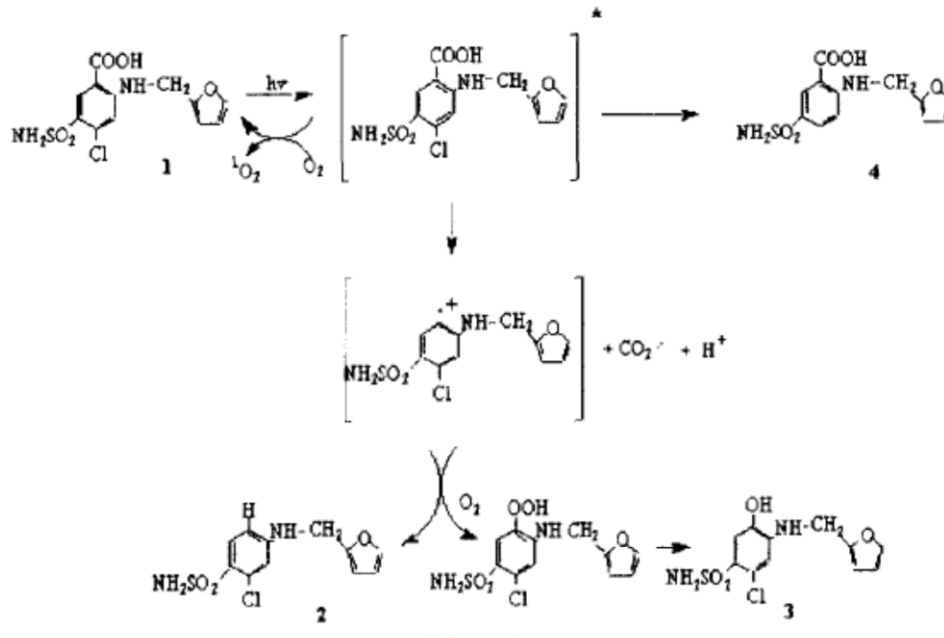
FIGURE 4-5: CONVERSION OF FUROSEMIDE (VARGAS, VOLKMAR ET AL. 1998).

Under aerobic circumstances products 2 (82%), 3 (8%), and 4 (10%) are formed, at a quantum yield of 0,38 (quantum yield is the number of reactions per photon absorbed). Under anaerobic circumstances the quantum yield appeared to be almost identical (0,37), and products 2 (83%) and 4 (17%) were formed. Obviously, the first step in photolysis is the

abstraction of a photon, resulting in products 2 and 4, whereas reaction with oxygen occurs later, in case oxygen is present.

In the photolysis of 2-chlorophenothiazine (CPH) at 313 nm it was found that in the absence of oxygen the solvent (in this case an alcohol) plays a significant role in the reactions, as is shown in Figure 4-6.
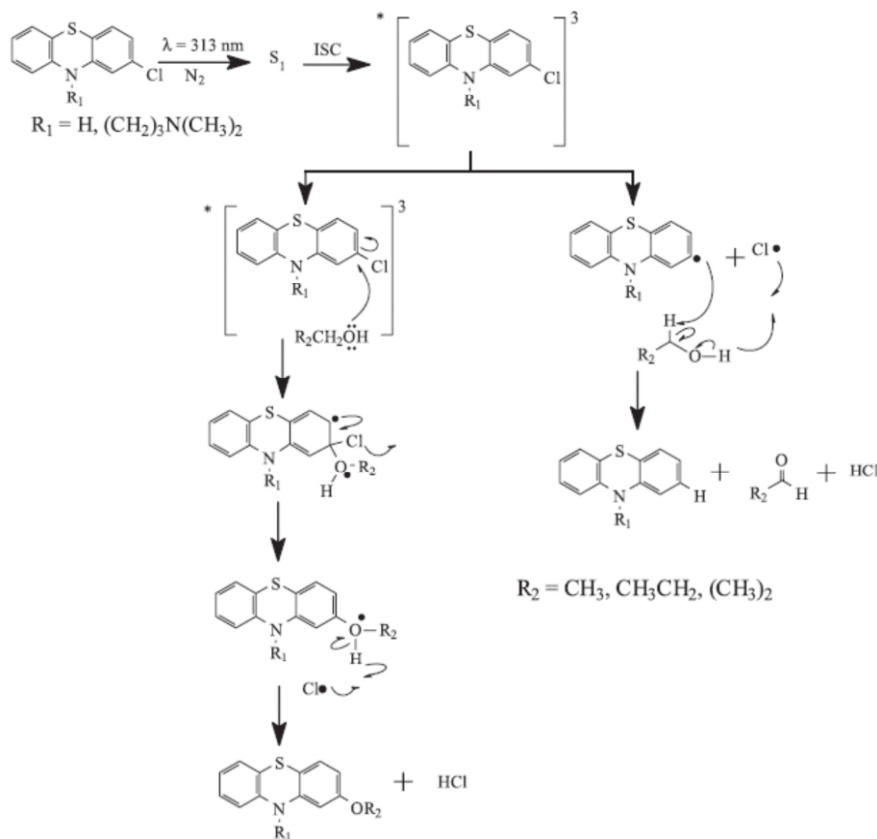
FIGURE 4-6:: DEHALOGENATION OF CHLOROPHENOTHIAZINE IN ALCOHOL BY MENAS OF PHOTOLYSIS

This shows that in the presence of organic molecules additional reactions should be taken into account. This probably also will apply to NOM. In this way it may be possible that an oxygen atom is incorporated into another molecule.

In general genotoxic effects of UV radiation are attributed to the absorption by pyrimidine and purine bases. (Lindqvist, Czochralska et al. 2002) studied the conversion of 2-chloropyrimidine (ClPy) by means of a LP UV lamp in an anaerobic solution. Mainly two products were formed: 2-hydroxypyrimidine (quantum yield $\approx 0,1$) en 2-chloro-4,2'-bipyrimidine (with a quantum yield $\approx 0,005$). It should be noted that under aerobic conditions only 2-hydroxy-pyrimidine was formed. It seems that by irradiation two molecules 2-chloropyrimidine react with each other, splitting off HCl. As a result of UV absorption ClPy comes into an excited singlet state (reaction 21). Then it rapidly returns to the ground state (reaction 22) and/or gets into a triplet state (reaction 23). In this situation the molecule shows an internal conversion (reaction 24), or bimolecular quenching may occur (reaction 25). In the presence of oxygen reaction steps 24-31 may occur:
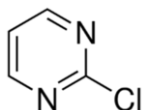
FIGURE 4-7: MOLECULAR STRUCTURE OF 2-CHLOROPYRIMIDINE

Anaerobic reactions:

$$ClPy + h\nu \rightarrow {}^1ClPy, \text{ excited state at 254 nm} \qquad (21)$$

$${}^1ClPy \rightarrow ClPy, \text{ no emission of radiation} \qquad (22)$$

$${}^1ClPy \rightarrow {}^3ClPy, \text{ "intersystem crossing"} \qquad (23)$$

$${}^3ClPy \rightarrow ClPy, \text{ internal conversion} \qquad (24)$$

$${}^3ClPy + ClPy \rightarrow 2ClPy, \text{ concentration quenching} \qquad (25)$$

Aerobic conversion

$${}^3ClPy + O_2 \rightarrow ClPy + {}^1O_2 \text{ (of } O_2\text{), triplet quenching by } O_2 \qquad (26)$$

$${}^1ClPy + H_2O \rightarrow HOPy + HCl, \text{ substitution reaction} \qquad (27)$$

$${}^3ClPy \rightarrow Py\cdot + Cl\cdot, \text{ homolytic elimination} \qquad (28)$$

$$Py\cdot + ClPy \rightarrow ClBiPy + H\cdot, \text{ addition} \qquad (29)$$

$$Py\cdot + O_2 \rightarrow \text{unidentified products} \qquad (30)$$

$$H\cdot + ClPyr \rightarrow \text{unidentified products} \qquad (31)$$

$$Cl\cdot + ClPy \rightarrow Cl_2 + Py\cdot \qquad (32)$$

$$Cl\cdot + O_2 \rightarrow ClO_2\cdot \qquad (33)$$

In the presence of oxygen UV radiation causes the exchange of a chloride atom by a hydroxyl group. These experiments, however, indicate that even under anaerobic conditions somehow oxygen containing groups can be incorporated into the molecule, probably originating from other, organic molecules present. Besides, it shows that under anaerobic circumstances larger molecules can be formed, which is in accordance with the results of (Trautwein and Kümmerer 2012)

Although the bond between carbon and fluor is stronger than between chlorine and carbon, the photolysis of fluorine compounds also has been studied. Experiments using a LP UV lamp, which emitted both radiation at a wavelength of 254 nm and of 185 nm (VUV radiation), showed that perfluoro-octanoic acid is very sensitive towards VUV, but much less sentitive towards 254 nm (Cao, Wang et al. 2010). Radiation in the VUV range is strongly absorbed by water molecules themselves, as a result of which the penetration depth is extremely small (Watanabe and Zelikoff 1953; Cantrell, Zimmer et al. 1997; Oppenländer, Walddörfer et al. 2005):

- At λ = 185 nm circa 0,1 cm
- At λ < 170 nm $10^{-3} - 10^{-5}$ cm

As a result reactions only can take place within a very thin layer of water, in the immediate vicinity of the UV lamp. In the presence of oxygen two hours of irradiation resulted in only 9% degradation, whereas VUV radiation resulted in 87% degradation, with a degree of defluorination of 25%. The products appeared to be molecules with a shorter chain length, including perfluoroheptanoic acid (PFHpA) and perfluorohexanoic acid (PFHxA).

Conversion reactions in the presence of oxygen are shown in equations (34-35) (Dillert, Bahnemann et al. 2007):

$$F - (CF_2)_n CF_2 COO^- + h\nu \xrightarrow[-e^-]{} F - (CF_2)_n CF_2 COO \cdot \xrightarrow[-CO_2]{} F - (CF_2)_n CF_2 \cdot \qquad (34)$$

$$F - (CF_2)_n CF_2 \cdot + 2[O] + [H] + 2e^- \rightarrow F - (CF_2)_n - COOH + 2F \cdot \qquad (35)$$
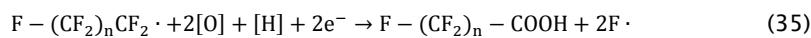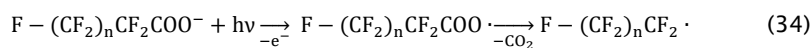
In the absence of oxygen the radical formed in reaction (34) will react with other organic compounds in the water.

The photolysis, with and without the presence of H_2O_2, of aldrin and dieldrin in ice and snow was studied by (Rowland, Bausch et al. 2011), but they didn't indicate a reaction mechanism. However, it was found that the penetration depth of the UV radiation played an important role in starting the reaction sequences. This indicates that the first step probably is activation or photolysis by means of radiation. The conversion of aldrin showed a significantly higher reaction rate than the conversion of dieldrin. The authors indicate that even the presence of low concentrations of organic compounds may play an important role in the degradation process.

4.3.2   Advanced reduction based on UV-processes

A fundamentally different type of process is "advanced recuction" (ARP). Examples have been described by (Qu, Zhang et al. 2010; Hara 2011; Liu, Yoon et al. 2013). This type of processes is characterized by the use of a reductor instead of an oxidizing agent, combined with UV irradiation. For this purpose in literature in general also a wavelength of 254 nm is applied. Liu et al. studied the photolysis of vinyl chloride (VC) at different pH values. A higher pH is favorable for the conversion of VC, in which Cl• is formed. Two reaction mechanisms for this conversion have been suggested:

- Photolysis, causing a hemolytic breakage, in which Cl$^-$ and acetylene are formed (β-eliminatie).
- Hydrogenolysis, in which an electron is transferred, resulting in the formation of a vinyl radical. This radical subsequently reacts with H$^+$, resulting in the formation of ethane and the splitting off of chloride.

This is shown in Figure 4-8.
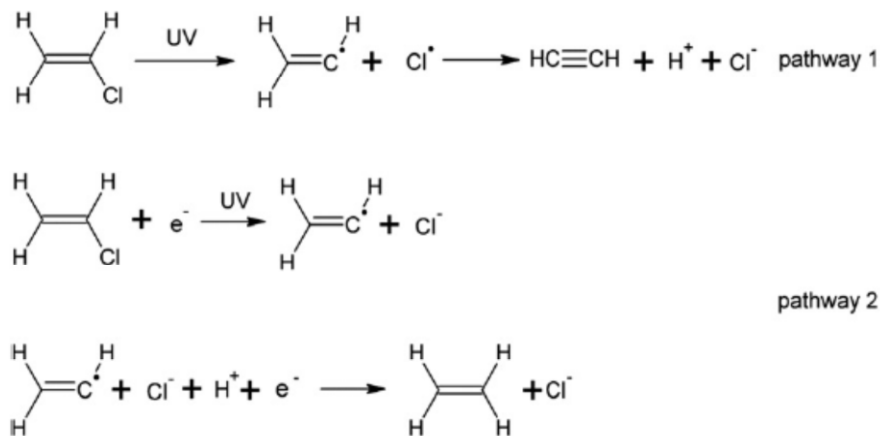
FIGURE 4-8: UV-PHOTOLYSIS OF VINYLCHLORIDE (LIU, YOON ET AL. 2013)

During the first reaction a hydrogen ion is formed, which causes a pH decrease, whereas during the second reaction hydrogen ion is taken on, causing an increase in pH. This effect cannot be observed in a buffered solution. Applying a solution without a buffer showed that indeed pH decreases (from 8.55 to 7.31), indicating that the first reaction mechanism takes place. However, both mechanisms proposed result in the formation of acetylene (ethyne), which was observed in other experiments.

Yoon et al. also applied advanced reduction for the conversion of 1,2-dichloro ethane, using two types of UV lamps:

- Medium pressure UV, with an emission spectrum between 200 and 300 nm
- A UV-N lamp with an emission spectrum between 280 en 320 nm, showing a maximum at 312 nm (Yoon, Han et al. 2014).

The energy of a 315 nm photon is slightly higher than the binding strength of a C-Cl bond. This means that in principle at 315 nm a C-Cl bond can be broken.

Qu et al. mainly studied the advanced reduction of perfluoro octanoic acid. This compound hardly absorps irradiation at 254 nm, so photolysis by means of LP lamps is not very effective. Reaction products, that have been identified, are F^- and shorter perfluoro chains, formic acid and acetic acid. Besides, gaseous CHF_3 and C_2F_6 were observed in low (Qu, Zhang et al. 2010).

The photolysis of perfluoro octanoic acid under anaerobic circumstances (in a N_2 atmosphere) starts with the absorption of radiation, resulting in the formation of free radicals (reaction 36). This results in subsequent reactions 37-39. Probably the reaction starts with the breaking of the bond between the carbonic acid group and the perfluoro chain.

$$C_nF_{2n-1}H_2COOH \rightarrow \bullet C_{n-1}F_{2n-1} + :CH_2 + \bullet COOH \qquad (36)$$

$$\cdot Cn\text{-}_1F_{2n-1} + \cdot COOH \rightarrow C_{n-1F2n-1}COOH \qquad (37)$$

$$:CH_2 + \cdot H \rightarrow \cdot CH_3 \qquad (38)$$

$$\cdot CH_3 + \cdot COOH \rightarrow CH_3COOH \qquad\qquad\qquad (39)$$

Degradation starts at the newly formed end of the chain.

(Hara 2011) studied the conversion of dieldrin in the presence of $_{FeS2}$. He concluded that depending on the presence of oxygen large differences in reaction mechanisms can occur. Under aerobic conditions mainly low molecular products like formic acid, lactic acid and oxalic acid were formed. However, under anaerobic circumstances mainly dibutyl phthalate and 3-chloro-4-methul-2-pentanol were observed (Figure 4-9).
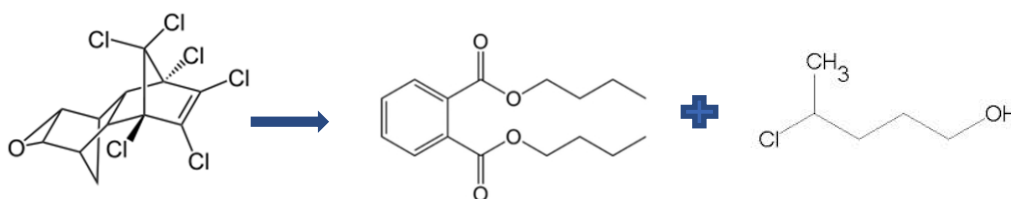
FIGURE 4-9: ANAEROBIC CONVERSION OF DIELDRIN IN THE PRESENCE OF IRONSULFIDE, ACCORDING TO (HARA 2011).

This is in accordordance with the findings of Trautwein en Lindqvist, who also found larger molecules after UV absorption under anaerobic circumstances (Lindqvist, Czochralska et al. 2002; Trautwein and Kümmerer 2012).

4.4   Toxicological tests

It is very difficult to exactly predict the formation of products during UV irradiation of mixtures. Obviously, Cl• radicals can be formed, but it is also possible that other (reactive) compounds may be formed, e.g. by reactions of other compounds present in the water like NOM. This may result in a very complex reaction scheme, and it will be fairly impossible to predict whether possibly toxic compounds may be formed.

In such a case it often appears to be better to use so called bio assays, which give information on the possible effect the mixture of compounds formed can have on organisms. (Isidori, Nardelli et al. 2006) studied the toxic and genotoxic properties of furosemide (Figure 4-10) and its photolysis products, which were formed during irradiation with a xenon lamp, which imitates sunlight (wavelength range 200-2400 nm). They applied the so called SOS Chromotest (a quantitative bacteriological colorimetric test on *Escherichia coli*) and the Ames test on *Salmonella typhimurium*. They found that both furosemide and its photolysis product showed a limited acute toxicity for the organisms tested. Although the SOS test did not give a significant positive response for both products, the photolysis product did show a significant positive response in the Ames test. This shows that reaction products indeed may cause other effects than their mother compounds, and that it is important to check this before application of photolysis to degrade certain compounds.
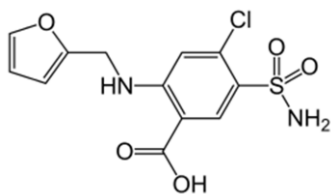
FIGURE 4-10: MOLECULAR STRUCTURE OF FUROSEMIDE

4.5   Conclusions of literature study on reaction pathways and possible formation of byproducts in UV processes with halogen containing organics.

Organic halogens in general are able to absorb UV radiation. How effectively this will result in activation of the molecule and possible subsequent reactions depends on the wavelengths applied and the molecular structures involved. However, in all advanced oxidation and reduction processes based on UV radiation it was found that the first step in a reaction sequence always is absorption of radiation.

This absorption can cause numerous reactions. Often the bond between carbon and a halogen (chlorine) is broken, but breaking of a C-H bond also is possible. This in general results in the formation of radicals that may react with other compounds that are present in the solution.

The presence of oxygen is very important for the type of products that are formed. Under anaerobic circumstances often relatively large molecules seem to be formed, e.g. by reaction of two organic radicals (termination). The most well-known toxic byproducts that are formed during photolysis of organic halogens are chloro acetaldehyde and phosgene. These products are formed when oxygen somehow is involved in the reaction.

It is possible that e.g. a hydroxyl group is incorporated into the molecule, that originates from another organic compound in the water (like NOM). Therefore, it cannot be excluded on forehand that possibly toxic byproducts are formed under anaerobic conditions. The oxygen atom required may originate from e.g. NOM.

As during the UV process several radicals can be formed, which can react with a broad variety of compounds present in the solution, a complex reaction scheme will follow, and a correct prediction of the final compounds formed will really be an enormous challenge. A complete chemical analysis of all compounds formed will be very difficult to obtain. Therefore, bio assays seem to be the recommended methods to determine whether possibly toxic byproducts may be formed.

5 UV-remediation of groundwater combined with Aquifer Thermal Energy Storage at Strijp

5.1 General

To investigate the possibilities to apply UV treatment for groundwater remediation of chlorinated ethenes, particulary in combination with ATES systems. The latter option was studied in an ATES system in Strijp-S. For this purpose a UV reaction was built into the existing ATES system in the "Klokgebouw".

To apply various UV doses the flow through the reactor could be adjusted. During the experiments 1,2- cis- and trans-dichloro ethane, vinylchloride, ethane, ethane, methane, 1,1-dichloro ethane and 1,2-dichloro ethane were measured, before and after UV treatment.

After some initial small complications the experimental set-up appeared to run according to plan. The UV-transmission (UV-T) was about 76%, the turbidity appeared to be negligible, and the UV radiation was stable. There was no leakage of oxygen into the reactor, as no particles could be observed (the presence of oxygen would immediately result in the formation of iron oxides). As water from a deep groundwater layer was used theoretically it would be possible that degassing might result in the formation of gas bubbles, which could affect the UV process. However, no significant gas bubbles were observed (see section 2.1), so it can be assumed that this will not have affected the results obtained.

The experimental details and the set-up of the installation were described in section 2.1.

5.2 Results obtained in January 2015

The results obtained with the UV reactor at Strijp-S at three different UV doses (69, 234 and 835 mJ/cm2) in January 2015 are shown in Figure 5 1 and Figure 5 2. Maybe some vinylchloride and 1,2-cis-dichloro ethene have been degraded, but the results are not clear: duplo measurements show relatively large differences. Some reaction must have occurred, as in the effluent 1,2-trans-dichloroethene was observed, which could not be measured in the influent. Theoretically trans-dichloro ethene can be formed from tetra-, tri-, or cis-di-chloro ethene, but as tetra- and tri-chloro ethene could not be found in concentrations above the reporting limit, it is unlikely that their conversion would have caused the formation of this concentration of the trans compound. The only explanation then is that cis-dichloro ethene was transformed into trans-dichloro ethene. This can be explained from the abstraction of a chlorine radical, which subsequently reacts with the remaining molecule, but now is added in a trans position (which energetically is the most favorable position).

Furthermore it can be concluded that some ethene was removed, whereas some ethane was formed by the UV radiation. Whether or not methane was formed cannot be concluded: the duplo measurements show relatively large differences.
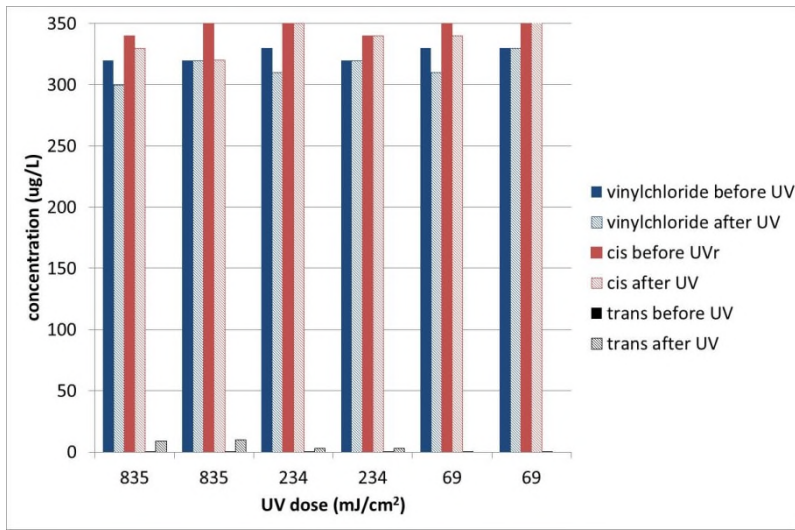
FIGURE 5-1: DEVELOPMENT OF CHLORO ETHENE CONCENTRATIONS DURING UV EXPERIMENTS (JANUARY 2015)
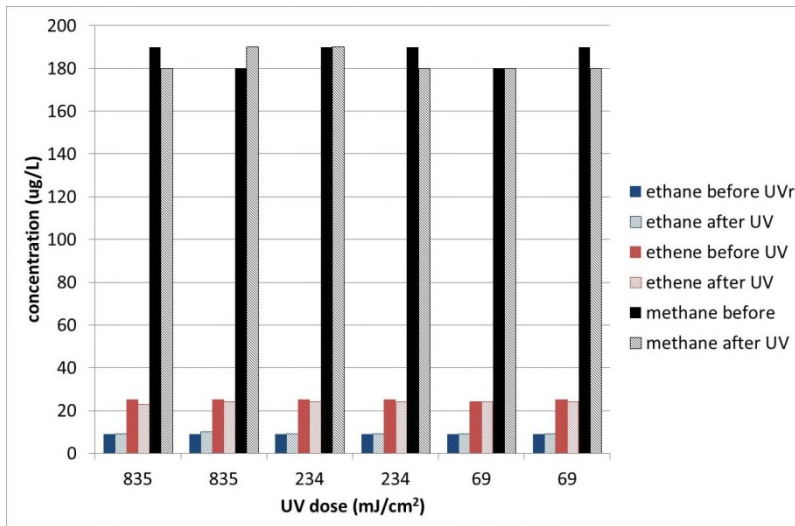
FIGURE 5-2: DEVELOPMENT OF CONCENTRATIONS OF ETHANE, ETHENE, AND METHANE DURING UV EXPERIMENTS (JANUARY 2015)

5.3   Results obtained in February 2015

The experiment described in section 5.1 was repeated in February 2015, again with three different UV doses. The results are shown in Figure 5-3 and Figure 5-4.

The results shown in Figure 5-3 are very unclear. The lack of reproducibility does not allow any definite conclusions on the process efficiency. The formation of a small amount of trans-dichloro ethene, indicates that some reaction must have taken place. As there were no "large" molecules like tetra- or tri-chloro ethene present, again it is likely that cis-dichloro ethene was converted into trans.

As the reproducibility of the methane analysis is very low, conclusions on methane production or formation cannot be drawn. It is possible that a small amount of ethene was degraded and that some ethane may have been formed during the process (Figure 5-4). The

analyses of dichloro ethane also shows a very low reproducibility, as a result of which no conclusions on this compound can be drawn (Figure 5-4).
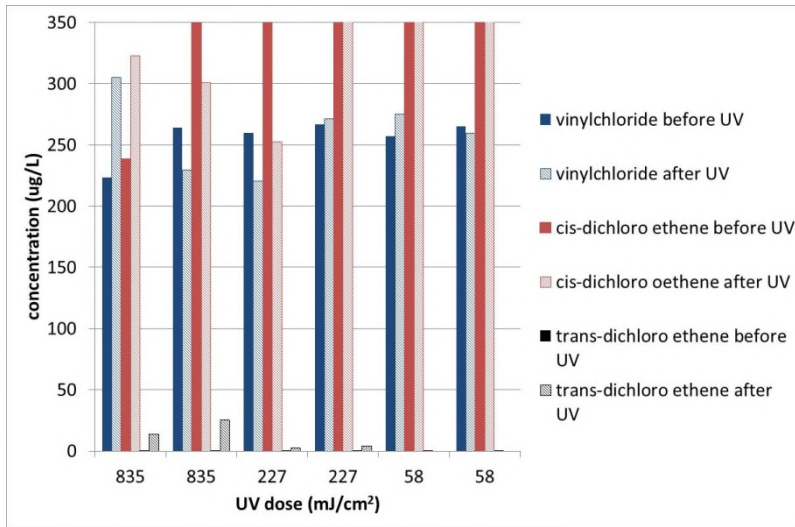
FIGURE 5-3: DEVELOPMENT OF CHLORO ETHENE CONCENTRATIONS DURING UV EXPERIMENTS (FEBRUARY 2015)
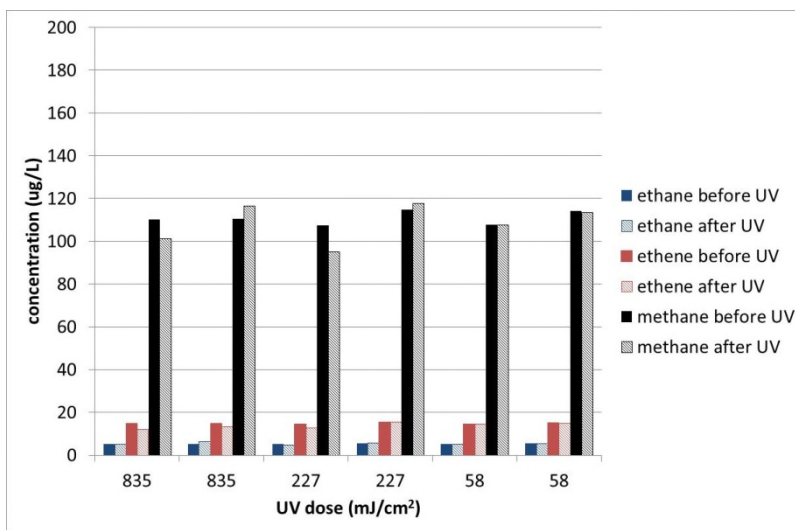
FIGURE 5-4: DEVELOPMENT OF CONCENTRATIONS OF ETHANE, ETHENE, AND METHANE DURING UV EXPERIMENTS (FEBRUARY 2015)
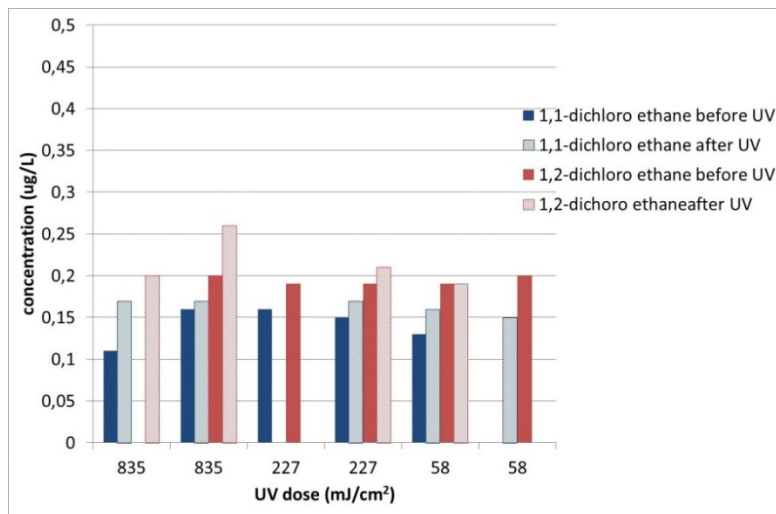
FIGURE 5-5: DEVELOPMENT OF CONCENTRATIONS 1,1- AND 1,2- DICHLOROETHANE BY UV TREATMENT (FEBR. 2015)

5.4   Results obtained in March 2015

As the experimental results obtained in January and February showed low reproducibility, for the next experiment in March it was decided to apply only one UV-dose (ca. 835 mJ/cm^2), and carry out the experiments in triplo.

Furthermore, two samples were analyzed for a broad range of compounds (a so called "Terrascan" was carried out), in order to obtain information on all compounds that are present in the water. These analyses, however, showed that no other compounds could be observed in significant concentrations, than the chlorinated ethenes already discussed. This also excludes the possibility that other compounds may have been present which can be regarded as precursors for the production of trans-dichloro ethene.

Thus, it is concluded that the formation of trans-dichloro ethene originates from UV photolysis of cis-dichloro ethene.
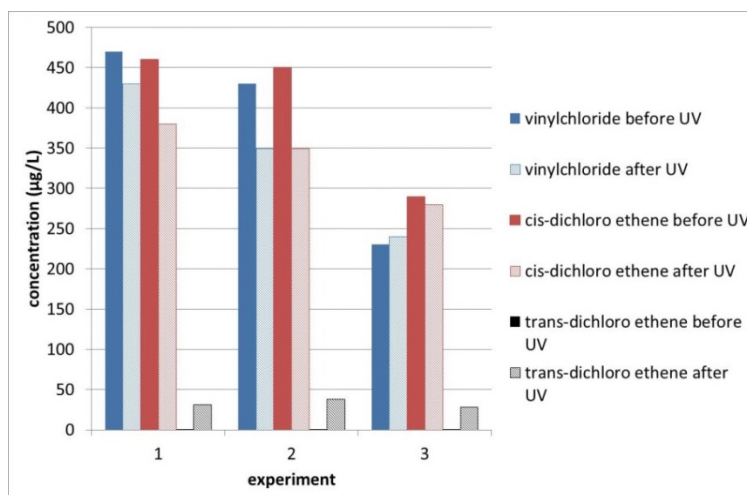
FIGURE 5-6: DEVELOPMENT OF CHLORO ETHENE CONCENTRATIONS DURING UV EXPERIMENTS (MARCH 2015).

Figure 5-6 shows that during the total experiment the influent concentrations of chloro ethenes can vary significantly. Probably this is caused by variations in the total flow through

the ATES system. Although the flow through the UV reactor was kept constant, significant fluctuations in the total flow may result in variations in the water composition, as a result of which the effluent concentrations measured do not correspond to the influent concentrations determined.
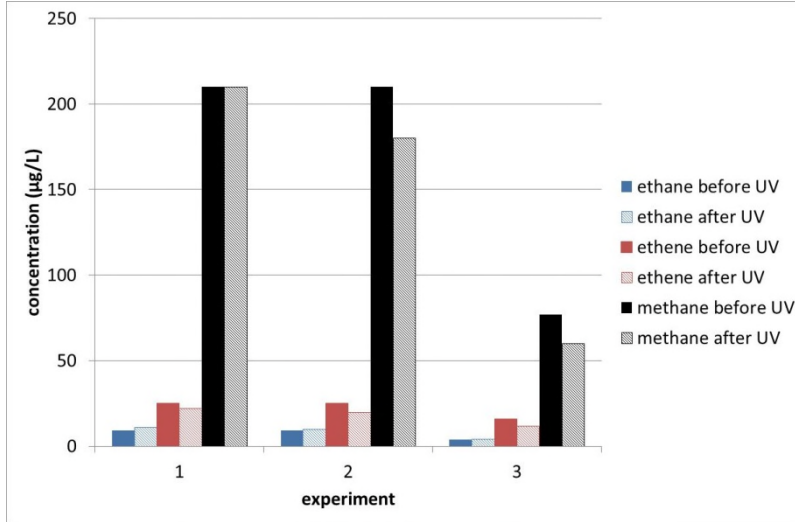
FIGURE 5-7: DEVELOPMENT OF CONCENTRATIONS OF ETHANE, ETHENE, AND METHANE DURING UV EXPERIMENTS (MARCH 2015).

From Figure 5-7 it can be concluded that some conversion of ethene and formation of ethane seems to take place, although the concentrations observed are very low. The methane concentrations are higher, but here the differences between the triplo measurements also are larger.
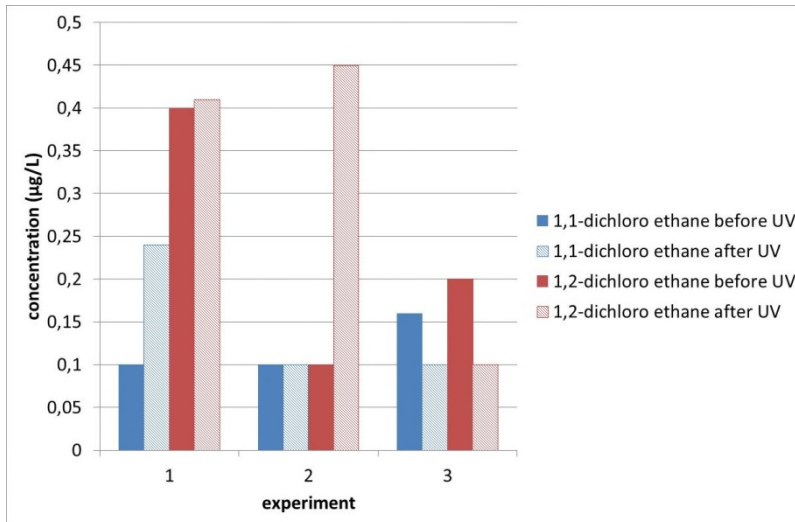
FIGURE 5-8: DEVELOPMENT OF CONCENTRATIONS 1,1- AND 1,2- DICHLOROETHANE BY UV TREATMENT (MARCH 2015)

Based on Figure 5-8 no clear conclusions can be drawn on the degradation of 1,1- and 1,2- dichloro ethane during this experiment.

These experiments show that variations in total flow through the system may cause significant variations in the influent composition. As a result no clear data on component degradation can be obtained. This explains the low reproducibility observed in both previous experiments. Therefore, in order to be able to obtain reliable results, it is important to fix the total flow through the system during an experiment.

5.5   Results obtained in June 2015

This time a different sampling procedure was followed, and the flow through the whole system was kept constant (see section 2.1.2.3)

The results obtained for this experiment are shown in Figure 5-9- Figure 5-11
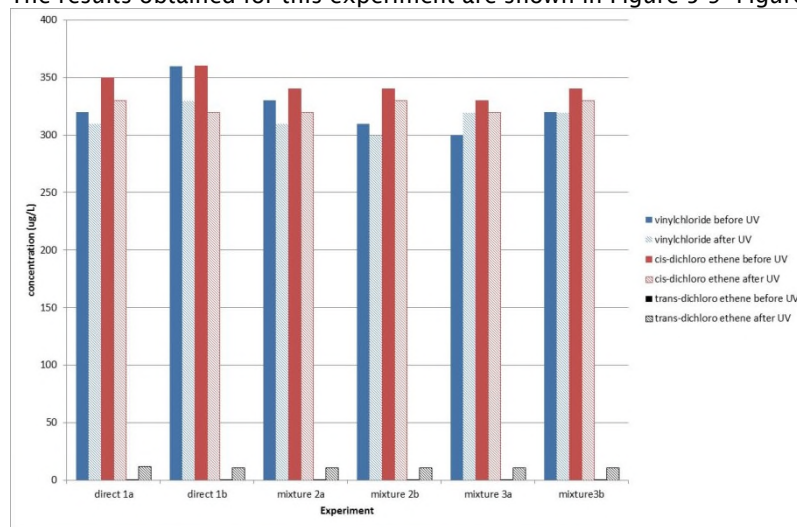
FIGURE 5-9: DEVELOPMENT OF CHLORO ETHENE CONCENTRATIONS DURING UV EXPERIMENTS (JUNE 2015).
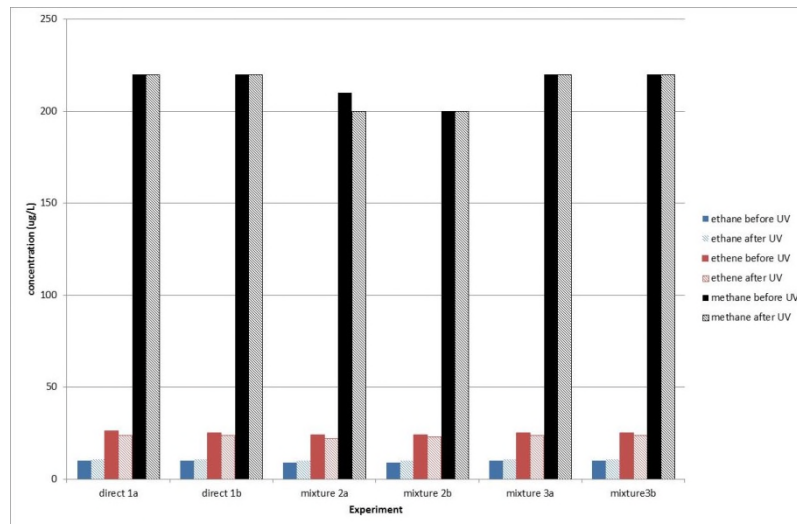
FIGURE 5-10: DEVELOPMENT OF CONCENTRATIONS OF ETHANE, ETHENE, AND METHANE DURING UV EXPERIMENTS (JUNE 2015).
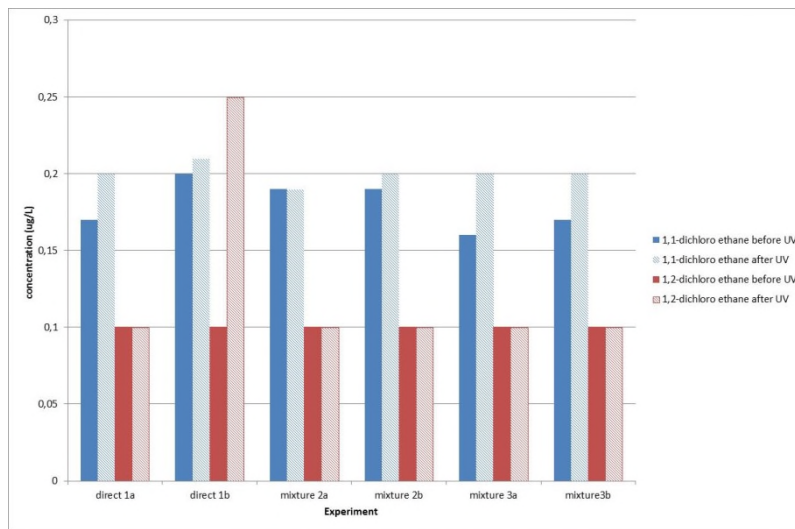
FIGURE 5-11: DEVELOPMENT OF CONCENTRATIONS 1,1- AND 1,2- DICHLOROETHANE BY UV TREATMENT (JUNE 2015)

It can be concluded that the reproducibility was strongly improved by applying the adapted experimental procedure. Thus, better reliable results were obtained. The concentrations seem to be a little higher in the direct samples than in the mixed sample, as during the longer sampling period some degassing seemed to occur, but the differences are small.

In general the concentrations of vinyl chloride and cis-1,2-dichloro ethene seem to decrease a little during the UV irradiation. The average conversion is about 5%. Again trans-1,2-dichloro ethene is observed, which probably is formed during photolysis of cis-1,2-dichloro ethene.

Furthermore, the amount of ethane formed is in the same order of magnitude as the amount of ethene degraded.

Finally, Figure 5 11 shows that some 1,1-dichloroethane is formed, whereas the concentration of 1,2-dichloroethane does not seem to change.

6   Experiments with the mobile UV unit at Strijp

6.1   General

Photolysis by means of UV irradiation may also be applied for groundwater remediation without the combination with an ATES system. The applicability of this technology was tested by using a mobile UV reactor. The UV reactor applied for this research has a smaller capacity than the reactor previously used in Maarheeze (Hofman-Caris., 2014). The UV dose applied was about 500 mJ/cm^2, and an LP UV lamp was used. Water was pumped from two different monitoring wells in Strijp: well nr. 11 with a depth of 60 m, the other, well 9, with a depth of 30 m. First experiments were carried out using well 11, later water from well 9 was taken.

Subsequently, additional experiments were carried out with water from monitoring well 4, which has a depth of 10 m, and had been found to contain higher concentrations of contaminants.

6.2   Results with monitoring wells nr. 11 and nr. 9.

Experiments were carried out on different days in September 2015. The results are shown in Table 6-2and

Table 6-3. Full experimental details can be found in Appendix II. The UV-dose applied was calculated based on Table 10-1, taking into account that the flow is inversely proportional to the UV-dose applied, and that the UV-dose depends on the log UV-T value. Thus, the following settings were applied for the experiments in monitoring wells 9 and 11 (Table 6-1). From this table it can be concluded that relatively large differences may occur in flow and water quality (UV-T) at different moments (although the flow and quality have been constant during the experiments). This, however, shows that it is very important to always adjust the reactor settings depending on water quality and flow, or to apply a relatively low flow, in order to be certain that the UV-dose applied is high enough.

TABLE 6-1: SETTINGS FOR EXPERIMENTS WITH MONITORING WELLS 9 AND 11

Date	Sample	Flow (m³/h)	UV-T (%)	Calculated UV-dose (mJ/cm²)
31-8-2015	Start up	0.5		
	11	0.7	70.2	
1-9-2015	First measurement			
3-9-2015	11 influent	0.70	77.7	583
3-9-2015	11 effluent	0.70	77.7	583
	9	0.64	70	
3-9-2015	First measurement			
4-9-2015	9 influent	0.82	64	363
4-9-2015	9 effluent	0.82	64	363
7-9-2015	9 influent	0.70	77	566
7-9-2015	9 effluent	0.70	77	566
8-9-2015	9 influent	0.48	75	800
8-9-2015	9 effluent	0.48	75	800

TABLE 6-2: ANALYTICAL DATA OBTAINED WITH MOBILE UV REACTOR, MONITORING WELLS 9 AND 11

Date	Well	Compound	UV-dose (mJ/cm²)	Inf. A (µg/L)	Eff. A (µg/L)	Inf. B (µg/L)	Eff. B (µg/L)
01/09/2015	11	tetra	--	<0.1		<0.1	
01/09/2015	11	tri	--	<0.1		<0.1	
01/09/2015	11	cis	--	60		40	
01/09/2015	11	vc	--	83		75	
03/09/2015	11	tetra	583	<0.1	<0.1	<0.1	<0.1
03/09/2015	11	tri	583	<0.1	<0.1	<0.1	<0.1
03/09/2015	11	cis	583	41	38	34	45
03/09/2015	11	vc	583	27	23	21	29
03/09/2015	9	tetra	--	0.19		0.18	
03/09/2015	9	tri	--	0.87		0.94	
03/09/2015	9	cis	--	210		220	
03/09/2015	9	vc	--	140		130	
04/09/2015	9	tetra	363	<0.1	<0.1	<0.1	<0.1
04/09/2015	9	tri	363	5.3	5.2	5.3	5.1
04/09/2015	9	cis	363	900	750	890	870
	9	trans	363	1.9	4.3	2	4.1
04/09/2015	9	vc	363	53	59	56	52
07/09/2015	9	tetra	566	0.17	<0.1	0.59	<0.1
07/09/2015	9	tri	566	23	24	23	22
07/09/2015	9	cis	566	3200	2800	3200	3200
	9	trans	566	7	16	7	16
07/09/2015	9	vc	566	450	440	430	520
08/09/2015	9	tetra	800	<0.1	<0.1	<0.1	<0.1
08/09/2015	9	tri	800	27	27	27	26
08/09/2015	9	cis	800	2500	2500	2500	2500
	9	trans	800	7.5	19	7.3	18
08/09/2015	9	vc	800	410	400	400	390

TABLE 6-3: CONVERSION DATA OBTAINED FOR MONITORING WELLS 9 AND 11.

Date	Well	Depth (m)	UV-dose (mJ/cm²)	compound	Conversion (%)	
03/09/2015	11	60	583	tetra	--	--
03/09/2015	11	60	583	tri	--	--
03/09/2015	11	60	583	cis	7	-32
03/09/2015	11	60	583	vc	15	-38
04/09/2015	9	30	363	tetra	--	--
04/09/2015	9	30	363	tri	2	4
04/09/2015	9	30	363	cis	17	2
	9	30	363	trans	-126	-105
04/09/2015	9	30	363	vc	-11	7
04/09/2015	9	30	566	tetra	40	83
04/09/2015	9	30	566	tri	-4	4
04/09/2015	9	30	566	cis	13	0
	9	30	566	trans	-128	-128
04/09/2015	9	30	566	vc	2	-21
04/09/2015	9	30	800	tetra	--	--
04/09/2015	9	30	800	tri	0	4
04/09/2015	9	30	800	cis	0	0
	9	30	800	trans	-153	-147
04/09/2015	9	30	800	vc	2.4	2.5

- From these data it can be concluded that in general only (very) low concentrations of chloro ethenes were present in both wells. As a result analytic data are less reliable. Tetra could not be observed in wells 9 and 11, and tri only in well 9 at a very low concentration.
- There are large differences in the influent concentrations of the chloro ethenes between different days. At the same day the duplicate measurements show sufficient agreement, but between different days differences can be very large, up to a factor 10-30 in well 9 and up to a factor 3 in well 11. This seems to indicate that the water composition from the monitoring wells varies significantly. The differences can be observed for all compounds.
- As tetra could not be detected, or only at a very low concentration, no conclusions can be drawn on the conversion of tetra in the mobile UV-unit.
- For tri a conversion of a few % may be possible, but concentrations are very low and thus the conversion data obtained are within the experimental uncertainty.
- For cis and VC the conversion data show large variations, even including (high) negative conversions. Therefore, it seems that these data are not reliable. Theoretically, a negative conversion might refer to the formation of the compound from decomposition of another compound. However, as no other compounds could be detected in the water, this seems very unlikely.
- There are no data available on trans-1,2-dichloro ethene.

Furthermore, it was concluded that fouling of the lamps was a problem in this mobile reactor, as a result of which it was not kept running in between experiments.

6.3   Results with monitoring well no. 4

Based on the results described above, it was decided to repeat the experiment using another monitoring well, with a higher concentration of chloro-ethenes. This monitoring well, nr. 4, also is present at the site in Strijp, and has a depth of 10 m. Experiments were carried out on February 18th 2016, and full details are shown in Appendix II. The average UV-dose applied was 1378 mJ/cm^2, based on influent and effluent UV-T. Although the difference was small, at high UV-T values even small differences affect the UV-dose applied, as there is a logarithmic relation between UV-T and dose. This also explains why this relatively high UV-dose was applied.

TABLE 6-4: SETTINGS FOR EXPERIMENTS WITH MONITORING WELL 4

Date	Sample	Flow (m³/h)	UV-T (%)	Calculated UV-dose (mJ/cm²)
18-2-2016	4 First measurement	0.8	86.5	
18-2-2016	4 influent	0.58	88.9	1367
18-2-2016	4 effluent	0.58	88.9	1389

TABLE 6-5: ANALYTICAL DATA OBTAINED WITH MOBILE UV REACTOR, MONITORING WELL 4

Compound	Inf. 0 (µg/L)	Inf. 1 (µg/L)	Eff. 1 (µg/L)	Inf. 2 (µg/L)	Eff. 2 (µg/L)	Conv. 1 (%)	Conv. 2 (%)
Tetra	3	3.1	2.6	3	2.5	16	17
Tri	7700	7800	7700	7700	6900	1	10
cis	430	440	420	430	410	5	5
Trans	1.5	1.6	7.2	1.5	6.7	-350	-347
VC	2.5	3.2	2.7	2.4	2.8	15	-17

From the data in Table 6-5 it can be concluded that:

- Most duplicate values agree well.
- The water contains significant concentrations of trichloroethene and cis-1,2-dichloroethene, and low concentrations of tetrachloroethene, trans-1,2-dichloroethene, and vinylchloride.
- Conversion of tetrachloroethene seems to be about 17%.
- The conversion of trichloroethene is about 5%., as is the case for cis-1,2-dichloroethene.
- Clearly, trans-1,2-dichloroethene is formed during the experiments. This can be explained from the conversion of other compounds, like tetra- or trichloroethene, or cis-1,2-dichloroethene. In chapter 5 it seemed that trans was formed by photolysis of cis, but in this case that cannot be definitely concluded.

Thus, indeed it seems that, at a high UV-dose, conversion of "larger" chloroethenes with about 10-20% is possible applying UV-photolysis. However, for small chloroethenes like cis-dichloroethene and VC, the conversion is limited.

7 Discussion on results obtained

7.1 Introduction

In order to judge the results described in section 6.2 and 6.3, a comparison was made with results obtained with the ATES experiment in Strijp-S, and with previously obtained in Maarheeze (Hofman-Caris, 2014). The latter experiments were carried out in 2012, and an extensive description of experimental details can be found in (Hofman-Caris 2014). In the present report the original analytical data from this project are evaluated in a different way.

In Maarheeze two diferent types of experiments were carried out:

- Recirculation-experiments: The UV reactor was positioned between two collecting tanks for water. The water from the monitoring well was collected in one of these tanks, and subsequently passed through the UV reactor, and collected in the second tank. Then, the process was reversed. In this way the water was recirculated through the UV reactor, and the concentrations of chloro organics were determined after 10, 20 and 30 irradiations. Experiments took place on 29/02/2012 (reaction a) and on 07/03/2012 (reaction b).
- Single-pass experiments: the water from the monitoring well was passed once through the UV reactor, and the concentrations of chloro organics were measured before and after the irradiation. These experiments took place on 19/6, 4/7, 10/7, 17/7, 24/7, 1/8, 7/8, en 12/8 in 2012.

In all experiments a UV dose of about 500 mJ/cm^2 was applied, using a LP UV lamp.

7.2 Recirculation experiments in Maarheeze

The results of the recirculation experiments are shown in Table 7-1.

TABLE 7-1: OVERVIEW OF THE RESULTS OF HET RECIRCULATION EXPERIMENTS IN MAARHEEZE (2012).

component	influent (µg/L)	after 20 irradiations (µg/L)	Conversion per cycle (%)	after 30 irradiations (µg/L)	Conversion per cycle (%)
Tetrachloroethene (a)	10,000	960	11.1	120	13.7
Trichloro ethene (a)	17,000	12,000	1.7	4,500	4.3
Cis-1,2-dichloro ethene (a)	18,000	12,000	2.0	4,900	4.2
Tetrachloro ethene (b)	6,500	1,200	8.0	530	8.0
Trichloro ethene (b)	11,000	6,400	2.6	4,600	2.8
Cis-1,2-dichloro ethene (b)	15,000	8,000	3.1	5,700	3.2

The conversion per individual cycle was calculated according to equation 40.

$$C_{eff} = a^n * C_{inf}$$
(40)

In this formula C_{efft} = concentration in effluent, C_{ing} = concentration in influent, a = 1-conversion, en n = number of cycli.

From these data it can be concluded that the highest conversion was obtained for tetrachloro ethene, and that the maximum conversion is about 10±2%. The average conversion both for trichloro ethene and cis-1,2-dichloro ethene is 3±1%. The vinylchloride concentrations in the influent were so low (10-30 μg/L) that no reliable data could be obtained.

7.3   Single pass experiments in Maarheeze

The results obtained with the single pass experiments in Maarheeze are summarized in Table 7-2.

TABLE 7-2: OVERVIEW OF THE RESULTS OF THE SINGLE PASS EXPERIMENTS IN MAARHEEZE (2012).

date	Tetrachloro ethene			Trichloro ethene			Cis-1.2-dichloro ethene			vinylchloride		
	Inf (µg/L)	eff (µg/L)	Conv. (%)	Inf (µg/L)	eff (µg/L)	Conv. (%)	Inf (µg/L)	Eff (µg/L)	Conv. (%)	Inf (µg/L)	Eff (µg/L)	Conv. (%)
19/6/12	4366	2341	46.4	1945	1892	2.7	4159	3694	11.2	69	50	27.3
4/7/12	3054	2307	24.5	1840	1774	3.6	6302	6011	4.6	131	116	11.4
10/7/12	2820	2191	22.3	1734	1761	-1.5	6670	6913	-3.6	156	163	-4.0
17/7/12	3171	2357	25.7	1905	1866	2.1	8047	7465	7.2	194	163	16.1
24/7/12	3137	1640	47.7	1813	1669	8.0	6825	6040	11.5	155	141	8.9
1/8/12	2490	1494	40.0	1590	1682	-5.8	6911	6921	-0.2	184	164	10.8
7/8/12	2756	1345	51.2	1748	1560	10.8	7698	6887	10.5	161	136	15.5
12/8/12	2903	1301	55.2	1800	1400	22.2	7900	6400	19.0	180	150	16.7

Based on these results the following conclusions are drawn:

1. The chloro ethene concentrations are relatively low (significantly lower than in the recirculation experiment).
2. The derived conversion of tetrachloro ethene was on average 39±16%.
3. The conversion of trichloro ethene is on average 6±10% . In comparison with tetrachloro ethene this is rather low, but it is possible that some trichloro ethene was formed by photolysis of tetrachloro ethene. This would explain the negative conversion observed, although it should be kept in mind that the experimental uncertainty is relatively large.
4. The conversion of cis-1,2-dichloro ethene on the average is 8±10%. Similar considerations as for trichloro ethene apply.
5. The conversion of vinylchloride on the average is 13±10%. However, the data probably are nor very reliable, as all concentrations are near the reporting limit.

7.4   Results obtained in the combined ATES and UV reactor

On June 9th 2015 the experiment with fixed flow through the system was carried out. Details on the results can be found in section 5.5, and are also shown in Table 7-3.

TABLE 7-3: DATA OBTAINED IN THE COMBINED INSTALLATION AT STRIJP-S (9/6/2015).

	influent 1A (µg/L)	Effluent 1A (µg/L)	conv (%)	Influent 1B (µg/L)	Effluent 1B(µg/L)	Conv (%)
Tetrachloro ethene	<0.1	<0.1	--	<0.1	<0.1	--
Trichloro ethene	<0.1	<0.1	--	<0.1	<0.1	--
Cis-1,2-dichloro ethene	350	330	**5.7**	360	320	**11.1**
Trans-1,2-dichloro ethene	0.21	12	-5614.3	0.2	11	-5400.0
vinylchloride	320	310	**3.1**	360	330	**8.3**

From Table 7-3 it is concluded that

1. The conversion of cis-1,2-chloro ethene is 8±3% (decrease of 20-40 µg/L). This conversion is in the same order of magnitude as the formation of trans-1,2-dichloro ethene (10 µg/L), indicating that probably part of the cis is converted into trans. As no larger chloro molecules appear to be present in the water, this seems to be the only logic explanation for the formation of trans-1,2-dichloro ethene.
2. The conversion of vinylchloride is about 5±3%.

7.5   Results obtained with the mobile UV reactor at Strijp

Full details on the experiments with the mobile UV reactor at Strijp are shown in chapter 6. As the concentrations of chloro ethenes in monitoring wells 9 and 11 were very low, only in monitoring well 4 reliable results could be obtained. It was shown that the conversion of tetrachloro ethene was about 17%, and of trichloro-ethene and cis-1,2-dichloro ethene both about 5%. However, a very high UV-dose (1378 mJ/cm^2) had been applied, as a result of the high UV-T values of the water in well 4. For vinylchloride no reliable results could be obtained.

7.6   Comparison of all results

It can be concluded that the degradation results in all experiments, both at Strijp and in Maarheeze, are rather consistent. However, it appeared to be difficult to obtain reliable

experimental results. This may be due to low concentrations, variations in concentrations, and e.g. fouling of the UV-reactor (in the energy storage system of Strijp the penetration of oxygen into the system effectively was prevented, so here no problems were observed with fouling of the UV-lamps). Overall the following observations have been made:

- Tetrachloro ethene can be degraded to about 20% in one single passage of the UV-reactor.
- On the average, the conversion of trichloro ethene in one single passage is about 5%. However, as in most cases a mixture of tetrachloro- and trichloro ethene was observed, it cannot be excluded that the actual conversion of trichloro ethene may have been higher, as this compound also may be formed during the photolysis of tetrachloro ethene.
- The degradation of cis-dichloro ethene seems to be about 5-10%. Here too it should be kept in mind that during the photolysis of tetra- or trichloro ethene dichloro-ethene may be formed.
- Also for vinylchloride it is difficult to reliable data on the conversion by UV-photolysis, as in the presence of larger chloro ethenes this compound too may be formed (this probably explains the low reproducibility of the data obtained with monitoring well 4 at Strijp). However, in the experiments in Maarheeze and at monitoring wells 9 and 11 at Strijp-S, the conversion seemed to be about 5% .
- At the ATES system it seemed that cis-1,2-dichloro ethene was converted into trans-1,2-dichloro ethene. Also at Strijp (and previously in Maarheeze) it could be seen that the trans compound was formed, although in that case its origin was less clear (it may also be formed by photolysis of tetra- or trichloro ethene). As in soils mainly cis-dichloro ethene is found, there is not much information on the biodegradation of this compound, and it cannot be excluded that this will be less efficient than the biodegradation of cis-dichloro ethene.

7.7   Possible explanations for the results obtained

Another way to look at the conversion data is to determine the degree of chlorination of the molecules themselves, or calculated as μg Cl/L. This is shown in

Table 7-4

Table 7-4

TABLE 7-4: EFFECT OF UV RADIATION ON THE DEGREE OF CHLORINATION DURING SEVERAL EXPERIMENTS

Sample	UV-dose (mJ/cm²)	Influent mol Cl/mol	Influent mol Cl/L	Effluent mol Cl/mol	Effluent mol Cl/L	conversion mol Cl/mol (%)	conversion mol Cl/L (%)
Recirculation experiments Maarheeze	1800	2.58	720	1.48	830	4.1	-15.3
	2100	2.66	1003	2.52	877	5.5	12.6
	3200	2.58	720	2.44	350	5.5	51.4
	4150	2.66	1003	2.44	565	8.2	43.7
	4600	2.58	720	2.40	246	6.9	65.8
	6400	2.66	1003	2.39	219	10.2	78.2
Single Pass Maarheeze	131	2.44	248	2.36	243	3.2	2.1
	147	2.49	248	2.42	226	1.6	9.0
	160	2.39	243	2.28	229	4.3	5.8
	164	2.46	261	2.35	205	4.8	21.4
Combined system Strijp Mobile reactor Strijp Monitoring well 9	800	1.41	12	1.42	12	-0.1	2.7
	800	1.39	13	1.39	12	0	8.2
	363	1.92	20	1.90	17	1.2	15.1
	363	1.92	19	1.92	19	-0.2	2.3
	566	1.83	74	1.81	66	0.8	11.1
	566	1.83	74	1.80	75	1.6	-2.2
	800	1.81	59	1.81	59	-0.3	-0.1
	800	1.81	59	1.81	58	-0.2	-0.1
reactor Strijp Monitoring well 4	1378	2.93	187	2.93	185	-0.1	1.4
	1378	2.93	184	2.92	166	0.2	10.1

From

Table 7-4 it can be concluded that photolysis is most effective if tetra and tri are present, but in case there are only less chlorinated ethenes i.e. dichloro ethene and vinylchloride, the process is significantly less effective. Furthermore, it can be noticed that UV photolysis in general may decrease the number of chlorine atoms per molecule. However, it also is shown that large differences in influent concentrations may occur, and that a high UV-dose (several passes through the UV-reactor) is required to obtain a significant decrease in chloro-compounds.

As mentioned in chapter 4 the biodegradation of tetra- and trichloro ethene is much faster than that of dichloro ethene and vinylchloride. Furthermore, (Gürtler, Möller et al. 1994) showed that mono- and dichloro- ethene can hardly absorb UV radiation with a wavelength of 254 nm. Vinylchloride is not converted at this wavelength, and 1,2-dichloro ethene can only be degraded by applying long irradiation periods. Tetra- and trichloro ethene are quickly converted at 254 nm, which results in the formation of chlorine radicals. This is in accordance with the findings of (Shirayama, Tohezo et al. 2001), who concluded that the conversion of tetrachloro ethene is the fastest reaction.

It is unlikely that the chlorine radicals formed will contribute to the further degradation of chloro ethenes. They will probably react with another molecule, and in most cases this will result in the formation of an organo chlorine, e.g. by addition of the chlorine radical to a double bond. As in general concentrations of NOM in the groundwater are much higher than those of chloro ethenes, reaction of chlorine radicals with NOM will be most likely. However, the formation of trans-1,2-dichloro ethene from cis-1,2-dichloro ethene can be explained in this way. Photolysis may remove one chlorine radical from the cis compound, which subsequently reacts to form the trans compound, as this compound suffers less from steric hindrance than the cis molecule. Similarly, conversion of trichloro ethene will probably also favor the formation of trans-1,2-dichloro ethene. However, during biodegradation cis-1,2-dichloro ethene is produced.

From a chemical viewpoint it is very likely that the photolysis of tetra and trichloro ethene is more effective than of less chlorinated ethenes like dichloro ethene and vinylchloride. The more chlorine atoms molecules contain, the greater their electron-withdrawing potential. This results in a lower stability of these molecules than of smaller molecules, which contain less chlorine atoms. In order to obtain proof of this mechanism photochemical constants of these compounds (quantum yield and molar absorption coefficient) should be determined. To date this information appears to be lacking, likely due to the high volatility and toxicity of these compounds which complicates the practical determination of these parameters.

8 Market analysis

At the Strijp-S site a recirculation system is applied for the ATES. In areas with a groundwater pollution often such a recirculation system is applied in order to limit spreading of the pollutants. A recirculation system is characterized by the fact that there isn't a warm (ca. 16 ºC) and cold (ca. 8 ºC) source available, as water always is withdrawn from the same source(s) (with a temperature of about 11 ºC) . As a result of this the temperature range available is smaller than in a conventional ATES, and thus the flow through the system will have to be about twice as high. This requires more pumping energy to transport the water through the ATES system, and involves higher investment costs. Theoretically a UV-reactor can also be applied in a conventional ATES system, but in practice probably a recirculation system will be required in an area with polluted groundwater.

The costs of an ATES/UV system are shown in Table 8-1.

TABLE 8-1

Table 8.1: Costs involved in application of an ATES/UV recirculation system at Strijp-S.

	1 doublet recirculation*)	Sanergy Cluster I + II**)
Capacity	80 m³/h	**360** m³/h
Power UV	2 kW	9 kW
Expected lifetime UV lamps	1,5 year	1,5 year
Expected lifetime UV installation	10 year	10 year
Service interval	0,7 Times/year	0,7 Times/year
Operating hours	8760 Hours per year	8760 Hours per year
Electricity costs	€ 0,10 /kW	€ 0,10 /kW
Investment for UV reactor with wiper	€ 15.000,00	€ 67.500,00
Installation costs	€ 5.000,00	€ 22.500,00
Lamp replacement costs	€ 2.300,00	€ 10.350,00
Duration of maintenance	4 hours	18 hours
Hourly rate maintenance	€ 65	€ 65
Pumping power	12,6 kW	56,7 kW
Additional electricity costs because of recirculation	25% of total electricity use	25% Of total electricity use
Costs		
Maintenance	€ 1.793,33	€ 8.070,00
	€ 1.752,00	€ 7.884,00
Electricity of pumps	€ 2.759,40	€ 12.417,30
Annuity	€ 2.717,36	€ 12.228,12
Subtotal	€ 9.022,09	**€ 40.599,42**
Risks & unforeseen 10%	€ 902,21	€ 4.059,94
Total	€ 9.924,30	**€ 44.659,36**

*) Power comparable with a common ATES system of 40 m³/hour. Because of the recirculation system, and the resulting higher flows required, additional sources will have to be taken into account. Additional costs involved are disregarded, as these depend strongly on the soil capacity. As an indication it can be assumed that 1 doublet for about 80 m3/hour will cost about 125 k€.

**) The UV-reactor in this project had been installed into one system. However, the total ATES system at Strijp-S is about 4.5 times as large. Therefore, all costs for one doublet were multiplied by a factor 4.5. This, however, will not be totally true, e.g. for maintenance, but

In this case 5% removal of the pollutants per passage of the UV reactor was assumed. It was found that the degradation of chlorinated ethenes strongly depends on the type of pollutants present. Compounds containing three or four chlorine atoms are more easily convertible than compounds like dichloro ethene and vinyl chloride. As the groundwater studied in Strijp mainly contained dichloro ethene and vinyl chloride, the process was relatively ineffective. Besides, it was found that cis-dichloro ethene probably is converted into trans-dichloro ethene, for which biodegradation efficiency still has to be studied.

Furthermore, the efficiency of the UV-reactor strongly depends on the water quality (UV-transmission, and in some cases the turbidity). The flow may vary in time, and as a result also the water quality and composition of the chlorinated ethene mixture may strongly vary. Thus, the reproducibility of the process may be relatively low. This can be compensated for by applying a UV-dose, which is high enough to deal with all pollutant concentrations within the expected range.

In order to make a thorough cost estimation, it will be necessary to determine how often the water will have to pass the UV reactor in order to obtain sufficient removal of the pollutants. This will depend on several factors:

- Concentrations of different pollutants
- Effect of biodegradation in between passages
- Required final concentrations in groundwater

The final concentrations required depend on agreements made with the authorities in the area where the pollutant groundwater is present. These concentrations may be the target concentrations or the thresholds, but, depending on circumstances, other values may be agreed upon. For the chlorinated ethenes in this study the targets and thresholds are shown in Table 8-2.

TABLE 8-2: TARGETS AND THRESHOLDS FOR CHLORINATED ETHENES IN GROUNDWATER

Volatile chlorinated hydrocarbons in groundwater	Target (µg/L)	Threshold (µg/L)
Perchloroethene	0.01	40
Trichloroethene	24	500
1,2-dichloroethene	0.01	20
vinylchloride	0.01	5

Under the present circumstances in the case of monitoring well 4, with an influent trichloroethene concentration of 7800 (µg/L) it would take 54 passages through the UV

reactor to reduce the concentration to below the threshold value at a conversion of 5% per passage, and 26 passages at a conversion of 10% per passage.

In order to define a market for this system it will be necessary to do more research into the relation between water composition and degradation of contaminants. The concentrations of the different pollutants may vary per treatment site and in time (e.g. depending on the flow through the ATES system). Biodegradation will depend on the type of pollutants and their reaction pathway upon photolysis, and will have to be studied in more detail.

For the present case in Strijp it does not seem to be profitable to apply UV photolysis as a remediation for contaminated groundwater, as the groundwater mainly seems to contain dichloro ethene and vinyl chloride. At other sites, with different ground water contamination, it may be effective, but this will have to be studied in more detail, also taking into account the variations in flow and composition of the groundwater.

9 Conclusions and recommendations

9.1 Overall conclusions

Combining an ATES system with a UV-reactor for simultaneous groundwater remediation can be a very elegant way to remove pollutants. The system can run stably for a long time period, and the technique is non-invasive. Furthermore, UV-photolysis may also be applied to groundwater remediation in an independent system (without ATES). The effectiveness, and thus the economic applicability of the process, however, strongly depends on the composition of the pollutants and the water matrix.

9.2 Specific conclusions of this project

The following conclusions can be drawn based on the results obtained with the combination of an ATES system with a UV reactor at Strijp-S (January-June 2015):

- It is unlikely that UV treatment of the groundwater will negatively affect the microbial population of the groundwater system, and thus the biodegradation processes that occur.
- Thusfar it cannot be excluded that some toxic transformation products or byproducts are formed during the process. This may be checked by applying bio assays, or by specifically determine the concentration of some well-known byproducts, like phosgene and chloro acetaldehyde.
- The combined reactor system is stable. The UV-T of the water (ca. 76%) is suitable for an effective UV process, and there are no problems with turbidity. The UV process itself, therefore, can be considered reliable.
- For experiments it is very important to keep the flow constant. Variations in the flow are associated with fluctuations in the groundwater composition, as a result a of which no reliable experimental data on the degradation of compounds as a function of UV dose can be obtained.
- Some degassing only seems to occur after a relatively long period of sampling. Neither in the samples, nor in the UV output degassing could be observed. There are no indications, neither experimentally nor from a theoretical point of view, that degassing would occur in the UV reactor, or would result in lower aqueous concentrations of organic halogens.
- At a constant flow the difference between a direct sample and a (large) mixed sample is very small. As it cannot be excluded that during a longer sampling period some gas might volatalize, it is recommended to take direct samples. At a constant flow water composition also stays constant, and therefore direct sampling should not be a problem.
- The conversion of vinylchloride and 1,2-cis-dichloro ethene is in the order of 5%, at a UV dose of about. 835 mJ/cm^2. In comparison with previous experiments in Maarheeze this is a low conversion, but it can be explained from differences in the groundwater composition, which at Strijp-S contains no tetra- or trichloro ethene.
- It is clear that some photolysis takes place, as 1,2-trans-dichloro ethene is formed, which hardly is present in groundwater. Based on the further composition of the groundwater, the parent compound can only be cis-1,2-dichloro ethene. For biodegradation this conversion may be unfavorable, as the cis compound probably is better biodegradable than the trans compound.

- Although the differences are small, there seems to be a trend that some ethene is converted into ethane. This reaction under the influence of 254 nm radiation is known from literature.
- Possibly a small amount of 1,1-dichloro ethane is formed during the process too.
- In groundwater systems tetra- and trichloro ethene are biologically degraded into dichloro ethene and vinylchloride. The rate determining step in the full biodegradation of such pollutants is the degradation of the latter two compounds. The present UV system will enhance the conversion of tetra- and trichloro ethene, but probably will only slightly enhance the conversion of dichloro ethene and vinylchloride.

For the experiments with the mobile UV reactor the following conclusions can be drawn:

- The monitoring wells applied only contain some dichloro ethene and vinylchloride, but no significant concentrations of tetra- or trichloro ethene.
- Degradation of 1,2-dichloro ethene and vinylchloride is about 5% at a UV dose of ca. 500 mJ/cm^2. This is in accordance with the findings in the combined reactor, described above, and with previous results obtained in Maarheeze.

9.3   Recommendations
- In order to obtain a good idea about the possible applications of UV photolysis for groundwater remediation, it is important to carry out some experiments at a site were compounds like tetra- and tri-chloro ethene are present in the water.
- For only dichloro ethene and vinylchloride removal the technology does not really seem to be efficient.
- It is recommended to study the possible formation of toxic byproducts, like phosgene and chloro acetaldehyde, before applying the technology on a full scale for groundwater remediation. However, this only can be done when enough conversion can be obtained, as otherwise the concentrations certainly would be below the detection limit.
- There are also other types of organic groundwater contaminants (not chlorinated ethenes, but e.g. BTEX, chlorate, etc.), for which UV photolysis may be more effective. Therefore, it is recommended to study the UV/ATES system with other contaminants.

10 Literature

Aulenta, F., R. Verdini, et al. (2013). "Electrochemical stimulation of microbial cis-dichloroethene (cis-DCE) oxidation by an ethene-assimilating culture." New Biotechnology **30**(6): 749-755.

Bürgmann, H., J. Kleikemper, et al. (2008). "Detection and quantification of dehalococcoides-related bacteria in a chlorinated ethene-contaminated aquifer undergoing natural attenuation." Bioremediation Journal **12**(4): 193-209.

Cantrell, C. A., A. Zimmer, et al. (1997). "Absorption cross sections for water vapor from 183 to 193 nm." Geophysical Research Letters **24**(17): 2195-2198.

Cao, M. H., B. B. Wang, et al. (2010). "Photochemical decomposition of perfluorooctanoic acid in aqueous periodate with VUV and UV light irradiation." Journal of Hazardous Materials **179**(1-3): 1143-1146.

Dillert, R., D. Bahnemann, et al. (2007). "Light-induced degradation of perfluorocarboxylic acids in the presence of titanium dioxide." Chemosphere **67**(4): 785-792.

Dilmeghani, M. and K. O. Zahir (2001). "Kinetics and mechanism of chlorobenzene degradation in aqueous samples using advanced oxidation processes." Journal of Environmental Quality **30**(6): 2062-2070.

Field, J. A., A. J. M. Stams, et al. (1995). "Enhanced biodegradation of aromatic pollutants in cocultures of anaerobic and aerobic bacterial consortia." Antonie van Leeuwenhoek **67**(1): 47-77.

Flynn, T. M. (2011). Microbial diversity and groundwater chemistry in a pristine aquifer. PhD, University of Illinois at Urbana-Champaign.

Flynn, T. M., R. A. Sanford, et al. (2008). "Attached and suspended microbial communities in a pristine confined aquifer." Water Resources Research **44**(7).

Flynn, T. M., R. A. Sanford, et al. (2008). "Attached and suspended microbial communities in a pristine confined aquifer." Water Resources Research **44**(7): W07425.

Foght, J., T. April, et al. (2001). "Bioremediation of DDT-contaminated soils: A review." Bioremediation Journal **5**(3): 225-246.

Gürtler, R., U. Möller, et al. (1994). "Photooxidation of exhaust pollutants: III. Photooxidation of the chloroethenes: Degradation efficiencies, quantum yields and products." Chemosphere **29**(8): 1671-1682.

Hage, J. C. (2004). Application of pseudomonas Sp. StrainDcal for the removal of chlorinated hydrocarbons, Wageningen University.

Hara, J. (2011). "The effect of oxygen on chemical dechlorination of dieldrin using iron sulphides." Chemosphere **82**(9): 1308-1313.

Himmelheber, D. W., K. D. Pennell, et al. (2007). "Natural attenuation processes during in situ capping." Environmental Science and Technology **41**(15): 5306-5313.

Hofman-Caris, C. H. M. (2014). Grondwatersanering met behulp van UV-straling.

Isidori, M., A. Nardelli, et al. (2006). "A multispecies study to assess the toxic and genotoxic effect of pharmaceuticals: Furosemide and its photoproduct." Chemosphere **63**(5): 785-793.

Lehman, R. M. (2007). "Understanding of Aquifer Microbiology is Tightly Linked to Sampling Approaches." Geomicrobiology Journal **24**(3-4): 331-341.

Lima, G., B. Parker, et al. (2012). "Dechlorinating microorganisms in a sedimentary rock matrix contaminated with a mixture of VOCs." Environmental Science and Technology **46**(11): 5756-5763.

Lindqvist, L., B. Czochralska, et al. (2002). "Photochemistry of 2-chloropyrimidine." Photochemical and Photobiological Sciences **1**(8): 600-606.

Liu, X., S. Yoon, et al. (2013). "Photochemical degradation of vinyl chloride with an Advanced Reduction Process (ARP) - Effects of reagents and pH." Chemical Engineering Journal **215-216**: 868-875.

Oppenländer, T., C. Walddörfer, et al. (2005). "Improved vacuum-UV (VUV)-initiated photomineralization of organic compounds in water with a xenon excimer flow-through photoreactor (Xe2* lamp, 172 nm) containing an axially centered ceramic oxygenator." Chemosphere **60**(3): 302-309.

Qu, Y., C. Zhang, et al. (2010). "Photo-reductive defluorination of perfluorooctanoic acid in water." Water Research **44**(9): 2939-2947.

Rowland, G. A., A. R. Bausch, et al. (2011). "Photochemical processing of aldrin and dieldrin in frozen aqueous solutions under arctic field conditions." Environmental Pollution **159**(5): 1076-1084.

Schaefer, C. E., C. W. Condee, et al. (2009). "Bioaugmentation for chlorinated ethenes using Dehalococcoides sp.: Comparison between batch and column experiments." Chemosphere **75**(2): 141-148.

Sedykh, A., R. Saiakhov, et al. (2001). "META V. A model of photodegradation for the prediction of photoproducts of chemicals under natural-like conditions." Chemosphere **45**(6-7): 971-981.

Shirayama, H., Y. Tohezo, et al. (2001). "Photodegradation of chlorinated hydrocarbons in the presence and absence of dissolved oxygen in water." Water Research **35**(8): 1941-1950.

Stroo, H., D. Major, et al. (2010). Bioaugmentation for Anaerobic Bioremediation of Chlorinated Solvents. In Situ Remediation of Chlorinated Solvent Plumes. H. F. Stroo and C. H. Ward, Springer New York**:** 425-454.

Stroo, H., D. Major, et al. (2010). Bioaugmentation for anaerobic bioremediation of chlorinated solvents. In situ remediation of chlorinated solvent plumes. H. F. Stroo, Ward, C.H. New York, Springer**:** 425-454.

Trautwein, C. and K. Kümmerer (2012). "Degradation of the tricyclic antipsychotic drug chlorpromazine under environmental conditions, identification of its main aquatic biotic and abiotic transformation products by LC-MS n and their effects on environmental bacteria." Journal of Chromatography B: Analytical Technologies in the Biomedical and Life Sciences **889-890**: 24-38.

Ugolini, F., R. Henneberger, et al. (2013). "In‐Situ Sonication for Enhanced Recovery of Aquifer Microbial Communities." Groundwater.

Vargas, F., I. M. Volkmar, et al. (1998). "Photodegradation and phototoxicity studies of furosemide. Involvement of singlet oxygen in the photoinduced hemolysis and lipid peroxidation." Journal of Photochemistry and Photobiology B: Biology **42**(3): 219-225.

Watanabe, K. and M. Zelikoff (1953). "Absorption coefficients of water vapor in the vacuum ultraviolet." Journal of the optical society of America **43**(9): 753-755.

Yoon, S., D. S. Han, et al. (2014). "Degradation of 1,2-dichloroethane using advanced reduction processes." Journal of Environmental Chemical Engineering **2**(1): 731-737.

Appendix I

Overview over set-up combined
aquifer thermal energy storage and
UV-reactor at Strijp

FIGURE 10-1: TECHNICAL SPECIFICATION SHEET OF UV-REACTOR:

11.077A

KappaLine UV-system

Technical specification sheet

Type : K4XL24.130 Ec

UV chamber type K4XL

Material chamber	stainless steel 316L (1.4404)
Roughness, internal	max. 0,6 to 1.0 micron
Shape of construction	I-shape
Connection, basic	NW300 EN-1092-1 PN10
Mounting	horizontal alt. vertical
Max. waterpressure	10 bar
Number of UV lamps and quartzsleeves	24
Type of UV lamp	E130
UV lampconnection	one-sided
Quartzsleeve(s)	one-side closed
Fixation of quartzsleeves	two-sides fixed
Type of quartz, standard	Q200
Protection class	IP54
UV sensor	included
Anti-fouling mechanism, electrical, Ec	included
Drain/deairationconnection (¼")	included
Flangeconstruction for easy access into the chamber	included
Dimensions	see drawing K4XL.300
Distance between in-and outletflanges	700mm
Width incl wipermotor	1000mm
Maintenance space	see drawing K4XL.300

Control cabinet (standard)

Material	painted steel
Dimensions at standard power supply (h x w x d)	1600 x 1200 x 400mm
Power supply	400Volt 3L+N
Connected power	max. 4.4 kW
Installed power	4,8 kVA
Frequency	50 or 60 Hz
Protection class	IP54
Electrical cables between chamber and cabinet	included (5 meters)

Controller type

Display for read-out	**Lambda 5** 4 x 16 character read-out
Remote control and Remote ON/OFF	included
Lampfailure detection, lampstatus and –control	included
Hourscounter, 'system ON', non-resetable	included
Hourscounter, 'lamp(s) ON' resetable	included
Warning messages for lampfailure and maintenance	included
Input for flowmeter, variable (4-20mA) or fixed	included
PFCs for UV WARNING, ALARM, READY, MAINTENANCE	included
Watertemperature input and protection	included
Cabinettemperature warning and alarm	included
UV dose read-out (mJ/cm²)	included
Alarm contact (3A)	included
Low UV outputsignal	included
Setpoints 'minimum UV dose' and 'UV dose warning'	included
4-20mA UV intensity output	included
Operation and control electrical anti-fouling mechanism	included

FIGURE 10-2: SPECIFICATIONS OF UV-T METER:

bUV.30.UVT.001.2008.EN

UV transmittance meter

Technical specification sheet   Type : bestUVT10

Technical specifications	
UV wavelength	253,7 nm
Lamp source	Low pressure UV lamp
Sample cell	10 x 10 mm quartz cuvette
Path length of sample cell	10 mm
Display	32 character back-lit LCD digital display
Calibration	With simple push of button
Operation temperature	0 – 50 °C
Measurement 1	**UV transmission (UVT10 @ 254nm)**
Units of measurements, UV transmission	%
Range, UV transmission	0 – 100%
Accuracy	± 0,5%
Resolution, UV transmission	0,1%
Measurement 2	**UV absorbance (A/cm @ 254 nm)**
Units of measurements, UV absorbance	cm^{-1}
Range, UV absorbance	0 – 2/cm (0 – 200/m)
Resolution, UV absorbance	0,0001
Response times	
Response time, warm-up	1 minute at roomtemperature
Response time, calibration	2 seconds
Response time, computation	2 seconds
Power supply	
Power supply, net	230VAC (110VAC)
Power supply, carkit	12 VDC
Power supply, battery (oploadable)	included
Packaging	
Case with carrying handle	Rugged, watertight, dustproof
Weight	1,8 kg
Dimensions (w x h x d), closed	22 x 10 x 19 cm

Key features

. easy

. quick

. portable

. UV transmission

. UV absorbance

Modifications reserved without prior notice of supplier (version 01/08)
Copyright© bestUV 2008

De UV-installation had been placed in the Technical Room (TR) of building O ("klokgebouw") , marked by the right square in the scheme. It had been connected to the source water circuit, before the heat exchanger of of the sources of cluster I. During the tests the ground water flow was set to 100 m³/h, in order to be able to adjust the flow through the UV-reactor.

FIGURE 10-3: SET-UP AT STRIJP:
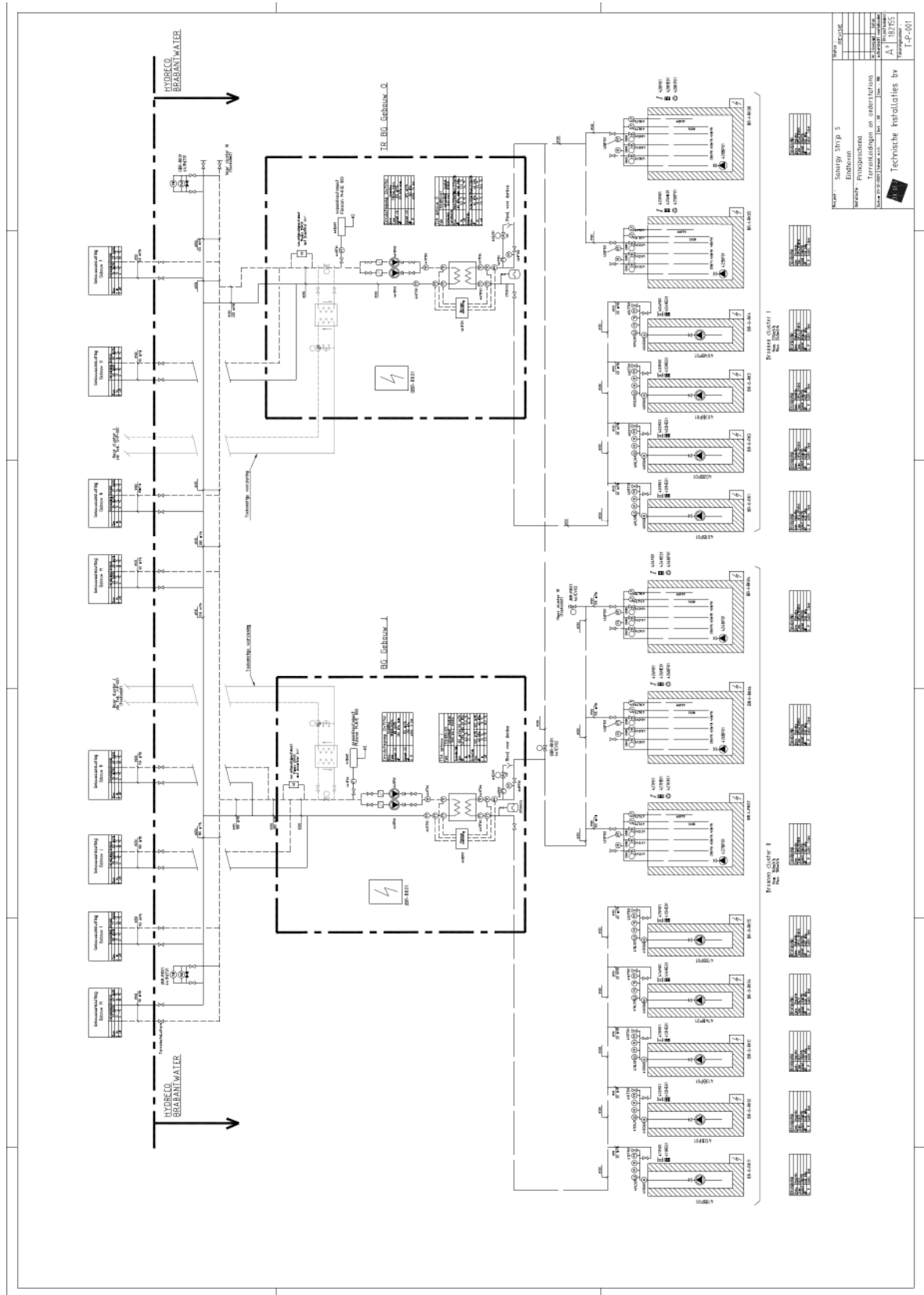
Appendix II

Data of experiments with the combined aquifer thermal energy storage and UV-reactor at Strijp

TABLE 10-1: OVERVIEW OF RELATION BETWEEN FLOW, UV-T AND UV-DOSE APPLIED

UV-T (%)	Flow for 400 mJ/cm² (m³/hour)	Flow for 600 mJ/cm² (m³/hour)	Flow for 400 mJ/cm² (m³/hour)
80	1.06	0.70	0.53
79	1.03	0.69	0.52
78	1.01	0.68	0.51
77	1.00	0.66	0.50
76	0.97	0.65	0.49
75	0.96	0.64	0.48
74	0.94	0.62	0.47
73	0.92	0.61	0.46
72	0.90	0.60	0.45
71	0.88	0.59	0.44
70	0.86	0.58	0.43
69	0.85	0.56	0.42
68	0.83	0.55	0.41
67	0.81	0.54	0.40
66	0.80	0.53	0.40

TABLE 10-2: ANALYSIS CERTIFICATES

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-1A-1)
Monsternr	8427761 / 853164402

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.00000000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.02067000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.13616000
1,2-Dichloorethaan	µg/L	0,33	0.33481000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00555000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	330	334.143650
trans 1,2-Dichlooretheen	µg/L	9,2	9.20720000
CKW (som)	µg/L	340	343.685660
Vinylchloride	µg/L	300	299.773960
1,2-Dichloorethenen (Som) factor 0,7	µg/L	340	343.350850

Overige org.-verontreinigingen

Methaan	µg/L	180	182.515125
Ethaan	µg/L	9	9.10812500
Etheen	µg/L	23	23.1725000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-1B-1)
Monsternr	8427762 / 853164403

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.16591000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000

Trichlooretheen	µg/L	<0,20	0.03177000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.16237000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	320	324.127830
trans 1,2-Dichlooretheen	µg/L	10	10.3290300
CKW (som)	µg/L	330	334.456860
Vinylchloride	µg/L	320	317.182580
1,2-Dichloorethenen (Som) factor 0,7	µg/L	330	334.456860

Overige org.-verontreinigingen

Methaan	µg/L	190	187.321875
Ethaan	µg/L	10	9.53712500
Etheen	µg/L	24	23.5706250

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-2A-1)
Monsternr	8427763 / 853164404

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.00000000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.00000000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	0,34	0.33596000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000

cis 1,2-Dichlooretheen	µg/L		350	353.564280
trans 1,2-Dichlooretheen	µg/L		3,4	3.43260000
CKW (som)	µg/L		360	357.332840
Vinylchloride	µg/L		310	311.289150
1,2-Dichloorethenen (Som) factor 0,7	µg/L		360	356.996880

Overige org.-verontreinigingen

Methaan	µg/L		190	185.875625
Ethaan	µg/L		9	8.96187500
Etheen	µg/L		24	24.2466250

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-2B-1)
Monsternr	8427764 / 853164405

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.16054000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.03905000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.15037000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	340	341.853700
trans 1,2-Dichlooretheen	µg/L	3,3	3.28309000
CKW (som)	µg/L	350	345.136790
Vinylchloride	µg/L	320	320.494360
1,2-Dichloorethenen (Som) factor 0,7	µg/L	350	345.136790

Overige org.-verontreinigingen

Methaan	µg/L	180	183.652625
Ethaan	µg/L	9	8.91312500
Etheen	µg/L	24	23.8615000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-3A-1)
Monsternr	8427765 / 853164406

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.15219000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.00000000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	340	342.600870
trans 1,2-Dichlooretheen	µg/L	1,1	1.07196000
CKW (som)	µg/L	340	343.672830
Vinylchloride	µg/L	310	309.484910
1,2-Dichloorethenen (Som) factor 0,7	µg/L	340	343.672830

Overige org.-verontreinigingen

Methaan	µg/L	180	175.032000
Ethaan	µg/L	9	8.57187500
Etheen	µg/L	24	24.2645000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Effluent UV (Effluent UV-3B-1)
Monsternr	8427766 / 853164407

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.00000000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.04369000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.15620000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	360	356.413710
trans 1,2-Dichlooretheen	µg/L	1,1	1.09818000
CKW (som)	µg/L	360	357.511890
Vinylchloride	µg/L	330	334.717380
1,2-Dichloorethenen (Som) factor 0,7	µg/L	360	357.511890

Overige org.-verontreinigingen

Methaan	µg/L	180	183.841125
Ethaan	µg/L	9	8.62712500
Etheen	µg/L	24	24.1865000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer   C05041.201404
Certificaatnummer   2015005051
Uw projectnaam   Strijp UV TKI
Uw ordernummer
Startdatum   16-01-2015
Rapportagedatum
Datum monstername   15-01-2015
Monsternemer   D. Harmsen
Monsteromschrijving   Influent UV (Influent UV-1)
Monsternr   8427767 / 853164408

Vluchtige organische halogeenkoolwaterstoffen

Startdatum   16-01-2015
Rapportagedatum
Datum monstername   15-01-2015
Monsternemer   D. Harmsen
Monsteromschrijving   Influent UV (Influent UV-1A-1)
Monsternr   8427768 / 853164409

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.18690000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.04865000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.14253000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	340	341.638000
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	340	341.638000
Vinylchloride	µg/L	320	319.532120
1,2-Dichloorethenen (Som) factor 0,7	µg/L	340	341.708000
Overige org.-verontreinigingen			
Methaan	µg/L	190	186.701125
Ethaan	µg/L	9	8.81075000

| Etheen | µg/L | 25 | 24.5830000 |

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Influent UV (Influent UV-1B-1)
Monsternr	8427769 / 853164410

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.16051000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.03617000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	350	351.264370
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	350	351.264370
Vinylchloride	µg/L	320	322.695420
1,2-Dichloorethenen (Som) factor 0,7	µg/L	350	351.334370

Overige org.-verontreinigingen

Methaan	µg/L	180	178.842625
Ethaan	µg/L	9	8.70512500
Etheen	µg/L	25	24.6203750

Voorbehandeling

Fysisch-chemische analyses
Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Influent UV (Influent UV-2A-1)
Monsternr	8427770 / 853164411

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.17527000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.03708000
Tetrachlooretheen	µg/L	<0,10	0.00513000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	350	346.125020
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	350	346.125020
Vinylchloride	µg/L	330	325.481280
1,2-Dichloorethenen (Som) factor 0,7	µg/L	350	346.195020

Overige org.-verontreinigingen

Methaan	µg/L	190	188.079125
Ethaan	µg/L	9	8.92775000
Etheen	µg/L	25	25.3012500

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	

Datum monstername | 15-01-2015
Monsternemer | D. Harmsen
Monsteromschrijving | Influent UV (Influent UV-2B-1)
Monsternr | 8427771 / 853164412

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.15656000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.04976000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	340	342.344280
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	340	342.344280
Vinylchloride	µg/L	320	321.896510
1,2-Dichloorethenen (Som) factor 0,7	µg/L	340	342.414280

Overige org.-verontreinigingen

Methaan	µg/L	190	186.348500
Ethaan	µg/L	9	8.93100000
Etheen	µg/L	25	24.7455000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer | C05041.201404
Certificaatnummer | 2015005051
Uw projectnaam | Strijp UV TKI
Uw ordernummer |
Startdatum | 16-01-2015
Rapportagedatum |
Datum monstername | 15-01-2015
Monsternemer | D. Harmsen
Monsteromschrijving | Influent UV (Influent UV-3A-1)
Monsternr | 8427772 / 853164413

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.14841000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.03986000
Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.15329000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	350	347.716080
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	350	347.716080
Vinylchloride	µg/L	330	333.651840
1,2-Dichloorethenen (Som) factor 0,7	µg/L	350	347.786080

Overige org.-verontreinigingen

Methaan	µg/L	180	183.391000
Ethaan	µg/L	9	8.91637500
Etheen	µg/L	24	24.4660000

Voorbehandeling

Fysisch-chemische analyses

Analysecertificaat

Uw projectnummer	C05041.201404
Certificaatnummer	2015005051
Uw projectnaam	Strijp UV TKI
Uw ordernummer	
Startdatum	16-01-2015
Rapportagedatum	
Datum monstername	15-01-2015
Monsternemer	D. Harmsen
Monsteromschrijving	Influent UV (Influent UV-3B-1)
Monsternr	8427773 / 853164414

Vluchtige organische halogeenkoolwaterstoffen

Dichloormethaan	µg/L	<0,20	0.17462000
Trichloormethaan	µg/L	<0,20	0.00000000
Tetrachloormethaan	µg/L	<0,10	0.00000000
Trichlooretheen	µg/L	<0,20	0.04302000

Tetrachlooretheen	µg/L	<0,10	0.00000000
1,1-Dichloorethaan	µg/L	<0,20	0.00000000
1,2-Dichloorethaan	µg/L	<0,20	0.00000000
1,1,1-Trichloorethaan	µg/L	<0,10	0.00000000
1,1,2-Trichloorethaan	µg/L	<0,10	0.00000000
cis 1,2-Dichlooretheen	µg/L	350	350.904670
trans 1,2-Dichlooretheen	µg/L	<0,10	0.00000000
CKW (som)	µg/L	350	350.904670
Vinylchloride	µg/L	330	329.751730
1,2-Dichloorethenen (Som) factor 0,7	µg/L	350	350.974670
Overige org.-verontreinigingen			
Methaan	µg/L	190	192.903750
Ethaan	µg/L	9	9.06587500
Etheen	µg/L	25	25.2460000

Voorbehandeling

Fysisch-chemische analyses

TABLE 10-3: MEASURMENT DATA 15-01-2015

Test	troe		UV-T		debiet			UV reactor	
	direct	lab	direct	lab	hoofdstroom	bypass	door UV reactor	UV intensiteit	Temp
	FNE		%		m^3/uur	m^3/uur	m^3/uur	W/m^2	^{0}C
1A	10.9	6.3	79	55.6	90	84	6	79	12
					90	84	6	79	14
2A	3.2	7.3	74	58.9	89	67	22	79	12
					89	68	21	79	
3A	6.6	7.2	73.4	58.4	88	0	88	79	12
					88	0	88	79	
1B	2.6	5.2	72.3	60.5	88	84	4	78	13
						0			
2B	5.5	5.5	70.7	58.8	88	65	23	79	12
					88	65	23	79	
3B	12	7.0	69	58.2	88	0	88	79	12
					88	0	88	79	12

TABLE 10-4: MEASUREMENT DATA 10-02-2015

Test	tijdstip monstername	troebelheid	UV-T gemeten	UV-T bl (na meting)	UV-T netto	debiet hoofdstroom	debiet bypass	door UV reactor	UV reactor UV intensiteit	temp	temp voor UV	
		FNE	%			m³/uur	m³/uur	m³/uur	W/m²	⁰C	⁰C	
1A	10:15	0,016	75,8	98,4	77,4	109	102-104	7-5	75	15	11,5	
1B	10:35	0,015	75,1	97,5	77,6	109	86-88	23-21	78	12	10,4	
1C	10:48	0,015	77,2	100	77,2	109	0	109	78	11	10,2	
2A	11:04	0,015	76,8	98,6	78,2	109	103-105	6-4	71	15	9,9	tijdens monstername neemt
2B	11:15	0,015	75,7	99,7	76	109	86-88	23-21	78	12	10,8	intensiteit af na 71 W/m2
2C	11:29	0,015	75,8	101,1	74,7	108	0	108	77	11		bij een temperatuur van 18 0C

TABLE 10-5: MEASUREMENT DATA

Veldmetingen TKI project 2014-2015

Projectnummer: C05041.201404
Datum: 10-Feb-15

Monsteromschrijving	Labcode	Influent/effluent	Datum	Debiet [m3/uur]	UV-dosis [mJ/cm2]		pH [-]	Geleidbaarheid [µS/cm]	Temperatuur [°C]	Troebelheid [NTU]
1Ainfl-1-1	8456279	Influent	10-Feb-15	6	835		7,2	540	11,5	0,2
1Aeffl-1-1	8456278	Effluent	10-Feb-15	6	835		7,1	530	11	0,2
1Binfl-1-1	8456281	Influent	10-Feb-15	22	227		7,2	530		0,2
1Beffl-1-1	8456280	Effluent	10-Feb-15	22	227		7	530	10,5	0,2
1Cinfl-1-1	8456283	Influent	10-Feb-15	109	58		7,2	530	10	0,2
1Ceffl-1-1	8456282	Effluent	10-Feb-15	109	58		7,2	530	10,2	0,2
2Ainfl-1-1	8456285	Influent	10-Feb-15	6	835		7,1	530	9,9	0,2
2Aeffl-1-1	8456284	Effluent	10-Feb-15	6	835		7,2	520	10,9	0,2
2Binfl-1-1	8456287	Influent	10-Feb-15	22	227		7,2	530	10,8	0,2
2Beffl-1-1	8456286	Effluent	10-Feb-15	22	227		7,2	530	10,1	0,2
2Cinfl-1-1	8456289	Influent	10-Feb-	109	58		7,2	530	10,5	0,2

TABLE 10-6: DATA OF EXPERIMENTS MARCH 2015

Test	tijdstip monstername	troebelheid	UV-T gemeten	UV-T bl (na meting)	UV-T netto	debiet hoofdstroom	debiet bypass	debiet door UV reactor	UV reactor UV intensiteit	UV reactor temp	
		FNE		%		m³/uur	m³/uur	m³/uur	W/m²	⁰C	
voor monstername	11:45	0,015	76,1	99,5	76,6	78	0	78	75	13	
Start test	11:50										voedingsdebiet aangepast
start monstername	12:25	0,015	77,1	100,5	76,6	78	74-72	4 - 6	37	36	tot 4 - 6 m3/uur
einde monstername	??					63	59 - 58	4 - 5	31	40	duur monstername ongeveer 15 minuten
na test	??	0,015				63	0	63	75	13	voedingsdebiet weer teruggezet na oorspronkelijke stand

Monstername procedure

Gestart met monstername infl 1, daarna effl 1, dan infl2, vervolgens effl2. Als laatst infl3 gevolgde door effl 3 (gestart tijdens monstername infl3)

TABLE 10-7: ANALYTICAL DATA OF COMBINED ATES AND UV-REACTOR, MARCH 2015

Analyse	Eenheid	infl-1-1	infl-1-2	infl-1-3	effl-1-1	effl-1-2	effl-1-3
Fysisch-chemische analyses							
EC-temp. corr. factor (mathematisch)		1,116	1,126		1,126	1,131	
Geleidingsvermogen 25°C	µS/cm	660	650		660	660	
Geleidingsvermogen 25°C	mS/m	66	65		66	66	
Geleidingsvermogen 20°C	mS/m	59	59		59	59	
Meettemperatuur (EC)	°C	20	19,6		19,6	19,4	
Meettemperatuur (pH)	°C	20,7	20,8		20,6	20,8	
pH		7,2	7,2		7,4	7,3	
DOC	mg/L	3,80	3,82		3,93	3,67	
TOC	mg/L	4,11	4,02		4,20	3,84	
Anorganische verbindingen & natte chemie							
Nitraat (NO3-N)	mg	0,05					
Nitraat (NO3)	mg/L	0,21					
Overige org.-verontreinigingen							
Methaan	µg/L	207,26	207,66	77,12	211,15	182,85	59,81
Ethaan	µg/L	9,31	9,16	4,39	11,12	10,19	4,30

Etheen	µg/L	25,36	24,90	16,09	22,37	20,41	11,99
Metalen							
Barium (Ba)	µg/L	46	38		37	37	
Koper (Cu)	µg/L	3,4	3		3,7	5,8	
Nikkel (Ni)	µg/L	3,7	3,8		5,2	4,2	
Vluchtige organische koolwaterstoffen							
Benzeen	µg/L	7,7	7,5		6,7	6	
Fenolen							
Polycyclische Aromatische Koolwaterstoffen							
Gehalogeneerde Koolwaterstoffen							
Vinylchloride	µg/L	470	430		430	350	
1,1-Dichlooretheen	µg/L	2,7	2,5		1,9	1,5	
trans 1,2-Dichlooretheen	µg/L	0,26	0,26		31	38	
cis 1,2-Dichlooretheen	µg/L	460	450		380	350	
Chloorethaan	µg/L				4,4	5,6	
1,1-Dichloorethaan	µg/L				0,24		
1,2-Dichloorethaan	µg/L	0,40			0,41	0,45	
Chloorbenzenen							
Chloorfenolen							
Polychloorbifenylen (PCB)							

PCB 180	μg/L	0,35	0,36			0,40	
PCB (som 6)	μg/L	0,35	0,36			0,40	
PCB (som 7)	μg/L	0,35	0,36			0,40	
Organo chloorbestrijdingsmiddelen							
cis-Heptachloorepoxide	μg/L	0,00	0,00		0,00	0,00	
trans-Heptachloorepoxide	μg/L	0,01	0,00		0,00	0,00	
Heptachloorepoxide	μg/L	0,01	0,00		0,00	0,00	
Minerale olie							
Minerale olie C12 - C16	μg/L	17	15		20	17	
Minerale olie C16 - C21	μg/L				16		
Fysisch-chemische analyses							
EC-temp. corr. factor (mathematisch) EC-temp. corr. factor (mathematisch)		1116	1126		1126	1131	
Geleidingsvermogen 25°C	μS/cm Geleidingsvermogen 25°C μS/cm 660 650 660	660	650		660	660	
Geleidingsvermogen 25°C	mS/m Geleidingsvermogen 25°C mS/m 66 65 66	66	65		66	66	
Geleidingsvermogen 20°C	mS/m Geleidingsvermo	59	59		59	59	

		gen 20°C mS/m 59 59 59						
Meettemperatuur (EC) Meettemperatuur (EC)	°C		20	19,6		19,6	19,4	
Meettemperatuur (pH) Meettemperatuur (pH)	°C		20,7	20,8		20,6	20,8	
pH			7,2	7,2		7,4	7,3	
Metalen								
Arseen	µg/L	<3,0	<3,0		<3,0	<3,0		
Antimoon	µg/L	<5,0	<5,0		<5,0	<5,0		
Barium	µg/L		46	388		37	37	
Beryllium	µg/L	<1,0	<1,0		<1,0	<1,0		
Cadmium	µg/L	<0,40	<0,40		<0,40	<0,40		
Chroom	µg/L	<2,0	<2,0		<2,0	<2,0		
Kobalt	µg/L	<1,0	<1,0		<1,0	<1,0		
Koper	µg/L		3,4	3		3,7	5,8	
Kwik	µg/L	<0,04	<0,04		<0,04	<0,04		
Lood	µg/L	<3,0	<3,0		<3,0	<3,0		
Molybdeen	µg/L	<2,0	<2,0		<2,0	<2,0		
Nikkel	µg/L		3,7	3,8		5,2	4,2	
Seleen	µg/L	<5,0	<5,0		<5,0	<5,0		
Tin	µg/L	<5,0	<5,0		<5,0	<5,0		
Vanadium	µg/L	<2,0	<2,0		<2,0	<2,0		
Zink	µg/L	<5,0	<5,0		<5,0	<5,0		

Vluchtige organische koolwaterstoffen							
Benzeen	µg/L	7,7	7,5		6,7	6	
Ethylbenzeen	µg/L	<0,01	<0,01		<0,01	<0,01	
Tolueen	µg/L	<0,01	<0,01		<0,01	<0,01	
0-Xyleen	µg/L	<0,01	<0,01		<0,01	<0,01	
m,p-Xyleen	µg/L	<0,01	<0,01		<0,01	<0,01	
Xylenen (som)	µg/L	<0.20	<0.20		<0.20	<0.20	
Styreen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2,4-Trimethylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,3,5-Trimethylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
n-Propylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
Isopropylbenzeen (cumeen)	µg/L	<0.10	<0.10		<0.10	<0.10	
n-Butylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
sec-Butylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
tert-Butylbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
p-Cymeen	µg/L	<0.10	<0.10		<0.10	<0.10	
Fenolen							
Fenol	µg/L	<0.5	<0.5		<0.5	<0.5	
o-Cresol	µg/L	<0.30	<0.30		<0.30	<0.30	
m-Cresol	µg/L	<0.30	<0.30		<0.30	<0.30	
p-Cresol	µg/L	<0.20	<0.20		<0.20	<0.20	

Cresolen (som)	µg/L	<0.80	<0.80		<0.80	<0.80	
2,4-Dimethylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
2,5-Dimethylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
2,6-Dimethylfenol	µg/L	<0.03	<0.03		<0.03	<0.03	
3,4-Dimethylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
o-Ethylfenol	µg/L	<0.03	<0.03		<0.03	<0.03	
m-Ethylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
Thymol	µg/L	<0.01	<0.01		<0.01	<0.01	
2,3/3,5-Dimethylfenol + 4-Ethylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
Polycyclische Aromatische Koolwaterstoffen						
Naftaleen	µg/L	<0.4	<0.4		<0.4	<0.4	
Acenaftyleen	µg/L	<0.04	<0.04		<0.04	<0.04	
Acenafteen	µg/L	<0.1	<0.1		<0.1	<0.1	
Fluoreen	µg/L	<0.01	<0.01		<0.01	<0.01	
Fenanthreen	µg/L	<0.02	<0.02		<0.02	<0.02	
Anthraceen	µg/L	<0.01	<0.01		<0.01	<0.01	
Fluorantheen	µg/L	<0.02	<0.02		<0.02	<0.02	
Pyreen	µg/L	<0.06	<0.06		<0.06	<0.06	
Benzo(a)anthraceen	µg/L	<0.04	<0.04		<0.04	<0.04	
Chryseen	µg/L	<0.02	<0.02		<0.02	<0.02	
Benzo(b+k)fluorantheen	µg/L	<0.06	<0.06		<0.06	<0.06	
Benzo(a)pyreen	µg/L	<0.1	<0.1		<0.1	<0.1	

Dibenzo(a,h)anthraceen	µg/L	<0.08	<0.08		<0.08	<0.08	
Benzo(ghi)peryleen	µg/L	<0.1	<0.1		<0.1	<0.1	
Indeno(123-cd)pyreen	µg/L	<0.06	<0.06		<0.06	<0.06	
PAK Totaal VROM (10)	µg/L	<0.8	<0.8		<0.8	<0.8	
PAK Totaal EPA (16)	µg/L	<1.1	<1.1		<1.1	<1.1	
Gehalogeneerde Koolwaterstoffen							
Chloormethaan	µg/L	<0.20	<0.20		<0.20	<0.20	
Dichloormethaan	µg/L	<0.20	<0.20	0	<0.20	<0.20	0
Vinylchloride	µg/L	470	430	228,46	430	350	239,79
1,1-Dichlooretheen	µg/L	2,7	2,5		1,9	1,5	
trans 1,2-Dichlooretheen	µg/L	0,26	0,26	0,20	31	38	28,28
cis 1,2-Dichlooretheen	µg/L	460	450	294,00	380	350	282,00
1,2-Dichlooretheen (som)	µg/L			294,20			310,28
CKW (som)	µg/L			294,20			310,28
Chloorethaan	µg/L	<0.10	<0.10		4,4	5,6	
Trichloorfluormethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Trichloormethaan	µg/L	<0.20	<0.20	0	<0.20	<0.20	0
Tetrachloormethaan	µg/L	<0.10	<0.10	0	<0.10	<0.10	0
1,1-Dichloorethaan	µg/L	<0.10	<0.10	0,16	0,24	<0.10	0
1,2-Dichloorethaan	µg/L	0,4	<0.10	0,20	0,41	0,45	0
1,1,1-Trichloorethaan	µg/L	<0.10	<0.10	0	<0.10	<0.10	0
1,1,2-Trichloorethaan	µg/L	<0.10	<0.10	0	<0.10	<0.10	0
Trichloorethaan (som)	µg/L	<0.20	<0.20		<0.20	<0.20	

1,1,1,2-Tetrachloorethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,1,2,2-Tetrachlooretheen	µg/L	<0.10	<0.10		<0.10	<0.10	
Tetrachloorethaan (som)	µg/L	<0.20	<0.20		<0.20	<0.20	
Trichlooretheen	µg/L	<0.10	<0.10	0,049	<0.10	<0.10	0
Tetrachlooretheen	µg/L	<0.10	<0.10	0	<0.10	<0.10	0
2,2-Dichloorpropaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2-Dichloorpropaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,3-Dichloorpropaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2,3-Trichloorpropaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,1-Dichloor-1-propeen	µg/L	<0.10	<0.10		<0.10	<0.10	
cis-1,3-Dichloorpropeen	µg/L	<0.10	<0.10		<0.10	<0.10	
trans-1,3-Dichloorpropeen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,3-Dichloorpropeen (som)	µg/L	<0.20	<0.20		<0.20	<0.20	
Broommethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Broomchloormethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Dibroommethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2-Dibroomethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Tribroommethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Broomdichloormethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Dibroomchloormethaan	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2-Dibroom-3-chloorpropaan	µg/L	<0.10	<0.10		<0.10	<0.10	
Broombenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	

Chloorbenzenen						
Monochloorbenzeen	µg/L	<0,05	<0,05		<0,05	<0,05	
1,2,3-Trichloorbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,2,4-Trichloorbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,3,5 Trichloorbenzenen	µg/L	<0.010	<0.010		<0.010	<0.010	
Trichloorbenzenen (som)	µg/L	<0.21	<0.21		<0.21	<0.21	
1,2,3,4-Tetrachloorbenzeen	µg/L	<0.020	<0.020		<0.020	<0.020	
1,2,3,5-/1,2,4,5-Tetrachloorbenzeen	µg/L	<0.020	<0.020		<0.020	<0.020	
Tetrachloorbenzenen (som)	µg/L	<0.040	<0.040		<0.040	<0.040	
Pentachloorbenzeen	µg/L	<0.010	<0.010		<0.010	<0.010	
Hexachloorbenzeen	µg/L	<0.030	<0.030		<0.030	<0.030	
1,2-Dichloorbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
1,3-Dichloorbenzeen	µg/L	<0.10	<0.10		<0.10	<0.10	
	µg/L						
1,4-Dichloorbenzeen		<0.10	<0.10		<0.10	<0.10	
Dichloorbenzenen (som)	µg/L	<0.30	<0.30		<0.30	<0.30	
Chloorfenolen						
o-Chloorfenol	µg/L	<0.1	<0.1		<0.1	<0.1	
m-Chloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
p-Chloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
Monochloorfenolen (som)	µg/L	<0.14	<0.14		<0.14	<0.14	
2,3-Dichloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
2,4/2,5-Dichloorfenol	µg/L	<0.01	<0.01		<0.01	<0.01	

2,6-Dichloorfenol	µg/L	<0.03	<0.03		<0.03	<0.03	
3,4-Dichloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
3,5-Dichloorfenol	µg/L	<0.03	<0.03		<0.03	<0.03	
Dichloorfenolen (som)	µg/L	<0.11	<0.11		<0.11	<0.11	
2,3,4-Trichloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
2,3,5-/2,4,5-Trichloorfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
2,3,6-Trichloorfenol	µg/L	<0.01	<0.01		<0.01	<0.01	
2,4,6-Trichloorfenol	µg/L	<0.05	<0.05		<0.05	<0.05	
3,4,5-Trichloorfenol	µg/L	<0.01	<0.01		<0.01	<0.01	
Trichloorfenolen (som)	µg/L	<0.11	<0.11		<0.11	<0.11	
2,3,4,5-Tetrachloorfenol	µg/L	<0.01	<0.01		<0.01	<0.01	
2,3,4,6 / 2,3,5,6-Tetrachloorfenol	µg/L	<0.020	<0.020		<0.020	<0.020	
Tetrachloorfenolen (som)	µg/L	<0.03	<0.03		<0.03	<0.03	
Pentachloorfenol	µg/L	<0.010	<0.010		<0.010	<0.010	
4-Chloor-3-methylfenol	µg/L	<0.02	<0.02		<0.02	<0.02	
Polychloorbifenylen (PCB)							
PCB28	µg/L	<0.01	<0.01		<0.01	<0.01	
PCB52	µg/L	<0.01	<0.01		<0.01	<0.01	
PCB101	µg/L	<0.01	<0.01		<0.01	<0.01	
PCB118	µg/L	<0.01	<0.01		<0.01	<0.01	
PCB138	µg/L	<0.01	<0.01		<0.01	<0.01	
PCB153	µg/L	<0.01	<0.01		<0.01	<0.01	

PCB 180	µg/L	0,35	0,36		<0.01	0,4	
PCB (som 6)	µg/L	0,35	0,36		<0.06	0,4	
PCB (som 7)	µg/L	0,35	0,36		<0.07	0,4	
Chloornitrobenzenen						
o/p-Chloornitrobenzeen	µg/L	<0.20	<0.20		<0.20	<0.20
m-Chloornitrobenzeen	µg/L	<0.20	<0.20		<0.20	<0.20
Monochloornitrobenzenen (som)	µg/L	<0.40	<0.40		<0.40	<0.40
2,3-Dichloornitrobenzeen	µg/L	<0.1	<0.1		<0.1	<0.1
2,4-Dichloornitrobenzeen	µg/L	<0.1	<0.1		<0.1	<0.1
2,5-Dichloornitrobenzeen	µg/L	<0.1	<0.1		<0.1	<0.1
3,4-Dichloornitrobenzeen	µg/L	<0.1	<0.1		<0.1	<0.1
3,5-Dichloornitrobenzeen	µg/L	<0.06	<0.06		<0.06	<0.06
Dichloornitrobenzenen (som)	µg/L	<0.46	<0.46		<0.46	<0.46
Overige gechloreerde KWS						
2-Chloortolueen	µg/L	<0.1	<0.1		<0.1	<0.1
4-Chloortolueen	µg/L	<0.1	<0.1		<0.1	<0.1
Chloortoluenen (som)	µg/L	<0.2	<0.2		<0.2	<0.2
1-Chloornaftaleen	µg/L	<0.02	<0.02		<0.02	<0.02
Organo chloorbestrijdingsmiddelen						
4,4'-DDE	µg/L	<0.01	<0.01		<0.01	<0.01
2,4'-DDE	µg/L	<0.01	<0.01		<0.01	<0.01

4,4'-DDT	µg/L	<0.20	<0.20		<0.20	<0.20	
4,4'-DDD/2,4'-DDT	µg/L	<0.02	<0.02		<0.02	<0.02	
,2,4'-DDD	µg/L	<0.01	<0.01		<0.01	<0.01	
DDT/DDE/DDD (som)	µg/L	<0.25	<0.25		<0.25	<0.25	
Aldrin	µg/L	<0.02	<0.02		<0.02	<0.02	
Dieldrin	µg/L	<0.02	<0.02		<0.02	<0.02	
Endrin	µg/L	<0.02	<0.02		<0.02	<0.02	
Drins (som)	µg/L	<0.06	<0.06		<0.06	<0.06	
alfa-HCH	µg/L	<0.08	<0.08		<0.08	<0.08	
beta-HCH	µg/L	<0.07	<0.07		<0.07	<0.07	
gamma-HCH	µg/L	<0.10	<0.10		<0.10	<0.10	
delta-HCH	µg/L	<0.04	<0.04		<0.04	<0.04	
HCH (som)	µg/L	<0.29	<0.29		<0.29	<0.29	
alfa-Endosulfan	µg/L	<0.05	<0.05		<0.05	<0.05	
alfa-Endosulfansulfaat	µg/L	<0.03	<0.03		<0.03	<0.03	
alfa-Chloordaan	µg/L	<0.01	<0.01		<0.01	<0.01	
gamma-Chloordaan	µg/L	<0.01	<0.01		<0.01	<0.01	
Chloordanen (som)	µg/L	<0.02	<0.02		<0.02	<0.02	
Heptachloor	µg/L	<0.01	<0.01		<0.01	<0.01	
cis-Heptachloorepoxide	µg/L	0	0		0	0	
trans-Heptachloorepoxide	µg/L	0,01	0		0	0	
Heptachloorepoxide	µg/L	0,01	0		0	0	
Hexachloorbutadieen	µg/L	<0.10	<0.10		<0.10	<0.10	

Isodrin	µg/L	<0.10	<0.10		<0.10	<0.10	
Telodrin	µg/L	<0.07	<0.07		<0.07	<0.07	
Tedion	µg/L	<0.07	<0.07		<0.07	<0.07	
Fosforbestrijdingsmiddelen							
Azinfos-ethyl	µg/L	<0.1	<0.1		<0.1	<0.1	
Azinfos-methyl	µg/L	<0.07	<0.07		<0.07	<0.07	
Bromofos-ethyl	µg/L	<0.07	<0.07		<0.07	<0.07	
Bromofos-methyl	µg/L	<0.06	<0.06		<0.06	<0.06	
Chloorpyrifos-ethyl	µg/L	<0.06	<0.06		<0.06	<0.06	
Chloorpyrifos-methyl	µg/L	<0.1	<0.1		<0.1	<0.1	
Cumafos	µg/L	<0.02	<0.02		<0.02	<0.02	
Demeton-S/Demeton-O-ethyl	µg/L	<0.1	<0.1		<0.1	<0.1	
Diazinon	µg/L	<0.04	<0.04		<0.04	<0.04	
Dichloorvos	µg/L	<0.1	<0.1		<0.1	<0.1	
Disulfoton	µg/L	<0.04	<0.04		<0.04	<0.04	
Fenitrothion	µg/L	<0.1	<0.1		<0.1	<0.1	
Fenthion	µg/L	<0.1	<0.1		<0.1	<0.1	
Malathion	µg/L	<0.1	<0.1		<0.1	<0.1	
Parathion-ethyl	µg/L	<0.2	<0.2		<0.2	<0.2	
Parathion-methyl	µg/L	<0.2	<0.2		<0.2	<0.2	
Pyrazofos	µg/L	<0.2	<0.2		<0.2	<0.2	
Triazofos	µg/L	<0.2	<0.2		<0.2	<0.2	

Stikstofhoudende bestrijdingsmiddelen						
Ametryn	µg/L	<0.10	<0.10		<0.10	<0.10	
Atrazine	µg/L	<0.08	<0.08		<0.08	<0.08	
Cyanazin	µg/L	<0.1	<0.1		<0.1	<0.1	
Desmetryn	µg/L	<0.10	<0.10		<0.10	<0.10	
Prometryn	µg/L	<0.10	<0.10		<0.10	<0.10	
Propazin	µg/L	<0.08	<0.08		<0.08	<0.08	
Simazin	µg/L	<0.20	<0.20		<0.20	<0.20	
Terbuthylazin	µg/L	<0.06	<0.06		<0.06	<0.06	
Terbutryn	µg/L	<0.10	<0.10		<0.10	<0.10	
Overige bestrijdingsmiddelen						
Bifenthrin	µg/L	<0.08	<0.08		<0.08	<0.08	
Carbaryl	µg/L	<0.10	<0.10		<0.10	<0.10	
Cypermethrin A,B, C en D	µg/L	<0.20	<0.20		<0.20	<0.20	
Deltamethrin	µg/L	<0.20	<0.20		<0.20	<0.20	
Linuron	µg/L	<0.10	<0.10		<0.10	<0.10	
Permethrin A	µg/L	<0.06	<0.06		<0.06	<0.06	
Permethrin B	µg/L	<0.06	<0.06		<0.06	<0.06	
Permethrins (som)	µg/L	<0.12	<0.12		<0.12	<0.12	
Propachloor	µg/L	<0.02	<0.02		<0.02	<0.02	
Trifluralin	µg/L	<0.02	<0.02		<0.02	<0.02	

Overige org.-verontreinigingen						
Bifenyl	µg/L	<0.01	<0.01		<0.01	<0.01	
Nitrobenzeen	µg/L	<0.3	<0.3		<0.3	<0.3	
Dibenzofuran	µg/L	<0.1	<0.1		<0.1	<0.1	
Minerale olie						
Minerale olie C10-C12	µg/L	<10	<10		<10	<10	
Minerale olie C12-C16	µg/L	17	15		20	17	
Minerale olie C16-C21	µg/L	<15	<15		<15	<15	
Minerale olie C21-C30	µg/L	<20	<20		<20	<20	
Minerale olie C30-C35	µg/L	<20	<20		<20	<20	
Minerale olie C35-C40	µg/L	<20	<20		<20	<20	
Minerale olie (som C10 - C40)	µg/L	<100	<100		<100	<100	

Appendix III

Set-up of mobile UV reactor system

FIGURE 10-4: PROCESS SCHEME OF MOBILE REACTOR:
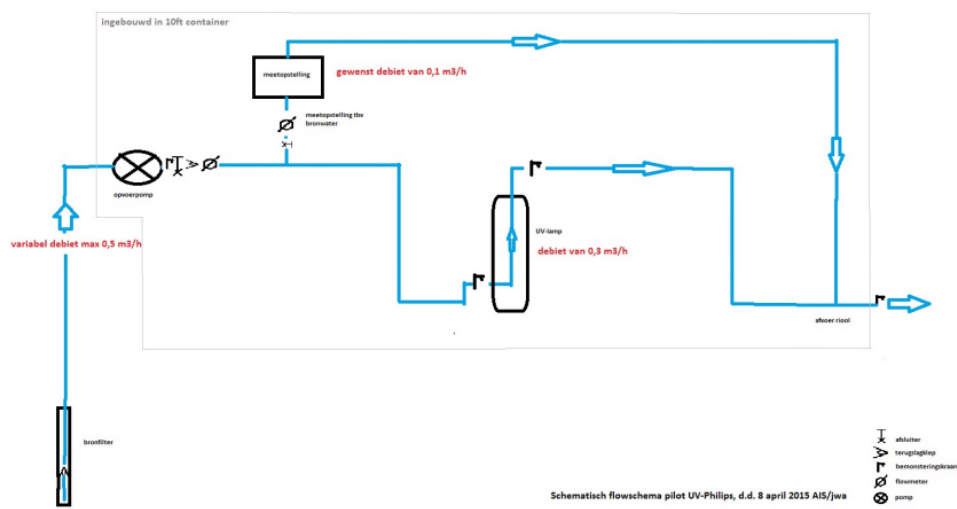
FIGURE 10-5:TECHNICAL SPECIFICATION SHEET OF UV-REACTOR:

bUV.01.GS.061.2012.EN.00

GammaLine UV-system

Technical specification sheet

Type : GS1.125L1

UV chamber type GS

Material	stainless steel 316L (1.4404)
Roughness, internal	max. 0,6 to 1.0 micron
Connections	1,5" BSP-M
Shape of construction	L-shape
Mounting	vertical (alt. horizontal)
Max. waterpressure	6 bar (higher waterpressure on request)
Number of UV lamps and quartzsleeves	1
UV lampconnection	single-ended
Quartzsleeve(s)	single-ended
Fixation of quartzsleeves	double-sides fixed
Type of quartz, standard	Q200
Protection class	IP54
External coating, Cx	option
UV sensor, Us1	option
Anti-fouling mechanism, manual	no
Anti-fouling mechanism, electrical	no
Dimensions	see drawing

Control cabinet (standard)

Material	Painted steel
Dimensions at standard power supply (h x w x d)	400 x 400 x 200 mm
Power supply, standard	230Volt 1L+N
Connected power	200W
Frequency	50 or 60 Hz
Protection class	IP54
Mounting	wall or skid
Electrical cables between chamber and cabinet	included (5m)

Controller type, without option 'UV sensor'   Lambda 1

Hourscounter, 'system ON', non-resetable	included
ON/OFF-switch	included
Lamp-ON/OFF indication, visual on chamber	included

In case of option 'UV sensor'

Controller type	Lambda 2
Dimension control cabinet (h x w x d)	400 x 400 x 200 mm
Material control cabinet	painted steel
Mounting cabinet	wall or skid
Electrical cables between chamber and cabinet	included (5m)
Alarm contact (3A)	included
Indication "UV good/ UV low/UV warning'	included
Low UV outputsignal	included
UV-intensity output (4-20 mA)	included
ON/OFF-switch	included
Individual lampfailure detection	included
Individual lampstatus	included
Individual lampcontrol	included
Hourscounter	included
Remote ON/OFF	included

Certification and directives

CE-conformity	acc to 98/37/EC
Machine directive	acc to 2006/42/EEC
EMC directive	acc to 2004/108/EG
Voltage directive	acc to 2006/95/EG

Appendix IV

Full data of the experiments with
the mobile UV-reactor at Strijp

TABLE 10-8: DATA FOR MONITORING WELLS 9 AND 11

Projectnummer	B02034.000349
Project TKI UV	C05041.201404
Peilbuis	9
Filterstelling	28-30

Datum		3-sep				4-sep							
Doel		**Nulmeting**				**400 mJ/cm2**							
		Influent				**Influent**				**Effluent**			
Veldmetingen													
Grondwaterstand	cm-kb	363				400							
debiet	m3	54739				71396							
Ec	uS/cm					750				750			
pH	-					6,2				6,3			
Temperatuur	°C					13,3				13,8			
Flow (voorpompen)	l/min					700				700			
Flow (monstername)	l/min					0,3				0,3			
Troebelheid	NTU					1,1				0,4			
zuurstof	mg/l					0				0			
redox	mV					-133				-92			
UVT	%					64							
Energieverbruik	kWh	80,79				113,05							
Troebelheid	FNU					0,403							
		Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden
Analyseresultaten		**Influent A**	**Influent A**	**influent B**	**influent B**	**Influent A**	**Influent A**	**influent B**	**influent B**	**Effluent A**	**Effluent A**	**Effluent B**	**Effluent B**
VOCI													
PER	µg/L	0,19	0,18877	0,18	0,18022	<0,1	0,07915	<0,1	0,07472	<0,1	0,06682	<0,1	0
TRI	µg/L	0,87	0,86576	0,94	0,93906	5,3	5,30583	5,3	5,15166	5,2	5,16693	5,1	5,11275
CIS	µg/L	210	213,8924	220	216,88765	900	898,7974	890	888,88022	750	755,60455	870	876,75111
VC	µg/L	140	135,67285	130	133,64589	53	53,34491	56	56,46975	59	58,73424	52	52,37278
Overige parameters													
Analysecertificaat		2015097240/1		2015097240/1		2015097856/1		2015097856/1		2015097856/1		2015097856/1	
Monsteromschrijving		9-30.0		9-30.0		9-30.0		9-30.0		9-30.0		9-30.0	
Monsternummer		8703393 (1)		8703394 (2)		8705421 (3)		8705422 (4)		8705419 (1)		8705420 (2)	
Dissolved Organic Car	mg/L					4,4		4,3		5,3		4,3	
TOC	mg/L					5,5		5,4		5,1		5,7	
Zwevend stof (droogrest)	mg/L					3,9		5,7		3,8		3,5	
Resultaten Aqualab													
Analysecertificaat						RT2015-097952		RT2015097950		RT2015097953		RT2015097951	
Monsternummer						1491868		1491872		1491866		1491870	
Monstercode						INJA		IB		EA		EB	
UV 254	1/m					8,4		9,2		8,5		9,2	

	7-sep								8-sep							
	600 mJ/cm2								800 mJ/cm2							
	Influent				Effluent				Influent				Effluent			
	376								353							
	120248															
	740				750				740				750			
	6,2				6,3				6,3				6,3			
	13,8				13,9				13,8				14,1			
	650				650				480				480			
	0,3				0,3				0,3				0,3			
	0,4				2,2				0,1				0,2			
	0				0				0				0			
	-130				-110				-139				-105			
	76															
	189,34															
	0,251															

Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden
Influent A	Influent A	influent B	influent B	Effluent A	Effluent A	Effluent B	Effluent B	Influent A	Influent A	influent B	influent B	Effluent A	Effluent A	Effluent B	Effluent B
0,17	0,16738	0,59	0,59286	<0,1	0,04532	<0,1	0	<0,1	0,01988	<0,1	0,00000	<0,1	0,01735	<0,1	0,00000
23	22,64263	23	22,76275	24	23,93252	22	22,22442	27	26,77345	27	26,55482	27	26,66422	26	25,62028
3200	3191,99452	3200	3196,85041	2800	2846,83483	3200	3251,51453	2500	2477,00231	2500	2492,36173	2500	2512,05393	2500	2491,57778
450	452,35241	430	431,3358	440	443,35098	520	515,375	7,5	414,10467	7,3	395,65762	19	399,95150	18	391,47614
2015098623/1		2015098623/1		2015098623/1		2015098623/1		2015098920/1		2015098920/1		2015098920/1		2015098920/1	
9-30.0 (9-30.0-infl A-3)		9-30.0 (9-30.0-infl B-3)		9-30.0 (9-30.0-effl A-2)		9-30.0 (9-30.0-effl B-2)		9-30.0 (9-30.0-infl A-4)		9-30.0 (9-30.0-infl B-4)		9-30.0 (9-30.0-effl A-3)		9-30.0 (9-30.0-effl B-3)	
8707517 (3)		8707518 (4)		8707515 (1)		8707516 (2)		8708499 (3)		8708500 (4)		8708497 (1)		8708498 (2)	
5,8		5,8		6		5,9		5,5	5,80800	5,8	5,86700	5,5	5,49800	5,5	5,50500
6,2		6,1		6,1		6,1		5,8	5,53500	5,9	5,78000	5,8	5,75800	5,8	5,80000
6,4		4,8		4,7		4,5		10	10,50000	14	13,80000	5,1	5,10000	3,5	3,50000
RT2015-097956		RT2015-097957		RT2015-097954		RT2015-097955		RT2015-097959		RT2015-097961		RT2015-097958		RT2015-097960	
1491869		1491873		1491867		1491871		1492243		1492244		1492239		1492242	
INJA		IB		EA		EB		INJA		IB		EA		EB	
10,2		10,9		10,9		11,3		10,8		10,9		9,4		9,7	

| Peilbuis | 11 |
| Filterstelling | 58-60 |

Datum		31-aug		1-sep			3-sep					
Doel		Opstart		Nulmeting			400 mJ/cm					
		Influent		Influent			Influent				Effluent	
Veldmetingen												
Grondwaterstand	cm-kb			307			310					
debiet	m3	390		14059			53374				440	
Ec	uS/cm			440			430				440	
pH	-			6,7			6,7				7	
Temperatuur	°C			13			12,4				12,6	
Flow (voorpompen)	l/min			900			1000				1000	
Flow (monstername)	l/min			0,3			0,3				0,3	
Troebelheid	NTU			0,1			1				1	
zuurstof	mg/l			0			0				0	
redox	mV			-193			-208				-174	
UVT	%			77			77,7					
Energie	kWh		0	26,96			78,25					
Troebelheid	FNU			1,508		0,136	3,44					
Debiet2				4,43			3,44					

Analyseresultaten		Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden
		Influent A	Influent A	influent B	influent B	Influent A	Influent A	influent B	influent B	Effluent A	Effluent A	Effluent B	Effluent B
VOCI													
PER	µg/L	0,1	0,01105	0,1	0,014	<0,1	0,00924	<0,1	0,00947	<0,1	0	<0,1	0,01144
TRI	µg/L	0,1	0	0,1	0	0,1	0,06758	0,1	0	0,1	0,07289	0,1	0
CIS	µg/L	60	60,47896	40	40,27258	41	40,63965	34	33,89667	38	37,81953	45	45,61461
VC	µg/L	83	83,1373	75	74,68095	27	27,36228	21	21,47491	23	23,00068	29	29,28326
Overige parameters													
Analysecertificaat		2015095973/1		2015095973/1		2015097242/1		2015097242/1		2015097242/1		2015097242/1	
Monsteromschrijving		11-60		11-60		11-60,0		11-60,0		11-60,0		11-60,0	
Monsternummer		8699763 (1)		8699764 (2)		8703399 (3)		8703400 (4)		8703397 (1)		8703398 (2)	
Dissolved Organic Carl	mg/L												
TOC	mg/L												
Zwevend stof (droogrest)	mg/L												
Resultaten Aqualab													
Analysecertificaat													
Monsternummer													
Monstercode													
UV 254	1/m												

TABLE 10-9: DATA FOR MONITORING WELL 4

Projectnu	B02034.000349
Project TK	C05041.201404
Peilbuis	4A
Filterstell	9-11 m-mv.
Datum	18-2-2016

Tijd	Infl/effl.	Grondwaterstand	debiet	Ec	pH	Temperatuur	zuurstof	redox	UVT	Energie	Opmerkingen
		cm-kb	m3/h	uS/cm	-	°C	mg/l	mV	%	kWh	
8:00		**1,81**	1,636364								
8:50		2,61									
9:30		2,33	1,16129								
9:55		2,33									
10:00		1,81									
10:03			0,8						86	233,9	
10:18		2,23							86		
10:21	Influent	227					0		85		Nulsituatie
10:22	Influent	227					0		85		
10:30	Influent	227		640	5,4	13,6	0	78	85,9		Lamp ingesteld op 800 mJ/cm2
10:46	Influent	227	0,58	620	5,3	13,7	0	99,7			
11:04	Effluent	227		650	5,3	13,9	0	143		235,1	
11:15	Effluent	227		660	5,3	13,9	0	160	89,4		
11:27	Influent	227		660	5,3	13,6	0	151	86,5	235,6	
11:41	Influent			640	5,2	13,6	0	144	86,5	236	
11:49	Effluent			660	5,2	13,9	0	161			
12:00	Effluent			640	5,2	13,9	0	169	88,9		
12:11	Influent			650	5,2	13,9	0	154	85,7	236,7	
12:25	Influent			650	5,2	13,6	0	151	86,3		
12:30	Effluent			660	5,2	13,9	0	162			Monstername influent
12:38	Effluent			650	5,2	13,5	0	170			
12:45				650	5,2	13,8	0	172		236,7	Monstername effluent
12:47	UV-lamp uit										
13:10	Pomp uit									237,9	

Projectnummer	B02034.000349
Project TKI UV	C05041.201404
Peilbuis	4A
Filterstelling	9-11 m-mv.
Datum	18-2-2016

		Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden	Certificaat	Ruwe waarden
Analyseresultaten		**Influent 0**		**Influent 01**	**Influent 01**	**Influent 02**	**Influent 02**	**Effluent 01**	**Effluent 01**	**Effluent 02**	**Effluent 02**
VOCI											
PER	µg/L	3	3,04072	3,1	3,115	3	3,02856	2,6	2,56512	2,5	2,54381
TRI	µg/L	7700	7660,09	7800	7776,42	7700	7702,08	7700	7721,73	6900	6927,62
CIS	µg/L	430	432,26504	440	443,3872	430	433,36338	420	424,8612	410	407,98724
Trans	µg/L	1,5	1,47267	1,6	1,55946	1,5	1,51311	7,2	7,17779	6,7	6,74956
VC	µg/L	2,5	2,521	3,2	3,15485	2,4	2,35903	2,7	2,72962	2,8	2,82189
Overige parameters											
Analysecertificaat		2016019615/1		2016019615/1		2016019615/1		2016019615/1		2016019615/1	
Monsteromschrijving		4A-0-sit-1 (-)		4A-influent01-1 (-)		4A-influent02-1 (-)		4A-effluent01-1 (-)		4A-effluent02-1 (-)	
Monsternummer		8911187 (1)		8911188 (2)		8911189 (3)		8911190 (4)		8911191 (5)	
Dissolved Organic Carl	mg/L				6,2		5,9		5,9		6,2
TOC	mg/L				4,4		4,3		4,4		4,3
Zwevend stof (droogrest)	mg/L				2		2		2		2
Resultaten Aqualab											
Analysecertificaat				RT2016-016211		RT2016-016213		RT2016-016214		RT2016-016212	
Monsternummer					1568917		1568919		1568918		1568920
Monstercode				4A influent 01		4A influent 02		4A effluent 01		4A effluent 02	
UV 254	1/m				8,4		8,2		7,6		7,6