PROJECT OF DEVELOPMENT COOPERATION OF THE CZECH REPUBLIC AND MACEDONIA

„OLD ENVIRONMENTAL BURDENS IN CHEMICAL PLANT OHIS, SKOPJE“

Feasibility Study

for Remediation of Groundwater
and Unsaturated Zone Contaminated
with Chlorinated Hydrocarbons

November 2008

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Acronyms and Abbreviations Used

a.s.l.	- above sea level
BTEX	- benzene, toluene, ethyl benzene, xylenes
CHC	- chlorinated aliphatic hydrocarbons
COC	- contaminant(s) of concern
CR	- Czech Republic
d.m.	- dry matter
DIV	- Dutch intervention value
FS	- Feasibility Study
HCH	- hexachlorocyclohexane
HM	– heavy metals
ISCO	- in situ chemical oxidation
ISCR	- in situ chemical reduction
m b.g.l.	- meters below ground level
MK	- Republic of Macedonia
MoEPP	– Ministry of Environment and Physical Planning,
PCB	- polychlorinated biphenyles
PPE	- personal protective equipment
RA	- Risk Assessment
SVE	- soil vapor extraction
VOC	- volatile organic compounds
ZVI	- zero valent iron

1. Introduction

The project „Old Environmental Burdens in Chemical Plant OHIS, Skopje“ is financed from the Official Development Assistance Programme of the Czech Republic. The project is being implemented by Czech company ENACON s.r.o. that has been contracted by Ministry of Environment of the Czech Republic.

This report presents the outputs of Feasibility Study carried out within the frame of the above project. The Feasibility Study arises out of the Risk Assessment performed in previous project phase.

In total, four separate Feasibility Studies were elaborated for the OHIS plant. The reason for this procedure is that for large remediation projects funding may not be available all at one time but in increments, it may therefore be appropriate to plan the implementation of remediation in increments that can stand alone from environmental and engineering feasibility perspectives.

This feasibility study proposes and assesses alternative remedial actions aiming at reducing and/or eliminating risks related to the existence of CHC and HCH contaminated groundwater and TCE contaminated soil gas.

This report has been prepared by DEKONTA a.s. (Jan Vana) – the main subcontractor of Enacon.

Data processing and graphic outputs were executed by Petr Pokorny and Hana Cudova (Enacon).

Report has been reviewed by Jan Nemecek, project manager (Enacon).

2. Site Settings

2.1 General Information

2.1.1 Geographical Site Definition

The chemical plant OHIS is located at the southeastern edge of the city of Skopje, about 5.5 km apart the city centre in an industrial area that is spread along the road connecting Skopje and the city of Dracevo (see Annex 1). The site was developed in the first half of the 60´s, the lindane was produced in the period from 1965 to 1972; the electrolysis plant was in operation in the period from 1965 to 1995.

The project deals with old environmental burdens originated from historical production of lindane, monochloracetic acid and chlorine. Facilities, storage buildings related to the above stated production, and HCH dumps are located in the western part of the OHIS plant further referred as the “site” (see Annex 2). The whole OHIS plant covers the area of approximately 0.9 km^2, the “site” covers the area of approximately 0.1 km^2 (10 ha).

General situation of the site is depicted in fig. 2.1 where the main contamination sources are indicated – i.e. lindane isomers dump, former monochloracetic acid production facility and former electrolysis plant.

Figure 2.1 – Site layout

1= ruins of monochloracetic acid production facility, 2 = dump of lindane isomers, 3 = ruins of electrolysis plant

2.1.2 Existing and Planned Land Use

At present, the site is mostly abandoned. Some production activities are performed with regards to repackaging of pesticides (produced off-site) from large containers to small retail packaging, and in the area of former electrolysis plant there is a chlorine distribution facility operating still, the chlorine is transported to this facility in pressurized vessels and it is used for production of salt acid.

The present surrounding land use is as follows:

To the North: railway with a railway station and beyond it a private agricultural land and further to the North within a distance of 150 m from the site residential houses of the village of Gorno Lisiče (part of Skopje).

To the Southeast: the part of the OHIS plant dealing with production of detergents.

To the Southwest: the road connecting Skopje and Dracevo and beyond it a mixed industrial/commercial area with an abandoned glass mill and further to the southwest rural area with dwellings of Kisela Voda.

To the Northwest: undeveloped part of OHIS plant and beyond it a small residential area.

2.1.3 *Basic Demographic Settings*

The nearest residential area is Gorno Lisiče located approximately 200 m to the Northeast of the site. Dwellings belonging to Kisela Voda are located about 300 m to the Southwest of the site. Based on the rough estimate, up to 1,000 residents live within a distance of 500 m from the site mainly in Gorno Lisiče.

The site itself is almost abandoned. During the filed work performed in March 2008 it was observed that first tens of people are involved in some minor production activities, maintenance and guarding at the site.

2.2 Natural Conditions

2.2.1 *Geomorphologic Settings*

The site is located at the southwestern edge of the flood plain of the Vardar River at an average elevation of 239 m a.s.l. The site area is almost flat, just very gently sloping to the Northeast. Further to the Southwest of the site there are the steep side hills of the Vodno Mountain range.

2.2.2 *Climatic Settings*

The average annual air temperature is 12.5 °C, and the maximum temperature is 41.2 °C. Usually the climate during the summer period is very dry and warm, in winter the climate is moderate cold. The average annual precipitation is 502.3 mm (Eptisa 2007).

2.2.3 *Geological Settings*

The bedrock beneath the site area is composed of Pliocene sediments comprising sandstone, marlstone, and conglomerate. The depth to bedrock rapidly increases in north-east direction from first tens of meters to more than 200 m along the Vardar River. The bedrock is overlain by Quaternary proluvial sediments comprising sandy, gravely and silty loams. Quaternary proluvial sediments fill the depression eroded in Pliocene sediments. The thickness of Quaternary proluvial sediments is about 70 m at the site and increases in northern direction to approximately 90 m. The Quaternary proluvial sediments are overlain by alluvial sediments of the Vardar river comprising mainly gravels, sandy, silty and loamy gravels intercalated with thin layers (first tens of centimeters) of sandy gravelly clay and silt. The uppermost layers of alluvial sediments comprise clayey silt to silty clay. The thickness of these fine grained sediments varies at the site from 1.5 m to 5.2 m. The alluvial sediments are locally overlain by fill comprising mostly crushed aggregate, gravelly clay and gravel. The thickness of the fill is less than 0.5 m. Allegedly, it was man-deposed during the various historic construction/revamping stages of the site.

2.2.4 *Hydrogeological Settings*

Phreatic aquifer is developed in the alluvial sediments of the Vardar River. The permeability of the aquifer is 10^{-3} m/s up to 10^{-2} m/s in formations of pure gravel. Underlying proluvial sediments can be also considered as water bearing strata, however of lower permeability. The depth to groundwater is about 8 to 8.5 m below the ground level (b.g.l). The saturated thickness of the aquifer is about 60 m at the site and increases in northern direction. Groundwater flows generally toward the east and finally discharges into the Vardar River and into the lowermost section of the Markova reka River.

Groundwater is abstracted in down-gradient and cross-gradient direction in number of domestic wells in the village of Gorno Lisiče. The nearest well is located within the distance of about 150 m to the northeast from the site border. Based on the interviews with the local residents, wells are rather shallow (about 10 to 12 m) and abstracted groundwater is used for irrigation only. Drinking water is supplied by municipal mains there. Two abstraction well fields of OHIS plant are located in the alluvial plain of the Vardar River. Well field "Lisiče 1" consists of 8 wells of the depth of approximately 30 m situated perpendicular to groundwater flow at the distance of 1.2 km to the northeast of the site border (thus cross-gradient with respect to groundwater flow). Well field Lisiče 1 is reportedly more than 6 years out of operation. At the distance of approximately 2.3 km to the northeast of the site (about 200 m to the south of the Vardar River) there is abstraction well Lisiče 2. It is a 23 m deep well 5.5 m in diameter with radial drains 17 to 33 m long. The annual amount of groundwater abstracted from this well was approximately 2 mil. m^3 in 2007 (average pumping rate of 63 l/s). According to information provided by OHIS representatives abstracted groundwater is used for sanitary purposes and as a source of process water. Groundwater is not used for drinking. Based on the location of well Lisiče 2 with respect to Vardar River and general direction of groundwater flow, the well abstracts mainly surface water of the Vardar River that recharge the alluvial aquifer rather than intercepts groundwater flowing from the site.

2.2.5 Hydrological Settings

The nearest surface water is the Colemni Kamenj creek flowing in direction southwest – northeast at the distance of 400 m to the northwest of the site. The Colemni Kamenj creek discharges into the Vardar River – a regional watercourse flowing in northwest –southeast direction at the distance of 2.3 km to the northeast of the site. Another watercourse in the site vicinity is the Markova reka River flowing in south – north direction within a distance of 1.6 to the east of the site. The Markova reka River discharges into the Vardar River some 1 km downgradient of the estuary of Colemni Kamenj to the Vardar.

The Vardar river covers a catchments area of 4,650 km^2, the mean flow rate (calculated for the profile in Skopje) is 63 m^3/s, the 90% flow rate ($Q_{min90\%}$) is 6,34 m^3/s.

Reportedly, the OHIS property has never been flooded by the Vardar River or by the Markova reka River. In 1962, the OHIS area was flooded by the storm water run-off from the Vodno Mountains. The capacity of the Colemni Kamnej creek was not sufficient to collect stormwater and did overflow.

2.2.6 Geochemical and Hydrochemical Settings

Hydrochemical properties of groundwater were investigated with the aim to assess potential groundwater contamination and the fate of contaminants in the shallow aquifer. Data presented further refer to the groundwater of the uppermost part of quifer which was investigated – the average depth of newly installed monitoring wells is in approx. 12 m b.g.l., except MW-5 (15 m b.g.l.). The boreholes discovered relatively impermeable layer of clayey/silty sediments in the depth 10 – 12 m b.g.l which is believed base of the shallow aquifer.

Concentration of dissolved oxygen (measured in September 2007 only) was 0.96 and 3.61 mg/l, respectively. The groundwater has content of nitrates in order of magnitude of tens of mg/l, content of sulphates from 83 to 163 mg/l and low content of iron and manganese (both below 1 mg/l). Based on the above given concentrations of the anions in groundwater and measured physical-chemical parameters the redox conditions of the aquifer can be considered as indifferent (between aerobic and nitrate reducing conditions).

Hydrochemical parameters of the shallow aquifer are summarized in Table 2.1 further. Positions of monitoring wells are depicted in Annex 3.

Table 2.1 – Summary of the hydrochemical parameters of groundwater in OHIS area

Well	Parameter									
	groundwater level m b.g.l.		pH		temperature °C		conductivity µS/cm		redox potential mV	
	March 08	July 08	March 08	July 08	March 08	July 08	March 08	July 08	March 08	July 08
MW-1	8,18	8,45	7,01	7,05	14,6	14,9	1166	702	-66	88
MW-2	8,39	8,95	6,95	7,01	14,8	15,0	1339	640	-14	-90
MW-3	8,17	8,68	7,12	7,16	15,2	15,0	1383	245	-	147
MW-4	8,44	8,97	7,14	6,97	15,7	14,5	1200	245	-	66
MW-5	8,59	9,12	7,06	7,16	14,8	14,4	1395	374	-42	158
MW-6	8,03	8,50	7,01	7,07	13,0	14,5	1127	244	-	121
MW-7	8,01	8,58	8,87	7,10	14,8	14,4	1086	234	-18	179
MW-8	7,94	8,52	7,27	7,52	14,8	14,4	1308	655	-108	134
HS-1	8,04	8,92	9,97	8,83	14,4	13,8	1576	928	-111	-104
HS-2	8,47	8,69	6,77	6,99	14,7	14,3	1303	248	-98	181

2.3 Previous Investigations

2.3.1 Results of Previous Investigations

No systematic soil and groundwater investigation has been performed at the site in the past.

In 2001, screening of soil and groundwater contamination was performed by company BENA, Thessalonica within the project CARDS in 2002. Within the frame of this project two monitoring wells HS-1 and HS-2 were installed next to the former electrolysis plant and next to the δ-HCH dump, respectively. Soil samples were taken from the core of both borings and samples of groundwater were taken. In addition, samples of sediment of an old wastewater canal and wastewater sample were taken and two soil samples of superficial soil were taken within near the monitoring wells HS-1 and HS-2. All the collected samples were analyzed for wide spectrum of inorganic as well as organic parameters.

In the first superficial soil sample elevated concentration of mercury was determined – 7 mg/kg d.m.; in the second sample laboratory analyses did not found elevated concentration of any analyzed metal. Soil analyses encountered elevated concentrations of total chlorinated hydrocarbons (127 µg/kg calculated as TCE) in the depth interval 4 to 5 m bgl. Of boring HS-1 and also in boring HS-2 in the depth interval 3 to 4 m bgl. (42.72 µg/kg).

Groundwater sample taken from well HS-1 contained elevated concentrations of trichloroethylene (TCE) – 104.95 µg/l, tetrachloroethylene (PCE) – 132.45 µg/l, α-HCH – 0.239, β-HCH µg/l – 0.282 µg/l, aldrine – 0.3 µg/l and of mercury – 1.1 µg/l. Groundwater sample taken from well HS-2 contained elevated concentrations of α-HCH – 2.4, β-HCH – 3.20 µg/l, γ-HCH – 0.38 µg/l and of tribromomethane – 18.39 µg/l. No elevated concentrations of polycyclic aromatic hydrocarbons (PAH) or of analyzed metals (Pb, Cr) were encountered in any of the groundwater samples.

Laboratory analyses of sediments of the old wastewater canal found elevated concentrations of γ-HCH in order of tens of µg/kg in the depth interval from 0 to 2.5 m below the canal bottom. Maximal concentration was 53.9 µg/kg in the depth interval 0 to 0.5 m below the canal bottom. The sample of OHIS wastewater discharged into the Vardar River contained elevated concentrations of TCE – 23.4 µg/l and of Hg – 0.11 µg/l.

In 2007, company EPTISA performed limited site investigation within a project managed by the European Agency for Reconstruction. The site investigation consisted of geoelectric (resistivity) mapping with the goal to evaluate possible anomaly zones indicating contamination of soil and groundwater by HCH and mercury and to propose strategy for site remediation. Four anomalies were detected by geoelectric mapping – to the east of the former electrolyses plan (Hg contamination), to the southeast of the former monochloracetic acid plant, along the north-eastern side of the α-HCH and β-HCH dump and to the east of this dump (contamination by HCH).

In 2007, the Institute of Public Health in Skopje collected four superficial soil samples (0.05 to 0.35 m b.g.l.) in the surroundings of the former electrolysis plant and analyzed them for the content of mercury. Apparently, content of mercury exceeded respective DIV only in just one sample collected next to the electrolysis plant (110 mg/kg d.m.).

3. Site Characterization

Following chapters 3.1 – 3.3 provide briefly the results of large site investigation carried out in OHIS so far. Data relevant to unsaturated zone and groundwater contamination are presented only. Detail characterization of the entire OHIS brownfield can be found in the RA elaborated in June 2008 (Enacon).

3.1 Method and Scope of the Site Investigation

During the soil investigation campaign (August-September, 2007) there were in selected locations, where contamination with VOC was expected (namely CHC in the area of former monochloracetic acid production – i.e. in sector C), soil gas samples were collected. Soil gas samples were sucked by soil gas sampling pump from the depth 2 m b.g.l. and sorbed onto charcoal tubes Anasorb (SKC Inc., USA). Soil vapor samples were analyzed for TCE, PCE, and BTEX. Laboratory analyzes were carried out by independent accredited laboratory ALP (CR).

In order to collect data important for the aquifer characterization and assessment of the groundwater contamination 8 new monitoring wells have been installed on the site (performed in March 2008) and a large set of groundwater has been collected for laboratory analyzes focused on determination of large range of possible contaminants. In addition, several domestic wells outside the OHIS premises were included in the groundwater monitoring as well as groundwater abstraction stations Lisiče 1 and Lisiče 2 (operated by OHIS within the Lisiče cadaster), locations of the wells incorporated in the groundwater monitoring objects network are depicted in Annex 3.

Within the course of groundwater samples collection (low pumping stress method) basic hydrogeochemical parameters have been logged (see Table 2.1, page 9).

Analyzes of the groundwater samples have been carried out in independent accredited laboratory ALP Plzen (CR).

Data gathered during the monitoring wells installation and groundwater sampling were further evaluated (RA, June 2008) with the aim to model groundwater flow and migration of COC identified. Within the frame of the RA, risks posed by contaminated groundwater to the human's health and to the environment were evaluated and target limits for the groundwater remediation have been proposed too (see further chapters).

3.2 Risk Assessment

Detail Risk Assessment has been produced in a separate document (Enacon, June 2008). This chapter provides a concise summary of the RA findings and recommendations regarding the soil vapors and groundwater contamination.

Unacceptable risk resulting from the assessment of inhalation of TCE vapors migrating into buildings from the underlying contaminated soil has been identified. Remediation of unsaturated zone containing TCE in soil gas above the target concentration refers to the area under the former monochloracetic acid production building and its close surroundings.

The planar area of this TCE contaminated unsaturated zone is approximately 3000 m^2. Target clean-up limit for the remediation of TCE contaminated soil was proposed considering the acceptable risk from inhalation of vapors intruding into the building (see Table 3.1).

It has to be highlighted that the unacceptable risk posed by TCE contamination of unsaturated zone was identified for workers in the building C 2 (former monochloracetic acid production) and/or in a case of soil excavation works within the footprint of C 2 building and its close vicinity. This risk can be well managed by use of proper PPE and necessity of a remedial action/mitigation measures should be assessed from the point of view of future land use. The RA was carried out with presumption that the future land use will remain for industrial purpose.

Risk assessment did not identify any unacceptable risk related to contaminated groundwater due to its limited use down-gradient with respect to groundwater flow.

Mobility of other groundwater constituents and their level of contamination are not considered of significant concern. It is also assumed that removal of primary and secondary contamination sources of chlorinated pesticides (HCH isomers) will results in gradual decrease of their concentration in groundwater.

Remediation of groundwater contaminated by CHC is recommended in the area of the former monochloracetic acid production building and its eastern surroundings. As a conservative approach target limits for groundwater "leaving" the site (along the down-gradient site boundary) were proposed for individual CHC on the level of the DIV (see Table 3.1).

Environmental risks related to the existing groundwater contamination were not identified.

Table 3.1 – Target limits for groundwater and unsaturated zone remediation – OHIS

Medium	Contaminant	Unit	Target concentration	Note
Groundwater along the OHIS down-gradient border	1,2-cis-DCE	µg/l	20	Proposed in order to meet DIV in groundwater migrating off-site
	TCE	µg/l	500	
	PCE	µg/l	40	
	PCA	µg/l	500	DIV is not defined for PCA, target limit set the same as for PCE
Soil gas	TCE	mg/m^3	35	Derived from acceptable risk for a on-site worker (inhalation of vapours intruded into buildings)

3.3 Characterization of Contamination

3.3.1 Contamination of the Unsaturated Zone

Results of laboratory analyses of soil samples were compared with the DIV which indicate when the functional properties of the soil for humans, plant and animal life is seriously impaired or threatened. They are representative of the level of contamination above which there is a serious case of soil contamination. Results can be summarized as follows:

- Among the VOC analyzed, only traces of TCE and PCE (in order of first tenths of mg/kg) were identified in sector C (former production of monochloracetic acid). Elevated contents of chlorinated ethenes in soil gas in this area indicate that results of soil analyses are underestimated due to extremely high temperature during the sampling campaign.
- Analyzes of soil gas samples (see Table 3.2) found elevated contents of TCE and PCE in sector C (former production of monochloracetic acid). Maximal TCE concentration was 2,940 mg/m^3 in boring S-C-4 located in the area of former above-ground tanks for this semi-product (see Annex 3).

Results of soil vapour analyzes are summarized in Table 3.2 together with comparison with the DIV.

Table 3.2 – Soil gas analyzes, OHIS

Sampling Location	Unit	S-C-1	S-C-2	S-C-3/A	S-C-4	S-C-5	S-C-6	S-E-1	S-E-2	DIV
Sampling Depth (m b.g.l.)		2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	
Sample ID		175	176	177	178	179	180	181	182	
Σ BTEX	mg/m^3	< 1,5	< 1,5	< 1,5	< 1,5	< 1,5	< 1,5	< 1,5	< 1,5	
benzene	mg/m^3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	5
toluene	mg/m^3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	10
ethylbenzene	mg/m^3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	10
xylenes	mg/m^3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	< 0,3	15
TCE	mg/m^3	90	547	97	2 940	193	640	0,767	0,867	10
PCE	mg/m^3	9,67	56,7	1,43	100	19	43,3	0,567	0,667	10
pentane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
hexane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
heptane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
oktane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
nonane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
dekane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
undekane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	
dodekane	mg/m^3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	< 0,3	< 0,3	

3.3.2 Groundwater Contamination

Two monitoring campaigns were carried out within the project frame in 2008 (March and July), focused on identification of the COC and contamination grade. Results of the laboratory analyzes of groundwater samples collected in 2008 are summarized in Annex 5. Results of groundwater monitoring focused on identification of COC and contamination grade were compared with the DIV which exceedance indicates case of contamination.

In the period 26th – 28th March 2008 groundwater samples were collected from all existing and new wells at the site (HS-1 and HS-2; MW1 to MW-8), additionally from both off-site abstraction wells of OHIS (Lisiče 1 and Lisiče 2) and also from 3 domestic wells in Gorno Lisiče marked as DW-1 to DW-3. Samples were collected in a dynamic "low flow" regime using sampling pump GIGANT. During sampling physical-chemical parameters were measured (temperature, O_2, pH and conductivity). Measurement was performed by instrument WTW pH/Cond 340i/SET, with probe SenTix 41 for measurement of pH and temperature and probe TetraCon 325 for measurement of conductivity. Domestic wells as well as OHIS abstraction well Lisiče 2 were sampled by installed pumps.

In July, 10 groundwater monitoring samples were collected from the monitoring wells inside the OHIS limits, 5 groundwater samples were collected from domestic wells situated in the north-east OHIS vicinity and 2 groundwater samples were collected from abstraction stations Lisiče 1 and 2 (i.e. in sum 17 samples). Samples were transported to CR and analyzed in independent accredited laboratory ALP Plzen. Comparing to the first monitoring campaign a reduced spectrum of contaminants was analyzed – i.e. identified contaminants of consideration (chlorinated pesticides, CHC, BTEX, chlorobenzenes, and Hg).

Further text is focused on the main COC identified in the groundwater – i.e. chlorinated hydrocarbons and hexachlorocyclohexane.

3.3.2.1 CHC Contaminated Groundwater

Hotspot of groundwater contamination by chlorinated aliphatic hydrocarbons was discovered in March 2008 at the eastern edge of the former monochloracetic acid production facility (see Annex 4).

In the well MW-6, located next to aboveground storage tanks for TCE and PCA, sum concentration of chlorinated aliphatic hydrocarbons of 12,097 µg/l was found. TCE content dominates (67%), followed by PCA (25%). Contamination plume migrates off-site. In wells MW-7 and MW-8 located along the northeastern site boundary sum concentration of chlorinated hydrocarbons was 7,723 µg/l and 2,170 µg/l, respectively.

In domestic well DW-4 located some 350 m downgradient the well MW-8 the content of chlorinated hydrocarbons in groundwater was 624 µg/l. The relative content of individual chlorinated aliphatic hydrocarbons is different from the contamination in the hotspot (PCA made 75% of total CHC content, TCE only 5%), obviously due to different mobility and degradability of individual chlorinated compounds.

Comparing concentrations of individual CHC with respective DIV, the limits for TCE and tetrachloroethene (PCE) were exceeded in all five on-site wells located downgradient of the monochloracetic acid production plant. In the very hotspot (well MW-6), the DIV was exceeded 16 times for TCE and 20 times for PCE.

Of all sampled downgradient domestic wells, the DIV for PCE was exceeded 3 times in the well DW-4. No DIV is defined for PCA that dominates there.

In groundwater of OHIS abstraction wells Lisiče 1 and Lisiče 2 traces of chlorinated hydrocarbons were found in order of tenths to units of µg/l, thus significantly below the respective DIV. Comparing results of laboratory analyses with Macedonian drinking water standards, standard defined for 1,2-dichloroethane (1,2 DCA: 3 µg/l) was exceeded in groundwater of well Lisiče 1 (8.17 µg/l). However, as stated above, groundwater of OHIS abstraction wells are not used for drinking purposes.

The data regarding CHC concentrations found during the March 2008 groundwater monitoring campaign are summarized in Table 3.3.

Low-permeable layer of clayey silt to silty clay overlying the aquifer serves as protective layer, nevertheless is not sufficient with regards to amounts of contaminants leaching from above ground contamination sources. Mathematical model of CHC transport (RA Enacon, 2008) estimates that 30 kg/year of PCE and 90 kg/year of PCA seep through the unsaturated zone to the aquifer.

Velocities of migration of CHC in groundwater were estimated considering advection and sorption – PCE and PCA migrate with the velocity approximately 0.2 to 2.4 m/day (70 to 900 m/year). Higher migration velocities refer to the surroundings of abstraction wells Lisiče 1 and Lisiče 2, where low concentrations of chlorinated aliphatic hydrocarbons were detected only.

Comparing to HCH, CHC are substantially more mobile pollutants. Model results for the year 2008 (i.e. after approximately 40 – year duration of the contamination source) show that the edge of the PCE and PCA plumes is about 2.0 km to the East to Northeast from the contamination source area and were attracted by the Lisiče 1 and Lisiče 2 abstraction wells. Thus, reflecting the model results, trace concentrations of CHC found in groundwater of the Lisiče 2 well and especially in groundwater of the Lisiče 1 well have very likely origin in the OHIS plant.

Table 3.3 – Concentrations of CHC found in OHIS area and its vicinity (March 2008)

Well	Parameter (µg/l)						
	1,1-DCE	1,2-cis-DCE	1,2-DCA	TCE	PCE	VC	PCA
HS - 1	< 0.1	13,3	1,93	859	224	< 0.1	4,50
HS - 2	< 0.1	< 0.1	0,16	3,56	6,23	< 0.1	0,34
MW - 1	< 0.1	< 0.1	< 0.1	0,55	0,5	0,639	0,11
MW - 2	< 0.1	2,18	7,31	8,5	8,11	< 0.1	0,62
MW - 3	1,39	8,23	2,54	2 420	368	< 0.1	160
MW - 4	< 0.1	< 0.1	0,32	10,6	5,11	< 0.1	0,39
MW - 5	< 0.1	< 0.1	1,15	2,97	6,24	< 0.1	0,34
MW - 6	< 0.1	102	2,13	8 150	792	0,937	3 050
MW - 7	< 0.1	96,2	3,73	3 980	582	0,493	3 060
MW - 8	< 0.1	12,8	3,55	663	505	< 0.1	986
DW - 1	< 0.1	< 0.1	0,62	1,53	2,22	< 0.1	< 0.1
DW - 3	< 0.1	0,45	0,68	3,65	10	< 0.1	0,97
DW - 4	< 0.1	8,41	2,03	29,4	134	< 0.1	450
Lisiče 1	< 0.1	< 0.1	8,17	4,08	6,91	< 0.1	0,38
Lisiče 2	< 0.1	< 0.1	1,23	0,94	1,5	< 0.1	< 0.1
Target limits	NA	20	NA	500	40	NA	500

Legend: the values highlighted with yellow color exceed the target limits proposed for groundwater "leaving" the site (represented by the wells along down-gradient site boundary – HS-1, MW-7, MW-8) on the basis of RA (Enacon, 2008)

With respect to predictions of the mathematical model, as long as the Lisiče 2 abstraction well is active, it will act as an interceptor of the CHC contaminant plume migrating from the OHIS plant. Even in the case of termination of groundwater abstraction from the Lisiče 2 well, the impact on surface water quality by draining of contaminated groundwater into the Vardar River will be negligible due to the high dilution factor. According to the model results the Markova reka River does not drain groundwater (groundwater level is below the surface water level thus cannot be affected either).

Natural attenuation processes are not very likely of such significance that would prevent further migration of groundwater contamination by CHC off-site.

Extent of the CHC contamination plume is illustrated in the figure 3.1 – by the PCE plume. Situations for all particular CHC are presented in Annex 4.

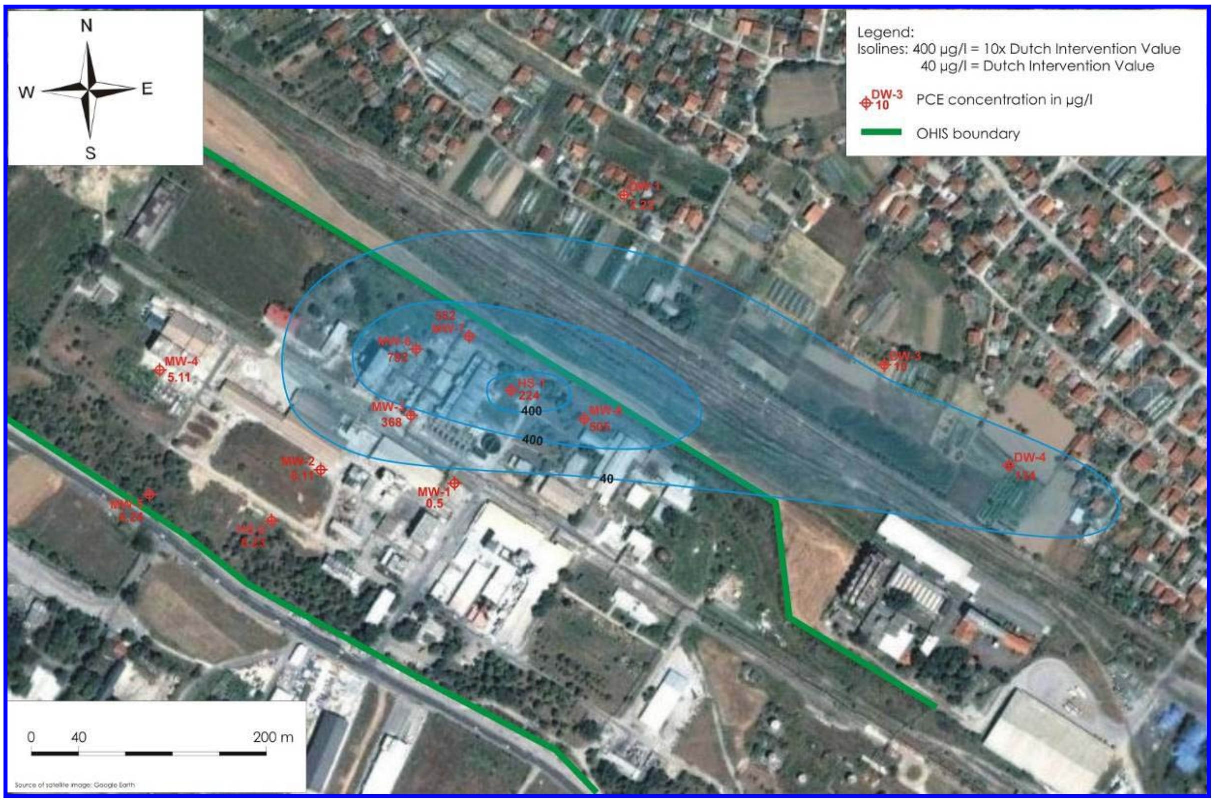

Figure 3.1 – PCE contamination plume as in March 2008

3.3.2.2 HCH Contaminated Groundwater

Contamination of groundwater by HCH isomers exceeding the DIV (1 µg/l) was found in groundwater of most on-site wells (except for wells HS-1 and MW-8). Maximal HCH concentrations were found in groundwater of wells MW-1 (49.8 µg/l) and MW-2 (28.8 µg/l) indicating source of contamination (lindane production and storage buildings and the dump of α-HCH and β-HCH, respectively). These maximal HCH concentrations in groundwater exceed DIV 50 times and 29 times, respectively.

Whereas in MW-1 δ-HCH dominates (99% of total HCH content), in groundwater of well MW-2 α-HCH prevails (61%). Just traces of HCH were found in well HS-2 – located downgradient of δ-HCH dump.

Contamination plume migrates in direction of groundwater flow to the East towards domestic well DW-4, where the sum HCH concentration was 0.92 µg/l (e.g. slightly below the DIV). No HCH in concentrations exceeding laboratory detection limits were found in samples collected from both OHIS abstraction wells Lisiče 1 and Lisiče 2.

Concentrations of HCH isomers determined in the groundwater samples collected in March 2008 are summarized in Table 3.4. Analyzes of groundwater samples are presented in Annex 5.

Table 3.4 – HCH concentrations found in groundwater in OHIS area and its vicinity

Well	Parameter (µg/l)				
	α- HCH	β - HCH	γ - HCH (lindane)	δ - HCH	Σ HCH
HS - 1	0,062	0,28	0,01	0,01	0,362
HS - 2	0,01	0,03	< 0,01	< 0,01	0,05
MW - 1	0,17	0,32	0,11	49,2	49,8
MW - 2	17,6	6,03	2,03	3,11	28,77
MW - 3	0,25	1,69	0,064	0,62	2,624
MW - 4	0,24	2,34	0,021	0,22	2,821
MW - 5	0,01	0,03	< 0,01	0,01	0,055
MW - 6	0,13	1,29	0,048	0,029	1,497
MW - 7	0,1	1,44	0,028	0,02	1,588
MW - 8	0,14	0,075	0,063	0,035	0,313
DW - 1	< 0,01	< 0,01	< 0,01	< 0,01	0,02
DW - 3	0,013	0,063	< 0,01	< 0,01	0,086
DW - 4	0,15	0,68	0,039	0,052	0,921
Lisiče 1	< 0,01	< 0,01	< 0,01	< 0,01	0,02
Lisiče 2	< 0,01	< 0,01	< 0,01	< 0,01	0,02
DIL	NA	NA	NA	NA	1

Legend: the values highlighted with yellow color exceed the target limits proposed on the basis of RA (Enacon, 2008); Σ HCH represents sum of α, β, γ, and δ HCH isomers.

Based on the mathematical modeling, HCH plume migrates from the source area (HCH dump and former HCH production areas) in direction of groundwater flow towards the East. After about 40 years of assumed duration of the contamination source (production of HCH started in the mid of 1960´s), the HCH contaminant plume extended to the south-eastern part of Gorno Lisiče. Based on the mathematical model the front edge of the HCH contaminant plume (expressed as 1µg/l isoline – see figure 3.1) is some 1.4 km downgradient (to the east) of the contamination source area. Migration of HCH in the period of years 2008 – 2028 was predicted by the mathematical model. Within this period front edge of the HCH plume will move further in easterly direction by another 300 m. The extent of HCH contamination plume (as in March 2008) is depicted in figure 3.2.

Analogically to the CHC contamination, the low-permeable layer of clayey silt to silty clay overlying the aquifer serves as protective layer, nevertheless it is not sufficient with regards to amounts of HCH contaminants leaching from the above ground contamination sources. Based on the mathematical model of contaminant transport, approximately 30 kg/year of HCH isomers seep through the unsaturated zone to the aquifer.

Migration velocities in groundwater were estimated considering advection and sorption. HCH isomers migrate in groundwater by velocity of approximately 0.08 to 0.9 m/day (30 to 330 m/year).

Natural attenuation processes are not very likely of such significance that would prevent further migration of groundwater contamination by HCH off-site. Sorption is the main process that prevents significant spread of HCH contamination in groundwater (in comparison to CHC). However sorption retards the migration rather than decrease the total content of the contaminant.

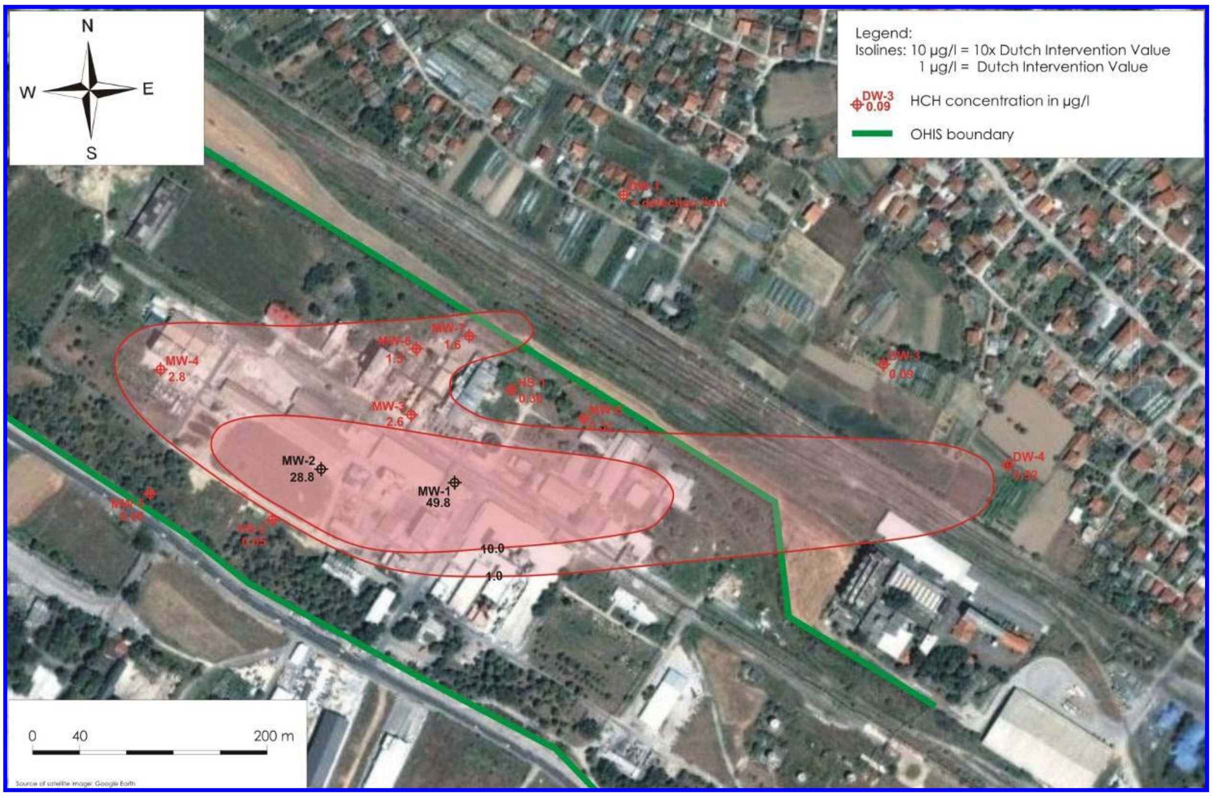

Figure 3.2 – HCH contamination plume as in March 2008

4. Remedial Objectives

Based on the RA, unacceptable human health risk was identified with regards to indoor inhalation of VOC (TCE) vapours by an on-site worker and by outdoor inhalation of VOC (TCE) vapours by an excavation worker in sector C. The first risky exposure does not currently exist as the former monochloracetic acid production building is abandoned. The second risky exposure can be well and easily managed by use of proper PPE. Nevertheless, corrective measures have to be adopted when rehabilitiation and future use of the land in sector C is considered.

No unacceptable risks related to contaminated groundwater were identified in RA considering present use of groundwater downgradient the site. As a conservative approach a target limits for chlorinated aliphatic hydrocarbons (as the most mobile contaminants) in groundwater along the down-gradient site boundary is proposed (see Table 3.2, page 9).

Mobility of other groundwater contaminants and their level of contamination are not considered of significant concern. It is also assumed that removal/isolation of primary and secondary contamination sources of chlorinated pesticides will result in gradual decrease of their concentration in groundwater.

Remediation of groundwater contaminated by CHC is recommended in the area of the former monochloracetic acid production building and its eastern surroundings.

Although the risk related to the groundwater contamination with HCH isomers has been evaluated in the RA as negligible, the remediation of HCH laden groundwater is considered in the FS too due to the fact that CHC and HCH contamination plumes overlap which implicates necessity to consider remedial methods capable to treat both contaminants.

With respect to the above written, these tasks have been adopted for this FS:

1. selection of a feasible method for the groundwater remediation/clean-up ensuring achievement of the target limits proposed for the groundwater "leaving" the site, or
2. selection of a feasible method for contamination plume control in order to ensure that the groundwater flow off-site meets the target limits proposed for the COC, and
3. selection of a feasible method for corrective measures to be adopted in case of the necessity to clean-up the unsaturated zone contaminated with TCE.

5. Assessment of Prospective Technologies

5.1 Identification of Promising Technologies

Due to the complexity of the old environmental burdens within the OHIS site, this FS refers to corrective measure related to the contamination of the unsaturated zone and the groundwater contaminated with CHC and/or HCH in the area of former monochloracetic acid production building (C 2) and its vicinity only.

Remediation of other contaminated media (i.e. HCH dumps, HCH laden soil, construction materials, and Hg contaminated soil and construction materials) has been assessed in separate studies.

Identification of promising technologies was focused on selection of a feasible method(s) for clean-up of TCE contaminated unsaturated zone and CHC contaminated groundwater (considering also HCH contamination) to ensure that the remedial goals will be met. The relationship between the general categories of remedial technologies and the remedial objectives is summarized in Table 5.1.

In general, a very limited number of options exist for general remedial response actions. Contrariwise, due to a long practice many alternative technologies appear to be applicable for the remedial action as well as for control of the contaminants migration.

Table 5.1 – Summary of remedial objectives and general remedial technologies

Contaminated Media	Remedial Objectives	General Remedial Response Actions	Types of Remedial Technologies
CHC and HCH contaminated groundwater	Protection of human health:	No action	NA
	Protect human health from threats caused by exposure to hazardous substances released from the contamination sources and transported off site via groundwater	Monitoring	Monitoring of the contamination progress or monitoring of attenuation
		Containment	Cutoff walls and capping
		Removal	Removal of the contaminated water and subsequent ex-situ treatment of contaminated water (e.g. air stripping, biodegradation, adsorption, treatment in existing industrial wastewater treatment plant, etc.) or in situ treatment (e.g. in situ chemical oxida
		Control	Control of the contaminants migration - hydraulic barrier, permeable reactive barrier, reactive zone.
Soil vapors contaminated with TCE	Protection of human health:	No action	NA
	Protect human health from threats caused by exposure to hazardous substances released from the contamination sources and transported off site via air transport.	Monitoring	Monitoring of the contamination progress or monitoring of attenuation
		Containment	Cutoff walls and capping
		Removal	Removal of the contaminated soil and subsequent ex-situ treatment (e.g. biodegradation, adsorption, etc.) or in situ treatment (e.g.soil vapor extraction, in situ chemical oxidation, bioremediation, ZVI treatment, etc.)

5.2 Screening of Remedial Technologies

5.2.1 Screening Method

The screening of available remedial technologies is organized by grouping the remedial technologies into a three-tier hierarchical system for describing the remedial processes. This system uses the following categories, in order of increasing specificity: general response action, remedial technology and process option. For example, removal is general response action; one of the remedial technologies is in-situ chemical oxidation and one of the several options is use of hydrogen peroxide.

On the basis of this organizational approach, the descriptions of the remedial technologies considered for clean-up of unsaturated zone contaminated with TCE and CHC and HCH laden groundwater are summarized in Table 5.2 on the next pages. These are remedial technologies that were carried forward and screened to assess which technologies merit further consideration for the remedial alternatives.

5.2.2 Screening Criteria

The remedial technologies are screened using three broad criteria to assess the suitability of each for the remediation/treatment of CHC and HCH contaminated groundwater. These criteria are:

Efficiency

Consideration of efficiency focuses on the degree of reliability of the process that can be expected for the types of hazardous substances and the physical condition at the site. Other considerations are the likelihood of meeting the remedial goals and the possible risks generated during implementation.

Implementability

Implementability encompasses the technical and administrative aspects for implementing a remedial technology. Factors in considering implementability include the availability of the special facilities in Macedonia, equipment and labor required for some remedial technologies.

Estimated Cost

Estimated cost is considered in a relative way. The estimated costs are judged as relatively low, medium, or high on the basis of general assumptions reflecting the site specific circumstances. At this screening stage, estimated cost does not have a substantial effect on the screening process except in cases where technologies are relatively equal and one has a substantially greater cost.

Table 5.2 – Overview of methods for treatment of contamination in unsaturated zone and in groundwater

General Response Action	Remedial Technology	Process Option	Description of Remedial Technology
No action	None	None	No remedial action at the site, the site remains as it is.
Monitoring	Monitoring	Monitoring	Only monitoring of the contamination.
		Monitoring of natural attenuation	Natural attenuation relies on natural processes to clean up or attenuate pollution in soil and groundwater. Natural attenuation occurs at most polluted sites. However, the right conditions must exist underground to clean sites properly. If not, cleanup will not be quick enough or complete enough. Scientists monitor or test these conditions to make sure natural attenuation is working.
Containment	Hydraulic barriers - cutoff walls	Slurry walls	Cutoff walls are structures used to prevent contaminants migration from either leaving an area, in the case of contaminated groundwater, or entering a contaminated area, in the case of clean groundwater.
		Cement walls	Slurry walls – are basically trenches refilled with a material (e.g. bentonite slurry) that combines low permeability and high adsorption characteristics to impede the passage of groundwater and associated contaminants.
		Sheet piling	Cement walls – are similar to the slurry walls, except that instead of low permeability clay-type slurry, cement based slurry is used. Construction may be by trench and fill as with the slurry walls.
			Sheet piling – steel sheets are hammered into the soil
	Capping	Synthetic liners	Capping is typically used to cover a contaminated area of waste unit to prevent precipitation from infiltrating an area, to prevent contaminated material from leaving the area and to prevent human or animal contact with the contaminated materials. An example of preventing releases is growing of vegetation on tailings to prevent fugitive dust from blowing off and being transported downwind. Capping could include: surface armoring, soil/clay cover, soil enhancement to encourage growth, geosynthetic or asphaltic cover system, polymeric/chemical surface sealers, revegetation, concrete and synthetic covers.
		Native liners	
		Evapotranspirative capping	

Table 5.2 – cont.

General Response Action	Remedial Technology	Process Option	Description of Remedial Technology
Removal	Pump and treat	Air stripping	Conventional treatment of contaminated ground water is done by extracting the contaminated water treating it above ground and reinjecting or discharging the clean water. The extracted contaminants must be disposed of separately. Air stripping uses equipment called air stripper to force air through polluted water. An air stripper usually consists of a large tank filled with a packing material, made of plastic, steel, or ceramics.The polluted water is pumped into the tank and sprayed over the packing material. The water trickles down through the spaces between the packing material toward the bottom of the tank. At the same time a fan at the bottom blows air upward. As the air passes upward through the trickling water, it causes the chemicals to evaporate. The off gas has to be treated.
		Adsorbtion	Suitable sorption media can be used to capture the contaminants.
		Filtering	Suitable filters can be used for separation of contaminants.
		Gravity separation	Differences in specific gravity used for partitioning of water and contaminants.
	In situ chemical oxidation (ISCO)	Treatment with potassium or sodium permanaganate	Chemical oxidation involves redox reactions chemically converting the contaminants to nonhazardous or less toxic compounds that are less mobile, more stable or inert. ISCO means delivery of the reactants into the contaminated groundwater in its natural position. Differences between the ISCO options are resulting from utilization of various possible reactants. Permanganates do not oxidate chlorinated alkanes.
		Treatment with hydrogen peroxide	
		Treatment with ozone	
	Air sparging	Air sparging	Air sparging involves the injection of air or oxygen through a contaminated aquifer. Injected air traverses horizontally and vertically in channels through the soil column, creating an underground stripper that removes volatile and semivolatile organic contaminants by volatilization. The injected air helps to flush the contaminants into the unsaturated zone.
		Air sparging + soil vapor extraction (SVE)	SVE can be implemented in conjunction with air sparging to remove the generated vapor-phase contamination from the vadose zone.

Table 5.2 – cont.

General Response Action	Remedial Technology	Process Option	Description of Remedial Technology
Removal	Bioremediation	Bioventing	Bioventing is a promising new technology that stimulates the natural in situ biodegradation of any aerobically degradable compounds in soil by providing oxygen to existing soil microorganisms. Oxygen is most commonly supplied through direct air injection into residual contamination in soil. In addition to degradation of adsorbed fuel residuals, volatile compounds are biodegraded as vapors move slowly through biologically active soil.
		Biological reductive dehalogenation	Redox manipulation - delivery of proper reactants (e.g. molasses, palm oil, etc.) into the groundwater in order create suitable redox conditions for anaerobic reductive dechloration. Applicable also in ex-situ mode for soil clean-up.
	In situ chemical reduction	ZVI treatment	Zero-valent iron has performed so successfully in PRB technology that it is now being applied directly for source zone treatment - the granular ZVI is delivered into the contamination source.
		ZVI treatment - Fe nanoparticles	Method modification where nanoparticles of ZVI are used.
	Excavation of contaminated soil	Excavation and landfilling	Excavation of contaminated soil, disposal of at landfill adequate to the contamination (hazardous waste landfill).
		Excavation and treatment	Excavation and ex-situ treatment, separated contaminants have to be disposed of or liquidated properly, treated soil can be disposed of or backfilled. Possible treatment methods are bioremediation, thermal desorption.
Control	Permeable reactive barriers (PRB)	Continuos PRB	PRB is an in situ method for remediating contaminated groundwater that combines a passive chemical or biological treatment zone with subsurface fluid flow management. Treatment media may include zero-valent iron, chelators, sorbents, and microbes to address a wide variety of groundwater contaminants (e.g chlorinated solvents, other organics, metals, inorganics) and radionuclides. The contaminants are concentrated and either degraded or retained in the barrier material, which may need to be replaced periodically.PRBs can be installed as permanent or semi-permanent units. The most commonly used configuration is a continuous trench in which the treatment material is backfilled. The trench is perpendicular to and intersects the plume of contaminated groundwater.
		Funnel and gate	Combination of cutoff walls directing the contaminated groundwater to the "funnel" with either subsurface or above ground permeable treatment zone.
		Reactive zones	Modification of continuos PRB - the treatment zone is created by injection of the treatment media either into wells either by the direct push technology.
	Hydraulic barriers	Active hydraulic barrier	Migration of the contaminants is eliminated/reduced by pumping of the water from properly situated wells - modification of the pump and treat method, i.e. the water has to be treated prior reinjection or discharge.

5.2.3 Screening Summary

On the basis of screening assessments of the available remedial/treatment technologies, some of the technologies were chosen to be incorporated in the overall remedial alternatives. The selected technologies are favored because of advantages in efficiency, implementability, cost, or a combination of features. The reasons for using the remedial technologies in the overall alternatives are presented in Table 5.3.

The results of technology screening are not intended to eliminate or preclude consideration of other remedial technologies during future stages of remedial study or design. The screening is intended to show the rationale for technology selection at this point in the FS. As new information will become available, other remedial technologies may become favorable, warranting changes to the remedial alternatives.

Table 5.3 – Remedial technologies screening

General Response Action	Remedial Technology	Process Option	Comments: Effectivity	Comments: Implementability	Comments: Relative Estimated Cost
No action	None	None	No action would allow continued spreading of the contamination plume and negative impact on the domestic wells in case of groundwater contamination.	Not applicable	Not applicable
			No action would allow continued spreading of the contamination via soil gas transport.	Conditionally implementable	Not applicable
Monitoring	Monitoring	Monitoring	Effective for tracking and evaluation the progress and effectivity of remedial actions and triggering contigency actions if unacceptable releases are detected during remedial actions. Ineffective in case of monitoring of the contamination plume progress	Conditionally implementable	Low
		Monitoring of natural attenuation	Effective when no immediate risk occurs.	Conditionally implementable	Moderate
Containment	Hydraulic barriers - cutoff walls	Slurry walls	Effective in elimination of further contaminants migration via groundwater transport.	Implementable	Low to moderate
		Cement walls	Effective in elimination of further contaminants migration via groundwater transport.	Implementable	Moderate
		Sheet piling	Effective in elimination of further contaminants migration via groundwater transport.	Not implementable due to unfavorable geology	Moderate
	Capping	Synthetic liners	Effective in elimination of precipitation infiltration into the contamianted soil. Ineffective in elimination/reduction of further contaminant plume spreading.	Implementable	Moderate
		Native liners	Effective in elimination of precipitation infiltration into the contamianted soil. Ineffective in elimination/reduction of further contaminant plume spreading.	Implementable	Moderate
		Evapotranspirative capping	Effective in elimination of precipitation infiltration into the contamianted soil. Ineffective in elimination/reduction of further contaminant plume spreading.	Implementable	Moderate

Table 5.3 – cont.

General Response Action	Remedial Technology	Process Option	Comments		
			Effectivity	Implementability	Relative Estimated Cost
Removal	Pump and treat	Air stripping	Effective, efficacy drops down with time.	Implementable	High
		Adsorbtion	Effective, efficacy drops down with time.	Implementable	High
		Filtering	Effective, efficacy drops down with time.	Implementable	High
		Gravity separation	Effective, efficacy drops down with time.	Implementable	High
	In situ chemical oxidation (ISCO)	Treatment with potassium or sodium permanaganate	Effective, efficiency may drop down due to origin of colloids clogging reducing the aquifer's permeabilty, efficiency may be further reduced by unfavorable geological settings.Ineffective in case of chlorinated alkanes.	Implementable	Moderate
		Treatment with hydrogen peroxide	Effective, efficiency may drop down due to origin of colloids clogging reducing the aquifer's permeabilty, efficiency may be further reduced by unfavorable geological settings.	Implementable	Moderate
		Treatment with ozone	Effective, efficiency may be reduced by unfavorable geological settings.	Implementable	Moderate to high
	Air sparging	Air sparging	Low effective due to unfavorable geological settings, efficacy drops down with time.	Implementable	High
		Air sparging + soil vapor extraction (SVE)	Low effective due to unfavorable geological settings, efficacy drops down with time.	Implementable	High
	Bioremediation	Bioventing	Not effective for chlorinated VOC	Not applicable	Moderate to high
		Biological reductive dehalogenation	Low effective due to unfavorable geological settings, efficacy drops down with time.	Conditionally implementable	Moderate
	ZVI treatment	ZVI treatment	Effective	Implementable	Moderate to high
		ZVI treatment - Fe nanoparticles	Effective, reinjection of Fe nanoparticles is probable.	Implementable	High
	Excavation of contaminated soil	Excavation and landfilling	Effective	Conditionally implementable	High
		Excavation and treatment	Effective	Implementable	Moderate
Control	Permeable reactive barriers (PRB)	Continuos PRB	Effective	Implementable	Moderate to high
		Funnel and gate	Effective	Conditionally implementable	High
		Reactive zones	Effective	Implementable	Moderate
	Hydraulic barriers	Active hydraulic barrier	Effective	Implementable	High

5.2.4 Screening Results

With respect to the risk posed by TCE contamination of **unsaturated zone** – i.e. unacceptable risk to human health is posed via inhalation of contaminated air in the buildings and or in case of excavation of contaminated soil, quite passive approach to remedial action was adopted for screening of methods applicable. The main reasons are:

- Risk posed by possible inhalation of TCE during excavation can be easily managed by use of proper PPE;
- Risk posed by indoor inhalation of TOC does not currently exist as the former monochloracetic acid production building is abandoned. This risk relates to potential future redevelopment of this area;

On the other hand unsaturated zone contaminated by TCE (and other CHC) can act as secondary source of groundwater contamination and can decrease efficiency of groundwater remediation.

In such a case when clean-up of TCE contaminated soil is not urgent, the clean-up has to be commenced after demolition of buildings and pavements removal in order to enable free access to the contaminated zone and thus reduce the cost.

Due to the above reasons and considering very unfavorable geological settings in the area affected with TCE and other CHC (i.e. thick layer of clayey/silty sediments in the uppermost part of the geological profile and frequent intercalations of clay/silt in coarse sediments beneath the upper fine grained low permeable layer) and with the aim to eliminate any blockage in future use of the area, just three viable methods were brought forward to further detail assessment:

1. monitoring of natural attenuation – which is conditionally acceptable in case that TCE (CHC) contaminated unsaturated zone will not disable future land use;
2. excavation of upper (the most contaminated) profile of contaminated soil (to the depth 3 m b.g.l.) and ex-situ treatment – as written above, prevailing portion of contaminated soil comprises low permeable clayey/silty material and ex-situ treatment will allow to manage the permeability (e.g. with addition of bulking material improving the permeability); treated soil should meet DIV to enable its backfilling;
3. in case that the future land use might be affected by residual contamination of the lower layers of the unsaturated zone, in situ techniques are further considered – bioremediation and ZVI treatment (nanoparticles).

Conservative approach has been adopted for the screening of remedial methods for the **groundwater contaminated** with CHC (and HCH) reflecting the remedial objectives that have been set up on the risk based approach. Just several options passed through screening to further assessment. The main arguments for selection of methods for CHC and HCH contaminated groundwater clean-up are:

- There is no need to remove groundwater contamination completely – the target limits are proposed for the water in contamination plume "leaving" the site and thus just partial removal of COC mass may be sufficient;

- o Respecting the main contaminant's properties (CHC) remediation/clean-up of the contamination source would reduce upward emanation of CHC vapors from the saturated zone into the unsaturated one;

- o Methods (e.g. PRB, ISCR, bioremediation) – although frequently considered as innovative – are already proven as efficient and effective. These methods may be alternatively used for clean-up of contamination sources as well as for control of the contaminants migration.

- o No action and/or monitoring of the natural attenuation are not acceptable due to the apparent low potential of natural attenuation and already impacted domestic wells.
- o It can be hardly expected that the relevant Macedonian authorities will have sufficient funds available for the overall site restoration in the near future at one time thus it may therefore be appropriate to plan the implementation of remediation in increments and clean-up of contaminated groundwater can stand alone as such increment.

These methods were brought forward to detail assessment:

1. Pump and treat – although it is becoming increasingly apparent that pump-and-treat technology requires considerable operational cost over a long time, although this method may not actually clean up the source of the contamination, and although its efficiency drops down with time this method is further considered because of the argument mentioned in bullet 1 above as well as due to easy implementability which is not affected by existing buildings/structures;

2. In situ ISCR treatment – both the modifications – granular ZVI and ZVI nanoparticles due to easy implementability, proven high efficacy and very low operational cost when designed as passive treatment system (just monitoring);

3. In situ bioremediation – easy implementability, proven efficacy, very low operational cost when designed as passive treatment system (just monitoring);

4. Control – i.e. passive treatment system controlling the COC concentration in the contamination plume "leaving" the site.

The results of remedial methods screening are summarized in the Table 5.4 further.

Table 5.4 – Results of remedial methods screening

General Response Action	Remedial Technology	Process Option	Comments
No action	None	None	Not brought forward to further consideration due to threatened groundwater sources.
Monitoring	Monitoring	Monitoring	Not brought forward to further consideration due to threatened groundwater sources.
		Monitoring of natural atenuation	Applicable only for contaminated soil vapors.
Containment	Hydraulic barriers - cutoff walls	Slurry walls	Not brought forward to further consideration due to large extension of the contamination plumes, clashes with underground utilities, data gapson contamination and properties of deepre parts of the aquifer, contaminants flux might be diverted to the deepr
		Cement walls	
		Sheet piling	
	Capping	Synthetic liners	Not brought forward to further consideration due to very limited efficiency.
		Native liners	
		Evapotranspirative capping	
Removal	Pump and treat	Air stripping	Brought forward to further consideration due to easy implementability..
		Adsorbtion	
		Filtering	
		Gravity separation	
	In situ chemical oxidation (ISCO)	Treatment with potassium or sodium permanaganate	Not brought forward to further consideration due to unfavorable geological conditions, necessity to manipulate with large amounts of strong oxidants, or expensive production of oxidants (ozone), ineffectivity of permanganates to destroy chlorinated alkane
		Treatment with hydrogen peroxide	
		Treatment with ozone	
	Air sparging	Air sparging	Not brought forward due to unfavorable geological conditions.
		Air sparging + soil vapor extraction (SVE)	
	Bioremediation	Bioventing	Not brought forward to further consideration due to unfavorable geological conditions as well as for long duration.
		Biological reductive dehalogenation	Brought forward due to easy implementability and relaively low cost.
	ZVI treatment	ZVI treatment	Brought forward to further consideration due to easy implementability and proven high effectivity...
		ZVI treatment - Fe nanoparticles	
Control	Permeable reactive barriers (PRB)	Continuos PRB	Brought forward to further consideration due to easy implementability, proven effectivity, low operational cost.
		Funnel and gate	
		Reactive zones	
	Hydraulic barriers	Active hydraulic barrier	Not brought forward to further consideration due to long duration.

5.3 Assembly of Alternatives for Corrective Measures

In this chapter, the remedial technologies that were brought forward through the screening evaluation in previous chapters are combined to create several site-wide remedial alternatives for the remediation and/or control of CHC and HCH contaminated groundwater and TCE (CHC) contaminated unsaturated zone at the OHIS site.

The development of the remedial alternatives was guided by the need for alternatives that will achieve the objectives of the remedial action and provide a range of remedial actions. Several remedial alternatives were developed using this approach. These alternatives intentionally differ in several respects, including:

- Remedial objectives they achieve and the degree to which they achieve them;
- Their reliance on contamination source treatment/removal, contamination plume control;
- Estimated cost.

These alternatives are consistent with the scope of work for this FS.

Alternatives for clean-up of TCE (CHC) contaminated soil

Reflecting the risk posed by TCE (CHC) contaminated soil vapors and available methods screening these alternatives were assembled for detail assessment:

1. Alternative S1 Monitoring of attenuation – this alternative comprises just regular long term monitoring of soil vapors contamination.

2. Alternative S2 Excavation and ex-situ treatment – this alternative comprises of excavation of uppermost (the most contaminated) part of soil profile (to the depth 3 m b.g.l., subsequent on-site treatment, and backfilling the treated soil.

3. Alternative S3 In situ clean-up – this alternative comprises in situ treatment of the lower part of contaminated soil profile by bioremediation and/or ISCR.

Major components of each of proposed remedial/control alternatives for soil vapor clean-up are summarized in Table 5.5.

Table 5.5 – Major components of alternatives for TCE (CHC) contaminated soil

Remedial Action	Remedial Technology	Process Option	Alternative S1	Alternative S2	Alternative S3
Clean-up of contaminated soil vapor	None	None	-	-	-
	Monitoring	Monitoring of clean-up	-	X	X
		Monitoring of attenuation	X	-	-
	Excavation and ex-situ treatment	Ex-situ bioremediation	-	X	-
		Ex-situ chemical treatment	-	X	-
		Ex-situ venting	-	X	-
	In situ teatment	In situ bioremediation	-	-	X
		In situ chemical treatment	-	-	X

Alternatives for clean-up/control of CHC/HCH contaminated groundwater

1. Alternative GW1 Pump and treat – to remove CHC contamination source zone in aquifer or reduce the mass of CHC in this contamination source zone by conventional method of pumping off the contaminated water and its ex-situ treatment (stripping) is proposed for detail evaluation.
2. Alternative GW2 ISCR – this alternative relies on in-situ manipulation of redox potential by injection of ZVI;
3. Alternative GW3 Bioremediation in situ – comprises in situ biodegradation of COC comprising creation of suitable conditions in the contamination source zone to enhance the reductive CHC/HCH degradation.
4. Alternative GW4 Contamination plume control – comprises installation of either continuous PRB or reactive zone with proper filling in order to control the COC concentration in groundwater "leaving' the site.

Major components of each of proposed remedial/control alternatives for groundwater clean-up are summarized in Table 5.6.

Table 5.6 - Major components of alternatives for groundwater clean-up

Remedial Action	Remedial Technology	Process Option	Alternative GW1	Alternative GW2	Alternative GW3	Alternative GW4
Clean-up of contaminated groundwater	None	None	-	-	-	-
	Monitoring	Monitoring of clean-up	X	X	X	X
		Monitoring of attenuation	NA	NA	NA	NA
	Removal	Pump and treat + stripping	X	-	-	-
		In situ chemical treatment	-	X	-	-
		In situ bioremediation	-	-	X	-
	Contamination plume control	PRB	-	-	-	X
		Funnel and gate	-	-	-	X
		Reactive barrier	-	-	-	X

5.3.1 Description of Alternatives Proposed

5.3.1.1 Description of Alternatives for TCE (CHC) Contaminated Soil Clean-up

Apparently, further partial modifications appear (see process options Table 5.5, page 28) for the alternatives brought forward to detail assessment. Detail description of the alternatives proposed as well as description of their possible modifications is provided further.

Alternative S1 Monitoring of attenuation

This is a simple alternative having no modification; it relies on long term regular monitoring of natural attenuation processes in order to monitor the fate of COC and update the risks posed human health and environment by existence of contamination.

The major components of this alternative are:

- Installation of properly spaced monitoring system – consisting of shallow and small diameter borings to the depth about 3 m b.g.l. cased with perforated casing and sealed against penetration of ambient air.
- Regular monitoring – 2 soil vapor monitoring campaigns per year, i.e. collection of soil gas samples using sampling pump and charcoal adsorption tubes (e.g. SKC) and laboratory analyzes of the soil gas samples;
- Evaluation and reporting.

Alternative S2 Excavation and ex-situ treatment

This alternative relies on partial removal of contaminated soil and its ex-situ treatment to address the remedial objectives. The major components of Alternative S2 are:

- o Excavation and transport of contaminated soil – the uppermost part of contaminated soil profile (to the depth 3 m b.g.l.) will be excavated and transported just within the site to the place designed for its ex-situ treatment (e.g. an abandoned warehouse);

- Ex situ treatment – for the ex-situ treatment several viable options exist:
    - Ex-situ bioremediation (further marked as Alternative S2.1 Ex-situ bioremediation) involving the maintenance of anaerobic conditions and supply of hydrogen in the treated soil via application of suitable substrate and, if necessary, application of a bacterial strain capable biodegrade the CHC,
    - Ex-situ chemical treatment (further marked as Alternative S2.2 Ex-situ chemical treatment) involving the redox manipulation in order to enhance reductive dechloration,
    - Ex-situ venting (further marked as Alternative S2.3 Ex-situ venting) consisting of piling the soil in an on-site abandoned warehouse, installation of ventilation system for extraction of soil vapors and treatment system for off gas clean-up,
- Process monitoring;
- Backfilling the treated soil;
- Evaluation and reporting.

Alternative S3 In situ clean-up

This alternative comprises in situ treatment of the lower part of contaminated soil profile to address the remedial objectives. The major components of this alternative are:

- In-situ bioremediation (further marked as Alternative S3.1 In-situ bioremediation) addressing the remedial objectives in deeper horizon of contaminated soil (approx. 3 – 8 m b.g.l.) by creation of anaerobic conditions and supply of hydrogen in the treated soil via application of suitable substrate and, if necessary, application of CHC degrading bacteria;
- In situ chemical treatment (further marked as Alternative S3.2 ISCR) relying on reductive dechloration, i.e. manipulation of redox conditions in order to improve reductive dechloration;
- Process monitoring;
- Evaluation and reporting.

5.3.1.2 Description of Alternatives for Groundwater Clean-up

Similarly to the alternatives for soil vapors clean-up, further partial modifications appear (see process options Table 5.6, page 29) for the alternatives brought forward to detail assessment. Detail description of the alternatives proposed as well as description of their possible modifications is provided further.

Alternative GW1 – Pump and treat

This alternative relies on CHC contamination source removal/reduction to address the remedial objectives. Major components of Alternative GW1 are:

- Site preparation – identification of the underground facilities, mobilization of staff and equipment;
- Pilot Test – on site test in order to obtain missing data for final design;
- Installation of wells - installation of properly spaced abstraction wells for pump off the contaminated groundwater and installation of complementary monitoring wells, installation of infiltration system for re-infiltration of cleaned water;
- Installation of technology for ex-situ groundwater treatment – installation of pumps, piping, stripper, off gas treatment (activated carbon filters);
- Long term clean-up;
- Process monitoring;
- Evaluation and reporting.

Alternative GW2 – In situ chemical treatment

This alternative relies on CHC contamination source removal and/or reduction of contaminants mass by chemical treatment (redox manipulation) to address the remedial objectives. Apparently, three viable modifications exist. Major components of Alternative GW2 are:

- Site preparation – identification of the underground facilities, mobilization of equipment, staff and reagents;
- Pilot Test – on site test in order to obtain missing data for final design;
- Wells installation – two viable options exist for the reagent and their introduction into the contamination source zone:
  - Wells installation – installation of properly spaced wells for introduction of reagents (further marked as Alternative GW2.1 Granulated ZVI) into the contamination source zone, and installation of monitoring wells, installation of complementary monitoring wells;
  - Injection of ZVI – application of ZVI into the contamination source zone by direct push technology (further marked as Alternative GW2.2 ZVI nanoparticles);
- Process monitoring;
- Evaluation and reporting.

Alternative GW3 Bioremediation in situ

This alternative comprises in situ biodegradation of COC comprising creation of suitable conditions in the contamination source zone to enhance the anaerobic CHC/HCH degrading bacteria and, if necessary, injection of CHC degrading bacteria. Major components of Alternative GW3 are:

- Site preparation – identification of the underground facilities, mobilization of equipment, staff and reagents;
- Pilot Test – on site test in order to obtain missing data for final design;
- Wells installation – installation of properly spaced wells for introduction of reagents and bacteria into the contamination source zone, and installation of monitoring wells, installation of complementary monitoring wells;
- Technology installation;
- Injection of reagents and bacteria;
- Process monitoring;
- Evaluation and reporting.

Alternative GW4 Contamination plume control

This alternative addresses the remedial objectives by installation of a passive treatment "objects" in order to reduce the concentration of COC in contaminated groundwater plume "leaving" the site to the level meeting target limits proposed. Major components of Alternative GW4 are:

- Site preparation – identification of the underground facilities, mobilization of equipment, staff and reagents;
- Pilot Test – on site test in order to obtain missing data for final design;
- Passive treatment system installation – apparently three applicable technologies appear:
  - installation of PRB across the contamination plume – comprising excavation of trench into the depth of 12 m b.g.l., filling with granulated ZVI to the depth 1 m above the groundwater Table (this alternative further marked as Alternative GW4.1 ZVI permeable reactive barrier), backfilling the trench;
  - installation of funnel and gate system – installation of impermeable walls diverting the groundwater flow to a "funnel" where a chamber containing proper filling (ZVI) for passive treatment of contaminated groundwater is installed (Alternative GW4 Funnel and gate);
  - installation of reactive zone – consisting of properly spaced wells serving for introduction of reagents (EHC® reactant comprising micro particles of ZVI + organic carbon source into the contamination plume (further marked as Alternative GW4.3 Reactive zone);
- Process monitoring;
- Evaluation and reporting.

Selection of Feasible Alternatives

Apparently, further selection of alternatives to be brought forward to the detailed comparative analysis can be done without deeper insight into the specific features of the particular alternatives proposed and without extensive analysis.

Regarding the alternatives assembled for soil vapors clean-up – all the three alternatives are brought forward to the comparative analysis.

Regarding the groundwater clean-up, with respect to the remedial objectives set up on the risk based approach and considering the site specific conditions some alternatives may be disqualified from comparative analysis. The main aspects considered for corrective measures selection are:

Alternative GW 1 Pump and treat– although some reservations exist (see chapter 5.2.4, page 24), this method is brought forward due its easy implementability.

Alternative GW2.1 Granulated ZVI – brought forward due to its potential to be applied as passive treatment system.

Alternative GW2.2 ZVI nanoparticles – brought forward to its relatively easy implementation although repetitive application is expected.

Alternative GW3 Bioremediation in situ – brought forward due to relatively easy implementation and low cost although long lasting clean-up might be expected.

Alternative GW4.1 ZVI permeable reactive barrier – brought forward, passive treatment system with low operational cost (monitoring only) although relatively high installation cost are expected.

Alternative GW4.2 Funnel and gate – disqualified from further evaluation due to lack of data on contamination and properties of the entire aquifer – impermeable walls may divert the contaminants into the deeper levels of aquifer.

Alternative GW4.3 Reactive zone – brought forward due to its relatively low installation cost and easy implementability.

5.3.2 Detail Comparative Analysis of proposed Alternatives

Within the process of screening and selection of applicable clean-up methods 5 alternatives for soil gas clean-up and 6 alternatives for groundwater clean-up were brought forward to comparative analysis.

The criteria used for evaluation of selected alternatives are technical, institutional, and economic considerations that decision-makers will take into account in selecting the remedial actions. The following criteria were used to evaluate each remedial alternative:

- Protection of Human Health and the Environment;
- Short-term Efficiency;
- Long-term Efficiency;
- Implementability;
- Compliance with current environmental regulations;
- Cost.

Each of these evaluation criteria is described below.

Protection of the human health and the environment

This evaluation criterion provides a final check to assess whether each alternative provides adequate protection of human health and the environment.

Short term effectivity

This evaluation criterion addresses the effects of the alternative during the construction and implementation phase until remedial response objectives are met. Under this criterion, alternatives are evaluated with respect to their effects on human health and the environment during implementation of the remedial action addressing following factors:

- Protection of community during remedial actions;
- Protection of workers during remedial actions;
- Environmental impacts that may result from the construction and implementation of a remedial alternative;
- Times until remedial action objectives are achieved.

Long term effectivity and permanence

The evaluation of alternatives under this criterion addresses the reset of a remedial action in terms of this risk remaining at the site after response objectives have been met. Long-term Efficiency will be evaluated according to (1) magnitude of residual risk remaining at the site after implementation of the remedial alternative and (2) the adequacy and reliability of remedial controls. The long-term reliability of the remedial actions is judged according to the need for replacing components of the remedy and consequences of the failure of those components.

Implementability

The implementability criterion encompasses the technical and administrative feasibility of implementation and the availability of required services and materials taking into account following factors:

- Ability to construct and operate the technology;
- Reliability of the technology;
- Ease of performing additional remedial work if necessary;
- Ability to monitor Efficiency of remedy;
- Ability to obtain approvals from authorities;
- Coordination with authorities;
- Availability of offsite treatment, storage, and disposal services and capacity;
- Availability of necessary equipment and specialists;
- Availability of prospective technologies.

An important aspect of implementability is the availability of equipment and services (i.e. equipment and services available in MK). For the FS assumption is that all workers would be trained in the specific health and safety procedures required by the Macedonian regulatory authorities.

Socioeconomic effects

The socioeconomic effects will be evaluated according to the economic effect of the land use after completion of each alternative.

Compliance with current environmental regulations

The assessment against this criterion describes how the alternative complies with the current Macedonian environmental legislation or if a waiver is required and how it is justified.

Cost

The cost for the corrective measures is made up of capital cost, operating and maintenance cost.

The capital cost consist of direct (construction) and indirect (non-construction and overhead) costs. Direct costs include expenditures for the equipment, labor and materials necessary to install remedial facility. Indirect costs include expenditures for engineering, financial and other services that are not part of actual installation activities but are required to complete the installation of remedial alternatives.

Operating and maintenance costs are post-construction costs necessary to ensure the continued efficiency of a remedial action.

Capital cost and operating and maintenance cost estimates for each of the remedial alternatives were prepared using information from Macedonian construction experience, estimates of remedial contractors and our practical experience with similar projects.

The cost estimates were prepared as the part of the overall evaluation of corrective alternatives. The estimates were based on information available at the time of the FS and on contraction assumptions that are reasonable for the state of the practice in Macedonia. The availability and cost of remedial services is expected to change, so these cost estimates should be refined in further stages of design or as new information becomes available.

Final project costs will strongly depend on actual labor and material costs, the capabilities of local contractors, the amount of imported equipment and labor, actual site conditions, productivity, actual health and safety requirements, competitive market conditions, final project scope, final project schedule, the firm selected for final engineering design and other factors.

The cost estimates in this FS are considered order of magnitude with an expected accuracy of plus 50% to minus 30%. The cost-estimate is an unavoidable consequence of the conceptual stage of this remedial project. The range does not account for changes in the scope of the alternatives.

These options/alternatives for TCE (CHC) contaminated soil clean-up were further analyzed in detail:

Alternative S1 Monitoring of attenuation – 30 monitoring points installation, 2 monitoring campaigns per year, laboratory analyzes (TCE, PCE, VC), five years monitoring, evaluation and reporting.

Alternative S2.1 Ex-situ bioremediation – laboratory bench tests, excavation and on-site transport of 9,000 m^3 of contaminated soil, ex-situ treatment by addition of organic carbon source and, if necessary, application of CHC degrading bacteria, monitoring, backfilling. This alternative is planned to be implemented after demolition of buildings and removal of pavements (not included and budgeted in this alternative).

Alternative S2.2 Ex-situ chemical treatment – laboratory test, excavation and on-site transport of 9,000 m^3 of contaminated soil, ex-situ treatment by addition of DARAMEND® technology combining the reductive dechloration and biodegradation by addition of amendment comprising ZVI and organic carbon source, 6 months of treatment, monitoring, backfilling, evaluation and reporting. This alternative is planned to be implemented after demolition of buildings and removal of pavements (not included and budgeted in this alternative).

Alternative S3.1 In situ bioremediation – laboratory bench test, repetitive direct push injection of organic carbon source, and CHC degrading bacteria (3 times, in quarterly intervals), monitoring, evaluation and monitoring. This method is assumed only in a case that the upper contaminated soil layer will be excavated and treated ex-situ, thus the depths of injections will be reduced to 5 m below the bottom of excavation (i.e. 8 m b.g.l.) This alternative is planned to be implemented after demolition of buildings and removal of pavements (not included and budgeted in this alternative) only in case that further land use might be disabled by existence of TCE (CHC) contaminated deeper soil horizon (3 – 8 m b.g.l.).

Alternative S3.2 ISCR – laboratory bench test, 1 direct push injection of EHC® preparation (patented technology of company Adventus, USA, combining the reductive dechloration and biodegradation by addition of amendment comprising ZVI and organic carbon source designed for in situ application). This alternative is planned to be implemented after demolition of buildings and removal of pavements (not included and budgeted in this alternative) only in case that further land use might be disabled by existence of TCE (CHC) contaminated deeper soil horizon (3 – 8 m b.g.l.).

The results of comparative analysis of alternatives for TCE (CHC) contaminated soil clean-up are summarized in Table 5.7.

Table 5.7 – Results of comparative analysis – alternatives for TCE (CHC) contaminated soil clean-up

Criteria	Alternative S.1	Alternative S 2.1	Alternative S 2.2	Alternative S3.1	Alternative S3.2
Protection of human health and the environment	Generally no protection of human health, just awareness of risk.	Ex-situ biodegradation will reduce/minimize further release of COC	Ex-situ chemical treatment will reduce/minimize further release of COC	In-situ biodegradation will reduce/minimize further release of COC	In-situ chemical treatment will reduce/minimize further release of COC
Short term effectivity					
- community protection	Acceptable - the fate of the contamination will be monitored and thus timely data will be available for case of need of clean-up; sufficient from the point of view of awarenes of the risk posed.	Quite large volume of contaminated soil will be uncovered during excavation and transportation. Temporary increase off-site emissions of vapors create negligible risk to the community.	Quite large volume of contaminated soil will be uncovered during excavation and transportation. Temporary increase off-site emissions of vapors create negligible risk to the community.	Quite large volume of contaminated soil will be uncovered during excavation and transportation. Temporary increase off-site emissions of vapors create negligible risk to the community.	Quite large volume of contaminated soil will be uncovered during excavation and transportation. Temporary increase off-site emissions of vapors create negligible risk to the community.
- worker protection	Air quality monitoring, use of proper PPE in case of need.	Air quality monitoring, use of proper PPE in case of need.	Air quality monitoring, use of proper PPE in case of need.	Air quality monitoring, use of proper PPE in case of need.	Air quality monitoring, use of proper PPE in case of need.
Short term effectivity					
- environmental protection	Negative impacts are not expected, no risk posed to the environment posed by TCE identified in RA.	Negative impacts are not expected if good installation and opearation practise adopted.	Negative impacts are not expected if good installation and opearation practise adopted.	Negative impacts are not expected if good installation and opearation practise adopted.	Negative impacts are not expected if good installation and opearation practise adopted.
- time requested for measures completion	Construction of monitoring system will require approx. 5 days.	1 year	6 months	9 months	6 months
	Another 5 years of regular monitoring	Another 6 months of designing and approval phase. In total about 18 months.	Another 6 months of designing and approval phase. In total about 12 months.	Another 6 months of designing and approval phase. In total about 15 months.	Another 6 months of designing and approval phase. In total about 12 months.
Long term effectivity					
- soil gas contamination	Risk not eliminated but controlled	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level
- adequacy and reliability of controls	Adequate method when the intended future land use will not be disabled.	Adequate method, proven in practise, a little bitt longer duration of clean-up.	Adequate method, proven in practise, fast and effective.	Adequate method, proven in practise, a little bitt longer duration of clean-up.	Adequate method, proven in practise, fast and effective.

Table 5.7 – cont.

Criteria	Alternative S.1	Alternative S 2.1	Alternative S 2.2	Alternative S3.1	Alternative S3.2
Socioeconomics effects					
- socioeconomics effects	Not applicable when disabling future land use, generally negligible socioeconomics effects.	Ex-situ biodegradation will reduce/minimize the contamination to acceptable level allowing future industrial use of the land.	Ex-situ chemical treatment will reduce/minimize the contamination to acceptable level allowing future industrial use of the land.	In-situ biodegradation will reduce/minimize the contamination to acceptable level allowing future industrial use of the land.	In-situ chemical treatment will reduce/minimize the contamination to acceptable level allowing future industrial use of the land.
Implementability					
- ability to construct and operate	Simple for construction and for operation,	Simple for construction, excavations stability may be an issue but technically feasible.	Simple for construction, excavations stability may be an issue but technically feasible.	Simple for construction.	Simple for construction.
- ease and performing more actions if needed	Simple to extend.	Simple to extend.	Simple to extend.	Simple to extend.	Simple to extend.
- ability to monitor the effectivity	Easy	Easy	Easy	Easy	Easy
- ability to obtain approvals and coordinate from/with authorities	No problems expected.	No problems expected.	No problems expected.	No problems expected.	No problems expected.
- availabilty of equipment and materials	Equipment and material available	Available.	Equipment available, reactants to be imported.	Available.	Equipment available, reactants to be imported.
- availabilty of technology	Available	Available	Reactant patented	Available	Reactant patented
Compliance with current regulations					
	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations
Cost estimated					
- construction cost (EUR)	2 500	60 000	2 500	15 000	10 000
- operational cost (EUR)	-	190 000	230 000	330 000	335 000
- 5 years post monitoring (EUR)	55 000	-	-	55 000	55 000

For the contaminated groundwater clean-up these alternatives were further assessed:

Alternative GW1 Pump and treat – with stripping – installation of 10 abstraction wells (12 m b.g.l., installation of 5 complementary monitoring wells, installation of infiltration object for infiltration of cleaned water, aeration unit, stripper, activated carbon filter, 5 years of operation, process monitoring, 5 years of post remedial monitoring, evaluation and reporting.

Alternative GW2.1 Granulated ZVI – drilling of 100 boreholes of diameter 500 mm to the depth 12 m b.g.l., installation of 5 complementary monitoring wells, introduction of 320 m^3 of granular ZVI, 5 years post-monitoring, evaluation and reporting.

Alternative GW2.2 ZVI nanoparticles – installation of 5 complementary monitoring wells, 50 injections points, injection of 90 kg of ZVI nanoparticles, injection of ZVI repeated after 1 year, 5 years post-monitoring, evaluation and reporting.

Alternative GW3 Bioremediation in situ – installation of 20 injection wells (diameter 120 mm, depth 12 m b.g.l.), repetitive injection of 6,000 m^3 organic carbon source (whey), 5 years post-monitoring, evaluation and reporting.

Alternative GW4.1 ZVI PRB – conventional excavation and forepoling of 250 m long trench to the depth of 12 m b.g.l., and installation of 1,000 m^3 of granulated ZVI PRB, backfilling, disposal of the excavated contaminated soil (on site), 5 years post-monitoring, evaluation and reporting.

Alternative GW4.3 Reactive zone – installation of 5 complementary monitoring wells, 50 injection points for direct push injection of 9,000 kg of EHC® (patented reactant of Adventus company, USA, comprising micro particles of ZVI + organic carbon source), 5 years of post-monitoring.

The results of comparative analysis of alternatives for groundwater clean-up are summarized in Table 5.8.

Comparative analysis of the remedial alternatives is intended to identify differences among alternatives and highlight the discriminating features listed in Tables 5.7 and 5.8. The comparative analysis discusses tradeoffs among remedial alternatives.

Protection of the human health and the environment

All of the remedial alternatives are considered protective of human health and the environment. The differences are in the techniques used. All the alternatives can reduce the COC migration out of OHIS limits to an acceptable level.

Short term effectivity

The effects on the community during the installations are related to the risks caused by excavation of contaminated soil and/or recovery of contaminated drilling core (Alternatives S2.1, S2.2, GW1, GW2.1, GW3, GW4.1), to the amount of truck traffic required to haul the generated waste (contaminated soil) for disposal of. These effects can be effectively reduced by preventive measures. Nevertheless, Alternatives S3.1, S3.2, GW2.2 and GW4.3 would generate significantly lower potential exposure and nuisances (noise, odor) than remaining alternatives.

With regards to workers protection, all alternatives consider protection of workers performing remedial activities. In case of Alternatives S 2.1, S 2.2, GW 2.1, and GW 4.1 continuous monitoring would be required to maintain the adequacy of the protective measures.

The differences in the environmental effects are similar to the issues raised regarding community protection. That is, environmental effects would be related to releases generated during excavation of contaminated soil and to transport of contaminated soil.

Table 5.8 - Results of comparative analysis – alternatives for groundwater clean-up

Criteria	Alternative GW 1	Alternative GW 2.1	Alternative GW 2.2	Alternative GW 3	Alternative GW 4.1	Alternative GW 4.3
Protection of human health and the environment	Pump and treat with stripper will reduce COC's mass in source zone.	Application of granular ZVI filling will reduce COC's mass in source zone.	Injection of ZVI nanoparticles will reduce COC's mass in source zone.	Application of in situ bioremediation will reduce COC's mass in source zone.	PRB with ZVI will reduce the concentration of COC in groundwater leaving the site to acceptable level.	Reactive zone with EHC® reduce the concentration of COC in groundwater leaving the site to acceptable level.
Short term effectivity						
- community protection	Off gas has to be treated and the waste has to be properly liguidated/disposed of	Small volume of contaminated soil will be uncovered during drilling and transportation. Temporary increase off-site emissions of vapors create negligible risk to the community. Need of proper disposal of approx. 320 m^3 contaminated soil.	No risk to the community.	No risk to the community.	About 2,000 m^3 of contaminated soil has to be properly disposed of. Temporary increase off site emmissions of vapors create negligible risk for the community.	No risk to the community
- worker protection	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.	Air quality monitoring will be necessary on the work site in order to manage the use of proper PPE.
Short term effectivity						
- environmental protection	Negative impacts are not expected if good construction and operational practise adopted.	Negative impacts are not expected if good construction and operational practise adopted.	Negative impacts are not expected if good construction and operational practise adopted.	Negative impacts are not expected if good construction and operational practise adopted.	Negative impacts are not expected if good construction and operational practise adopted.	Negative impacts are not expected if good construction and operational practise adopted.
- time requested for measures completion	5 years Another 6 months of designing and approval phase. In total about 5.5 years.	3 months. Another 6 months of designing and approval phase. In total about 9 months.	1 to 1.5 years Another 6 months of designing and approval phase. In total about 2 years.	2 - 4 years Another 6 months of designing and approval phase. In total about 2.5 - 4.5 years.	Three months. Another 6 months of designing and approval phase. In total about 9 months.	1 year Another 6 months of designing and approval phase. In total about 1.5 year.

Table 5.8 – cont.

Criteria	Alternative GW 1	Alternative GW 2.1	Alternative GW 2.2	Alternative GW 3	Alternative GW 4.1	Alternative GW 4.3
Long term effectivity						
- groundwater contamination	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level	Risks eliminated or reduced to acceptable level
- adequacy and reliability of controls	Adequate method, proven in practise, decrease of effectivity with time.	Adequate method, proven in practise, longevity can be managed by the volume of filling , the filling may need periodical replacement.	Adequate method, proven in practise, longevity can be managed by the volume of ZVI injected (injection may be repeated after 1 year).	Adequate method, proven in practise for CHC.	Adequate method, proven in practise, longevity can be managed by the volume of filling (thickness of the the PRB) and may reach even decades.	Adequate method, proven in practise, longevity can be managed by the volume of filling (thickness of the the PRB), the filling may need periodical replacement.
Socioeconomics effects						
- socioeconomics effects	Pump and treat can maintain the COC on acceptable level allowing further use of downgradient groundwater for irrigation.	ZVI source zone treatment will maintain the COC on acceptable level allowing further use of downgradient groundwater for irrigation.	ZVI nanoparticles source zone treatment will maintain the COC on acceptable level allowing further use of downgradient groundwater for irrigation.	In situ bioremediation of source zone will maintain the COC on acceptable level allowing further use of downgradient groundwater for irrigation.	PRB with ZVI filling will reduce the COC concentration in groundwater leaving the site to acceptable level allowing further use of downgradient groundwater for irrigation.	Reactive zone will reduce the COC concentration in groundwater leaving the site to acceptable level allowing further use of downgradient groundwater for irrigation.

Table 5.8 – cont.

Criteria	Alternative GW 1	Alternative GW 2.1	Alternative GW 2.2	Alternative GW 3	Alternative GW 4.1	Alternative GW 4.3
Implementability						
- ability to construct and operate	Relatively simple for construction although various pipelines and cables might complicate site accessibilty. Regualr maintenance needed,active approach requesting long term energy and various media supply.	Simple for construction. Except monitoring, no operational cost.	Simple for construction. Except monitoring, no operational cost.	Simple for construction. Repetitive reinjections of whey,	Simple for construction, excavations stability may be an issue but technically feasible.	Simple for construction. Except monitoring, no operational cost.
- ease and performing if more actions needed	Easy	Simple to extend.	Simple to extend.	Simple to extend.	Simple to extend.	Simple to extend.
- ability to monitor the effectivity	Easy	Easy	Easy	Easy	Easy	Easy
- ability to obtain approvals and coordinate from/with authorities	Groundwater managing authority has to issue a permit, no obstacles expected.	Groundwater managing authority has to issue a permit, no obstacles expected.	Groundwater managing authority has to issue a permit, no obstacles expected.	Groundwater managing authority has to issue a permit, no obstacles expected.	Groundwater managing authority has to issue a permit, no obstacles expected.	Groundwater managing authority has to issue a permit, no obstacles expected.
- availabilty of equipment and materials	Equipment and material available	Equipment and material available	Equipment available, material has to be imported.	Equipment and material available	Equipment and material available	Equipment available, material has to be imported.
- availabilty of technology	Available	Available	Available	Available	Patented	Patented reactants.
Compliance with current regulations						
	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations	Most likely would meet current regulations
Cost estimated						
- construction cost (EUR)	125 000	305 000	170 000	95 000	1 250 000	180 000
- operational cost (EUR)	500 000	0	0	205 000	0	0
- 5 years post monitoring (EUR)	25 000	25 000	25 000	25 000	25 000	25 000

All the technologies in selected alternatives are considered environmentally friendly. Products and by-products of in-situ treatment are stable and remain captured in the treatment zone beneath the surface.

There are no remarkable differences among alternatives in the time required for completing the installations.

Long term effectivity and permanence

For all remedial alternatives residual risks at the site were judged according to whether hazardous substances would remain or would be removed from the site, with or without treatment.

In case of alternative S1 the contamination will not be removed, due to risk posed in case of excavation of contaminated soil, this is conditionally acceptable variant, the fate of contamination will be monitored and thus relevant preventive measures can be adopted in case of risky scenario. In cases of alternatives S2.1 and S2.2 the most contaminated soil will be cleaned and COC destroyed. In alternatives S3.1 and S3.2 the contaminants will be destroyed in situ and further risks will be eliminated. Alternatives S2.1, S2.2 and S3.1 will reduce/eliminate potential migration of COC into aquifer and thus will accelerate groundwater remediation.

All the alternatives assessed for groundwater clean-up can reduce the contamination to acceptable level and thus eliminate the risk posed. All the technologies are effective and proven.

In case of alternative GW 1, the mass of COC in groundwater can be removed or, at least, significantly reduced and further COC migration can be reduced to acceptable level, this alternative requires long time operation (5 years). COC will be removed from groundwater and further disposal/liquidation of generated waste is necessary. Alternatives GW 2.1 and GW 2.2 can destroy COC in situ and reduce the mass of COC quickly (in order of months). However, repetition of injection of the reactant under Alternative GW 2.2 may be needed. Alternative GW3 can also reduce the mass of COC to acceptable level in-situ without by-products (waste) requiring disposal of/liquidation but duration of the remedial action can be estimated in order 2 – 4 years. Alternatives GW 4.1 and 4.3 destroy the contaminants in situ beneath the surface, when properly designed they may reach sufficient longevity without need to replace the active filling (5 years minimum).

Socioeconomic effects

All the alternatives will limit the future land use of the site to industrial one in such a case that the contamination source zones as well as contaminated media will not be completely cleaned-up. Nevertheless the site itself is located within the industrial zone and change of the land use in future is unlike.

Implementability

All the alternatives are technically easy to implement and would require mainly conventional construction procedures modified to meet health and safety rules. Alternatives S2.1, S2.2, GW2.1, and GW4.1 that involve large excavation are technically feasible but rather difficult to implement due to following factors:

- risks involved in excavation – clashes with underground facilities,
- stability issues – walls of the deep excavations must be protected against collapse;
- control of air emissions during excavation (dust and organic vapors);
- liquidation/treatment of hazardous waste generated by the excavations in contaminated soil.

Compliance with current environmental regulations

The conceptual remedial alternatives considered in this FS were developed to comply with the expected requirements of the pending Macedonian environmental regulations and requirements defined in EU regulations. As Macedonian environmental legislation is being developed, the final design of the remedial actions must be tailored to comply with the exact requirements of the regulations that will be in effect when remedial activities are implemented.

Cost

Among the alternatives for soil gas clean-up negligible cost would be required for implementation of alternative S1. Alternatives S2.1 and S2.2 considering ex-situ treatment of approximately 37 % of volume of contaminated soil would require low cost about 235,000 – 250,000 € (lower cost estimated for variant S2.2). Variants S3.1 and 3.1 are the most expensive – both the alternatives about 400,000 €.

Among the alternatives proposed for groundwater clean-up/contamination plume control significant cost differences have been found - the lowest cost were estimated for in situ treatment of contamination source zone by application of Alternative GW 2.2 – injection of ZVI nanoparticles – 195,000 €, low cost were also estimated for alternative GW 4.3 - installation of reactive zone with EHC® filling intended for contamination plume control – 205,000€. A bit higher cost were estimated for alternative GW 2.1 application of granular ZVI in contamination source zone and alternative GW 3 in situ bioremediation – each of them with cost about. Alternative GW 1 – pump and treat would cost about 650,000 €. Installation of PRB with granular ZVI filling has been identified as the most costly alternative – 1,275,000€.

6 Summary and Discussion of the Results

The comparison of the remedial alternatives revealed four areas of relatively clear distinctions:

- Short-term efficiency;
- Long term efficiency, and
- Estimated cost.

There are no significant differences between individual alternatives with regards to protection of human health and the environment.

With regards to the TCE (CHC) contaminated soil, the most feasible alternative is monitoring of natural attenuation – impacted area is currently abandoned, the contamination fate will be monitored and in case of any excavations in the impacted area proper preventive measures can be easily adopted (just proper PPE) with very low cost. However, this alternative will not prevent potential migration of contaminants into underlying aquifer. Considering efficient and sustainable groundwater remediation, ex-situ treatment of contaminated soil is preffered and is applicable with relatively low cost. Such active approach will allow future land redevelopment.

In case of groundwater clean-up technologies negative impacts on the environment are not expected. With regards to short-term efficiency, alternatives GW1, GW2.1 will generate small volume of waste to be disposed of/liquidated, alternative GW4.1 would require disposal of about 2,000 m^3 of contaminated soil. Alternatives GW2.1 and GW4.1 (considering installation in excavations) would generate significantly higher degree of potential exposure to hazardous substances and nuisances (noise, odor) than other alternatives. All the alternatives were judged as technically feasible. Alternatives involving excavations would be more difficult to implement mainly due to likely clashes with the underground facilities and stability issues relate to deep excavations (up to 12 m b.g.l.).

There are significant differences in time requested for corrective measures completion where the in-situ methods (based on ISCR) require significantly shorter period for completion (in order of months to first years) while ex-situ treatment requires operation in order of years (5 years).

The lowest cost were estimated for in situ treatment of contamination source zone by application of Alternative GW 2.2 – injection of ZVI nanoparticles – 195,000 €. Low cost were also estimated for alternative GW 4.3 - installation of reactive zone with EHC® filling intended for contamination plume control - 205,000€. A bit higher cost were estimated for alternative GW 2.1 application of granular ZVI in contamination source zone and alternative GW 3 in situ bioremediation – each of them with cost about 330,000 €. Alternative GW 1 – pump and treat would cost about 650,000 €. Installation of PRB with granular ZVI filling has been identified as the most costly alternative – 1,275,000€.

Regarding cost, the most feasible alternatives identified are those relying on in-situ chemical reduction - ZVI nanoparticles injection into contamination source zone and reactive barrier with EHC® filling intended for contamination plume control requiring the lowest cost (155,000 and 205,000 € respectively), quite low cost were also estimated for in-situ bioremediation (alternatives GW 2.1 and GW3, about 330,000 €). The highest cost were identified for ex-situ treatment and continuous PRB (alternatives GW1 and GW4.1 with estimated cost 650,000 € and 1,275,000 € respectively).

7 Conclusion and Recommendations

Based on the multicriterial comparative analysis, three areas of distinctions among the proposed alternatives were distinguished:

- Short-term efficiency;
- Long term efficiency, and
- Estimated cost.

With regards to TCE (CHC) contaminated soil, currently there is no urgent need for active remediation, i.e. monitored natural attenuation can be conditionally applied. However, this approach will not prevent potential migration of contaminants into underlying aquifer. Considering efficient groundwater remediation, ex-situ treatment of contaminated soil is preffered and is applicable with relatively low cost. Such active approach will allow future land redevelopment.

In sum, alternatives S2.1 or S2.2 are proposed for adoption. Both alternatives can be implemented only after demolition of on-site buildings and paved surfaces.

For CHC and HCH contaminated groundwater two alternatives were identified as the most feasible – i.e. alternatives relying on in situ chemical reduction applied in contamination source zone (alternative GW2.2 ZVI nanoparticles) or used for contamination plume control by reactive zone (alternative GW4.3 reactive zone utilizing patented reactant EHC®). These alternatives are recommended for further consideration mainly due to relatively short time needed for achieving remedial objectives, low exposure to hazardous substances during corrective measures implementation, and low cost in comparison to other alternatives. These alternatives are easily implementable within a short period that should not exceed 2 years (including the permitting).

8 Closing Remarks

It has to be noted that the FS was elaborated on the basis of data gathered during only a limited site investigation carried out within the frame of the project „Old Environmental Burdens in Chemical Plant OHIS, Skopje“. Data gaps still exists regarding exact delineation of contaminated soil and regarding the contamination of deeper levels of the aquifer. This feasibility focused on selection of feasible corrective measures addressing the risks identified in RA (Enacon, 2008) only – i.e. those potential risks that have not been identified due to lack of data are not addressed in this FS.

ANNEX 1

Site location map

ANNEX 2

Site layout map

ANNEX 3

Borings and monitoring wells location map

ANNEX 4

Groundwater CHC contamination plume

ANNEX 5

Laboratory analyzes