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EVOLUTION OF A GROUNDWATER CONTAMINATING PLUME ORIGINATING FROM TAR WASTE – CURRENT CONDITIONS AND REMEDIAL STRATEGIES

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Abstract: Hydrogeological numerical simulation was performed to evaluate the migration of a contaminant plume at a decommissioned tar manufacturing plant, situated in the floodplain of the Main River, Manitoba. The finite element computer software FEFLOW was used to simulate groundwater flow and contaminant transport. The current mass distribution of the contaminant plume is a result of the historical spills of chemical compounds during the manufacturing process or leaching from the fill materials situated below the former plant and on the riverbank. Based on the characterization and delineation of the impacted groundwater, further simulation was performed to assess the impact of several remedial strategies. Numerical case studies were conducted for each remedial strategy, from which conclusions were drawn regarding the most suitable scenario for the clean-up of the Site. Based on the modeling results, there are currently no chemical compounds at the Site which will result in a future exceedance of the compliance criteria at the Main River boundary if half of the waste fill is removed and backfilled with clean material, while the remaining impacted area is entirely covered at the surface with a low permeability material.

Keywords: numerical modeling, hydrogeology, hydrostratigraphy, groundwater, contaminants.

1. INTRODUCTION

The characterization of groundwater flow pattern and the evolution of contaminating plumes has always been a challenging task. An early approach to the investigation of leachate migration through porous media formerly involved expensive and labour intensive drilling for closely spaced point sampling (Granato & Smith, 1999). In order to minimize site characterization costs and to assess the most suitable remedial strategies, it is advantageous to investigate theoretical patterns of groundwater flow before any extensive field investigations programs. Based on this approach, less costly and environmentally benign investigation techniques were developed as aids for interpreting the groundwater flow and mass transport pattern; groundwater flow and mass transport are modeled based on spot sampling of groundwater levels and chemistry and overall knowledge of the hydrostratigraphy, hydrogeology and hydraulics in the investigated area (Fatta et al., 2000).

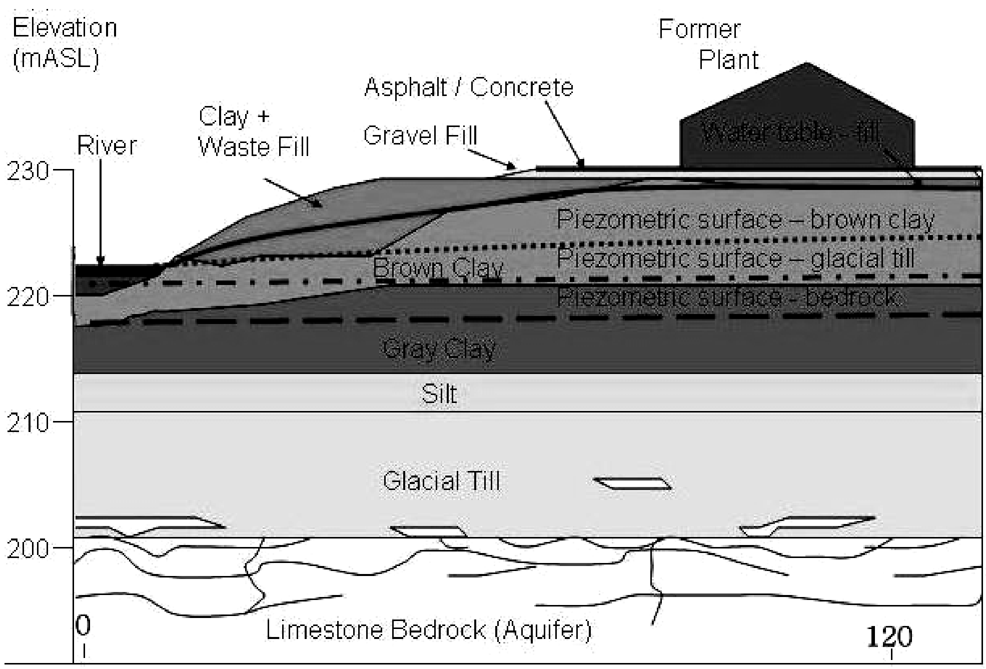

Figure 1. Geology and stratigraphy of the investigated area

The current study area occupies approximately 3.7 hectares of land in the floodplain of the Main River, Manitoba. A crude coal tar distillation facility, designed to manufacture roofing products, operated at the Site from 1919 until 1958, when the manufacturing process was converted to use asphalt flux instead of coal tar. The manufacturing activities at the Site were discontinued in 2004. Historically, the waste material included spilled coal tar, asphalt flux, diesel fuel and creosote; broken shingles and roofing paper were also disposed in the vicinity of the tar manufacturing plant. The water soluble tar components spilled into the local groundwater system, while the generated waste was used to consolidate and enlarge the riverbank. Soil sampling revealed concentrations in the soil of petroleum hydrocarbons and polynuclear aromatic hydrocarbon exceeding applicable guidelines (CCME, 2004).

Currently, the horizontal surface on the south-east side of the river (Figure 1) is covered with asphalt, in an attempt to reduce the meteoric infiltration while increasing the surface run-off. However, the current state of the asphalt cover, as a cracked surface, is quite permeable to water infiltration. According to the local piezometric surface, the groundwater flow occurs towards the Main River. Given these conditions, leaching of the chemical organic compounds into the groundwater occurs, followed by flow of the contaminated groundwater into the river. Additionally, releases of oil into the Main River were visually documented.

The first aim of the current study was to define the chemicals of concern at the Site which pose a threat to potential receptors in the area, principally the Main River, through groundwater flow and mass transport. The comprehensive frame of the natural processes at the Site responsible for groundwater flow, mass transport and natural attenuation of the chemicals of concern involved previous complementary studies such as: geological/hydrogeological investigations, statistical analysis of the groundwater chemistry data and field parameters characterization.

Based on the initial findings, special attention was given to the development of a conceptual model for the numerical modeling of the groundwater flow and mass transport of the chemical compounds of concern leached from the contaminated soil. In the first stage, the numerical models evaluated the current conditions at the Site. Consequently, simulations were performed for several remedial strategies, designed to achieve the regulatory groundwater compliance criteria (Ontario MOE, non-potable groundwater criteria in the Soil, Groundwater and Sediments, March 9, 2004) at the receptor, given transport and fate of the chemical compounds along the flow path. The obtained results were used to bring insight into the groundwater flow and mass transport and to evaluate the potential of the remedial strategies to act as a viable cleaning strategy at the investigation Site.

2. GEOLOGICAL SETTING AND HYDROSTRATIGRAPHIC UNITS

The local geology in the area of the study is generally represented by (from top to bottom): 1 to 7 meters of fill material, 20-30 m of glaciolacustrine deposits and the dolomitic limestone bedrock (Figure 1).

The fill material, consisting of excavated soils/clay, gravel, tar, shingles, and debris, was used in the past for paving, buildings foundation, fill for low-lying areas, or to stabilize riverbanks.

The glaciolacustrine deposits are formed by clay/silty clay and glacial till. The clay/silty clay sequence, extending to depths of 10 to 15 meters below ground surface, consists of (from top to bottom): brown (weathered) clay with a greater degree of fracturing, gray (unweathered) clay generally unfractured, with an increasing abundance of silt seams with depth and silt deposits at the base of the sequence. Below the glaciolacustrine silt lie 15 meters of glacial till, formed of compacted and poorly sorted silt to sandy silt, with trace gravel and cobbles. The till becomes increasingly gravelly and cobbly near the contact with the Ordovician-aged dolomitic limestone bedrock.

The fluvial sediments, consisting of 1 to 3 meters thick clay with natural organic material, accumulated on top of the glaciolacustrine clay.

The glaciolacustrine stratigraphy hosts three hydrostratigraphic units: the upper brown clay-fill complex, the glacial till-lower lacustrine silt complex and the bedrock.

The shallow groundwater flow system is contained within the fractured brown clay–fill and the silty, dark gray clay and alluvium deposits (Fig. 1). The top of the brown clay unit situated 5 to 10 meters lower beneath the Main River supports the groundwater flow directions towards the Main River, with groundwater partially infiltrating through the clay by vertical recharge into the lower lacustrine silt-glacial till formation and bedrock aquifer.

The shallow groundwater flow system is separated from deeper groundwater flow systems by the gray clay, which is an extremely low permeability unit, and is regarded as an aquitard. Consequently, the top of the confining layer within the local aquifer system coincides with the top of the gray (unweathered) clay unit.

3. MODELING CONCEPT

In order to evaluate the potential of several remedial strategies as a clean-up mechanism of the contaminated groundwater, the following questions were addressed:

a) What is the geologic, hydrostratigraphic and hydrogeological frame of the contaminant plume? Do the overall hydrogeological conditions at the Site enable the leachate to spread towards areas of environmental concern?

b) What is the history of the leachate as groundwater chemistry data at the Site and which are the contaminants of concern? Are the contaminants of concern naturally biodegradable?

c) Is it possible to rely on the proposed remedial strategies as a viable clean-up procedure at the Site?

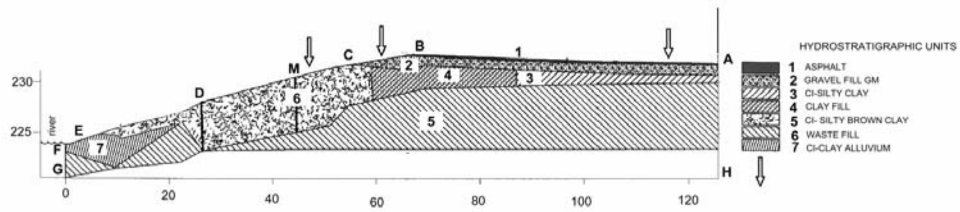

Figure 2. Conceptual stratigraphic model

A two-dimensional transient groundwater flow and mass transport model was developed, describing the current state, followed by various remedial strategies, according to different hydraulic conditions. The conceptual hydrostratigraphic model represents the basis for the construction of the numerical hydrogeological model (Fig. 2).

The model was run under unsaturated conditions. The unsaturated material was described by the Van Gentuchen - modified (α, n, m parameters) empirical law for capillary pressure and relative conductivity.

The initial fluid velocity throughout the model has been assumed to be equal to zero. At this stage of the study, focussing on finding the best remedial configuration which addresses the leachate spreading through the riverbank into the river, the chemistry of the plume and the natural degradation rates of the modeled compounds represented crucial parameters. Given the significant concentration of the contaminant mass, the hydrogeological simulation was run accounting for the density effect of the spreading plume.

The numerical simulation was performed for all the presented models in transient state, over a period of 10000 days. On average, steady state of groundwater flow has been achieved after approximately 700 days. Therefore, it can be concluded that the groundwater flow at the investigated Site currently occurs under steady state conditions.

The post-processing of simulated data was used as an evaluation tool for fluid flux, Darcy flow velocity, distribution of hydraulic head, mass and graphical output for fluid flow and mass transport.

3.1 Basic principles of the modeling code

The hydrodynamic fluid flow coupled with mass transport was simulated with the finite element subsurface flow and transport simulation software FEFLOW® (**F**inite **E**lement subsurface **FLOW** system), developed by WASY (WASY GmbH, 2005). FEFLOW is a 3D finite element code capable of performing numerical modeling of density-dependent fluid flow, mass and heat transport (Diersch, 1992, 1993).

The Post Conditioned Bi-Conjugate Gradient Stable Matrix Method (BICGSTABP) was used to solve the groundwater flow equation. The model accounted for variable fluid density, according to extended Bousinesq approximation.

The solution of the governing differential equations and boundary conditions is achieved using an implicit adaptive time stepping scheme (adaptive error controlled time steps), with variable time steps (Diersch, 2005). FEFLOW performs in discrete time steps, imposed by the stability criteria required during the numerical simulation. A number of 12-36 iterations per time step were used to obtain the convergence of the solutions, depending on each case.

Numerical stabilization is achieved with Petrov-Galerkin least-square upwinding (PGLS), an alternative numerical scheme used to solve advective dominant flow and transport (Nguyen & Reynen, 1984, Diersch, 2002). The PGLS is based on a Petrov-Galerkin weak formulation where a “modified” weighting function is derived from the least-squares finite element concept. The symmetric sparse flow equations systems are solved using a preconditioned conjugate gradient PCG solution (a conjugate gradient method using an optional preconditioning technique). The model simulates a transient evolution of the system until reaching steady state.

3.2 Mesh generation

The model domain limits were selected such that the location of the boundaries is consistent with the hydrogeological conditions. The model domain is 125 m long in the horizontal direction and 14 m deep, designed to include all the hydrostratigraphic units. The finite elements mesh used for the model domain accounts for elaborate representation of topography and stratigraphy in the conceptual model. Triangle, a specialized code for creating two-dimensional finite element meshes (Shewchuk, 1996, 2002) was used to build Delaunay triangulations during mesh generation. The mesh used the Divide and Conquer (Lee & Schachter, 1980) and Incremental (Lawson,

1977) algorithms. A minimum angle of 20 degrees was used for each triangle, aiming to obtain a more uniform structure of the mesh. The mesh generator supports the dimensions and structure of the model, allowing the realistic representation of the investigation area discretized into triangular elements. FEFLOW generates the triangular finite elements meshes based on prior so-called “superelements”, which represent the hydrostratigraphic frame. A mesh consisting of approximately 10000 elements was designed to provide good resolution for the investigation area. The obtained mesh was further discretized, to account for the numerical oscillations which could occur as a result of the increased hydraulic conductivity contrast between different hydrostratigraphic units.

3.3. Hydraulic parameters

Porosities and hydraulic conductivities have been assigned for various simulation strategies according to the remedial strategies and the types of fill used on the riverbank. The used porosities and hydraulic conductivities were constrained against the general frame of specific values mentioned in the literature (Domenico & Schwartz, 1990, Bear, 1972). Less permeable layers were assigned lower hydraulic conductivities of 10^{-6}m/s to 10^{-8} m/s, representing clays, while more porous layers were assigned higher conductivities of 10^{-5} m/s, typical of gravel aquifers. The units of the hydrostratigraphic conceptual model are as follows (where K denotes hydraulic conductivity and φ porosity): 1-new asphalt, $K=10^{-8}$m/s, φ=10%; 2- gravel fill, $K=1.65*10^{-5}$m/s, φ=30%; 3- silty clay (grey black clay), $K=1.9*10^{-7}$m/s, φ=25%; 4- clay fill, $K=1.2*10^{-6}$m/s, φ=25%; 5- CI-Silty clay (brown clay), $K=4.7*10^{-7}$m/s, φ=20%;6- waste fill, $K=1.5*10^{-4}$m/s, φ=30%;7- CI-Clay (alluvium), $K=1.8*10^{-7}$m/s, φ=20%; 8- backfilling of waste, $K=1.5*10^{-4}$m/s, φ=20%.

3.4. Boundary conditions

The hydraulic boundaries for the Shallow aquifer were assigned as follows (Figure 2): the upper limit of the model domain, AE, as exposed ground surface, was initially assigned a constant recharge rate from precipitation (535 mm/year, of which 125 mm falls as snow, KGS/Acres/UMA, 2004), adjusted with surface run-off and evapotranspiration according to the weather conditions and surface characteristics in the area, which leads to an incoming flux of 300 mm/year (Manitoba Energy and Mines, 1983); the river section EF was assigned a head-dependent flux condition, as groundwater discharge to stream, characteristic for a transfer boundary; the left side of the model, FG, being permeable to groundwater flow, was assigned a constant hydraulic head; the lower boundary of the model GH, within the gray silt clay, was assigned as impermeable to groundwater flow; the right boundary of the model domain AH, a surface water divide, was assigned as a no-flow section.

The initial contaminant mass conditions through the model were assigned based on the maximum concentrations in the groundwater, as a conservative approach for the current groundwater contamination. The mass boundaries were assigned as (Fig. 2): unspecified (impervious for total fluxes) for the side limits of the model domain, FG, AH and the lower limit GH; a predefined constant concentration for the upper limit AE, corresponding to the fluid flux boundary region. For modeling purpose, the predefined groundwater concentrations assigned for the upper limit AE (see Fig. 2) present linear variation (Tab. 1).

Table 1: Predefined constant concentrations for the upper limit AE

Chemical of concern	Compliance criteria (mg/l)	Mass boundaries (mg/l)		
		AB	BC	CE
Anthracene	0.000012	0.0004 to 0.013	0.013 to 0.015	0.015 to 0.00001
Benzene	0.370	10 to 2.2	2.2 to 2.65	2.65 to 0.005
Fluoranthene	0.00004	0.0002 to 0.024	0.024 to 0.0034	0.0034 to 0.0011
Naphthalene	0.0011	0.323 to 9.5	9.5 to 4.46	4.46 to 0.001

Where the contaminant waste has been removed as part of the remedial strategies, the input for mass boundary conditions of predefined concentration was regarded as fresh water, with a concentration of 0 mg/l.

The simulations were run accounting for the density effect of the spreading plume. The fluid density changes due to mass concentration throught the model were expressed by the fluid density difference ratio, termed as the density ratio α (WASY GmbH, 2005). The fluid density ρ^f at maximum concentration Cs (for each simulated compound) as derived from Baxter and Wallace, 1916:

$$\rho^f(C_s) \approx \rho_0^f + 0.7 \times C_s \qquad (1)$$

which leads to an estimation of density difference ratio α:

$$\alpha \approx \frac{0.7 \times C_s}{\rho_0^f} \qquad (2)$$

4. SELECTION OF CHEMICALS OF CONCERN

A crucial task for the effectiveness of the present study was the selection of contaminants of concern as Site-specific chemical substances for further evaluation of groundwater exposure pathways. The identification of contaminants of concern was based on a comprehensive review of concentrations of sampled chemical compounds, quality of environmental sampling data, and potential for receptors. The concentrations of contaminants of concern were compared to groundwater compliance criteria values, selected for additional data review if exceeding the criteria and analyzed with regard to the potential for exposure at sensitive receptors. Based on the number and magnitude of detections, the number of exceedances of the compliance criteria as well as potential harmful and toxic effects on humans and natural receptors, anthracene, benzene, fluoranthene and naphthalene were selected as indicator parameters to delineate the extent of the chemical plume at the Site. The most conservative degradation rate was assigned to the selected contaminants of concern (Tab. 2), based on comprehensive literature review.

Table 2. Degradation rates of chemicals of concern

Compound	Anthracene	Fluoranthene	Naphthalene	Benzene
Reference	degradation rate(day $^{-1}$)			
CCME, 2004	0.0190	-	-	-
CCME, 2004	0.0004	-	-	-
Howard et al, 1991	0.0008	0.0008	0.0027	0.0010
Howard et al, 1991	0.0069	0.0025	0.6930	0.0693
Aronson & Howard, 1997	-	-	0.00001	0.000001
Aronson & Howard, 1997	-	-	0.0072	0.0036

5. MODEL CALIBRATION AND RESULTS

The groundwater flow model was calibrated under groundwater flow steady-state conditions to obtain a reasonable match between the simulated/average observed groundwater elevations and the associated groundwater flow directions. The input parameters used during the calibration are conservative in terms of predictions of groundwater flow within the impacted area, towards the riverbank. The model calibration consisted of the adjustment of hydraulic conductivity values with PEST while manually adjusting the recharge rate. The model calibration was evaluated using both quantitative and qualitative measures.

The quantitative evaluation consisted of scattered plots of calculated versus observed water levels, a standard method of providing a visual evaluation of the accuracy of the fit for a steady state model (ASTM, 1993). The line of equality (Fig. 3) represents an exact match between the simulated and observed water levels while the scattered groundwater elevation values are distributed in a reasonably uniform manner about the line of equality, indicating that the model provides an unbiased match between groundwater elevations in the Shallow Aquifer.

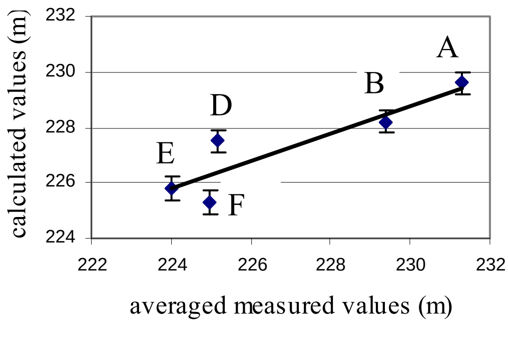

Figure 3. Residual calibration for hydraulic heads distribution.

Additional qualitative evaluation was performed by visual comparison of groundwater flow direction. Based on the contoured potentiometric surface obtained from mapping of the groundwater levels, groundwater flow is generally directed from the southeast to the northwest across the Site, under unconfined conditions within the fill/upper brown clay complex. The simulated groundwater flow condition is consistent with the potentiometric contours for the Shallow Aquifer developed from groundwater monitoring. The groundwater flow pattern is shown in Figure 4. According to the hydrostratigraphic conditions, the most significant groundwater flow occurs mainly within the upper sections of the model.

The quantitative and qualitative assessment of the calibrated values indicates that the model is able to reasonably reproduce both the observed groundwater elevations in the Shallow Aquifer and the observed direction of groundwater flow.

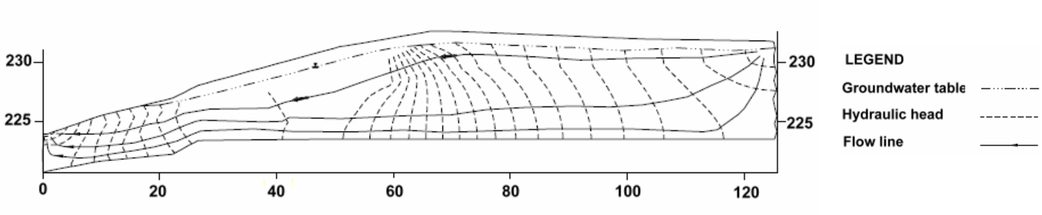

Figure 4. Distribution of hydraulic heads and flow lines

The hydraulic conductivities applied in the final model are summarized as follows: unit 1-new asphalt, $K=10^{-8}$m/s; unit 2- gravel fill, $K=1.25*10^{-5}$m/s; unit 3- silty clay (grey black clay), $K=1.4*10^{-7}$m/s; unit 4- clay fill, $K=1.4*10^{-6}$m/s; unit 5- CI-Silty clay (brown clay), $K=4.2*10^{-7}$m/s; unit 6- waste fill, $K=1.36*10^{-4}$m/s; unit 7- CI-Clay (alluvium), $K=1.4*10^{-7}$m/s; unit 8- backfilling of waste, $K=1.36*10^{-4}$m/s.

The calibrated recharge rate of 200 mm/year is within the range of values reported in the area by Manitoba Energy and Mines, 1983.

6. MODELING RESULTS

6.1 Hydraulic parameters and shape of the plume

The heterogeneous hydraulic parameters throught the model and an increased contrast of hydraulic conductivities between the fill and host formations enabled a complex pattern of the plume. A higher conductivity of the fill material resulted in a more diffuse spreading of the contaminants, at lower concentrations when compared to a lower hydraulic conductivity of the fill material, which favoured the development of a more sharply delineated plume, with higher concentrations.

More than two orders of magnitude contrast between hydraulic conductivities of contiguous layers can be regarded as a physical shield, causing refraction of the flow line such that flow in the higher conductivity layer is mainly horizontal, meanwhile flow in the lower conductivity medium in essentially vertical. As a result of this phenomenon (Freeze & Witherspoon, 1967, Neuman & Whiterspoon, 1969), the contaminant plume spreads at higher concentrations mainly above and below the higher conductivity medium.

A sensitivity analysis performed for different hydraulic conductivities of the fill, within the various remedial strategies, showed that a lower hydraulic conductivity favoured the retention of high concentrations of contaminant in a smaller area, whilst the overall spreading of the contaminant in the host rock at lower concentrations was significantly enhanced. A higher hydraulic conductivity of the fill enabled a more sharply delineated, elongated plume of the contaminants, at higher concentrations.

It is important to keep the same hydraulic parameters for the backfilling materials as the initial waste fill, at high hydraulic conductivity and porosity. More impermeable backfilling material allows only a reduced groundwater flow in the clean area and, consequently, the significant fluid flow occurs below the backfilling area, enabling mass transport of the contaminants from the impacted section of the model towards the river.

Overall, the density effect due to high concentrations of the pollutant generated a decrease in fluid flow velocities. A higher hydraulic conductivity layer associated with reduced fluid velocity enabled the accumulation of the contaminant within the layer. The phenomena can be regarded as a vertical restriction of the plume development.

6.2 Effects of various remedial strategies

Anthracene, benzene, fluoranthene and naphthalene were selected as indicator parameters of pollution. The simulations were performed to assess the effect of several remedial strategies for the distribution of the compounds of concern on the river bank. Given the wide range of literature references regarding the degradation rates of the selected compounds, the most conservative strategy was assumed and the lowest values were used during the simulations.

The remedial strategies were developed as follows (Fig. 2):

Remedial strategy I- the lower third section of the most impacted soil on the waste disposal area on the riverbank (unit 6) is removed (section ED, Fig. 2), followed by backfilling with clean excavation spoils. Location "D" is on the surface, at the contact between the clean, backfilled/contaminated areas. The horizontal surface AB is covered with fresh asphalt to increase the surface run-off while decreasing the infiltration of meteoric water into the ground.

Remedial strategy II - the lower half section of the most impacted soil (unit 6) is removed (section EM, Fig. 2), followed by backfilling with clean excavation spoils. Location "M" is on the surface, at the contact between the clean, backfilled/contaminated areas. The horizontal surface AB is covered with fresh asphalt.

Table 3 summarizes the results of the simulations based on remedial strategies I, II, indicating how the compliance criteria are met at the current location of the Main River.

Table 3. Summary of results of the simulations based on remedial strategies I, II.

Compounds of concern	Anthracene	Benzene	Fluoranthene	Naphthalene
Crt. conditions	No	No	No	No
I	No	Yes	Yes	Yes
II	Yes	Yes	Yes	Yes

Notes: No: compliance criteria not met at the current location of the river
Yes: compliance criteria met at the current location of the river

Figures 5-8 present snapshots of the current conditions and respectively, effects of the remedial strategy II for each of the selected compounds of concern (the vertical exaggeration ratio scale of the hydrogeological model has been modified for better visualization).

Figure 5.a presents the distribution of the contamination mass for anthracene, according to the current state of the waste fill. At present, the plume reaches the riverbank at concentrations of approximately 0.1 mg/l, compared to a compliance criterion of 1.2e-5 mg/l. Figure 5.b shows the mass distribution at steady state for remedial strategy II, where compliance criterion is met at the edge of the river.

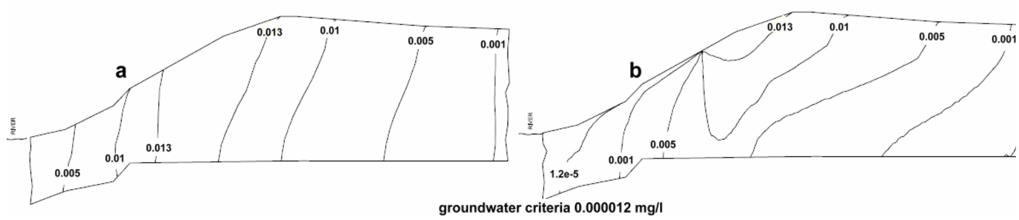

Figure 5. Anthracene: a) current conditions; b) remedial strategy II, half of the waste removed, horizontal impacted area covered with asphalt.

Figure 6.a presents the current mass distribution for benzene, where the plume reaches the riverbank at concentrations of approximately 0.38 mg/l, compared to a compliance criterion of 0.37 m/l. Figure 6.b shows the mass distribution at steady state for remedial strategy II, where compliance criterion is met at the edge of the river.

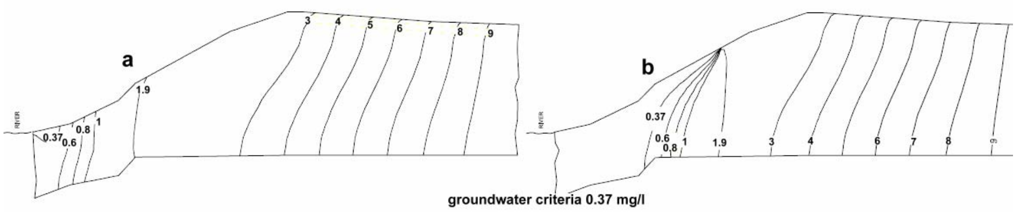

Figure 6. Benzene: a) current conditions; b) remedial strategy II, half of the waste removed, horizontal impacted area covered with asphalt.

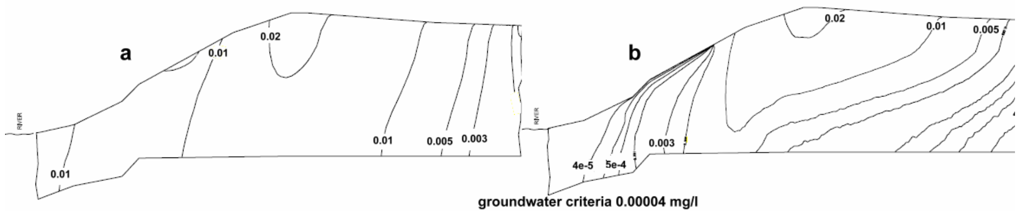

Figure 7. Fluoranthene: a) current conditions; b) remedial strategy II, half of the waste removed, horizontal impacted area covered with asphalt.

Figure 7.a presents the current mass distribution for fluoranthene, where the plume reaches the riverbank at concentrations of approximately 0.001 mg/l, compared to compliance criterion of 4e-5 mg/l. Figure 7.b shows the mass distribution at steady state for remedial strategy II, where compliance criterion is met at the edge of the river.

Figure 8.a presents the current mass distribution for naphthalene, where the plume reaches the riverbank at concentrations of approximately 0.1 mg/l, compared to compliance criterion of 0.0011 mg/l. Figure 8.b shows the mass distribution at steady state for remedial strategy II, where compliance criterion is met at the edge of the river.

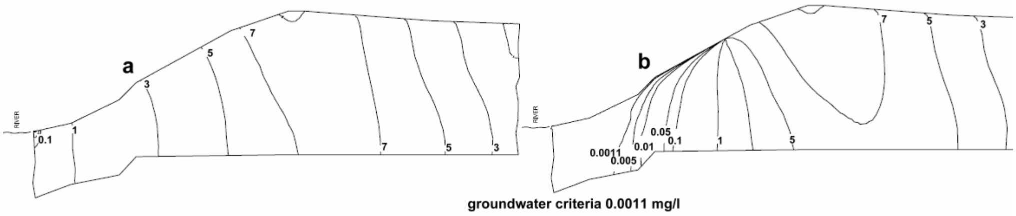

Figure 8. Naphthalene: a) current conditions; b) remedial strategy II, half of the waste removed, horizontal impacted area covered with asphalt.

7. DISCUSSION OF RESULTS AND CONCLUSIONS

The present study investigated the current contaminant conditions at the Unnamed Site and, based on the findings, conservatively assessed remedial strategies that predict concentrations of selected chemical compounds in the Shallow Aquifer at the Main River within the compliance criteria.

The results of the model are considered to be highly conservative based on the following assumptions: the lowest degradation rate was used for the selected compounds of concern, based on literature references; the longitudinal dispersivity at the site was calculated based on Xu & Eckstein, 1995, resulting in a lower value compared to other commonly-used alternative methods; the retardation was disregarded by being assigned a factor of 1, consequently decreasing the residence time in the model domain; the initial mass conditions used the highest concentrations detected historically at the Site.

Based on the modeling results, there are currently no chemical compounds at the Site which will result in a future exceedance of compliance criteria at the Main River boundary if half of the waste fill is removed and backfilled with clean material, while the remaining impacted area is entirely covered at the surface with a low permeability material such as fresh asphalt (Remedial Strategy II).

Observations of the contaminant mass pattern show that the most important factor of the remedial strategy is represented by the extent of asphalt cover over the surface. Overall, the excavation of one third versus half of the waste fill, followed by backfilling of the excavated volume with clean material with the same hydraulic parameters, creates a similar distribution of contaminant within the model domain. However, the asphalt cover extended over the whole impacted surface has a significant impact upon the pattern of contaminant mass. A lower permeability of the backfilling material is part of a negative scenario, as it favors significant fluid flow below the backfilling area, followed by mass transport of the contaminants towards the river.

As part of the long-term strategy, continued groundwater monitoring is required to determine if additional remedies might be required in the future.

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