Activated drains

Generic guideline

Target audience: Consultancies, contractors, authorities, site owners

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1 INTRODUCTION

The activated drain technology is an innovative in-situ technology to improve the quality of groundwater in a number of situations. The activated drain technology refers to trenches for draining water in which pollutant treatment processes (like for instance biodegradation, sorption, abiotic degradation, etc.) are stimulated and/or induced. This document intends to provide information about this technology and its application area and boundary conditions for consultants, authorities, contractors and feasibility testing labs. The aim is to offer support when evaluating the feasibility and the impact of the activated drain technology to rehabilitate degraded waters, as well as when designing and implementing activated drains.

This document was composed in the frame of the FP7 project AQUAREHAB (GA 226565), and comprises outcomes and lessons learned during this project.

DISCLAIMER: Although the information described in this document is believed to be reliable and accurate, the guideline does not offer warranties of any kind.

2 GENERAL PRINCIPLES OF THE ACTIVATED DRAIN TECHNOLOGY

2.1 CONCEPT

The activated drain technology refers to a (ground)water remediation approach where superficial (3-4 m depth) trenches/pipes are installed (1) to drain shallow contaminated (ground)water and (2) in which pollutant treatment processes are stimulated and/or induced (Figure 1.A). The flow within the drain is controlled via for instance pumping. This implies that the contaminated groundwater is treated while it is transported through the draining system. The pollutant treatment processes may be different processes like for instance biodegradation, sorption, and chemical reactions and are to be selected in function of the pollutants that are present.

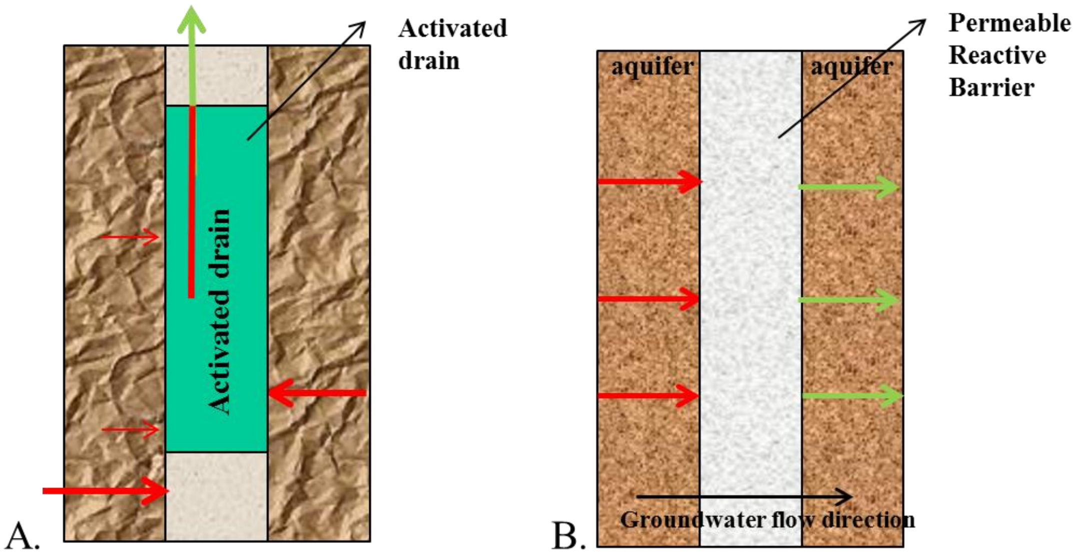

Figure 1. Schematic representation (top view) of (A) an activated drain and (B) permeable reactive barrier.

There are similarities between the activated drain technology (Figure 1.A) and the reactive permeable barrier (PRB) technology (Figure 1.B) as both aim at (ground)water treatment in the subsurface in delineated permeable zones where pollutant removal processes are activated. The major difference, however, is the flow direction and flow velocity of water in treatment zone. In activated drains the flow path is along the drain (which can easily be several 100 m) and the flow velocity is a function of the hydraulic gradient **along** the drain. On the other hand, in permeable reactive barriers the water generally flows in the direction of the groundwater flow and at the groundwater flow velocity, with a flow path **across** the thickness of the barrier (generally limited to 0.5 to a few meter).

In case different pollutants enter the drain at distinct points, the pollutant removal processes induced may be altered with a train of treatment zones along the drain as indicated in Figure 2. This approach may avoid the need to treat complex mixtures of pollutants at the end of the drain.

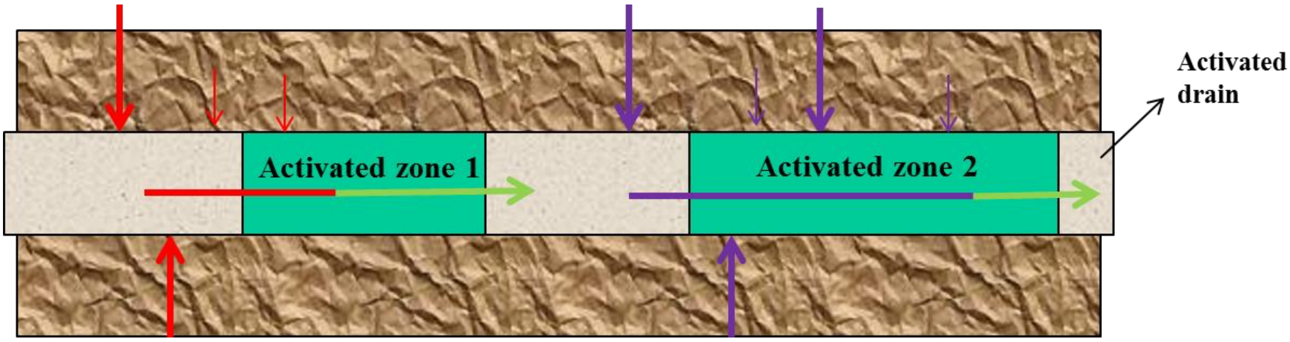

Figure 2. Schematic representation (top view) of an activated drain comprising 2 treatment activated zones. Red and purple arrows represent flows of groundwater with a different pollution, while green arrows represent flows of clean water.

2.2 TARGETED SUBSTANCES & REACTION MECHANISMS

In principle, the activated drain technology can be used to treat pollutants for which a contaminant removal process had been developed and that can be activated in the subsurface. An overview of some substances that can be targeted by the activated drain technology is given in Table 1 along with potential emission sources of the different substances and examples of associated removal processes.

Table 1 Examples of substances that can be tackled by the activated drain technology.

Targeted substances		Emission sources	Potential pollutant removal processes
Class	Specific substance		
CAHs (chlorinated aliphatic hydrocarbons)	Trichloroethylene (TCE) Tetrachloroethylene (PCE) Cis-dichloroethylene (cDCE) Vinylchloride (VC) Chlorinated ethanes Brominated organics …	Drycleaner activities, degreasing activities, industrial productions, landfills	• Chemical reduction via zerovalent iron (see DL4.3 part A) • Biodegradation-anaerobic (see DL4.3 part B) • Sorption • …
BTEX	Benzene, Toluene, ethylbenzene & xylenens	Petrochemical industry	• Biodegradation – aerobic and anaerobic

Targeted substances		Emission sources	Potential pollutant removal processes
Class	Specific substance		
		Petrol gas filling stations	• gas extraction and vapours sorption • Sorption
Inorganics	Ammonium	Landfill leachate	• Biologically: nitrification – denitrification • Ion exchange • Sorption
Oxygenates	Methyl-tert-butyl ether (MTBE) Tert-butyl alcohol (TBA) ethanol	Petrol gas Petrochemical Chemical industry	• biodegradation • Gas extraction and vapours sorption
Metals	Nickel, zinc, ..	Metal industry, military industry	• Sorption • Bioprecipitation processes • …
micropollutants	Herbicides, pesticides, biocides, pharmaceuticals, drug residues, hormones …	Agriculture & industrial activities, wastewater reuse	• Biodegradation • Sorption
Flame retardants	Aliphatic and aromatic brominated organic	Production, municipal landfill leachate	• biodegradation aerobic or anaerobic • Chemical reduction via zerovalent iron
…			•
Mixed pollutions	Mixtures of pollutants mentioned above	Industrial sites Overlapping groundwater plumes Sites within water shades where multiple sources are found	combination of the above mentioned processes

2.3 DEVELOPMENT STAGE OF THE TECHNOLOGY

Within technology development, the following stages can be defined:

- A technology is <u>very emerging</u> when it is at the research stage (not even implemented in other sectors).
- It is <u>emerging</u> when it is implemented in another sector and is being developed in the concerned sector (but it is no at the pilot plant trial stage yet).
- It is <u>becoming transferab</u>le when it is at the pilot plant trial stage in the concerned sector.
- It is <u>transferable</u> when it is at the full scale trial stage in the concerned sector.
- It is <u>available</u> when it is commercially available and in use in the concerned sector.

The activated drain technology is between 'emerging' and 'becoming transferable as':

- Subsurface drains have been used already for decades to collect excess of (ground)water via for instance deep open trench based or buried pipe drains.
- The activated drain technology has been studies on lab scale, but further research on smart carrier materials is needed to increase for instance the abatement rate for micropollutants.
- The activated drain has been studied on pilot scale in the field (for instance with the AQUAREHAB project).
- A number of practical aspects can be deduced from the reactive barrier technology, which has been studied extensively and has been demonstrated and applied at pilot and full scale.

At an industrial site within the Negev desert (Israel) above fractured aquitard, overall a series of 9 draining trenches were installed in the studied site that range from a few m in length to about 1000 m. The short trenches (few meters) were installed for crossing fractures and collecting high-level contaminated groundwater from a specific source where flow direction was defined. The longer trenches typically cross a series of fractures. As the contaminated water flows within the trench, more and more water flows into the trench from specific fractures crossed by the trench along the way. In other words, both flux and chemistry vary along the trench as more local sources flow into it. Both discharge and water chemistry in each trench vary over time. Seasonal changes as well as changes related to specific leaking episodes may occur.

Table 2 examples of (activated) drains.

Location	Scale & drain design	Pollutants & removal processes	References
Negev desert (Israel)	Full scale drain (9): Length: few m up to 1000 m Carrier material: chalk Pilot activated drain: 300 x 30 x 30 cm	Mixed pollution containing pesticides – biodegradation/sorption	Nativ et al., 2003
Iowa	In situ denitrification bioreactor	denitrification	Christianson et al., 2013
France	Wetland connected to drain	Pesticides degradation/sorption	Tournebize et al., 2013

3 Applicability and boundary conditions of the technology

The activated drain technology is especially useful for larger areas where contaminated water needs to be intercepted for treatment purposes and flooding prevention purposes. Two application areas are explained as examples:

Groundwater treatment in low permeability fractured rocks. Traditional "pump and treat" methods are often impossible to implement in low permeability fractured rocks as it cannot be assumed that groundwater is flowing around the pumping station. Permeable reactive barrier

(PRB) (*Day et al.*, 1999) techniques for groundwater remediation have become more and more popular over the last decade. Numerous pilot-scale PRB studies have been successfully tested in Europe, USA, and Canada (e.g., *Gillham*, 1993, *Tratnyek*, 2002, *http:/www.prb-net.org*). The PRB concept is a well-established technology for treating contaminated groundwater based on natural or directed flowing of the groundwater through porous barriers of reactive materials, such as metallic iron, adsorbing media or fixed bacteria, or a combination of reactive materials. This technique enables passive on-site treatment, which, if properly implemented, provides a more efficient and much cheaper method for groundwater remediation compared to conventional pump & treat techniques (e.g., *Matheson and Tratnyek*, 1994; *Schlim and Heitz*, 1996; *Simon and Meggyes*, 2000). Nevertheless, in a low permeability fractured medium, the classic PRB procedure is unsuitable for several reasons: (1) most of the transport is through fractures that occupy a very small portion of the porous media (typically less than 3%); (2) the conductive fractures, through which most of the flow occurs, are connected via a network of junctions in unknown locations and their hydraulic apertures vary in space, hence the exact contaminant pathway is difficult to predict; and (3) the velocities in the conductive fractures are relatively high, possibly resulting in a short interaction time between the contaminated groundwater and the active porous media within the PRB. Therefore, the first and most important challenge in a low-permeability fractured formation is to capture the contaminated water and funnel it to the appropriate remediation technique.

The activated drain technology is recommended under the following conditions:

- The flow in the subsurface is via fractures or pumping wells and “traditional” PRBs are not an optional way to force the water to go through the reactive materials.
- When pollutants are present mostly in the dissolved phase.
- The depth of the groundwater contaminant plume is preferably not located deeper than 4-8 m bgs. For deeper plumes, the installation cost (digging trenches) will increase significantly.
- With respect to the hydrogeological characteristics of the site:
    - The groundwater flow direction is known and relatively stable during the year.
    - The type of matrix enables to excavate trenches at reasonable costs.
    - The hydraulic conductivity of the trench porous materials (gravel for example) is higher than the permeability of the surrounding aquifer.
- The geochemical characteristics of the groundwater do not result in large quantities of precipitates, which can block the trench over time. For instance, when envisioning aerobic biodegradation, high level of iron in the water may lead to clogging.
- The conditions of the drain water need to be compatible with the envisioned pollutant removal process. For instance, when envisioning aerobic biodegradation of pollutants,
    - high levels of dissolved oxygen are needed before entering the porous drainage system, or alternative oxygen delivery systems need to be used.
    - the water temperature must be kept within a certain range (for instance 25-37°C for biological processes studied within AQUAREHAB);
    - pollutant degrading microorganisms must be present. When possible, it is advised to use native bacteria as an inoculum, rather than introducing foreign microorganisms (even if they are adapted to the site conditions). However, there may be circumstance where addition of specialised bacteria (bioaugmentation) may be required.
    - carrier material to improve the activity of microbes in the drain must be compatible with the micro-organisms are to be used.

- The impact of **co-pollutants** in the groundwater on an envisioned removal process needs to be evaluated and taken into account when designing the activated drain.

Treatment of water pumped to prevent flooding. Nowadays, in many cities and areas around the world water is (semi)continuously pumped and drained to prevent flooding. The water in these industrialized areas can be polluted. The activated drain technology offers here a solution to treat the water before the discharge. As the amount of pumped water is largely influenced by the weather conditions, the water flow and hydraulic retention time can largely fluctuate in time.

4 PERFORMANCE OF THE ACTIVATED DRAIN TECHNOLOGY

The **abatement rate** can be defined as the substance concentration after the technology implementation divided by the substance concentration before implementation of the technology. The activated drain technology aims at an abatement rate close to 100%, which means that flux reduction rate in the drain for the pollutants is almost 100%. In situations where the activated drain technology is applied for micropollutants or complex mixtures of pollutants, the abatement rate can be lower. The local regulatory limits are determining for the exact targeted abatement rates that need to be taken into account during the barrier design.

Efficiency drivers are (1) the degradation/removal rates of the different pollutants and their breakdown products, (2) the water flow velocity in the drain, (3) the length of activated drain and (4) the deterioration in performance of the activated drain over time (permeability & reactivity).

Longevity of the activated drain technology: In most cases, it is needed that the technology is operational for several years up to decades. Practically, there may be needs for additional investments during these long times as is the case for permeable reactive barriers: The longevity is depending on the barrier type:

- ZVI-barriers: 10-30 years (expected & deduced from field data)
- Bio-barriers: years
- Sorption barriers: months (depending on pollutants loading)
- Multibarriers: months till years

5 COST OF THE TECHNOLOGY

Cost considerations for the trenches and the treatment system are comprised of: (1) the dimensions of the trench needed (depth, length and thickness, depending on flow characteristics); (2) the price of the reactors and their maintenance; (3) the local situation on the site (accessibility, surrounding buildings, underground constructions, type of subsurface); and (4) the local labour costs (country dependent).

Cost assessment for excavating a trench for a drain in rocky terrain (chalk, limestone)* based on current basic prices in Israel:

- 8 Euros for one m^3 of excavation.
- 20 Euros for m^3 of gravel.
- 15 Euros for one meter of 8" of PVC perforated pipe.
- 3 Euros per one m^2 of geo-technic fabric/cloth.

This results in a total cost of approximately **58 Euros per one meter length** for two meters pipe deep drain with a draining. Costs may be increased by 10% for hard rocks, and decrease by 15% for soft or loose sand.

6 GENERIC APPROACH TO DETERMINE APPLICABILITY OF A MULTIBARRIER FOR A SPECIFIC SITE OR AREA

For a successful application of the activated drain technologies, the following stepped approach is recommended:

Step 1: Site characterisation

A site characterisation is required for checking the application and boundary conditions associated with the technology (see section 3). The site characterisation comprises:

- Identification of the hydrology and collecting information on the geology (type of layer, permeability, flow directions, etc.)
- Identification of the type and concentration of pollution that is present
- Evaluation of groundwater chemical data including conductivity, pH, redox potential, temperature, oxygen content as well as inorganic parameters such as Ca, Fe, K, Mg, Na, Si, Cl, SO_4, NO_3, alkalinity, TOC and DOC.
- Examining the engineered feasibility of creating draining system (depth, gradients etc.)
- Evaluation of the accessibility of the area

Step 2: Selection of pollutant treatment process

For the present pollutants that need to be reduced in concentration, potential pollutant removal processes need to be identified. In some cases small lab scale feasibility tests can have benefits. Next, a set of pollutant removal processes needs to be selected that can jointly cope with the present (mixed) pollution.

Step 3: Feasibility test at lab scale

Feasibility tests refer to lab scale test where the selected removal process(es) is/are evaluated more in detail. It is strongly advised to verify the functioning of the activated drain concept via a lab scale feasibility test, preferably a column test, with real representative water from the site. Aims of these tests are (1) To evaluate the performance of the activated drain, (2) to evaluate the impact of co-pollutants, drain filling materials and the interaction between the different removal processes, and (3) to deduce degradation/removal rates and other parameters that are needed for the design of a larger scale activated drain system.

Step 4: Design & dimensioning of pilot/full scale

Design parameters comprise (1) dimension and orientation of the drain to intercept to water and (2) engineering of the pollutant removal process (selection carrier, additives, required hydraulic retention time, required length of the activated drain, …).

Step 5: Implementation of the activated drain

This step comprises the installation of the activated drain conform to the design parameters.

Step 6: Monitoring performance & corrective actions

A post installation monitoring aims at following the performance of the activated drain, where reduced pollutant concentrations along the activated drain, and at the discharge point are followed in time.

7 GENERIC APPROACH FOR DESIGNING AND APPLYING ACTIVATED DRAINS IN LOW-PERMEABILITY FRACTURED ROCKS.

7.1 INTRODUCTION

Fractured rocks and soils cover large areas around the world (Figure 3)**;** the approach needed for groundwater remediation in such formations is very different from the approach typically used for porous media. Nevertheless most studies dealing with groundwater and soil remediation were carried out in porous media, while very few have dealt with fractured formations.

Figure 3. Examples of fracture networks in different settings (upper panels). The low left panel depicts the fracture network in an outcrop at the study area (Northern Negev, Israel) and the low right is a conceptual schematic of a fractured rock. The massive fracture network can be easily seen in all pictures.

Traditional "pump and treat" methods are often impossible to implement in such environments as it cannot be assumed that groundwater is flowing around the pumping station. Permeable reactive barrier (PRB) techniques for groundwater remediation have become more and more popular over the last decade and became a well-established technology for treating contaminated groundwater based on natural or directed flowing of the groundwater through porous barriers of reactive materials, such as metallic iron, adsorbing media or fixed bacteria, or a combination of reactive materials. Nevertheless, in a low permeability fractured medium, such as the chalk, the classic PRB procedure is unsuitable (see section 3), but the activated drain technologies has potential.

7.2 GENERAL PRINCIPLES OF THE GROUNDWATER CAPTURING TECHNOLOGY IN FRACTURED FORMATION (PART OF STEP 1)

In fractured rock, most of the transport is through fractures that occupy a very small portion of the porous media (typically less than 3%). Further, the conductive fractures, through which most of the flow occurs, are connected via a network of junctions in unknown locations and their hydraulic apertures vary in space, hence the exact contaminant pathway is difficult to predict. The velocities in the conductive fractures can be are relatively high.

The first and most important challenge in a low-permeability fractured formation is to capture the contaminated water and funnel it to the appropriate remediation technique. A comprehensive study needs to be performed to define the most active fractures in the study area**.** A possible approach to realise this is to drill slanted boreholes across fractures below the water table (*Nativ et al*., 1997; *Nativ et al*., 2003; Figure 4). Pumping tests (in some cases with packers) are useful to define the hydraulic properties of the various fractures covering the study area (*Nativ et al*., 2003). Main flow direction, or the most active fracture network, can be determined according to a water level map made from boreholes penetrating the fracture network.

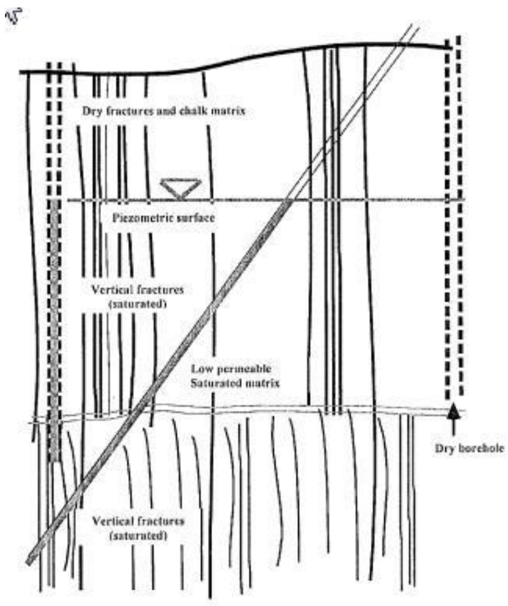

Figure 4. A schematic of a method to identify active fracture networks: inclined borehole crossing vertical fracture (after *Nativ et al*., 2003).

7.3 GENERIC APPROACH FOR FEASIBILITY TESTING FOR BIOLOGICAL REMOVAL OF CONTAMINANTS (STEP 3)

The basic idea of bio-activated drains is to treat the pollutants in trenches (1) that drain intercepted contaminated groundwater and (2) that contain porous tailored materials as support for microbial biofilms which degrade the pesticides in the passing contaminated drainage water (when biodegradation is considered).

When envisioning biological degradation of pollutants in the activated drain, the following aspects are to be considered:

- Pollutant degrading micro-organisms (mostly bacteria) need to be present at the site, or need to be introduced in the drain.
- The filling material of the trench needs to serve as carrier material of biofilm
- The conditions in the trench (temperature, oxygen level, pH, presence of nutrients and other growth supporting substances, electrical conductivity, salt composition) need to be within the activity area of the micro-organisms selected. When the natural conditions are not appropriate, it needs to be evaluated whether it is feasible (technically and cost-wise) to adapt/modify the conditions.

A number of tests may be needed to evaluate the feasibility of the technology for a specific site and to determine input for the design phase (degradation rates, adaptation to the site water chemistry and ability to form biofilm).

7.3.1 Selection of bacteria

7.3.1.1 Native bacteria

Preferably, native microorganisms present in the polluted water and/or on the fractured rock are to be used for degrading the contaminants, as they are already adapted to the pollutants and site conditions. If present, these bacteria can be stimulated in the activated drain and propagate till amounts sufficient to realise the required degradation level.
The presence of a suitable biodegradation potential at a site can be tested by lab scale batch degradation experiments. This involves the following steps:

A. <u>Collection of representative site material containing the site bacteria.</u>
This material can be representative water or biofilm containing the site matrix parts. Within AQUAREHAB, a passive technique for sampling degrading microorganisms was evaluated and found more representative than the use of directly sampled water. This technique is based on a solid matrix (can be natural rock or other appropriate carrier) that is contacted in the field with site water to capture biofilm. The material can be packed in permeable bags and lowered into a the contaminated water (Figure 5). A contact time of 1 month was proven to be sufficient to trap bacteria. Carrier materials that performed well for this passive microbial sampling comprise: Gray chalk (typical for the tested site), White chalk (typical for the tested site), Sand and Silica. In case aerobic degradation is envisioned, more representative biomass is sampled in case the well or shaft used contains aerobic water.

Figure 5. Passive sampling method for capturing biofilms that can be used for lab scale degradation experiments to evaluate the presence of certain biodegradation potentials. (A) A clean bag packed with carrier, before lowered into the shaft; (B, C) After 1 month in the field.

B. Degradation experiment in the lab

Glass bottles can be used to contact the collected biomass (water, or biofilm containing carriers) with the pollutants of concern in a representative liquid medium (site water or representative medium). The bottles are spiked with growth supporting compounds when needed, and incubated. Overtime the evolution of the pollutant concentration is followed. It is strongly recommended to include poisoned controls to verify the removal of the pollutants via abiotic processes such as sorption, volatilisation or hydrolysis

Within AQUAREHAB, as an example, lab tests were performed to evaluate the presence of a biodegradation potential for pesticides. As these compounds are present is low concentrations, carrier material incubated *in-situ* at the site was tested in the lab for mineralisation of ^{14}C-ring-labelled compounds (linuron, atrazine, MCPA and as positive control benzoic acid (F)). Within each flask, a small vial containing a strong base solution was installed to trap the $^{14}CO_2$ produced from biodegradation of the ^{14}C-labelled contaminants. At regular intervals the base solution was sampled and fresh solution was added. The sampled base solution was analyzed on a liquid scintillation counter for quantifying the ^{14}C-amounts. The results were expressed as cumulated $^{14}CO_2$-curves over time. Figure 6 shows that atrazine is mineralised by the biofilm collected on sand as carrier material during the passive sampling.

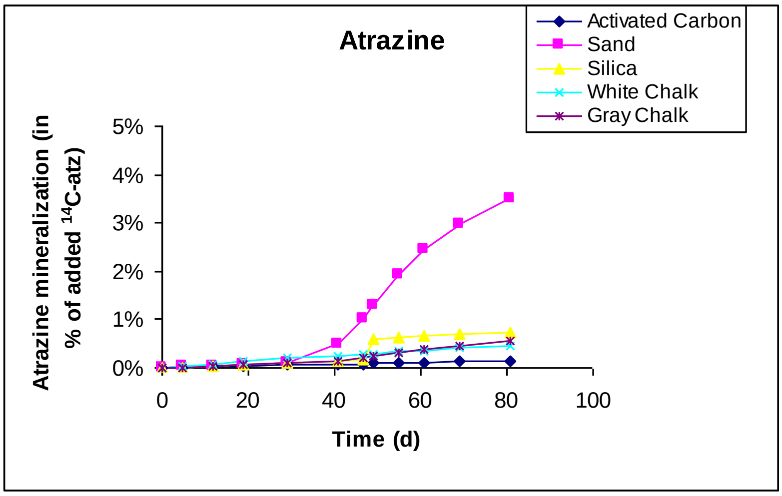

Figure 6. Mineralisation of the herbicide atrazine (Unpublished results).

7.3.1.2 Bioaugmentation

In case no suitable or only an insufficient biodegradation potential is found at the site, specialised bacteria can be grown in the lab and transferred to the site for colonising the drain. This procedure is named bioaugmentation. It is advised to test the degradation activity of the selected bacteria under condition representative for the site. A similar procedure as described in the previous section can be used.

In case of bio-augmentation with non-native microorganisms it is advised to test also the survival of the introduced microorganism/s under natural site conditions (salinity etc). For instance, AQUAREHAB results demonstrated that an inoculated strain degraded the target contaminant at a slower rate in non-filtered site water in comparison to filtered water (w/o native microflora). This is despite the fact that the introduced strain was adapted to the site water salinity. Thus, potential competition with native microorganisms should be considered as a factor that may reduce the efficacy of bio-augmentation.

7.3.2 Selection of carrier material

Although it is possible that the catabolic potential exists in the site water, it is well possible that the residence time of the contaminants is relatively short. Thus, biodegrading microorganisms will not have sufficient time to degrade them. It is possible to overcome this shortcoming by introducing tailored carriers that will allow retarding the rate of pollutant transport by sorption. The degrading bacteria will be able to adhere to these carriers.

Ideal carrier/filling materials for bio-activated drains have the following characteristics:

- Allow high permeability, so porous material is needed (large pores within the drain)
- Allow and enhance formation of degrading biofilms
- Sorb reversibly the pollutants in such a way that they will still be bio available for the pesticide degraders which colonize the materials. As such, the residence time of the pesticides in the trenches is increased.
- Protecting degrading micro-organisms from toxic compounds or protozoa.
- Release growth supporting compounds like nutrients (N, P) to enhance the microbial activity

The selection of carrier material for a specific application depends mostly on the properties of the pollutants (solubility and hydrophobicity) as well as the carrier's ability to adsorb and release the contaminants. Within AQUARHEAB a range of different carrier types was considered, comprising:

- mineral carriers that did not adsorb the pollutants but allowed biofilm formation (natural and artificial),
- organic carriers that strongly adsorbed the chemicals and allowed biofilm formation, and
- a polymeric material sorbant that allowed adsorption of the pollutants and biofilm formation.

The latter carrier appeared to be most suitable for retarding the studied pesticides (with concurrent biodegradation. It is recommended to determine pollutant sorption as well as desorption properties of the carrier materials. Examples of desorption (release) curves collected within the AQUAREHAB project are given in Figure 7.

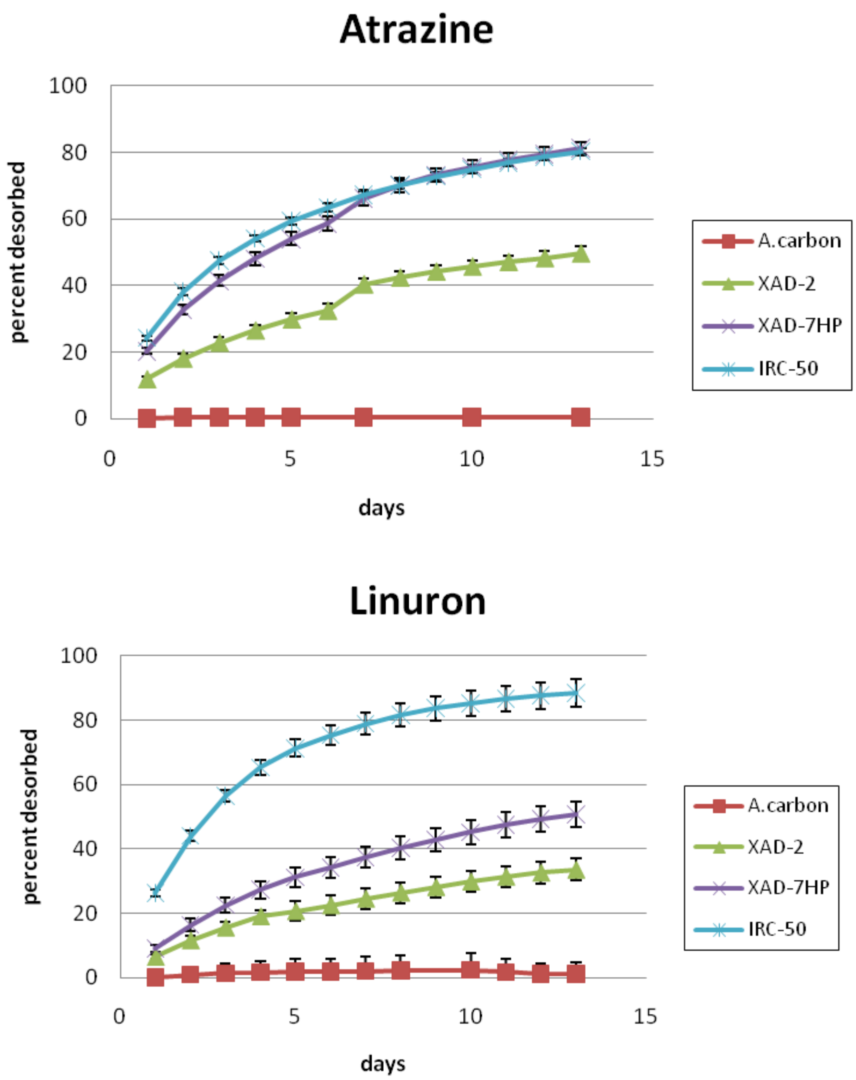

Figure 7. Desorption (efficiency) curves of linuron and atrazine after sorption onto different carriers (activated carbon, XAD-2, XAD-7HP and IRC50).

Two additional factors should be considered when taking into account the application of the carriers: cost and required dose (kg per pore volume) as well as the potential transport of the carriers along the trench. For example, application of 1:100 of the polymeric carrier material XAD-7HP in sand columns (~50% porosity) allowed sustainable biodegradation at a variety of flow regimes when the biodegrading organisms were presented.

7.3.3 Simulation of the activated drain

It is advised to evaluate the functioning (pollutant degradation, hydraulics, abiotic reactions) of the activated drain under the envisioned conditions at smaller scale, prior to a full scale installation in the field. These tests can also be used to optimise the processes.

To test pollutant removal process in activated drains at pilot scale, an above ground pilot apparatus can be used. Within AQUAREHAB, for instance, three large scale reactors (300 x 30 x 30 cm) were used as depictured in Figure 8. The reactors were filled with three types of gravel, being the same as that used to fill the trenches. One was filled with fresh gravel from a quarry, the second with gravel taken from a highly-contaminated trench that has been active for about 10 years and the third with gravel taken from a different trench that has also been active for a similar length of time, but with better water quality. Both the reactors and the containers are isolated to minimize the impact of the extreme temperatures (day and night) in the study area.

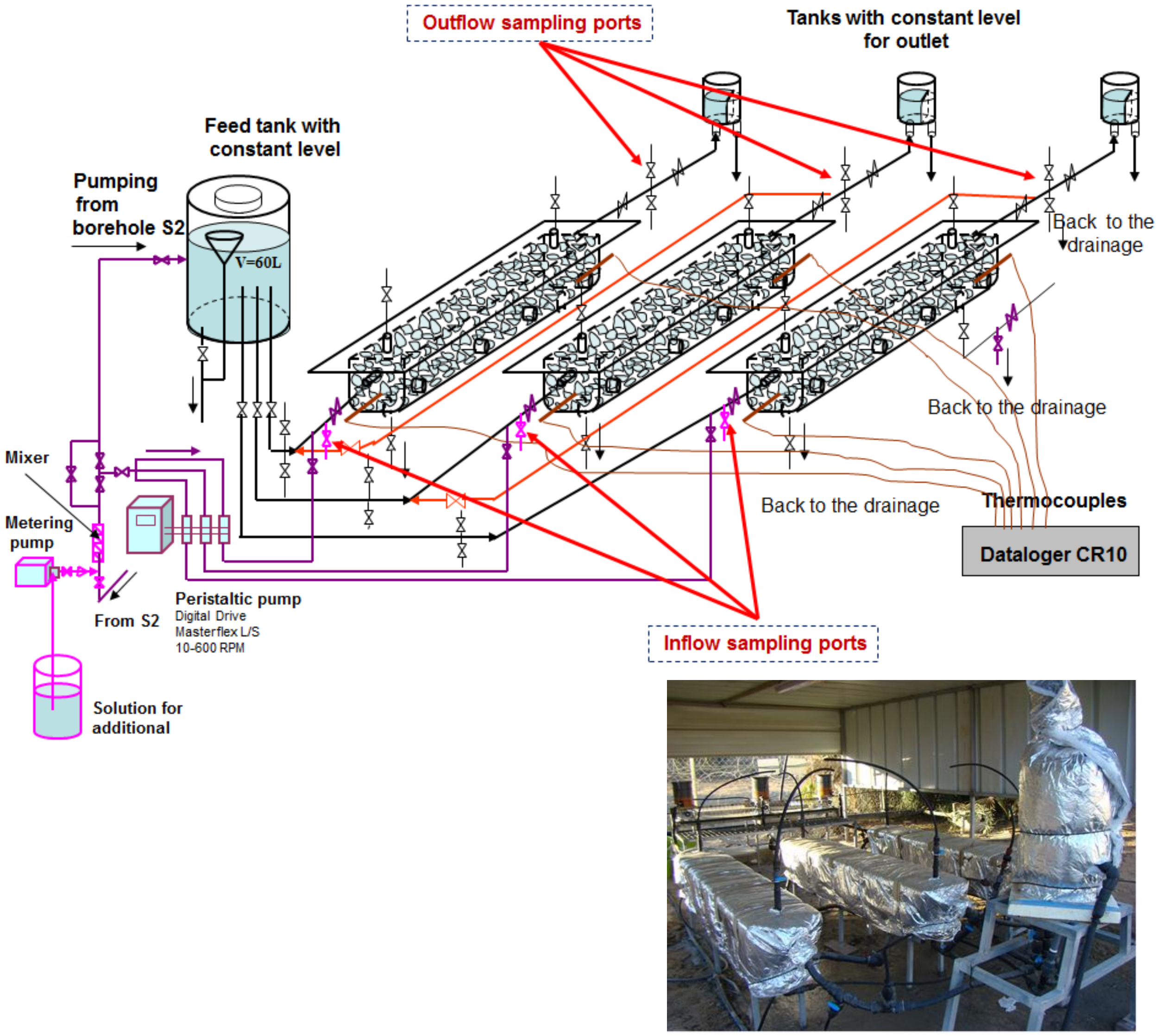

Figure 8. A schematic representation and picture of the AQUAREHAB pilot scale activated drain system constructed in the field.

7.4 Design of activated drains (Step 4)

Once the major fracture network and flow directions are determined, the direction of the drains can be defined with the aim to cross the major networks identified during the site investigation. The trenches are preferable installed perpendicular to the flow direction of the groundwater, acting as drainage system. The trenches are to be deeper than the groundwater level to collect the water flowing through the fractures that are crossed by the trench into the trench. A typical active fracture discharging water into a trench is depictured in Figure 9.

Figure 9. A typical active fracture, crossed by the trench, discharging into the drain.

An example of a drain in fractured rock (studied within AQAUREHAB) is given in Figure 10. The trench is filled with course gravel, where the flow occurs, and on top covered with fine sediments. Flow occurs along the trench according to the hydraulic gradient and the constructed inclination. As mentioned, the number of fractures flowing into the trench varies and can change seasonally as the water table increases/decreases. The fine materials on top of the trench enable to keep to redox conditions developed inside the trench as in the natural fractured system and prevent, or minimize, odor.

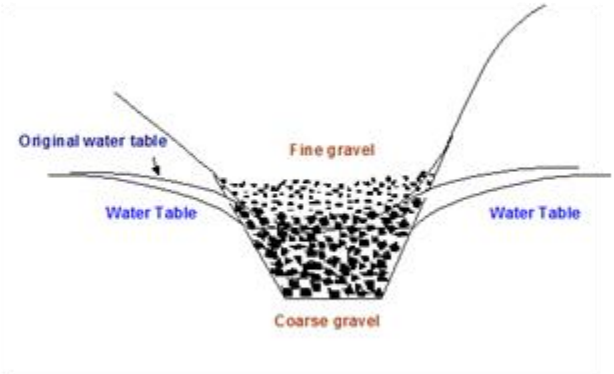

Figure 10. The excavated trench is filled with permeable gravel. The cross section (right) shows schematically the internal filling of the trench.

Typically, trench ends with an approximately 1m-diameter shaft. The shaft is deeper than the trench and the contaminated water flowing in the trench drains into the shaft (Figure 11). A pump is installed inside the shaft, automatically pumping water from the shaft to keep the hydraulic gradient and then deliver it into a treatment facility once the water level exceeds the threshold defined by the site operator. In some cases, like the long trench shown in Figure 11, two shafts were dug to increase the operational volume.

The efficiency of pollutant removal along the trenches draining the polluted groundwater depends on: (1) hydrological parameters such as discharge rate and hydraulic residence time; (2) environmental conditions such as temporal temperature changes and oxygen availability; and (3) biological factors such as the presence of pollutant degrading microorganisms.
Controlling the hydrological parameters is possible via adjustment of the pumping rate at the end of the drain system as seen in Figure 11. Temperature control is also possible, to some degree, via insulation of the top of the trench with a layer of soil. Yet, this layer will affect oxygen diffusion

and therefore oxygenation should be considered using diffusers inserted into the water through piezometers placed along the trenches (Figure 11).

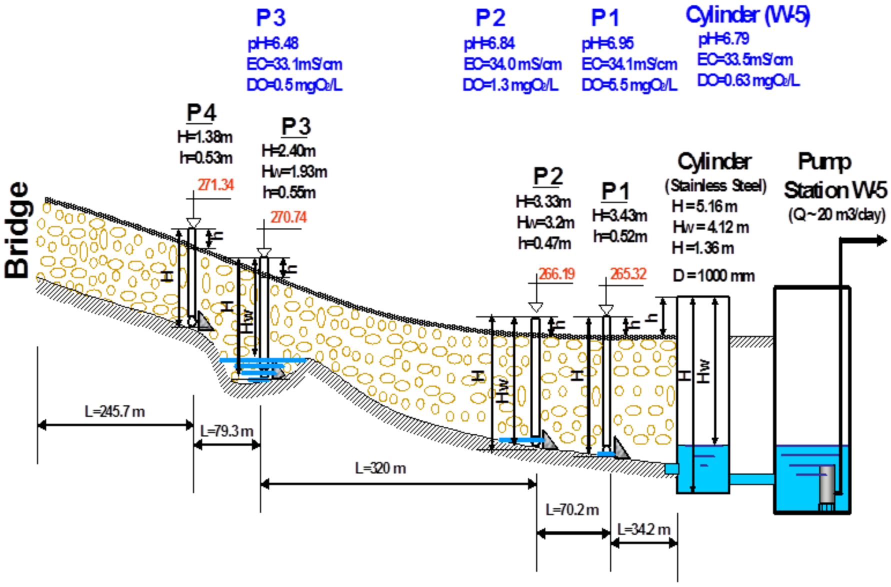

Figure 11. A schematics of one of the trenches installed in the study site. The system includes observation wells along the trench, enables monitoring of the water composition evolution as well as changes in water level. At the end of the trench, a shaft with an automated pump is installed.

7.5 Implementation of activated drains (Step 5)

The activated drains are implemented by digging a trench conform the design (Figure 12), and are subsequently filled with the selected carrier material that was found suitable for the selected pollutant removal process (either natural or artificial). It may be needed to integrate dosing systems (oxygen, nutrients, pHcontrol) in the drain. It is advised to install the equipment needed for activating the drain immediately when constructing the drain; It has been found that it requires much more efforts and resource to adapt an existing drain for inducing the pollutant removal processes.

Figure 12. Pictures showing the trenches dug perpendicular to the main flow direction in fractures to focus groundwater flow technology.

7.6 CONCLUSION

In conclusion, key steps for applying the technology for bioreactive drains in fractured rock comprise:

- Designing a trench towards which the contaminated water can be drained (central drain)
- Verifying the required pollutant degrading bacteria are present (native bacteria or bioaugmented bacteria); if not, bio-augmentation may be considered.
- Filling the drain with carrier materials that support and enhance biofilms
- Creating in the drain the conditions required to stimulate the bacteria; this may comprise addition of nutrients, or oxygen (in case of aerobic biodegradation, pH adjustments, …)

It is important that the contact time between the water and the activated drain is sufficiently long to degrade the pollutants below the required levels. It may be required to determine degradation rates under in-situ conditions via lab scale degradation tests.

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