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APPLICATION OF POLLUTANT REMOVAL AND PRODUCTION WELL REMEDIATION METHODS IN NUMERICAL MODELING ENVIROMENT

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1 Abstract

In the production of drinking water finding a sufficient and reliable source is hard however keeping it clean and running is even harder. Most settlements around the world rely on some kind of surface water, be it a river or lake, as a source for their water production. Most of the time using water from these sources directly is not an option, the use of some sort of pollution removal is required. Most commonly Bank Filtration Systems are utilized in these cases if the environmental characteristics allow it. BFSs provide many benefits, most importantly a natural filtering that removes bacteria and a substantial portion of pollutants. Problem arises however when the environment experiences an increased load of pollution. In these scenarios both the soil and the production wells themselves can get contaminated, rendering them unusable.

Well-developed systems can handle the loss of some production, however over time without ways to restore and protect their sources, even these are set to fail.

In our work we tried to find ways for well and soil remediation as well as for the protection of these elements. For the prior we have run small scale laboratory experiments in which we tested various kinds of zeolite filter media. In these experiments we used Iron and Manganese as pollutants as these are the most prevalent types of pollutants present in our area.

With coproduction of local utility providers, models were built in Modflow, incorporating all available information of soil stratification, production characteristics of existing wells and time dependent environmental factors. The models were calibrated then from these models we selected a small pilot area which contained a known to be problematic production well, a large land area and a waterbody.

In this pilot area we used MT3D(MS), a pollutant simulation program, to design and model a protective system consisting of flow barriers and filtering media. Pollutant and filtering media properties were set according to literary values and to our own laboratory test results. In model runs we experimented with different setups and “tested” the capacity of the system. We aimed to find an optimal geometric setup that provides the best removal and protection characteristics whilst being cost effective and feasible to install with technologies available and used today.

We assessed the final designs feasibility and cost. Based on the results we concluded that it can be a cost-effective alternative, paired with shallow depth (maximum of 15m) wells, to other drinking water (pre-)treatment methods and could help mitigate further damages to BFSs. Further real-life large-scale testing is required to validate and to further calibrate the models.

2 Introduction

Providing good quality drinking water to the population of a settlement or a larger region is one of the most important tasks, however it is a complicated and relatively vulnerable process. Various problems can arise on any point of the supply network that contaminate the system and the water, out of all these locations the most sensitive is the production and production site itself. We focus on production systems that rely on some form of surface water as their source and utilize bank filtration as a primary way of pollution removal method.

This work is part of a longer running project, the modelling explained in this paper collects both literary and our own experimental data and uses it to build, calibrate and help iterate an optimal design that helps in the protection and amplification of BFS systems. The modelling results were then assessed factoring in costs of installation, maintenance and upkeep as well as possible savings on subsequent removal steps due to lower pollutant concentrations.

3 Materials and methods

3.1 Laboratory tests

3.1.1 Reactor setup

The sorption tests were carried out simultaneously in controlled and uniform environments. We prepared six glass reactors of equal volume, shape and orientation. Each reactor was fitted with two flexible PVC pipe from one of which we delivered the load. The load delivery was done and controlled by a peristaltic motor set to a fixed output volume. The effluent left the system through the other PVC pipe at the bottom of the reactors, this line was not motorized, it solely relied on gravity. Due to the reactors shape and the nature of the zeolite media the bottom and top ends of the reactors were stuffed with cotton. This prevented the escape of the sorption material and simplified the geometry of the chamber. The complete setup can be seen on figure 3.1. Note that the pollutants were measured separately.

figure 3.1. – Experiment setup

The following table 3.1. shows the grades of zeolite used in the reactors:

	2R. Reactor [mm]	3R. Reactor [mm]	4R. Reactor [mm]
Material	Zeolite	Zeolite	Zeolite
Grain size [mm]	0,5-1,0	1,0-3,0	2,5-5,0

table 3.1. – Materials and grades used in reactors

3.1.2 Load

In order to measure the sorption capacity of the different grade zeolite media we introduced load with a known iron ion and manganese ion concentration and known volumetric flow.

For manganese initial concentration was set to 1mg/l for iron was set to 5mg/l. These represent the observable amounts of pollution found in nature. However, as the media has a high sorption capacity the initial effluent waters contained no trace of pollutants. In order to exhaust the media in a reasonable timeframe the concentrations were increased tenfold.

3.1.2.1 Iron

Its important to note that the iron solution degrades overtime, the iron II ions react with atmospheric oxygen and oxidate to iron III. Whilst iron II passes through the cotton stuffing with little loss iron III gets trapped in the fabric. This alters the results of the measurement. In order to slow down the oxidation we covered the reservoirs. To further control the oxidation the pH in the reservoirs were acidic, kept around 4 pH throughout the experiment. The acidic environment does not affect the measurements done on the effluent waters, since the reaction used reduces all forms of iron present to iron II. However, even against these measures the formation of iron III and iron oxide cannot be avoided, to compensate for the changing concentration the control samples were taken directly from the reservoirs as the concentration measurements were done.

3.1.3 Concentration measurement

3.1.3.1 Iron measurement procedure

The measurement of iron concentration in the effluent water was done according to the MSZ 448/4-83 standard protocol. The procedure described measures both iron II and iron III ions.

The procedures steps are the following:

- Take 25 ml of sample and pour it in a clean beaker. (We measured both the influent and effluent water)
- Pipette 2 drops of concentrated HNO3 into the sample
- Add 1ml of Ammonium-acetate buffer solution
- Add 0,5 ml hydroxyl-amin solution
- Add 1ml of phenanthroline solution
- Stir and let the reaction sit for 15 minutes protected from direct sunlight
- Measure the ready samples with spectrophotometer set to 510 nm wavelength and record the displayed concentration reading.

During the reaction the samples will turn orange, the colours intensity will depend on the amount of iron ion concentration found in the water. Some of our measured samples ca be seen on figure 3.2.

figure 3.2. – iron measurement

3.1.3.2 Manganese measurement procedure

The measurement of manganese concentration in the effluent water was done according to MSZ 1484-2/1993 standard protocol. The procedure is order sensitive, keeping to the procedure instructions is important. Stirring the samples after each step is necessary.

The procedures steps are the following:

- Take 25 ml of sample and pour it in a clean beaker. (We measured both the influent and effluent water)
- Pipette 2 drops of concentrated HNO3 into the sample
- Prepare a fresh batch of additive solution, according to the recipe on the protocol and add 0,75ml of it to the sample
- Add 2,5ml formaldoxime reagent
- Add 2ml of ammonia solution
- Add 2,5ml EDTA solution
- Add 2,5ml of hydroxyl-ammonium-chloride reagent
- Stir and let the samples rest for 60 minutes.
- Measure the ready samples with spectrophotometer and record the displayed concentration reading.

The samples will produce colour as the result of the reaction; the colours intensity depends on the Mn ion concentration in the sample. Some of our measured samples can be seen on fig3.3.

figure 3.3 - Manganese measurement

3.2 Modelling

In order to implement laboratory results and to be able to test ideas and various structural designs and monitor its effects a complex understanding of the environment is required. With coproduction of local utility providers, we were able to gain access to operational and observation data of a major drinking water production site. The provided data included measured water levels both within production wells as well as levels around them measured in observation wells. We were provided with detailed geotechnical information of the area and the operational data and parameters of the production wells found on site. Data regarding critical environmental elements, such as waterbody levels and rain could be accessed as public information on the web.

Using all of this information we built a hydrogeological model of the site in Modflow5.3. The model built focused on the production wells refined so that the wells were represented as close to size as possible. Due to both computational and modelling software limitations the model could not be set to model the exact geometries of wells and its components, however that is not needed for correct simulations and calibrations either. The minimal cell size was set to 5*5 meters viewed from the top.

The calibration of the model was done using observed data and a set of campaign measurements done in the area. The campaign measurements were done over two weeks in multiple observation wells scattered around the site. The data collected was used to validate operational data and to calibrate the models. During the campaign data collection was done by two Dataqua DA-S-L(a)RB 122 high precision submersible sonde, see figure 3.4. and 3.5. Technical specifications of the instrument is listed in table 3.2 below.

figure 3.4. - Dataqua DA-S-L(a)RB 122 sonde

figure 3.5. – Data recovery

Technical data	DA - S - LRB 122
Measurement limits:	0 ...1 ... 0 ... 160 m
Linearity error:	< ± 0,1 % FS
Temperature error:	± 0,003 % FS/°C
Compensated temperature range:	0 ... 60 °C
Long-time stability:	< ± 0,1 %/year
Resolution:	0,01 % FS
Memory:	30.000 - 120.000 pcs data
Time recording accuracy:	<±10 min/year
Data recording frequency:	programmable from 1s to 24h
Energy supply:	Lithium battery, 3,6V
Battery life:	5 years, if recording frequency is higher than 15min/record
Data transfer rate:	9600 bit/s
Interface:	RS232/D9 or USB2.0
System requirements:	BM compatible Notebook, or PC - Windows 95/98/NT/2000/XP
Data format:	binary, HAFTER, EXCEL, ...
Housing material:	KO-36S
Rating:	IP68

table 3.2. - Dataqua DA-S-L(a)RB 122 sonde technical parameters

Modflow5.3 is an FDM numerical model, it models space as discretized units (cells) between which interactions get defined by a complex set of codependent equations. Detailing these equations is not within the scope of this paper, for further information consult the user manual listed in the references [Chiang Wen-Hsing & Kinzelbach, Wolfgang (1998): *Processing Modflow. A Simulation System for Modeling Groundwater Flow and Pollution*].

The model of the site can be seen on figure 3.6. The total model spans 5544*5095 meters, includes four distinct layers for a maximal depth of 20 meters. The cross sections are exaggerated 25 times. Production wells are numbered on each side of the site and their markings represent their actual extents. The modelled site uses horizontal collector wells.

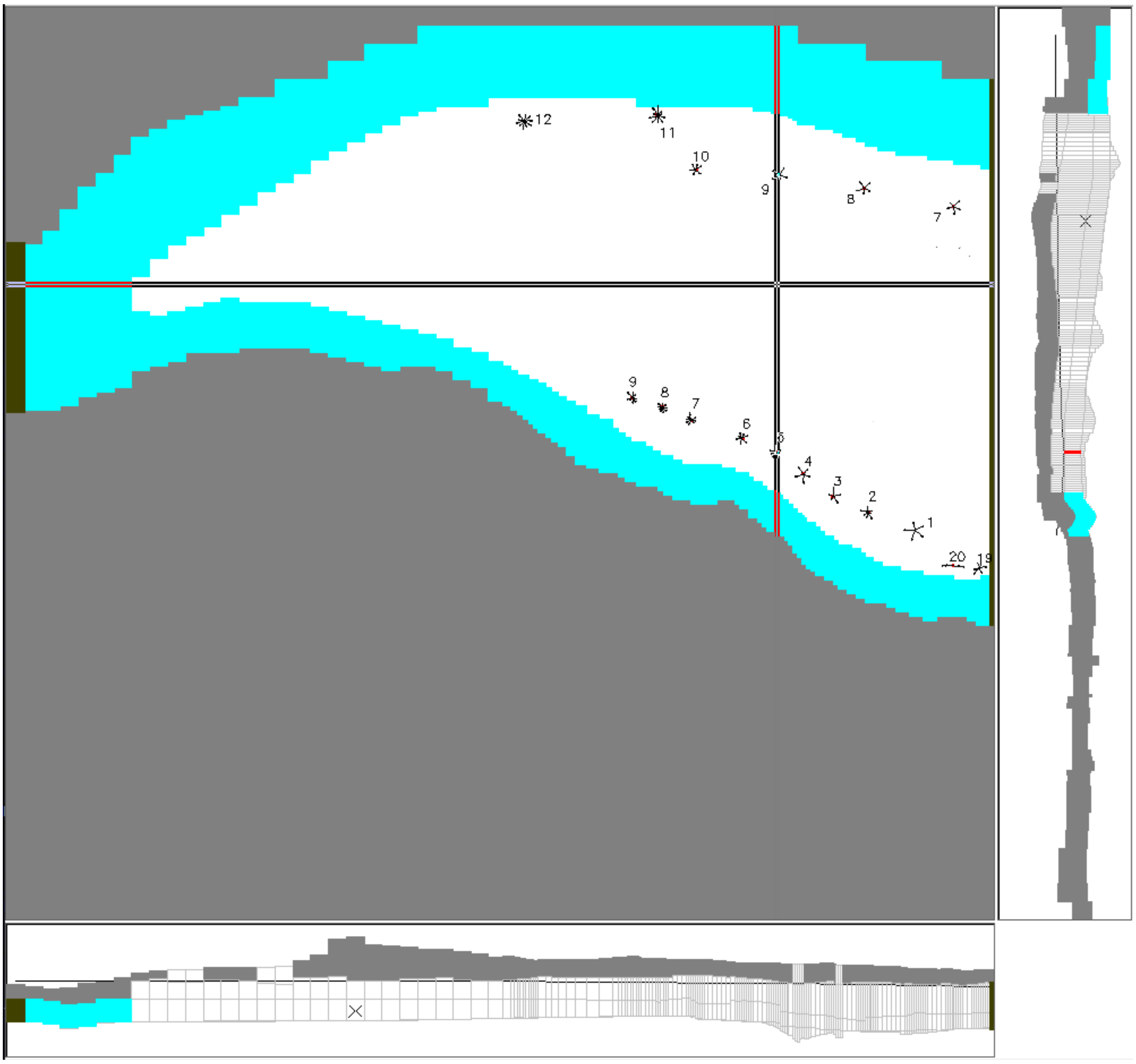


figure 3.6 – Overview and cross sections of the large model

4 Results and discussion

Following the calibration of the model, where we achieved 20cm maximum divergence between measured and modelled levels at the production wells a small pilot area was selected. Two examples observed and modelled water levels form the calibrated model is illustrated on figure 4.1.

The pilot area contains a shallow depth well, a section of the waterbody and a relatively large land piece. With the calibration of the large-scale model the boundary stability of the pilot area is provided, the smaller modelled area follows and is affected by events of the large model. It worth noting that the pilot area was run at the same time period as the original large model so the environmental variables and other characteristics previously defined did not change.

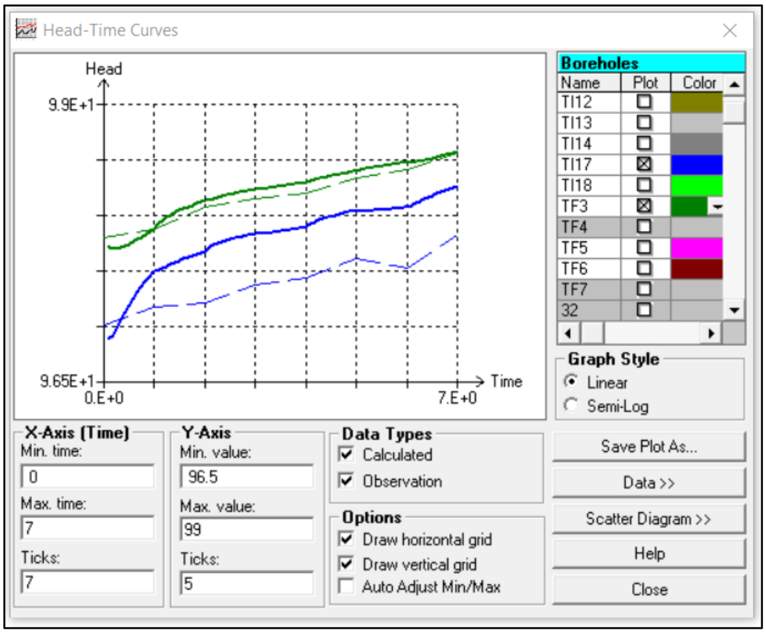


figure 4.1. – Observed (dashed)-Modelled(cont.) water levels

The pilot area then got prepared to be able to run PMPATH particle tracking simulation module. As stated before the area contains a singular production well, its technical data is listed in table 4.1. and its geometry is displayed on figure 4.2. the drawing is in meters. The pilot area is shown on fig4.3. below.

Item	Value
Technical data	
Average production	3400m3/day
Peak factor	1.3
Fe(II) concentration	0.3mg/l
Geometric data	
Arm -waterbody distance	~61 meter
Arm depth below ground level	8-10 meter
Arm depth below waterbody basin	2-4 meter

table 4.1. – Technical data of well

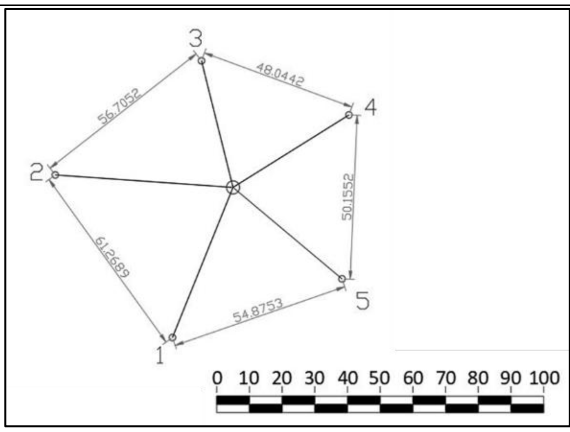


figure 4.2. – Geometry of well

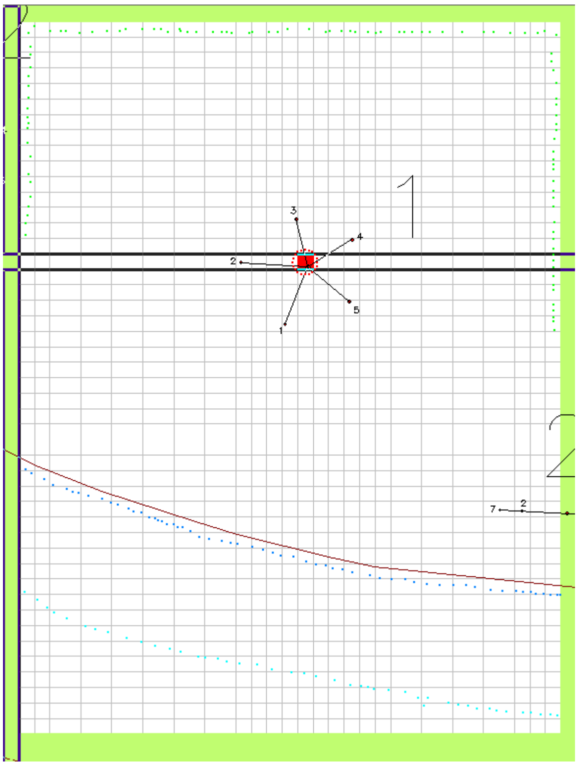


figure 4.3. – Pilot area

The area was tested in an undisturbed state, i.e. without addition of flow barriers to gain a base ground for flow paths. To do that particles were placed arbitrarily according to the following categorization and logic:

- Particles coded light blue are set at around the middle line of the water body
- Particles coded dark blue are set at around the shoreline of the water body
- Particles coded green are set at around the perimeter of the model but only on land
- Particles coded red are set at around the production well in a 10m diameter circle

The set particles were set to all layers, however comparison of flowlines shown that the 3rd layer, containing the cell defined as the production well in the model, was the most responsible and descriptive of the flow characteristics. Particles originating from this layer did not tend to change layers, and particles originating from upper layers usually moved to this layer along their path. From on all figures depicting flowlines the color-coding is following the logic previously stated. The undisturbed state is illustrated on figure 4.4. below. All particles, save from the red, are tracked going forwards in time. In the case of the red particles this method cannot be used, since the well pulls them in and lifts them out of the model, in order to get valuable information these particles movements were tracked backwards, using the MMOC approach.

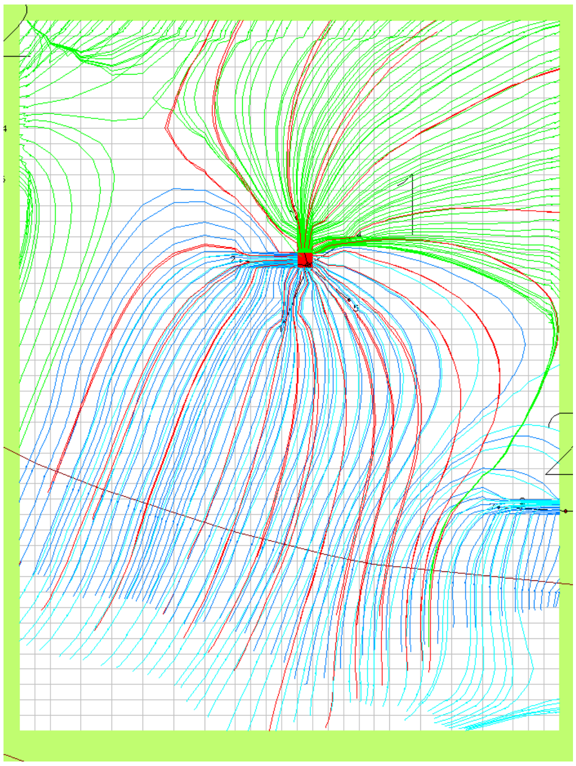


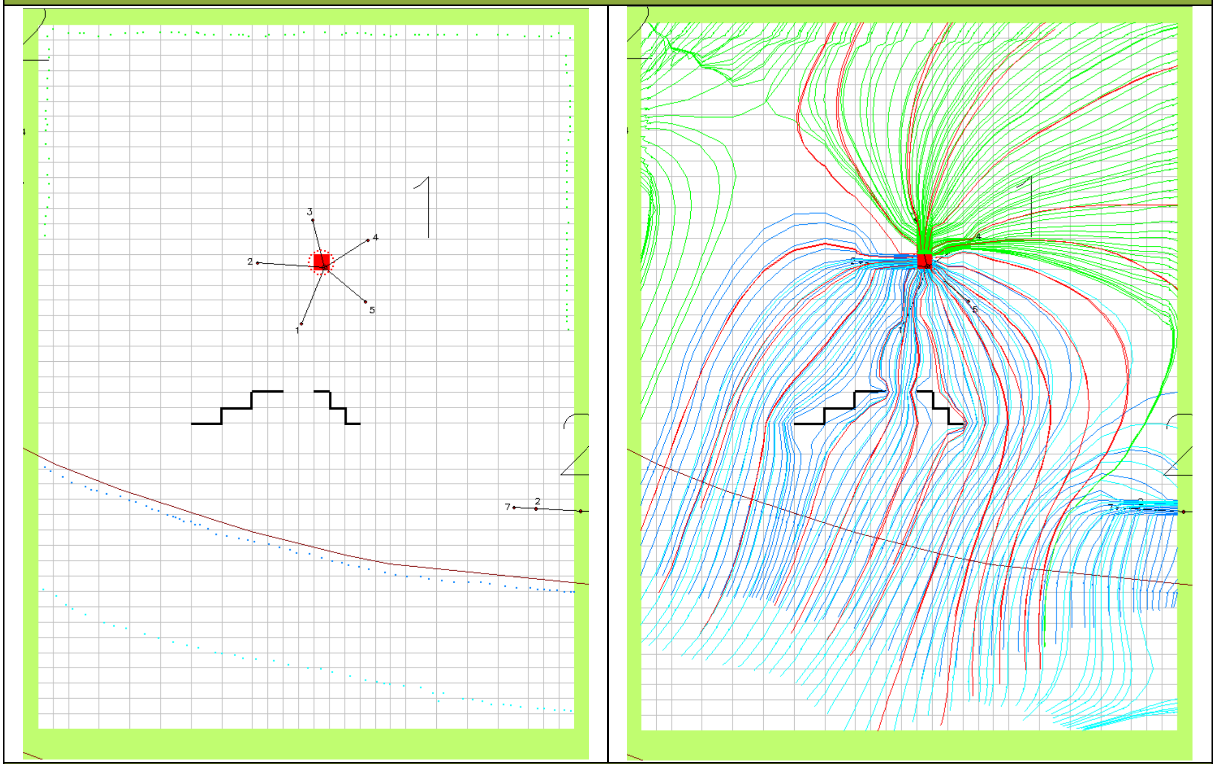
figure 4.4. – Undisturbed flowlines

With the understanding of the dominant flow characteristics, we experimented with various flow barrier placements and geometries. Considering the characteristics of the area, the selected zeolite grade, existing remediation and pollutant control technologies and practices we decided to use a funnel and gate design for our technology as well. The classic funnel and gate design is used in case of semi localized groundwater pollution cases, where a high concentration pollutant source is present and due to the flow of groundwater, be it natural or controlled, a plume develops. A system consisting of three parts is placed in the way of the plume. In the main path of the plume a filtering media/extraction technology is placed this is the "gate" element of the system. On either side of the gate two walls are placed that are made of off an impermeable material, this is the "funnel". The funnel itself is not meant to clean or trap pollution, it is responsible for directing the flowlines towards the gate, preventing the horizonal spread and escape of the plume.

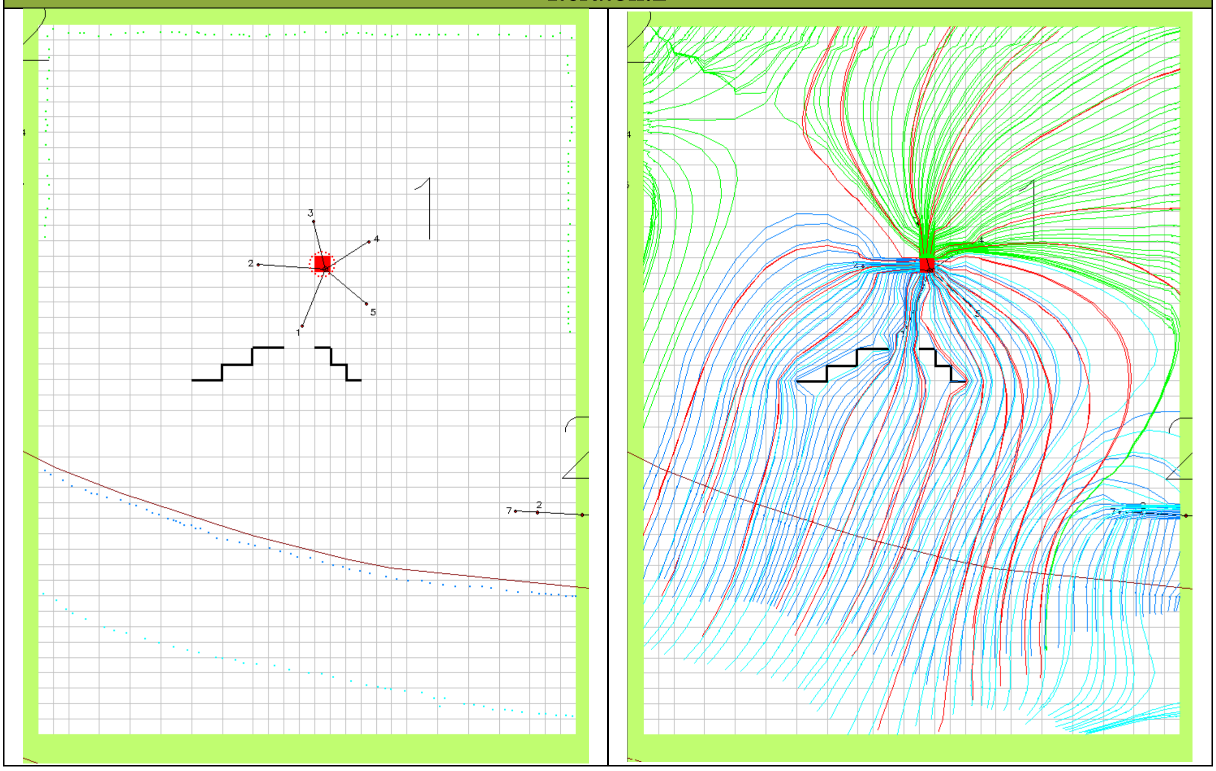
In our case the system is faced with a disperse pollution source, where an exact origin cannot be identified, only a general direction. In our case the pollution source is believed to be the waterbody and its sediment, thus the main pollution load will arrive from there, consequently the funnel should be positioned that way. As setting the flow barriers themselves is not complicated we decided to look at three purely experimental setups, in two cases the barriers were perpendicular to the shoreline and in one case the funnel was flipped and faced towards the well. In the latter case we were interested in the changes in the emerging flow pattern because if they have shown that the water coming from the waterbody was blocked and taking a significantly longer route to get to the well this setup could have been improved upon and researched further as well. However, the flowlines are not diverted by a significant degree, the idea was abandoned.

The setup variations can be seen in the following 4.2. table, where the lefthand side shows the geometry whilst the righthand side shows the modified flowlines of particles.

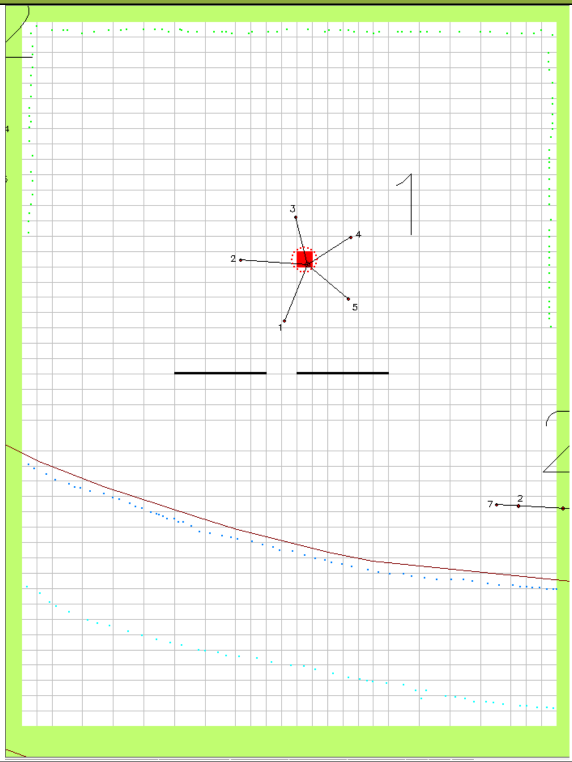
Iteraton:1

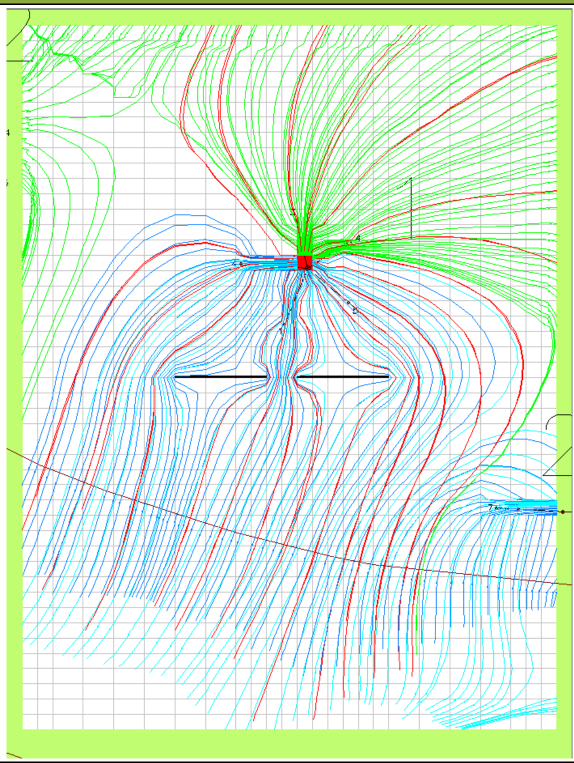


Iteraton:2

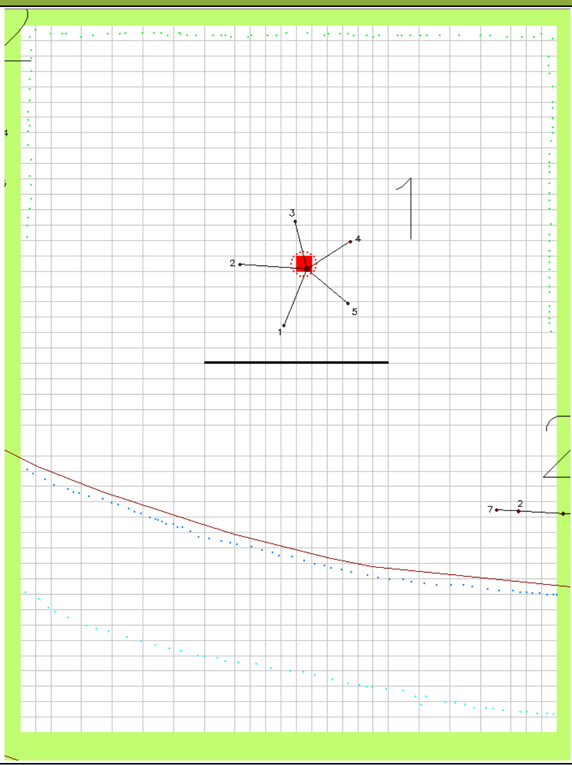


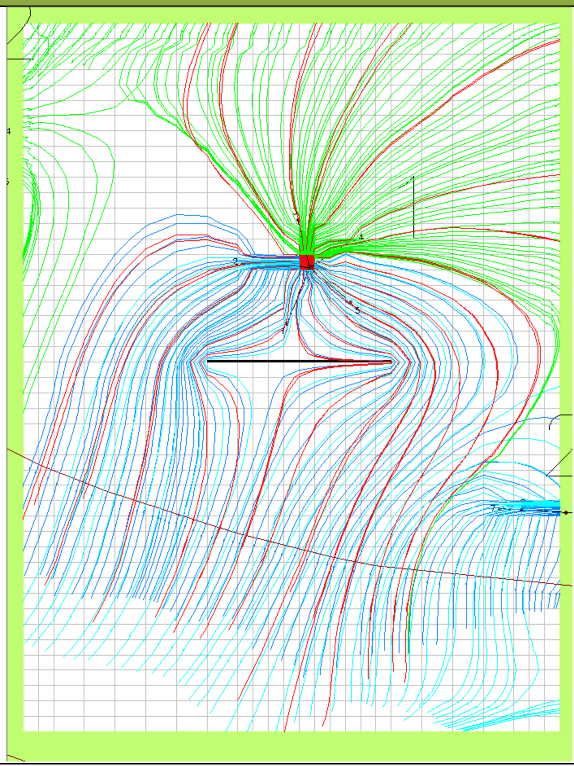
Iteraton:3



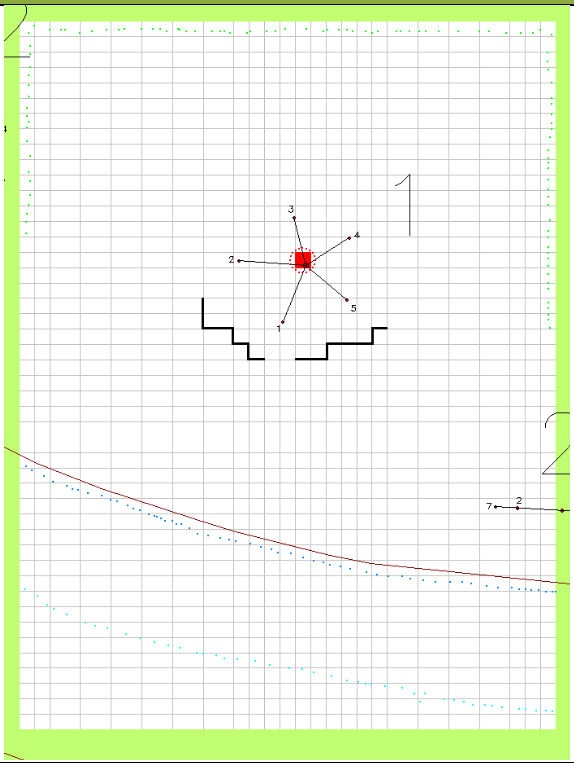


Iteraton:4





Iteraton:5



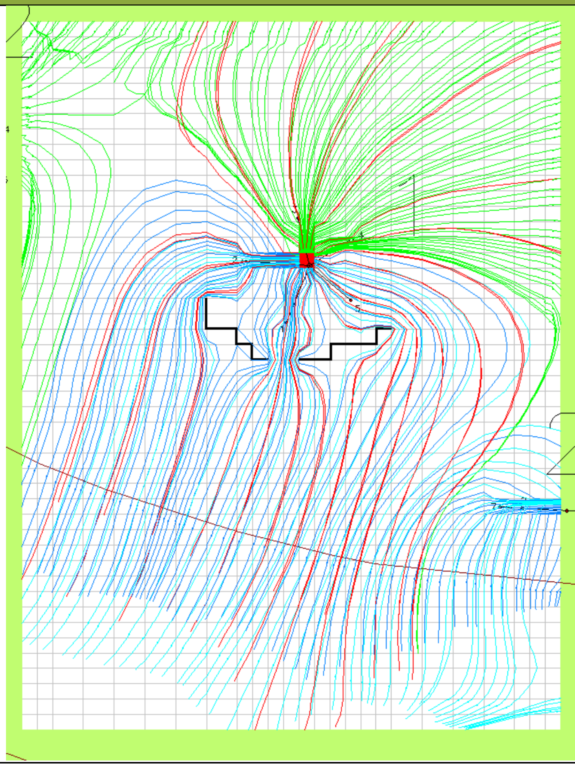


table 4.2. – Setup variations

Out of the five setup variations a sixth was synthetized, learning from the experimental setups the barrier was moved closer to the well (~25 meters), adjusted to face the shoreline as much as possible and the angle of the barriers were increased. The total length of the barrier hasn't changed as the total available barrier wall area was fixed at maximum 1000m2. The limit was set due to available installation techniques and costs. The final design can be seen on figure 4.5 and 4.6.

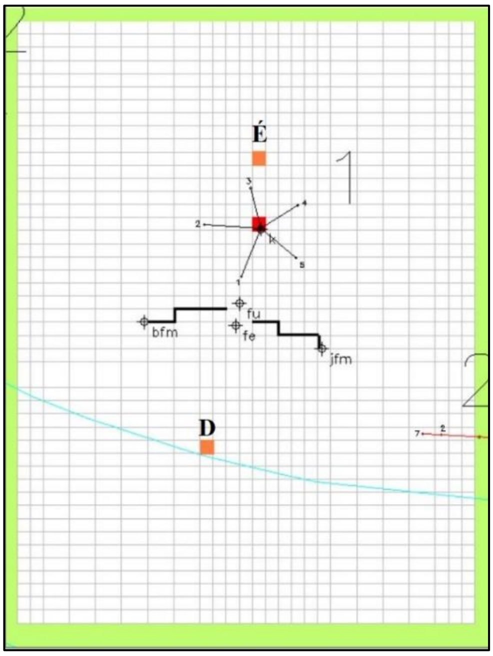


figure 4.5. – Final setup geometry

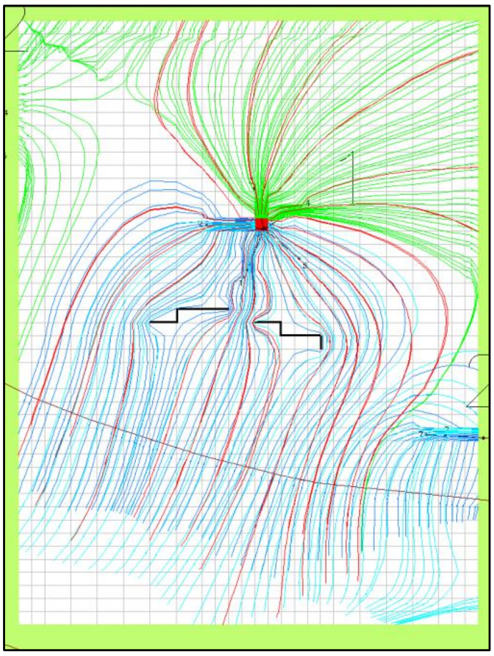


figure 4.6. – Final setup flowlines

In this model we introduced another modelling tool, namely MT3DMS in order to simulate the pollutants. In this final model version, we set several observation points, coded:

- BFM – left edge of the funnel
- JFM – right edge of the funnel
- FE – in front of he gate
- FU – behind the gate
- K – production well

Points "bfm" and "jfm" are placed to check for pollutants escaping the system. Point "fe" is introduced to monitor the change in concentration before the filter. Point "fu" is placed to monitor the delay introduced to the appearance of pollutants and to see how much material it removed from the water. Point "k" is set on the well itself to monitor the observable concentration within the well itself, thus the raw drinking water produced.

Cells labelled D and É are sources of pollution. Cell É represents contamination coming from the background, the land., simulating pollution due to human activity. Cell D is the main source of pollution. We previously stated that the real-life source is disperse and cannot be defined, however in order to properly set, model and test the capacity of the system we needed to work with a point like source.

The MT3DMS Chemical Reaction Package offers various kinds of options regarding the source, we decided to set both of our cells to be permanent, thus delivering a constant mount of material over each step of the simulation, instead of delivering a high concentration of pollution at once or in a burst.

On figure 4.7. and 4.8. we present the values set for the gate cells. The values are based on the laboratory test results and are modified to fit into the model. Fitting the results means that the total sorption capacity defined on a gate cell is equal to the total sorption capacity of the zeolite fill material divided by the number of gate cells (given all have the same volume) and as the complete cell acts as a filter adjusted for the difference in real real-life media volume and the model cell volumes.

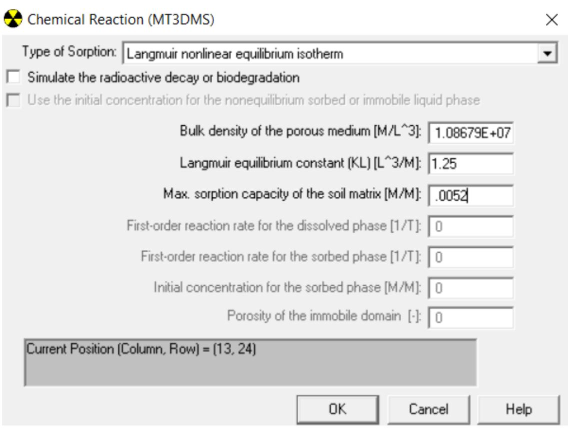


figure 4.7. – Values set for iron

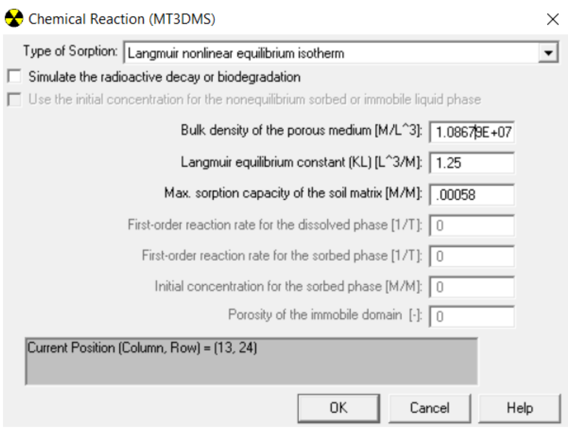


figure 4.8. – Values set for manganese

4.1.1 Simulation and results

Next the models were run in two variations. The first one had "no gate" as we did not simulate a filtering media between the barriers. This step was necessary to determine a zero case, where the pollution is not held back and reaches the production well in the least amount of time possible within the simulation. The plumes forefront reaches the wells around 40-50 days whilst the bulk arrives at around 70-80 days after the start of the simulation. Plotted graphs form the no gate run can be seen on figure 4.9 and 4.10. below. The development of the plume during the simulation can be observed on figures listed in figures4.11.-4.16.

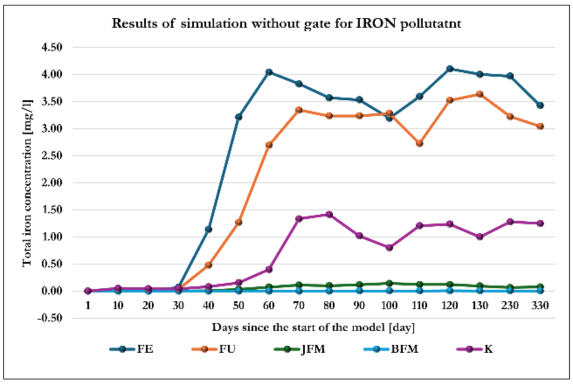


figure 4.9. – MT3DMS Simulation results for iron without gate

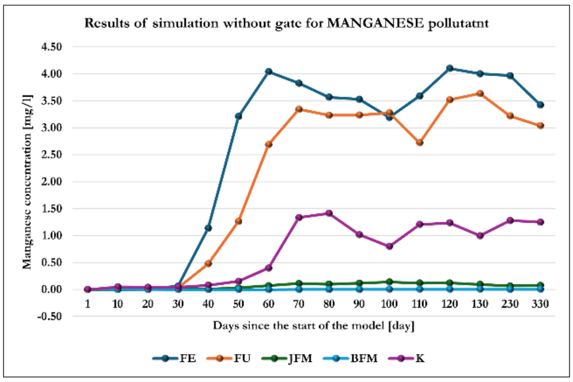


figure 4.10. – MT3DMS Simulation results for manganese without gate

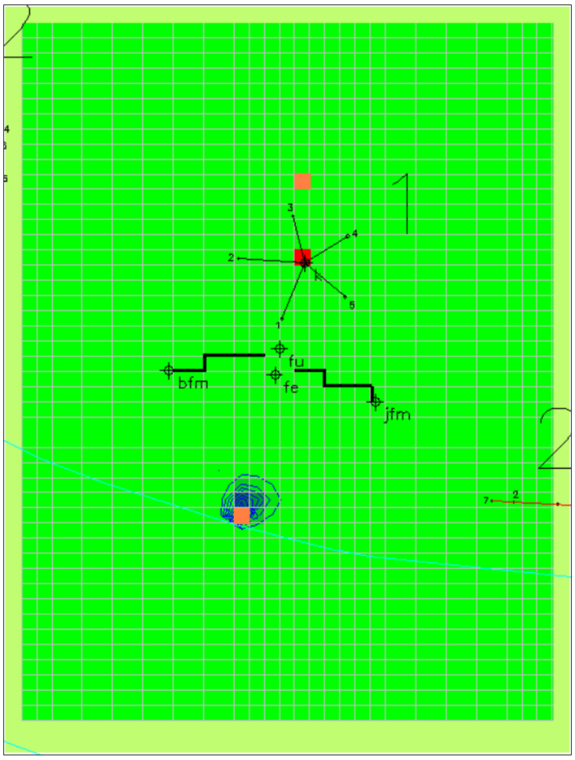


figure 4.11. – MT3DMS simulation – plume development after 10 days

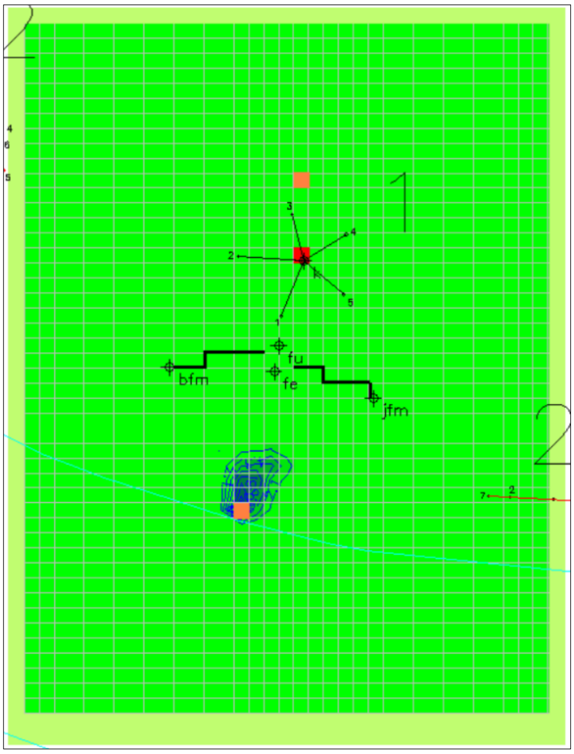


figure 4.12. – MT3DMS simulation – plume development after 20 days

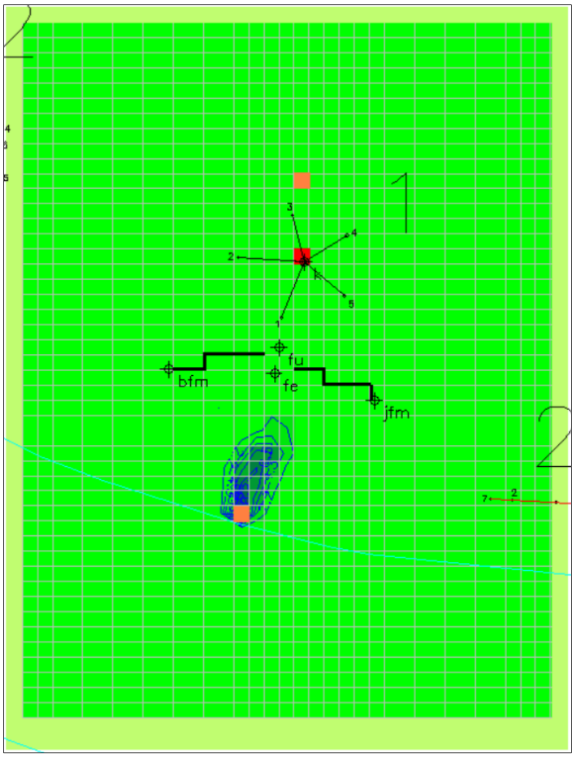


figure 4.13. – MT3DMS simulation – plume development after 30 days

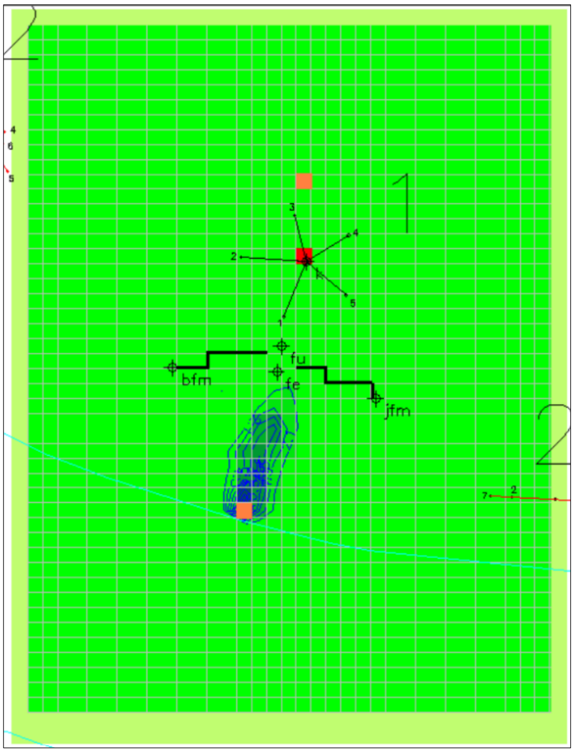


figure 4.14. – MT3DMS simulation – plume development after 40 days

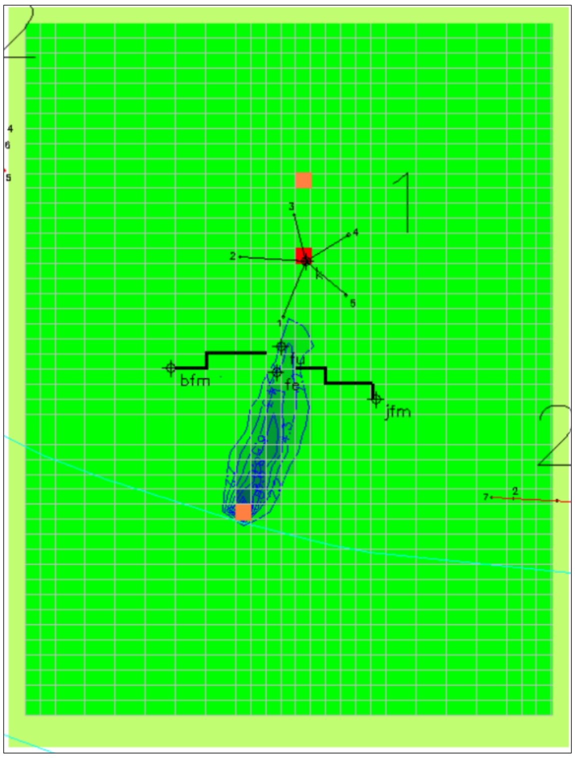


figure 4.15. – MT3DMS simulation – plume development after 60 days

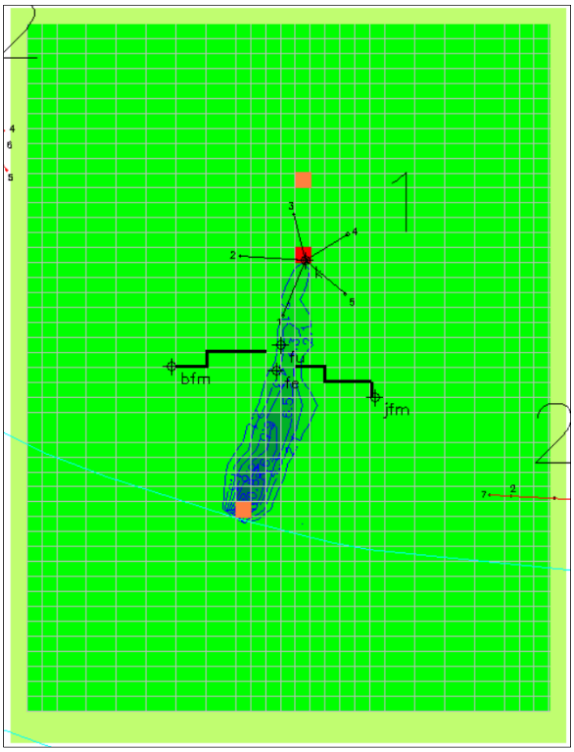


figure 4.16. – MT3DMS simulation – plume development after 80 days

Next the model was run with the introduction of the filter media. The shape of the developing plume is not affected, as the media very closely resembles the native gravely soil type around it thus it does not disturb the flow of water by a significant degree. However the plume itself is greatly delayed as the gate binds the particles. The leakage or in other words the first signs of the exhaustion or overload of the media show up around 100-150 days from the start of the simulation but it is only after 550-650 day that the gate is completely exhausted and lets the incoming pollutants through. Simulation results from runs containing the gate are shown on figure 4.17. and 4.18.

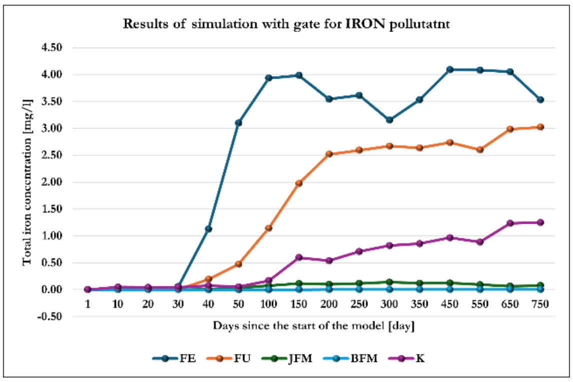


figure 4.17. -- MT3DMS Simulation results for iron with gate

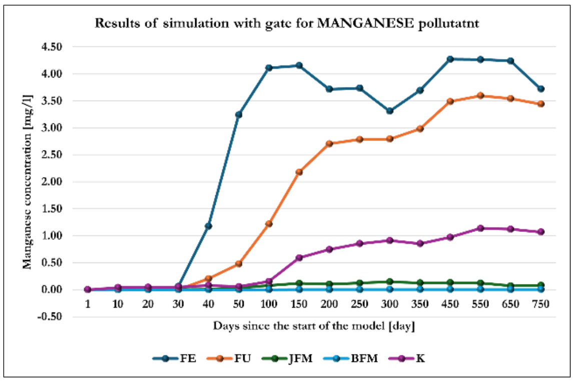


figure 4.18. -- MT3DMS Simulation results for manganese with gate

4.1.2 Cost analysis

To have perspective on the technology and its potential uses, we have analysed potential expenses both during installation and over the lifespan of the system, for comparison we have done the process for an alternative technology as well. The alternative is a cascade aerator scaled to the size necessary to handle the production wells output.

In table 4.3. we collected the values used in the estimate for the following items in unit. The expenses are based on design and operational experience:

Item	Price	Unit
production well ~30 m lift height, 2 operating +1 pcs in reserve	6 000	HUF/(m^3/day)
solid concrete structure	400 000	HUF/m^3
pool structure	300 000	HUF/m^3
excavation (from depths exceeding 2 m)	300 000	HUF/m^3
pumps (2+1)	6 000	HUF/(m^3/day)
chemical dispenser (hypo, flocculent)	450 000	HUF/(l/day)
pressurized sand filter	20 000	HUF/(m^3/day)
zeolite infill (gate)	150	HUF/kg

Item	Price	Unit
soil backfill	1000	HUF/m^3
electricity	120	HUF/kWh
chemicals (hypo, flocculent)	40	HUF/l
sludge transport	15	HUF/kg
wages	10 000 000	HUF/year

table 4.3.– Prices used in the estimation

The cascade aerator will be referred to as "A" modelled funnel and gate technology will be referred to as "B" in text and tables. According to the table above the costs for A and B follows:

Investment			**Cost *[HUF]***	
well	existing			
deforestation in construction area	193	m^2	19 291 370	HUF
pumps with raised bed and 2+1 configuration	4 320	m^3/day	25 920 000	HUF
cascade aerator	96	m^3	38 220 023	HUF
flocculent dispenser	1	l/day	448 615	HUF
collection pool	45	m^3	13 500 000	HUF
settler	0	m^3	-	HUF
extraction pumps (2+1)	4 320	m^3/day	25 920 000	HUF
chlorinator	0,07	l/day	32 400	HUF
pressurized sand filter	4320	m^3/day	86 400 000	HUF
			209 732 408	**HUF**
Operation			**Cost *[HUF/year]***	
submersible pump (30 m lift)	25 269	kWh/year	3 032 308	HUF/year
extraction pump (10 m lift)	8 423	kWh/year	1 010 769	HUF/year
chemical dispenser	390	l/year	15 606	HUF/year
sludge transport	700	kg/year	10 447	HUF/year
Wages	1	person	10 000 000	HUF/year
			14 069 130	**HUF/year**

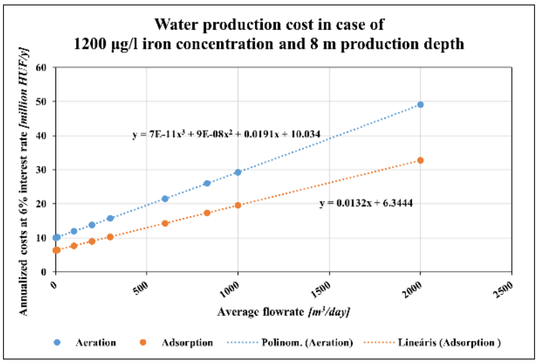
table 4.4. – Investment and operational costs for technology A

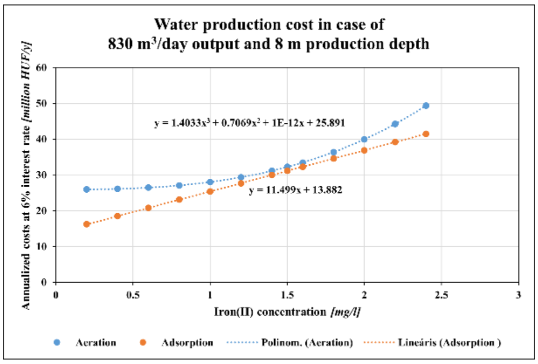
Investment			**Cost *[HUF]***	
well	existing			
excavation	96	m^3	955 385	HUF
flow barrier	1000	m^2	100 000 000	HUF
gate installation	96	m^3	28 661 538	HUF
zeolite infill	130	t	19 440 000	HUF
soil backfill	63	m^3	315 692	HUF
submersible + extraction pup (2+1)	4320	m^3/day	25 920 000	HUF
chlorinator	0,07	l/day	32 400	HUF
			175 325 015	**HUF**
Operation			**Cost *[HUF/year]***	
Submersible pump (30 m lift)	25 269	kWh/year	3 032 308	HUF/year
zeolite fill (replacement)	total volume	every ~5 year	3 860 576	HUF/year
			6 892 883	**HUF/year**

table 4.5. – Investment and operational costs for technology B

Looking at the breakdown of the two technologies, it is apparent that version B is cheaper to install and operate. It is important to note however that whilst the cascade aerator costs more the technology proposed in version B requires a complete gate replacement around every 5 years. The replacement involves the periodic disturbance of the local environment in a considerable sized area, since the gate must be excavated, replaced and the soil backfilled again. Furthermore, during maintenance, the production well needs to be shut down. With these parameters the technology used in A could be more economical.

A dynamic cost evaluation was carried out to further explore the feasibility of technology B. We will not go into the details of the calculations in this paper. The following charts include calculated costs over time adjusted by 6% interest rate.





figures 4.19.-4.20. – Dynamic cost evaluations

The dynamic evaluation shows that technology A requires more investment, is above the calculated costs of A by a variable margin. However, the use of cascade aeration is comparable with option B, given certain levels of pollutant concentration. With the consideration of the forementioned environmental disturbances, the use of technology A is more recommended, outside of this range however the funnel and gate technology is significantly more cost effective.

4.1.3 Best case scenario

In case of a new well installation, unlike the case of existing wells, the zeolite could be installed around the well itself during construction. This eliminates the need for large, linear barriers. With proper design there is a way for less invasive sorption media replacement method which could reduce the environmental impact of the system maintenance as well.

5 Conclusion

In conclusion we found that based on the simulation results the use of a funnel and gate style sorption system can be an option in the protection and lifespan elongation of BFS production wells and can potentially help in improving raw water qualities as well as reducing costs of treatment on subsequent technological steps. However, the results need to be validated and tested in real life as well.

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