INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

Linked Simulation Optimization Modeling for Management of Polluted Land Sites

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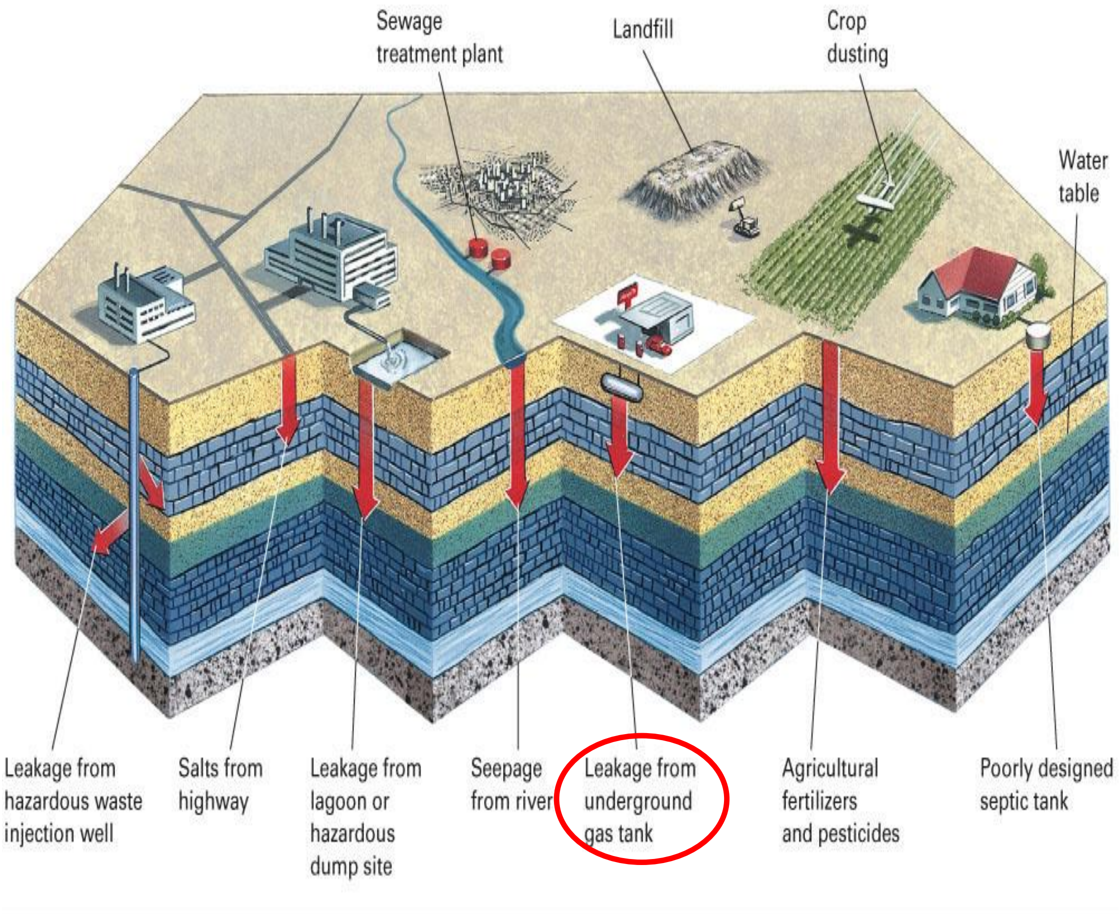
Outline of the Presentation

- Design of a optimal in-situ- bioremediation system for sites contaminated with BTEX compound
- Consideration of well clogging during cost optimization
- Groundwater table fluctuation and its impact on biodegradation
- Impact of soil moisture and temperature on system design cost

Groundwater Contamination and Remediation

- **Contaminants enter groundwater through variety of sources**



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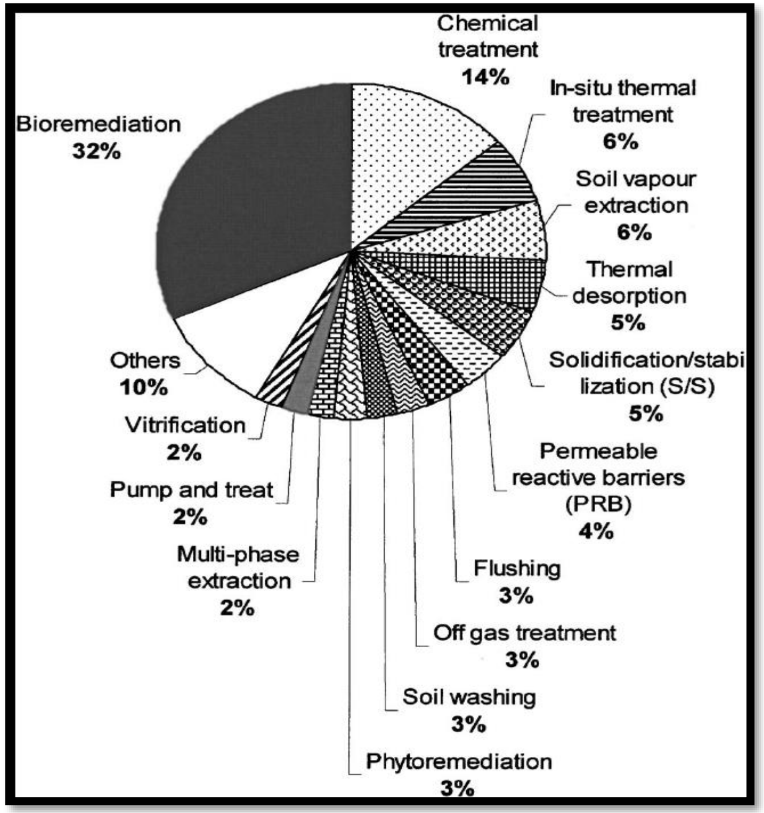
Guntur district=100,000 liters

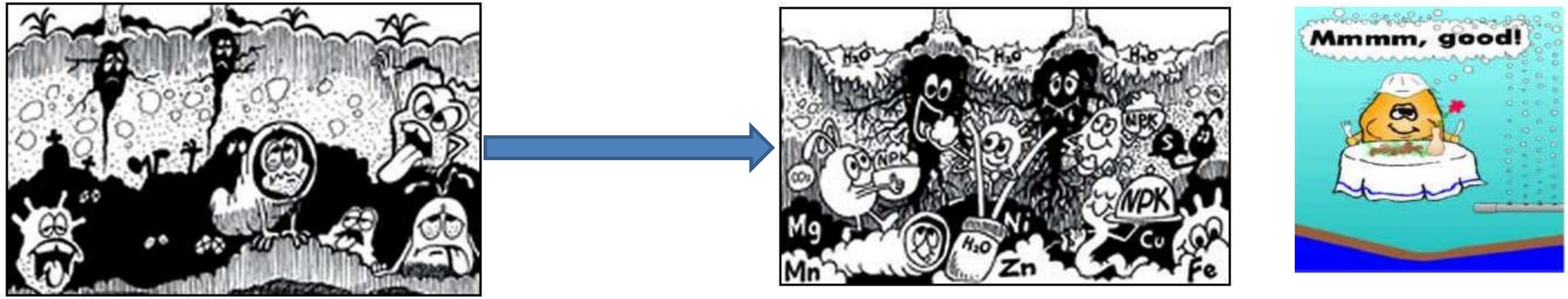


Different technologies adopted for remediation
(Source: Satinder K. Brar, 2006)

1 liter of petroleum can contaminate 10^6 litre of groundwater

What is Bioremediation??

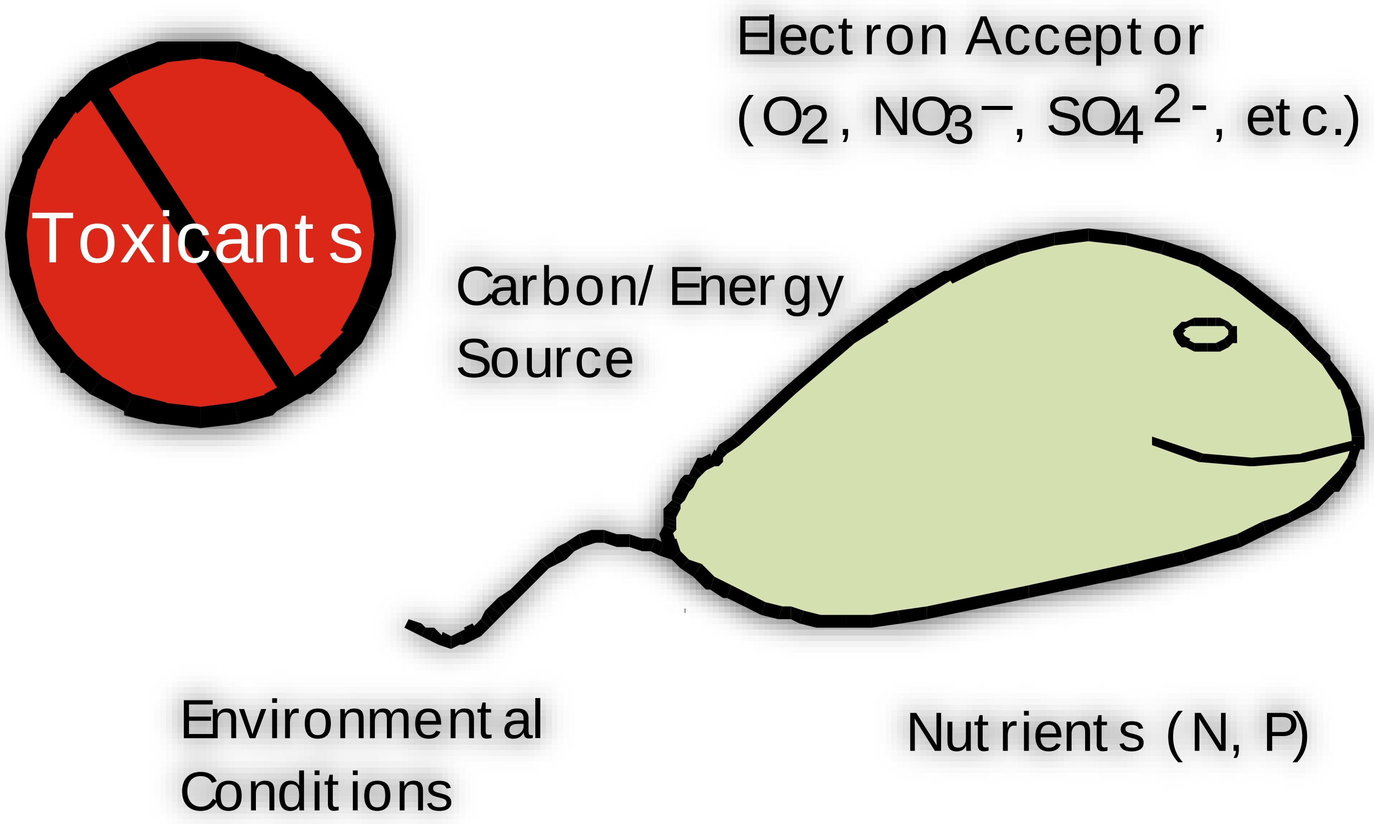
- Using subsurface microorganisms to transform petroleum hydrocarbons into harmless byproducts, such as carbon dioxide and water
- Techniques or types of bioremediation:
  - A component of Natural Attenuation (Not fast enough, Not complete enough – 16 % of 40 ppm degraded in 5 years (Shieh & Peralta 2005)
  - Enhanced Bioremediation- stimulate/enhance microbial growth



Addition of electron acceptors/adequate nutrients

Lack of proper condition to survive & growth

Requirements of Enhanced Bioremediation



Electron Acceptor

(O_2, NO_3^-, SO_4^{2-}, etc.)

Carbon/ Energy Source

Environmental Conditions

Nutrients (N, P)

O_2 = +820

Reaction for Benzene

$$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$$

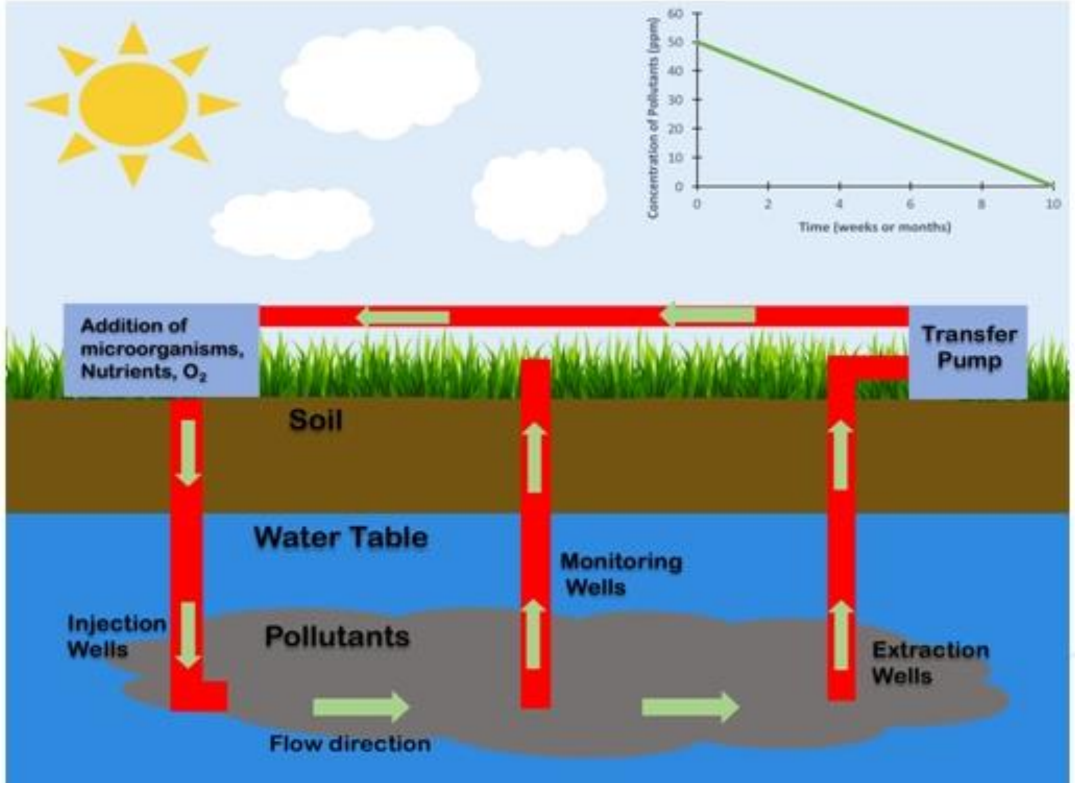
Reaction for Toluene

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$$

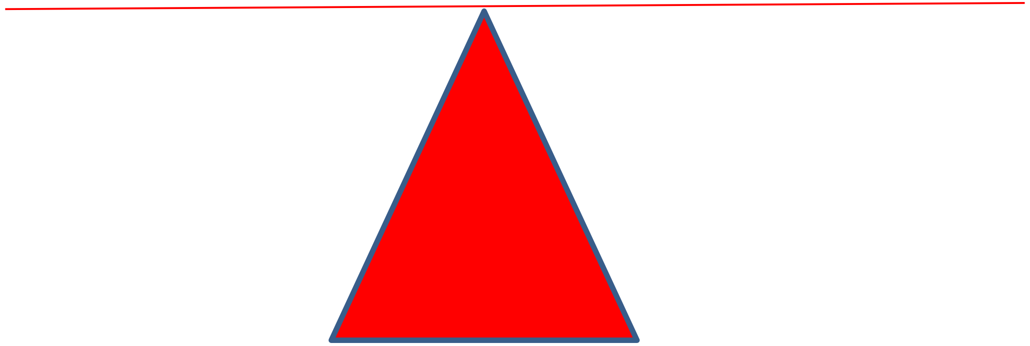
Reaction for Ethylbenzene and Xylene

$$C_8H_{10} + 10.5O_2 \rightarrow 8CO_2 + 5H_2O$$

Bioremediation system design issues



- What is ideal location and number of wells (Injection/extraction /monitoring)
- What are the optimum pumping rates?
- What would be the system/ operational cost?



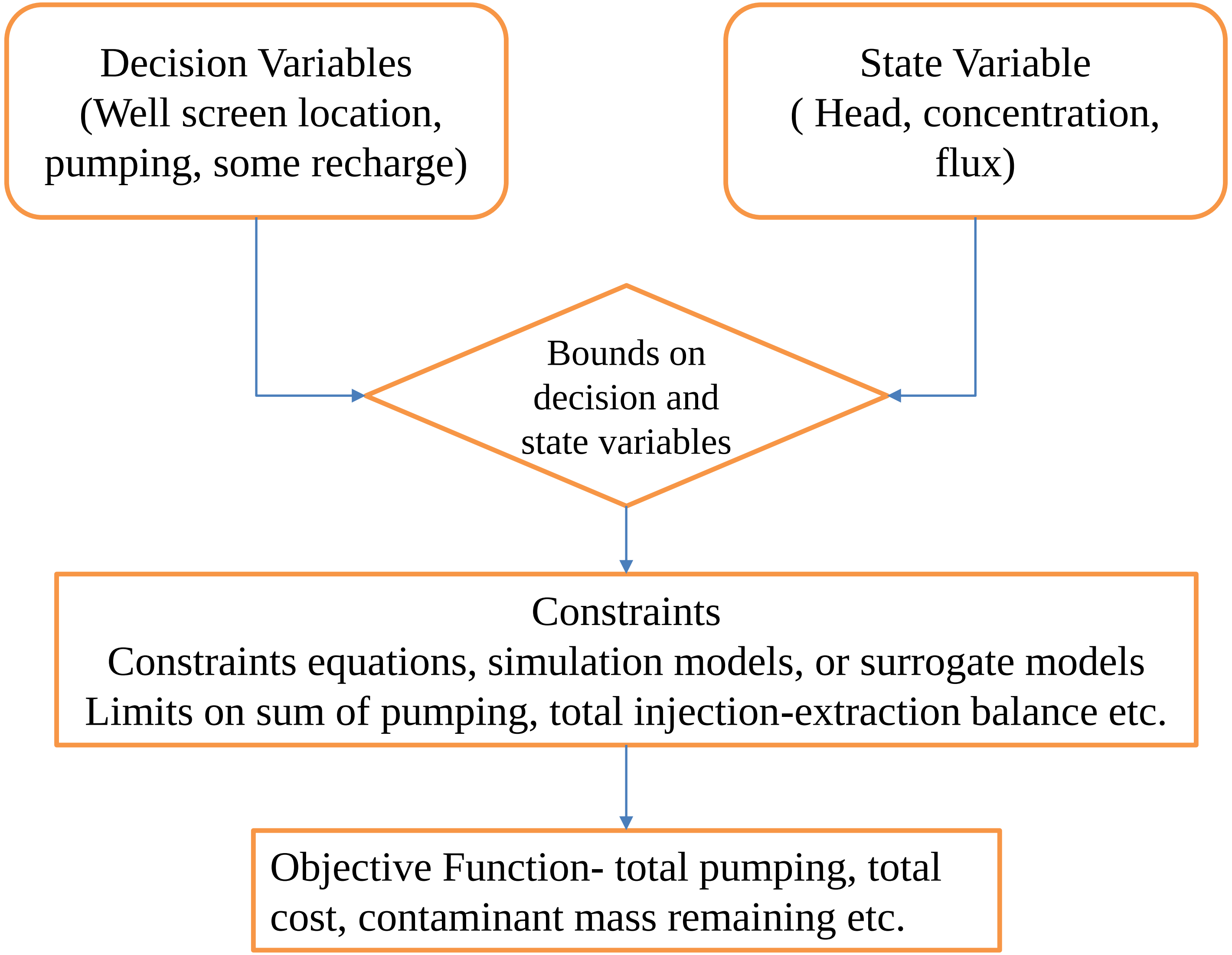
Toxicological Risk

Ecosystem Impact

How do we weigh it?

- **Goal**-to provide water for human activities- other species and prerequisite ecosystem- Extended to consider laws, regulations, needs, costs, and benefits

Optimization component in Groundwater System Design



Decision Variables
(Well screen location,
pumping, some recharge)

State Variable
(Head, concentration,
flux)

Bounds on
decision and
state variables

Constraints
Constraints equations, simulation models, or surrogate models
Limits on sum of pumping, total injection-extraction balance etc.

Objective Function- total pumping, total cost, contaminant mass remaining etc.

Simulation of in-situ Groundwater System

Technique	Summary/recommendations
Physically based models- BIOPLUME III, MODEFLOW, HYDRUS, SEAWAT	
➢ Captures the process completely and used as a physical simulator	
➢ Requires many parameters	
➢ Time consuming when requires multiple recalling in case of optimization	
➢ Problem of source code	
Data based models- ANN, SVM, ELM	
➢ Very few parameters requires to develop them	
➢ Simulation is very quick and can be used in simulation-optimization as code is available	
➢ Requires large number of data to be trained effectively	

BIOPLUME III

- Simulate- aerobic and anaerobic biodegradation with advection, dispersion, sorption.

$$\frac{\partial (bC_s)}{\partial t} = \frac{1}{R_s}\left[\frac{\partial}{\partial x_j}\left(bD_{ij}\frac{\partial C_s}{\partial x_j}\right) - \frac{\partial (bC_s v_i)}{\partial x_i}\right] - \frac{qC'_s}{\theta}$$

$$\frac{\partial (bC_o)}{\partial t} = \left[\frac{\partial}{\partial x_j}\left(bD_{ij}\frac{\partial C_o}{\partial x_j}\right) - \frac{\partial (bC_o v_i)}{\partial x_i}\right] - \frac{qC'_o}{\theta}$$

- Instantaneous reaction kinetics (Borden and Bedient, 1986).

1. How long will the plume extend if no engineered/source controls are implemented?

2. How long will the plume persist until natural attenuation processes completely dissipate the contaminants?

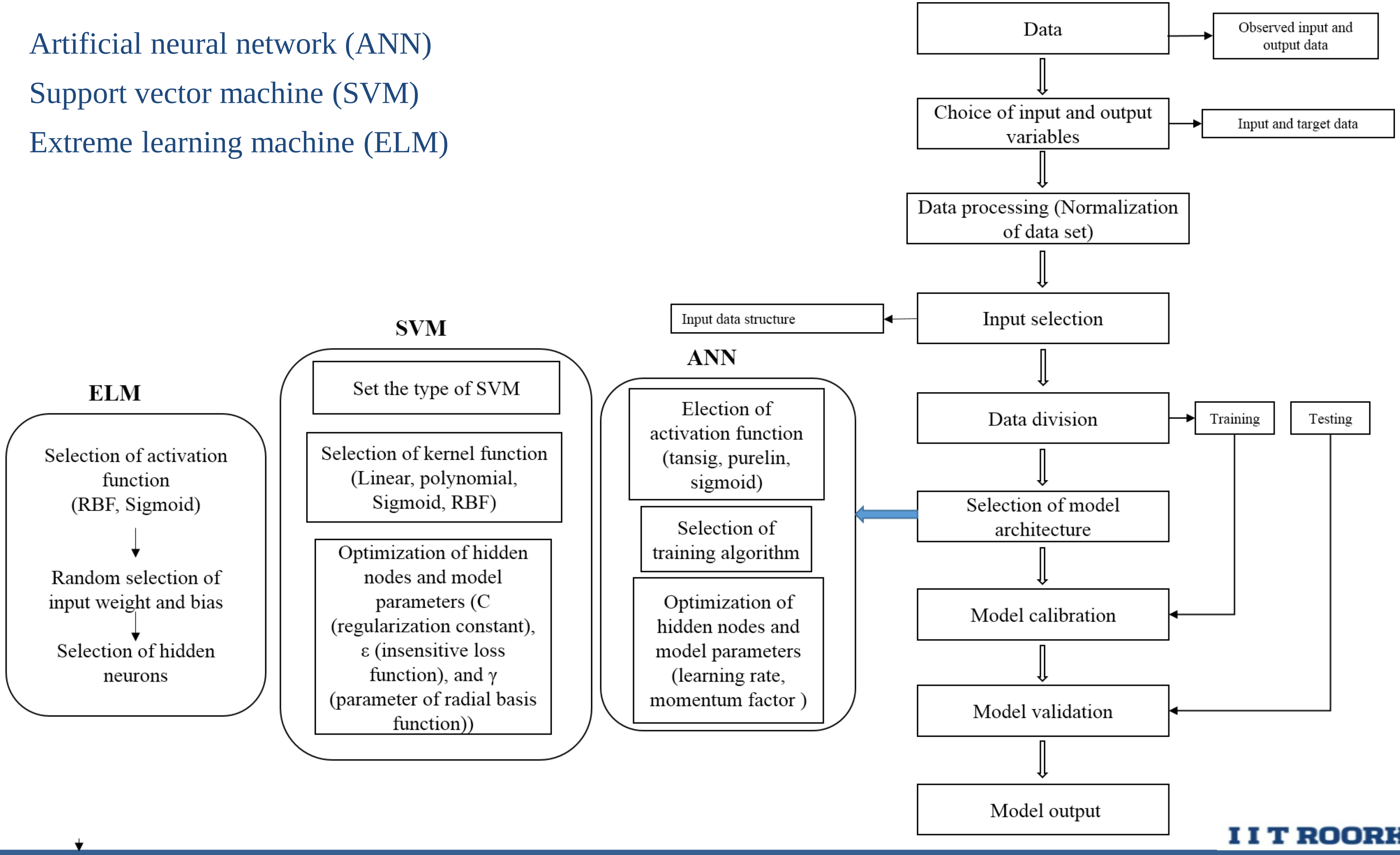
3. How long will the plume extend or persist if some engineered controls or source reduction measures are undertaken (for example contamination removal)?

Types of data based models

Artificial neural network (ANN)

Support vector machine (SVM)

Extreme learning machine (ELM)



Data → Observed input and output data

Choice of input and output variables → Input and target data

Data processing (Normalization of data set)

Input selection → Input data structure

Data division → Training, Testing

Selection of model architecture

Model calibration

Model validation

Model output

ELM

Selection of activation function (RBF, Sigmoid)

Random selection of input weight and bias

Selection of hidden neurons

SVM

Set the type of SVM

Selection of kernel function (Linear, polynomial, Sigmoid, RBF)

Optimization of hidden nodes and model parameters (C (regularization constant), ε (insensitive loss function), and γ (parameter of radial basis function))

ANN

Election of activation function (tansig, purelin, sigmoid)

Selection of training algorithm

Optimization of hidden nodes and model parameters (learning rate, momentum factor)

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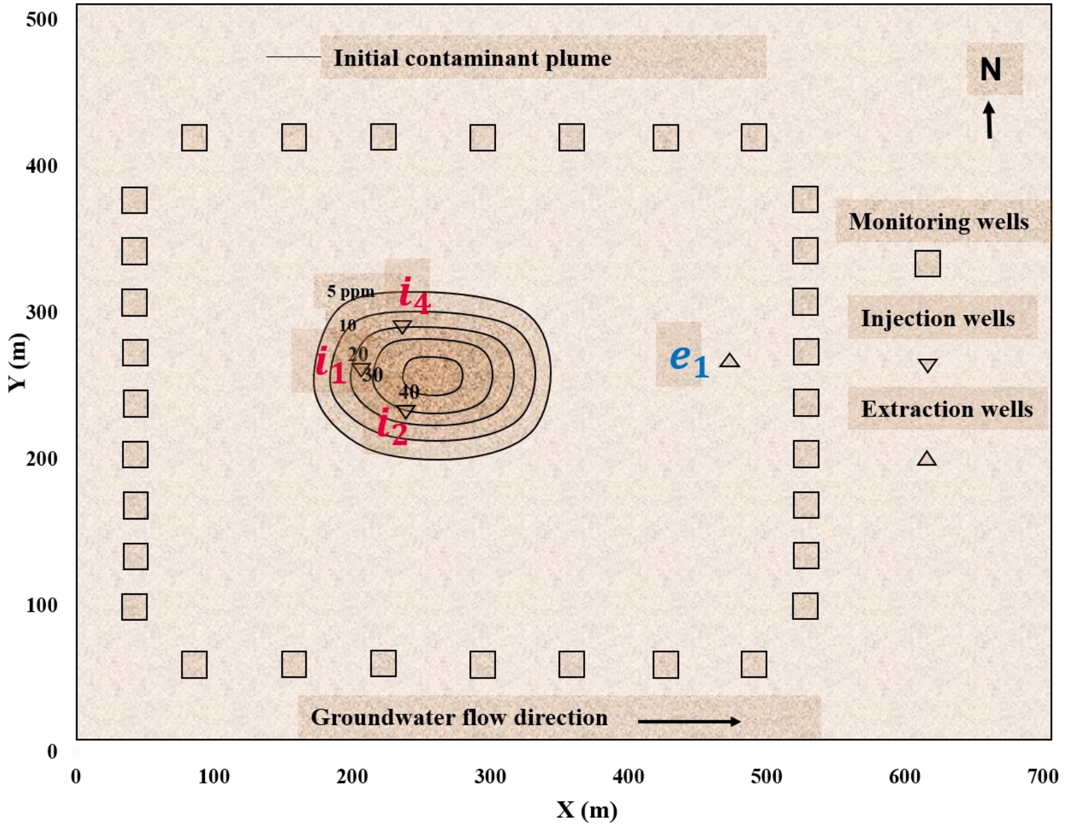
Remediation system design using Simulation-optimization approach

Initial concentration – 40 ppm

3 years

Permissible concentration – 5 ppm



Requirements and Constraints

Simulation code or other data source

BIOPLUME III

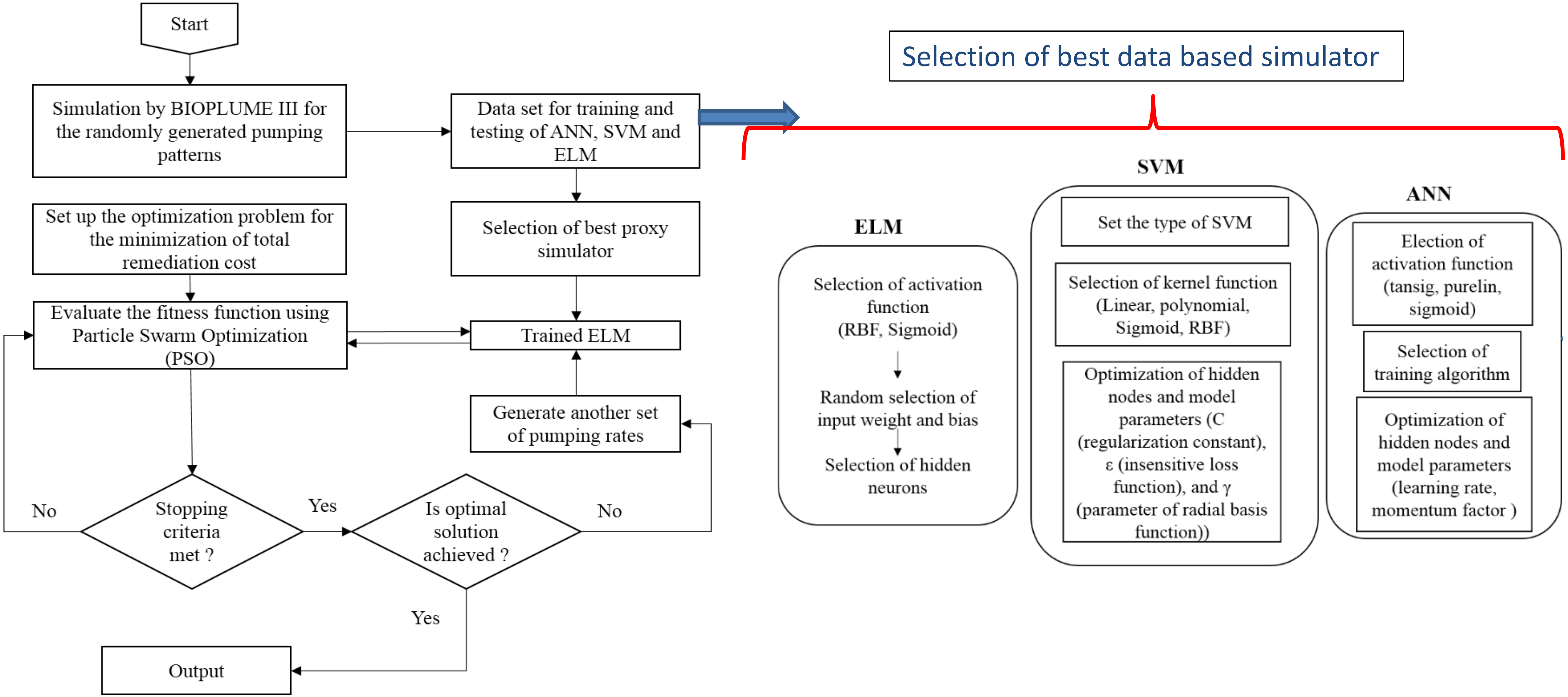
Input and output combinations
For data based models
(ANN, SVM, ELM)

Response surface for optimization

New pumping rates

Yadav, B., Ch, S., Mathur, S., & Adamowski, J. (2016). Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. ***Journal of Hydrology***, 543, 373-385.

Simulation-optimization approach with data based simulator



Start

Simulation by BIOPLUME III for the randomly generated pumping patterns

Data set for training and testing of ANN, SVM and ELM

Selection of best proxy simulator

Set up the optimization problem for the minimization of total remediation cost

Evaluate the fitness function using Particle Swarm Optimization (PSO)

Trained ELM

Generate another set of pumping rates

Stopping criteria met ?

No

Yes

Is optimal solution achieved ?

No

Yes

Output

Selection of best data based simulator

ELM

- Selection of activation function (RBF, Sigmoid)
- Random selection of input weight and bias
- Selection of hidden neurons

SVM

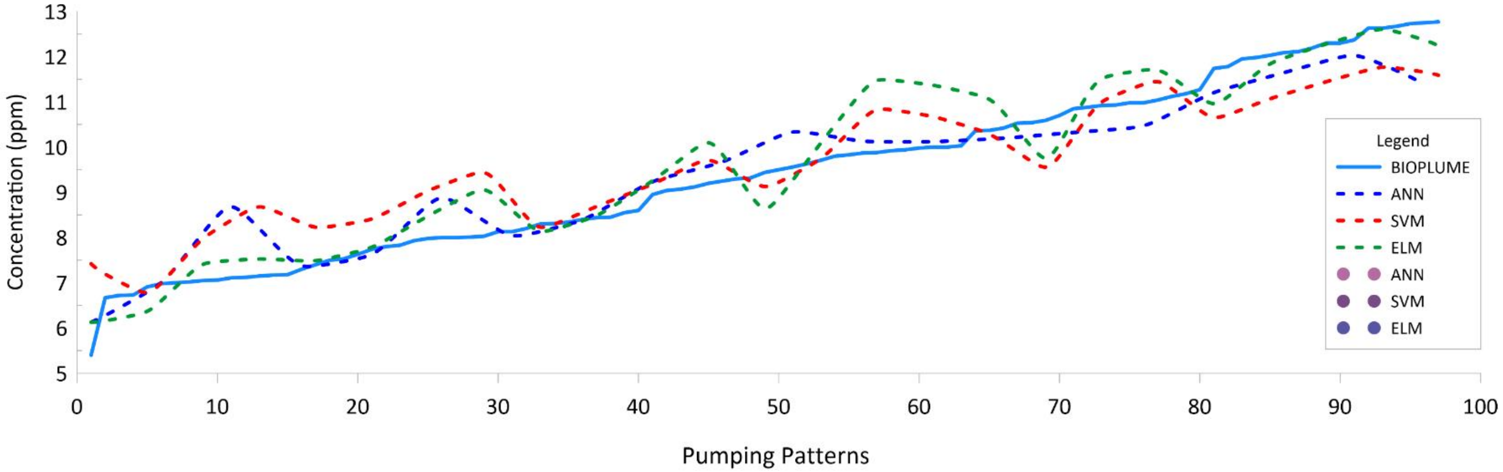
- Set the type of SVM
- Selection of kernel function (Linear, polynomial, Sigmoid, RBF)
- Optimization of hidden nodes and model parameters (C (regularization constant), ε (insensitive loss function), and γ (parameter of radial basis function))

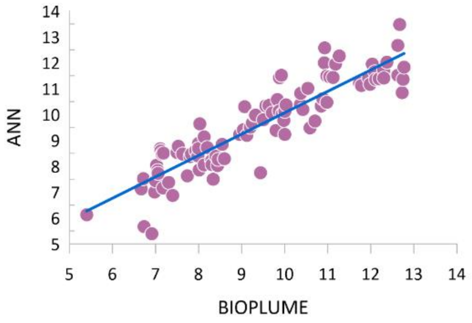
ANN

- Election of activation function (tansig, purelin, sigmoid)
- Selection of training algorithm
- Optimization of hidden nodes and model parameters (learning rate, momentum factor)

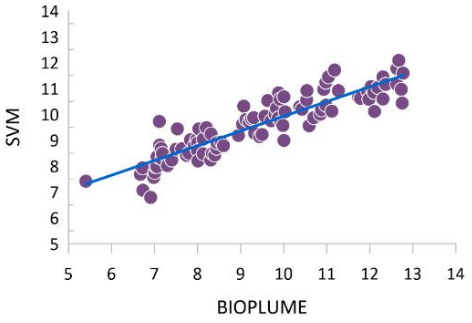
Yadav, B., Ch, S., Mathur, S., & Adamowski, J. (2016). Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. ***Journal of Hydrology***, 543, 373-385.

Comparison of ANN, SVM and ELM for the simulation of maximum allowable Concentration

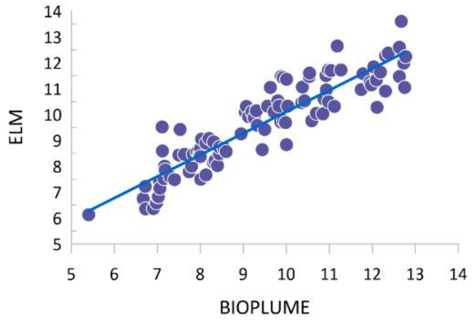




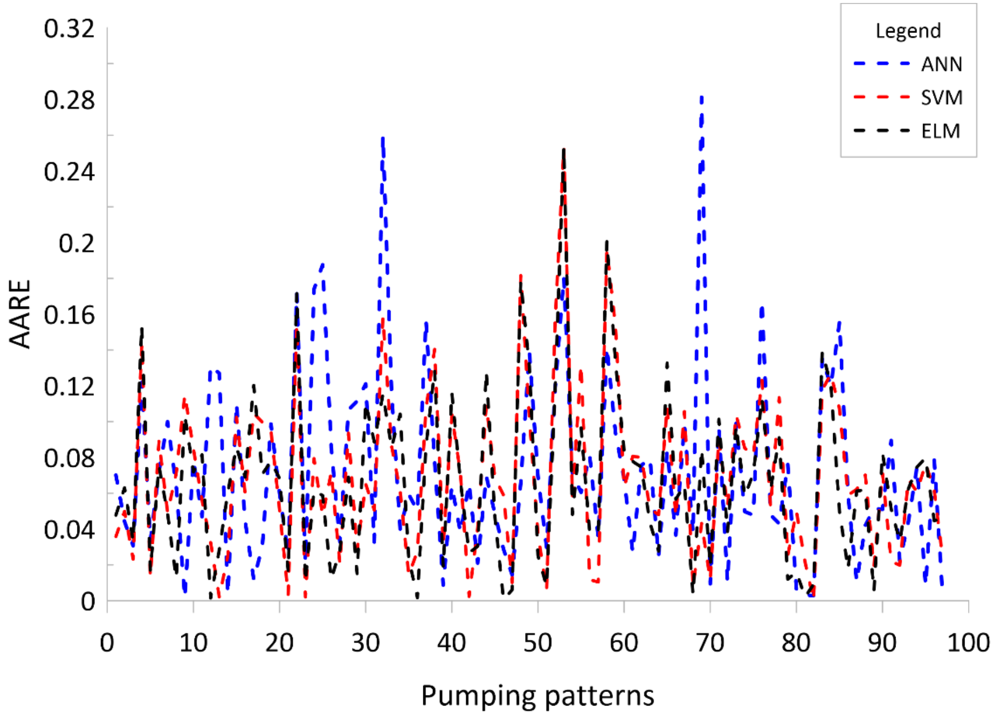
Coefficient of determination, R-sq'd = 0.8199866
Correlation coefficient, R = 0.9055311



Coefficient of determination, R-sq'd = 0.8089238
Correlation coefficient, R = 0.8994019



Coefficient of determination, R-sq'd = 0.8243671
Correlation coefficient, R = 0.9079466



Yadav, B., Ch, S., Mathur, S., & Adamowski, J. (2016). Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. ***Journal of Hydrology***, 543, 373-385.

Minimize the design and operational cost

Cost Coefficient	Numerical Value
Discount rate	0.05
Injection cost, which include oxygen, nutrient and pumping operation	4,755 ($ per lps-yr)
extraction cost, it include treatment and pumping operation	15,850 ($ per lps-yr)
well installation cost	12,000 ($ per well)
injection facility cost	$D_{1.26\ lps}$ = $ 20,000
treatment facility capital cost	$E_{1.26\ lps}$ = $ 30,000

$$Minimize\ F = \sum_{k=1}^{T}\left(\frac{1}{(1+i_r)^k}\right)\sum_{x=1}^{Nw} C^q(x)q(x,k) + \sum_{x=1}^{Nw} C^{IP}(x)IP(x)$$

$$+Max\left\{D\left(\sum_{x=1}^{Nw^i} q(x,k)\right)\right\}_{k=1}^{T}$$

$$+\ Max\left\{E\left(\sum_{x=1}^{Nw^e} q(x,k)\right)\right\}_{k=1}^{T}$$

Simulation-Optimization approach ELM-PSO

Contaminant concentration

$$0 \le C_s^T(j_0) \le C_{max}(j_0) \quad \forall j_0 \in \Phi$$

$$0 \le C_s^k(j_0) \le C_{max}(j_0) \quad k = 1, \dots, T \quad \forall j_0 \in \psi$$

Hydraulic heads

$$h^k(j_0) \le h^{max}(j_0)\ k = 1, \dots, T \quad \forall j_0 \in \Phi$$

$$h^{min}(j_0) \le h^k(j_0)\ k = 1, \dots, T \quad \forall j_0 \in \Phi$$

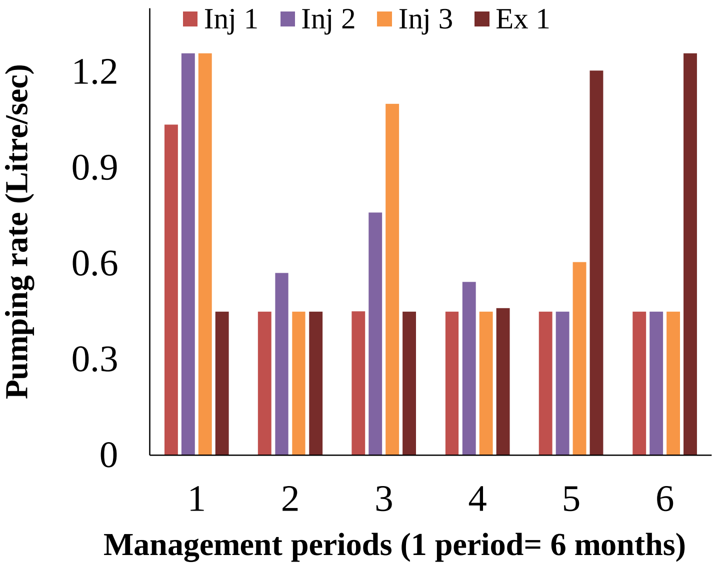
Extraction rate and injection rate

$$0 \le q_{ex}^k \le q_{ex}max^k \quad k = 1, \dots, T$$

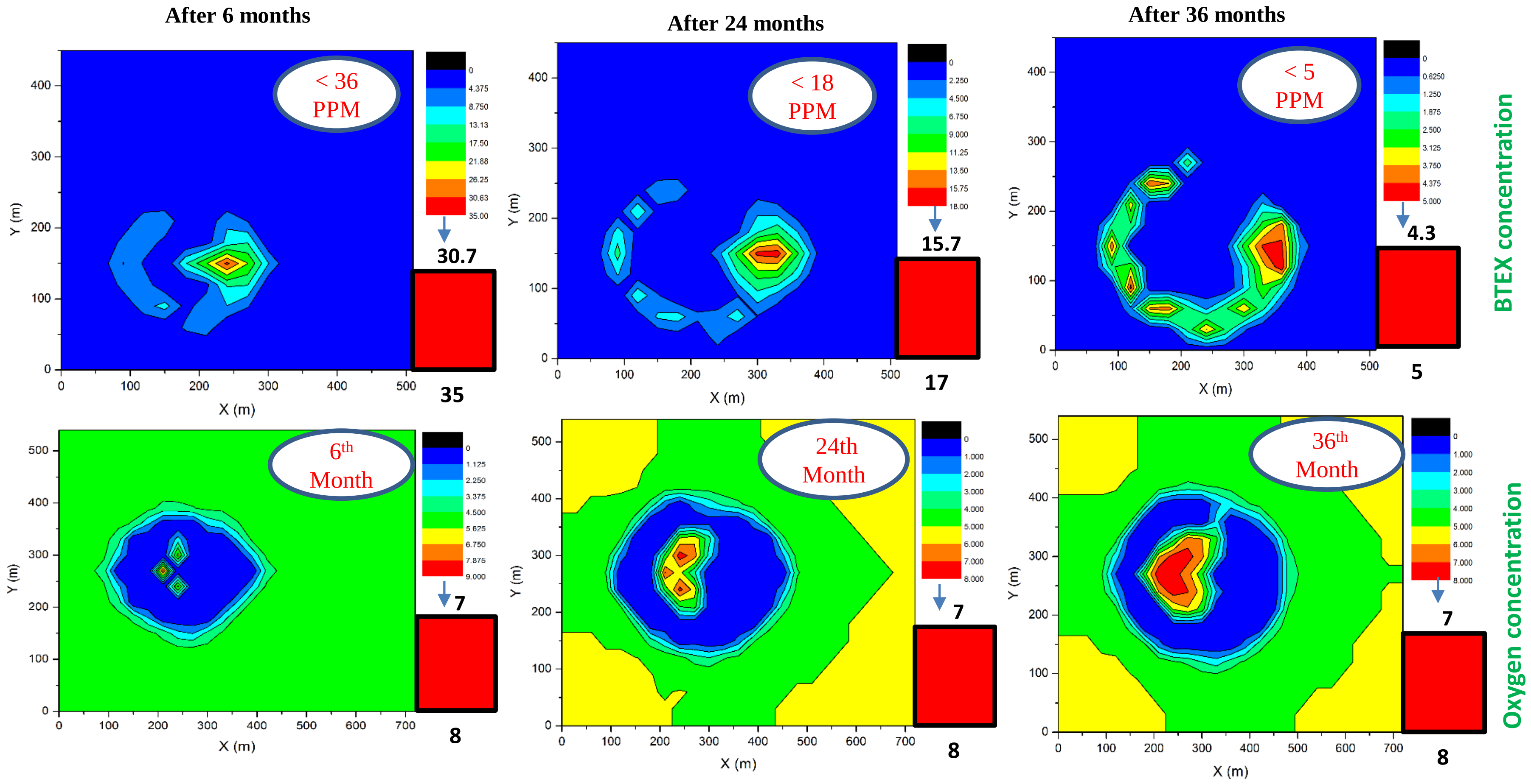
$$0 \le q_{ix}^k \le q_{ix}max^k \quad k = 1, \dots, T$$

Yadav, B., Ch, S., Mathur, S., & Adamowski, J. (2016). Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. ***Journal of Hydrology***, 543, 373-385.

Optimized pumping rates, BTEX-Oxygen concentration and cost for remediation



Maximum injection/extraction rate is 1.26 Litre/Sec

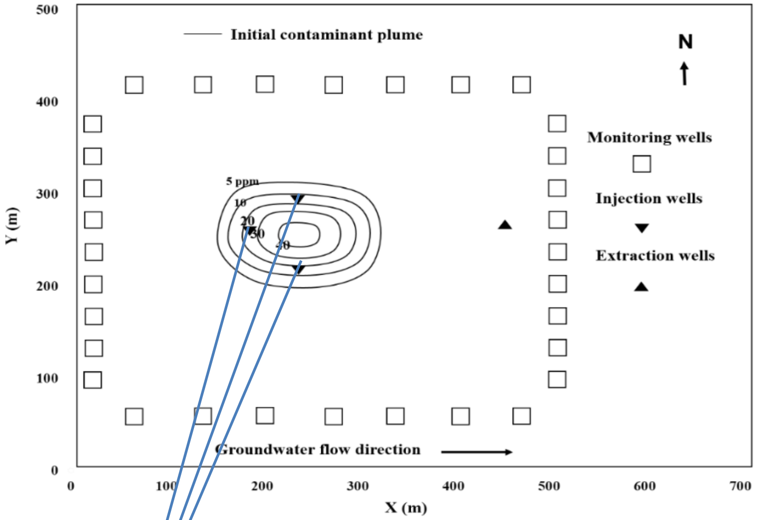


Simulation-Optimization algorithm	Pumping strategy	Number of wells	Total cost ($)
ELM-PSO	**Time varying**	i_1, i_2, i_4, e_1	**158,229**

Yadav, B., Ch, S., Mathur, S., & Adamowski, J. (2016). Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. ***Journal of Hydrology***, 543, 373-385.

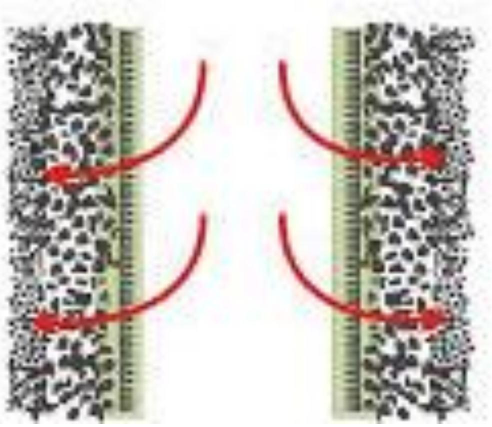
Consideration of well clogging in remediation cost estimation

Consideration of Well clogging



Three injection wells

Consideration of Well clogging



Biological clogging

Enhanced biodegradation by biological, chemical and physical processes

Changes in hydrodynamic and transport properties

clogging, i.e., the reduction of porosity and permeability

Reduction in efficiency or failure of the system (Wu et al., 2006, 2010, 2013)

Time overrun

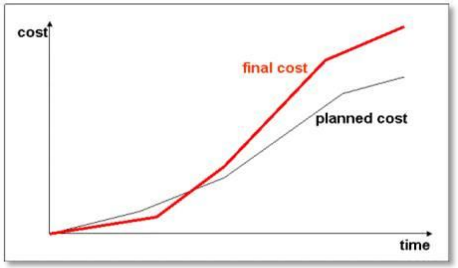
Increase the injection rates
(Shieh and Peralta 2006)

Additional cost/ aquifer capacity

Clean the clogging
(Wu et al., 2006, 2010, 2013)

Additional cost

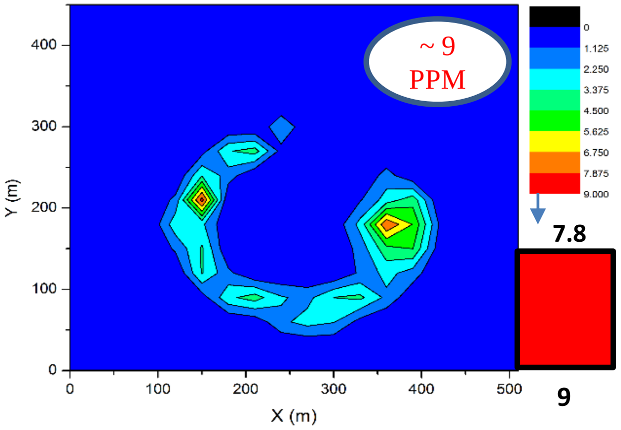
Cleaning frequency depends on injection rates



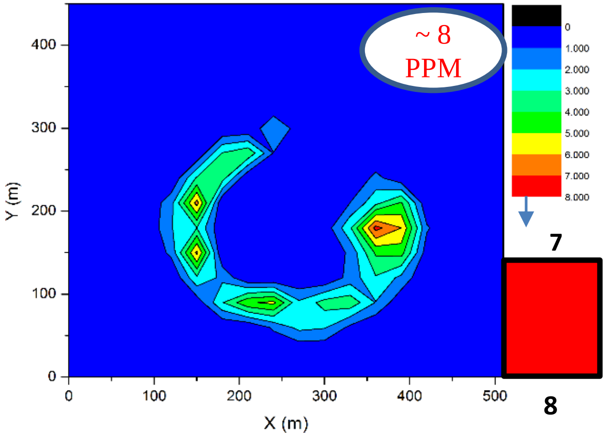
Yadav, B., Mathur, S., & Yadav, B. K. (2018). Simulation-Optimization Approach for the Consideration of Well Clogging during Cost Estimation of In Situ Bioremediation System. ***Journal of Hydrologic Engineering***, 23(3), 04018001.

Optimal system design with well clogging assumed to the extreme case

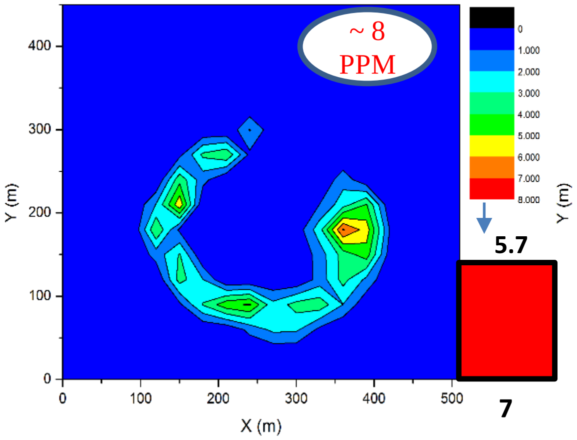
BTEX concentrations



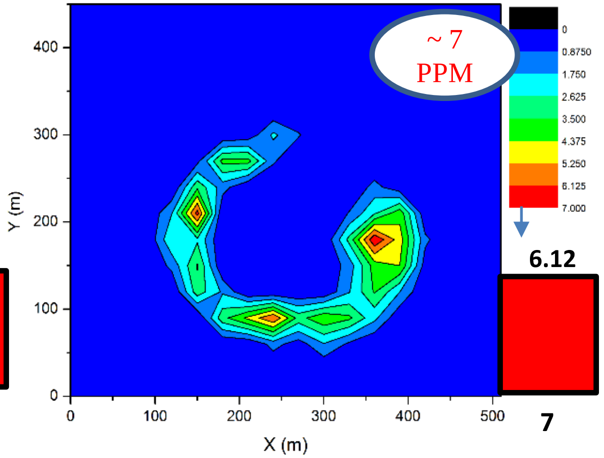
Well 1 fails after 24 months



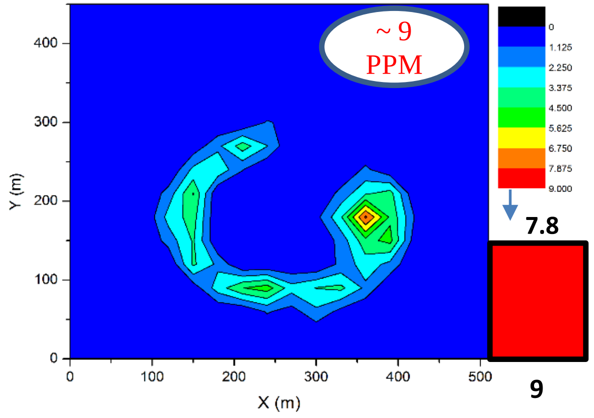
Well 1 fails after 30 months



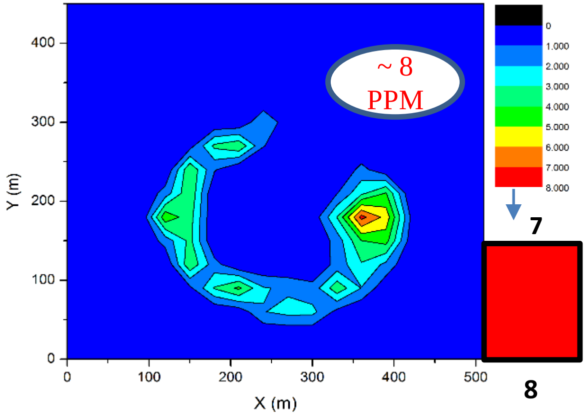
Well 3 fails after 24 months



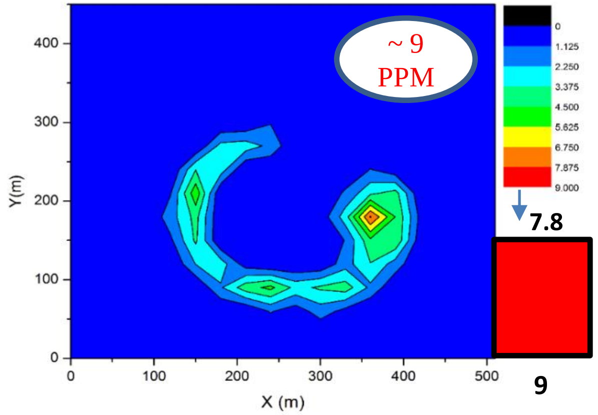
Well 3 fails after 30 months



Well 2 fails after 24 months



Well 2 fails after 30 months



All three wells fails after 30 months

Yadav, B., Mathur, S., & Yadav, B. K. (2018). Simulation-Optimization Approach for the Consideration of Well Clogging during Cost Estimation of In Situ Bioremediation System. ***Journal of Hydrologic Engineering***, 23(3), 04018001.

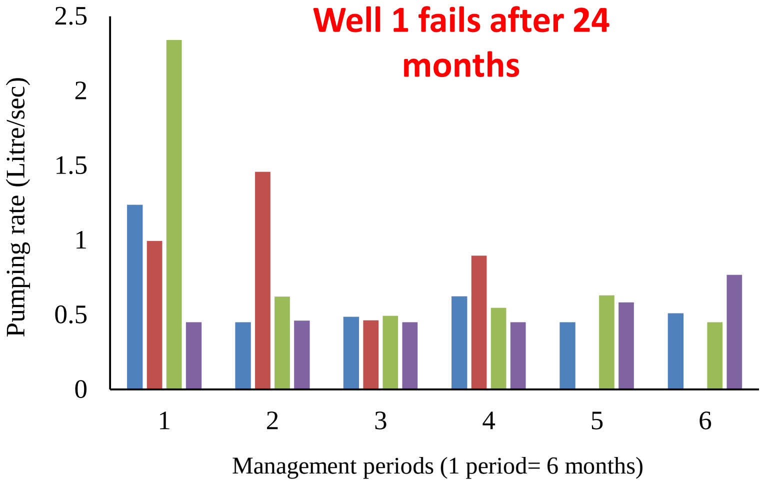
The objective function- if increase of injection rates is the option

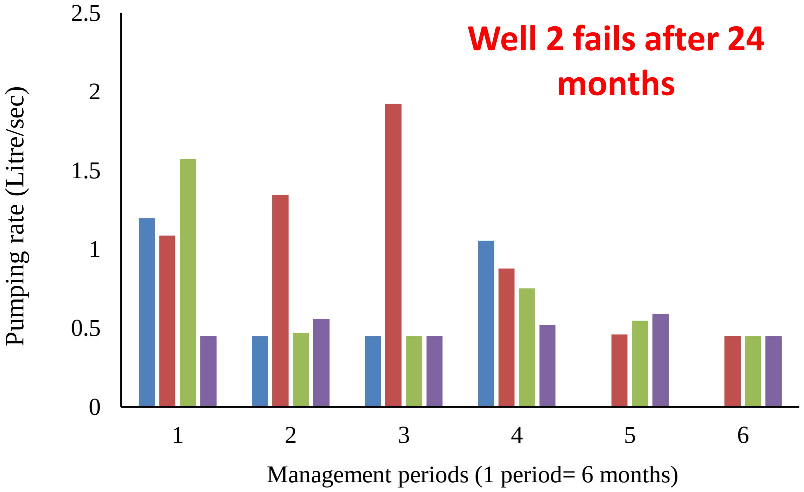
$$Minimize\ Z = \sum_{k=1}^{T}\left(\frac{1}{(1+i_r)^k}\right)\sum_{x=1}^{Nw} C^q(x)q(x,k) + \sum_{x=1}^{Nw} C^{IP}(x)IP(x) + Max\left\{D\left(\sum_{x=1}^{Nw^i} q(x,k)\right)\right\}_{k=1}^{T}$$

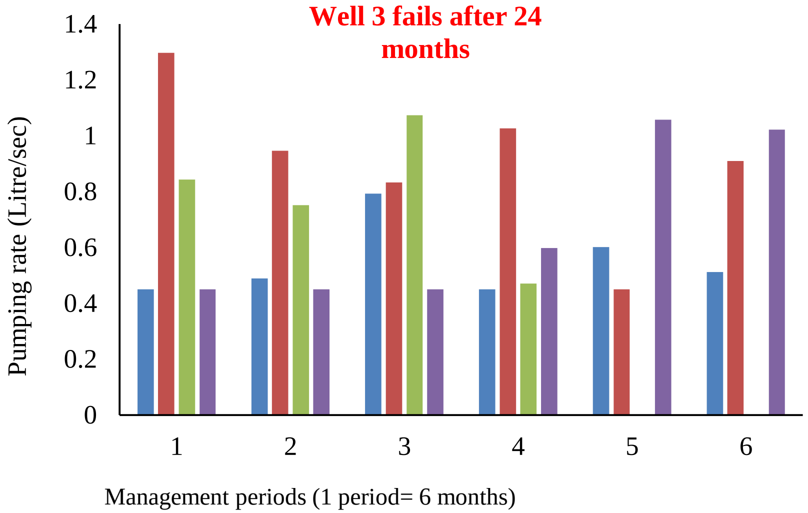
$$+Max\left\{E\left(\sum_{x=1}^{Nw^e} q(x,k)\right)\right\}_{k=1}^{T}$$

Constraints relaxed- $0 \le q_{ix}^{k} \quad k = 1, \dots, T$

If increase of injection rates is the option







Maximum injection/extraction rate is >1.26 Litre/Sec

The objective function- if cleaning is the option

$$Minimize\ Z = \sum_{k=1}^{T}\left(\frac{1}{(1+i_r)^k}\right)\sum_{x=1}^{Nw} C^q(x)q(x,k) + \sum_{x=1}^{Nw} C^{IP}(x)IP(x) + Max\left\{D\left(\sum_{x=1}^{Nw^i} q(x,k)\right)\right\}_{k=1}^{T}$$

$$+Max\left\{E\left(\sum_{x=1}^{Nw^e} q(x,k)\right)\right\}_{k=1}^{T} + Max\left\{CL\left(\sum_{x=1}^{Nw^i} q(x,k)\right)\right\}_{k=1}^{T}$$

- $CL\left(\sum_{x=1}^{Nw^i} q(x,k)\right)$= Well cleaning cost which is a function of the total injection rate ($)
- Material cost and Pump cost were added in the well installation cost as it is a constant value

The cost factor and optimized cost

Approximate cost for the cleaning of well by surge block method

Factor	Cost
Material cost	\$150/block
Pump cost	\$2000
Average wage rate (Bureau of Labour Statistics, 2016)	\$25.61/hr

Cost function coefficient 'CL' (excluding instrument and material cost)

Coefficient	Value with frequency of cleaning for one well
CL (cleaning cost)	$C_{0\text{-}3.78\ L/s}$ = \$921.96 (6 times/year) $C_{3.78\text{-}6.30\ L/s}$ = \$614.64 (4 times/year) $C_{6.30\text{-}8.82\ L/s}$ = \$460.98 (3 times/year)

The objective function- if increase of injection rates is the option

Comparison of total remediation cost for time varying pumping strategy for the possibility of well failure due to extreme well clogging.

Optimization algorithm	Pumping strategy	Number of wells	Total cost ($)
(Shieh and Peralta, 2005)	Time varying	i_1, i_2, i_4, e_1	163,300
(Kumar et al., 2013)	Time varying	i_1, i_2, i_4, e_1	160,684
ELM-PSO	**Time varying**	$\boldsymbol{i_1, i_2, i_4, e_1}$	**158,229**
ELM-PSO (with cleaning)	**Time varying**	$\boldsymbol{i_1, i_2, i_4, e_1}$	**160, 503**

- The study suggest that the cleaning of the injection well is the best choice.
- The cost obtained is higher than what was projected in the earlier studies, however with this system the cost is more realistic and feasible.

Yadav, B., Mathur, S., & Yadav, B. K. (2018). Simulation-Optimization Approach for the Consideration of Well Clogging during Cost Estimation of In Situ Bioremediation System. ***Journal of Hydrologic Engineering***, 23(3), 04018001.

Role of groundwater fluctuations and environmental parameters on bioremediation

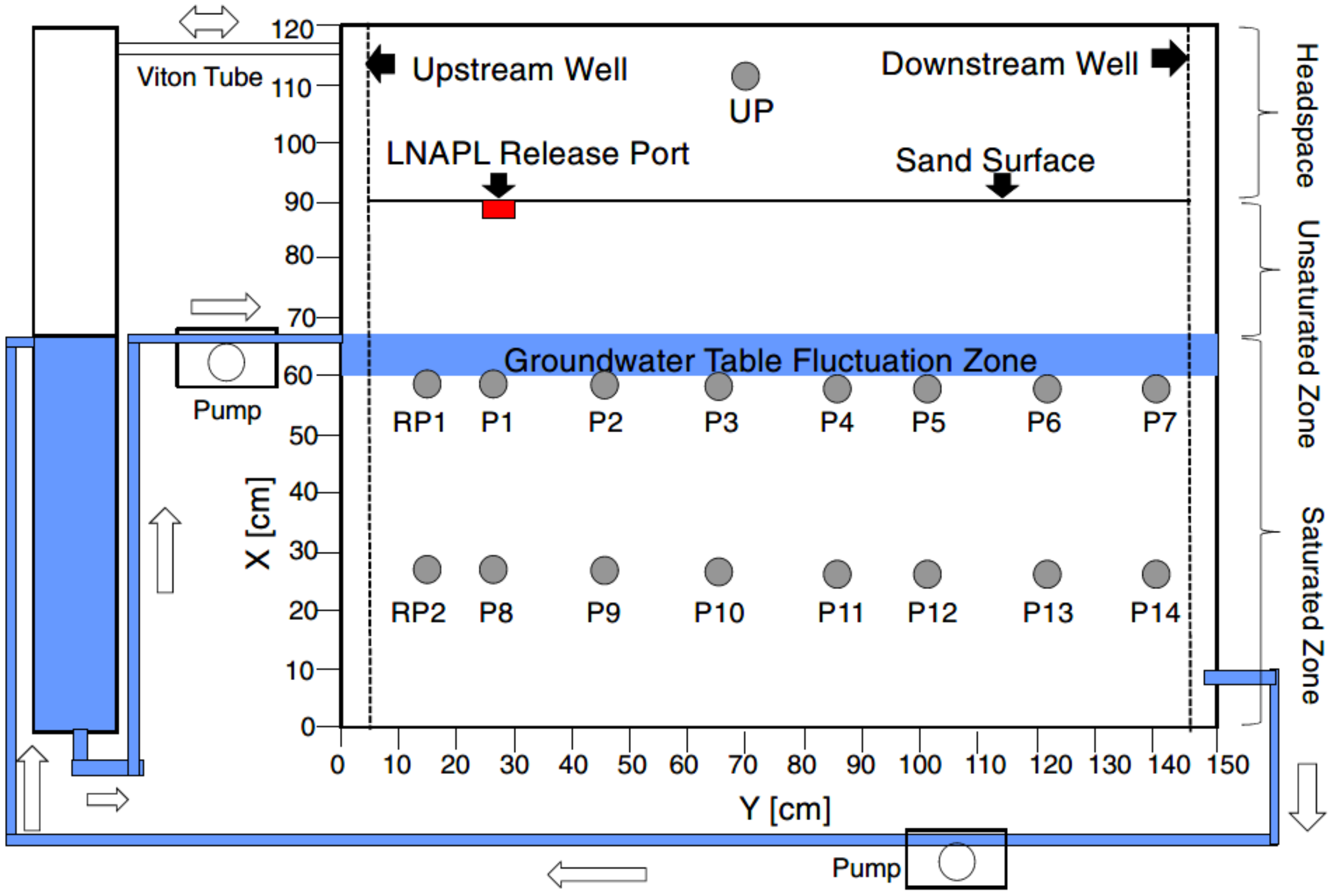
-How groundwater table fluctuations affect the toluene plume?

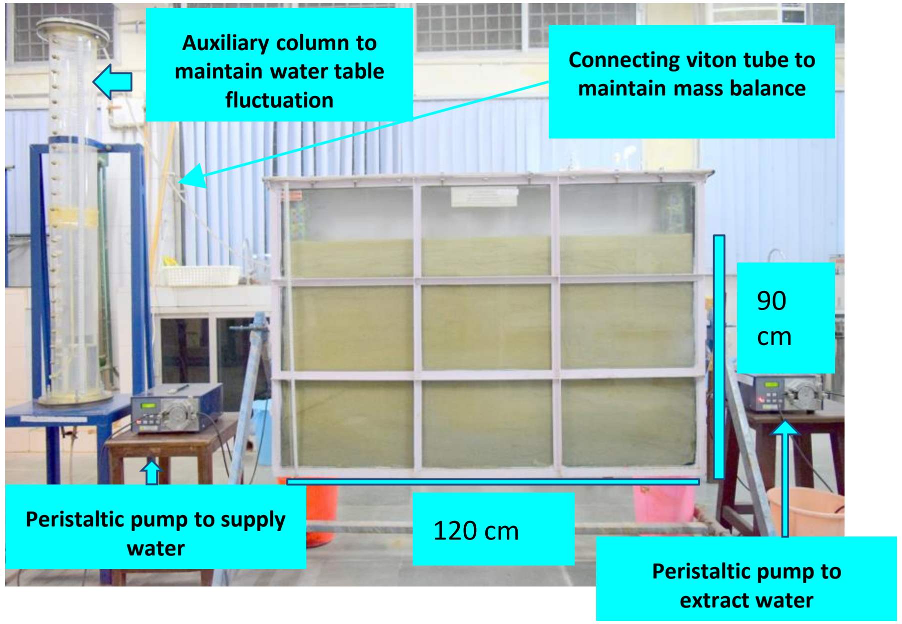
-Is there any impact on biodegradation rates?

-Toluene concentration and microbial growth.

- Soil moisture and temperature.

Experimental setup and selected level of fluctuations




Auxiliary column to maintain water table fluctuation

Connecting viton tube to maintain mass balance

90 cm

Peristaltic pump to supply water

120 cm

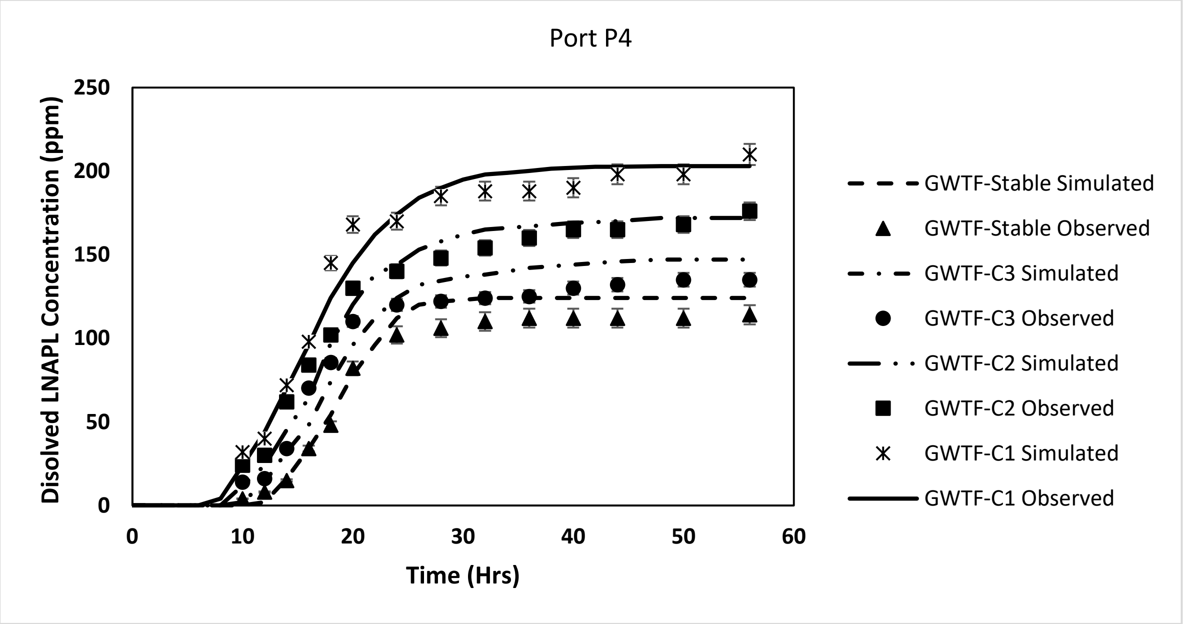
Peristaltic pump to extract water

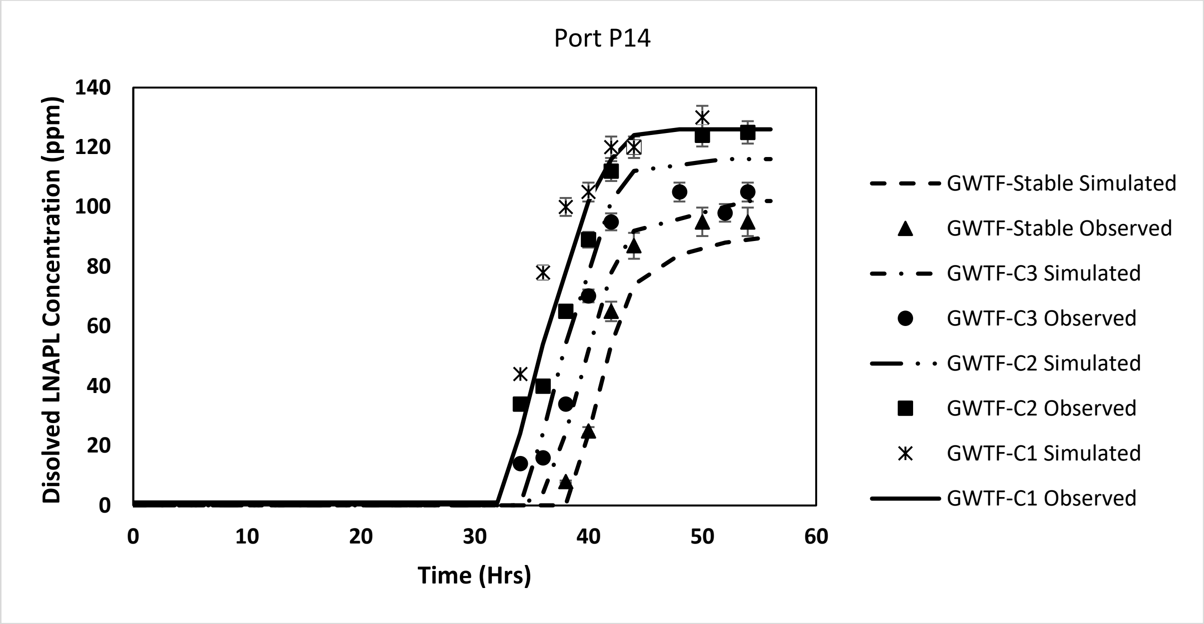
Selected level of fluctuations and pumping rates

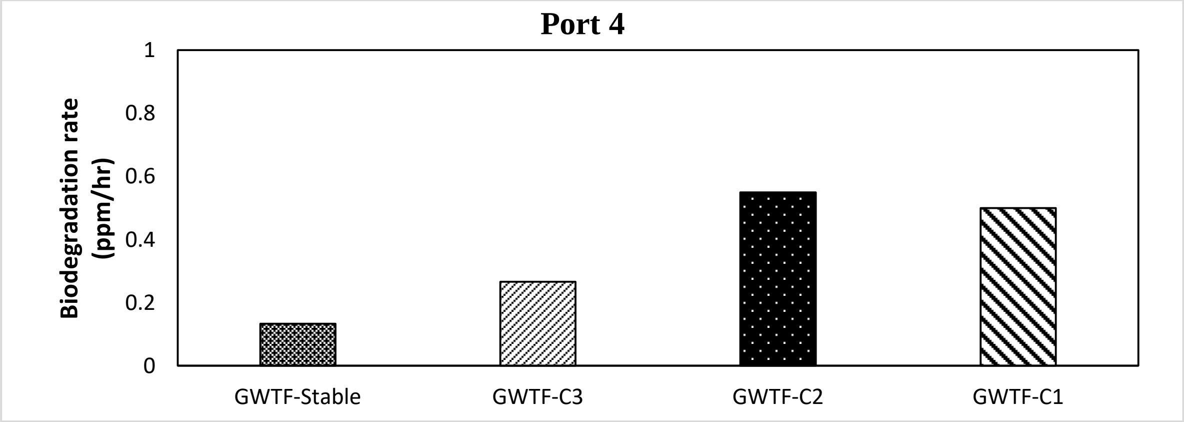
	Conditions	Inflow pumping		Outflow pumping		Total duration (h)	Pumping rate (mL/h)
		Rise (h)	Fall	Rise	Fall (h)		
C1	Rapid fluctuation	1	—	—	1	2	2,475.0
C2	General fluctuation	2	—	—	2	4	1,237.5
C3	Slow fluctuation	4	—	—	4	8	6,18.7

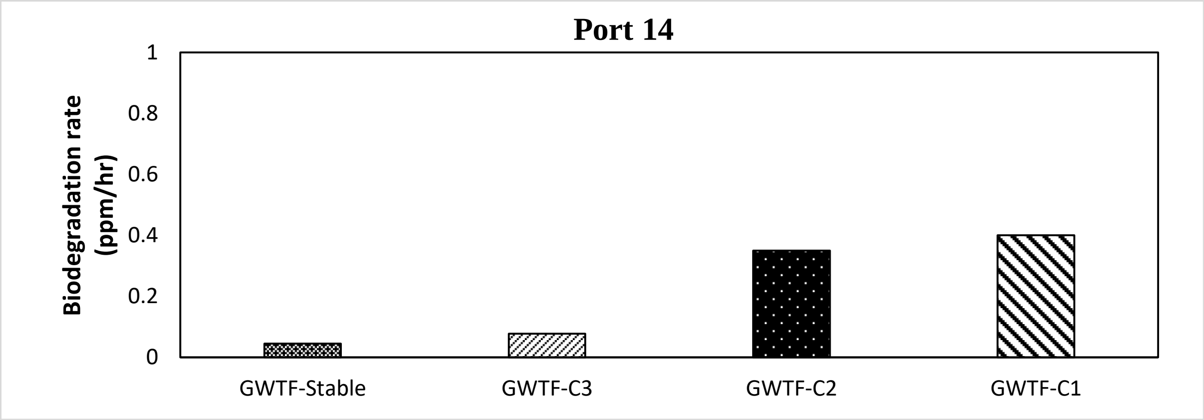
Gupta, P. K., **Yadav, B.**, & Yadav, B. K. (2019). Assessment of LNAPL in subsurface under fluctuating groundwater table using 2D sand tank experiments. ***Journal of Environmental Engineering***, *145*(9), 04019048.

Transport of dissolved LNAPL



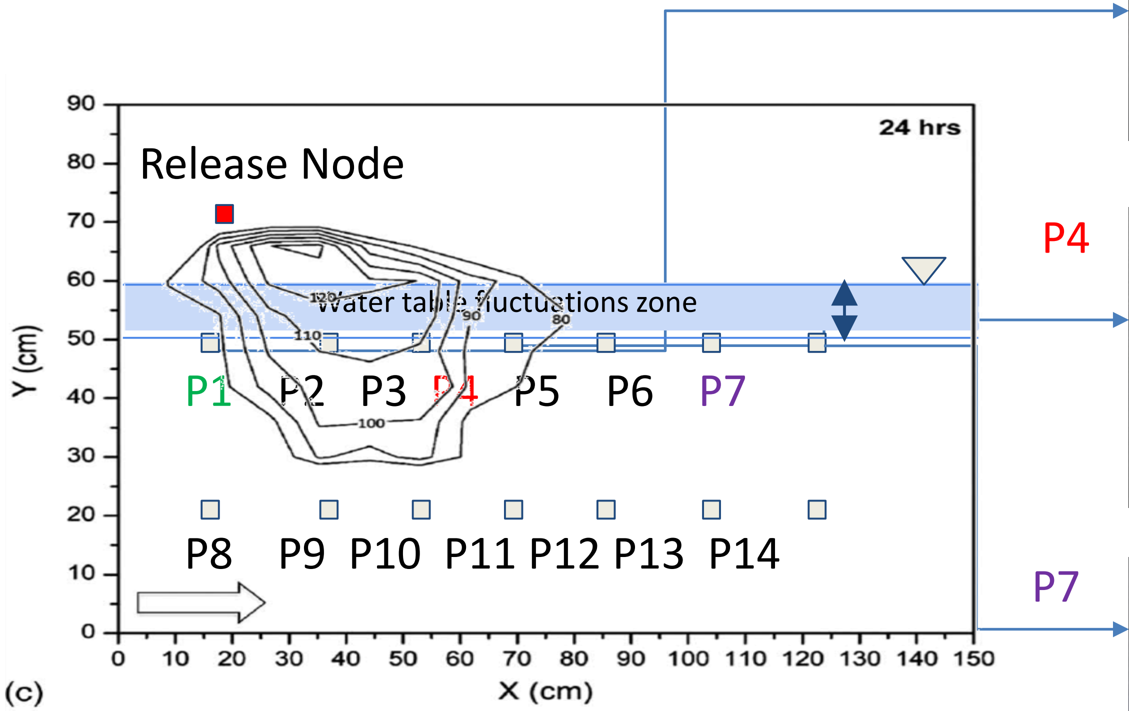




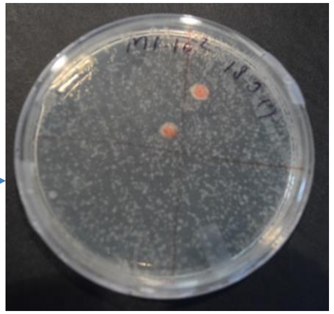


Gupta, P. K., **Yadav, B.**, & Yadav, B. K. (2019). Assessment of LNAPL in subsurface under fluctuating groundwater table using 2D sand tank experiments. ***Journal of Environmental Engineering***, *145*(9), 04019048.

Microbial growth at different locations

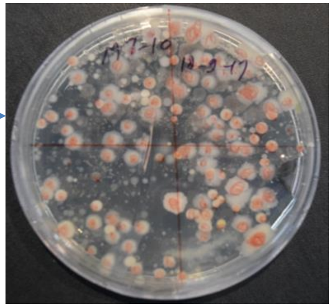


P1



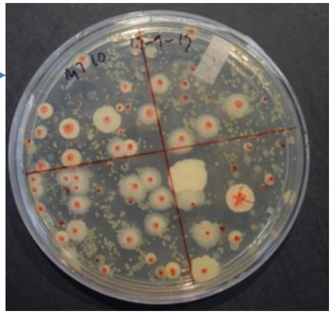
72 (10^4 CFU/mL)

P4

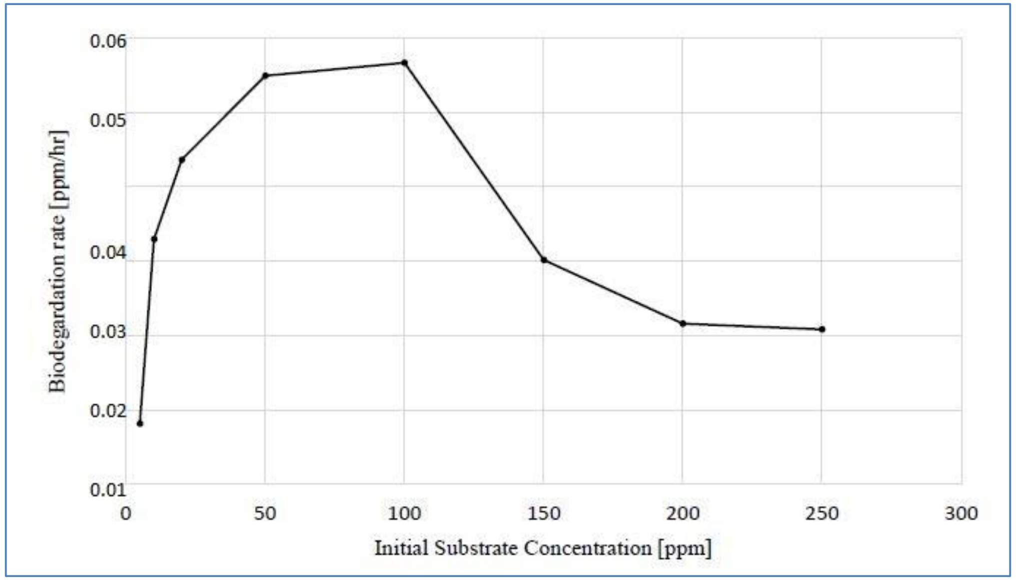


512 (10^4 CFU/mL)

P7



315.65 (10^4 CFU/mL)



Biodegradation rates

Gupta, P. K., **Yadav, B.**, & Yadav, B. K. (2019). Assessment of LNAPL in subsurface under fluctuating groundwater table using 2D sand tank experiments. ***Journal of Environmental Engineering***, *145*(9), 04019048.

Impact of various environmental conditions on biodegradation rate

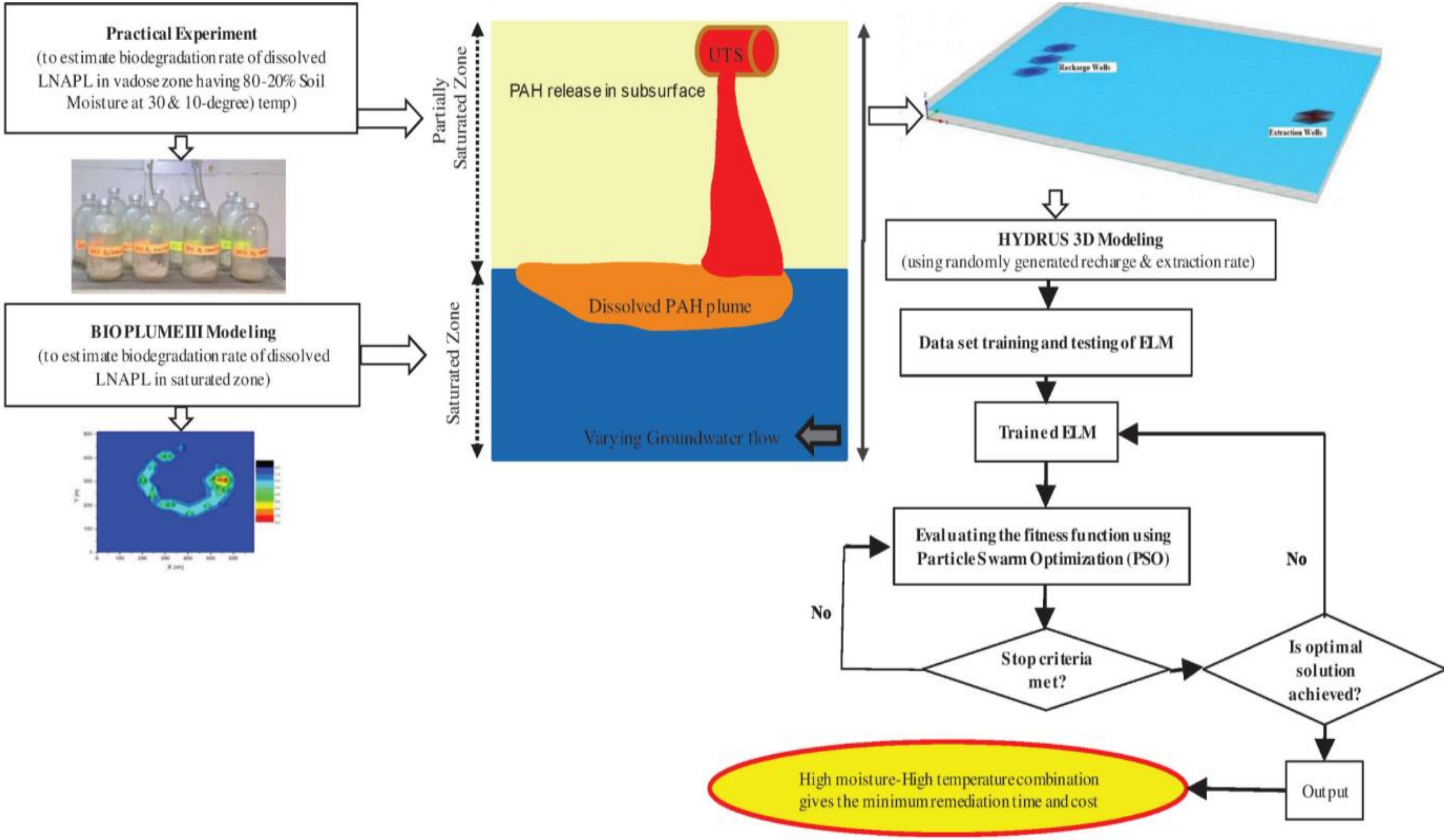
To estimate the biodegradation rate of dissolved Toluene moving towards groundwater through partially saturated zone having different soil moisture level under normal and cold environmental conditions

Batch system having different soil-moisture conditions.

Moisture Levels	Temperature	Total degradation time [hours] in batch system	Rate of Biodegradation [mg/L hr]
80%	10±0.5^{0}C	72	0.0025
	30±2^{0}C	42	0.0154
60%	10±0.5^{0}C	105	0.0018
	30±2^{0}C	75	0.0120
40%	10±0.5^{0}C	120	0.0010
	30±2^{0}C	84	0.0092
20%	10±0.5^{0}C	128	0.0008
	30±2^{0}C	90	0.0028

Yadav, B., Gupta, P., Yadav, B. K., (2021) Biodegradation system design using a simulation-optimization approach to remove Toluene from groundwater and partially saturated zone. **Journal of Environmental; Engineering** (In review)

Remediation system for removal of Toluene from groundwater and partially saturated zone



Practical Experiment
(to estimate biodegradation rate of dissolved LNAPL in vadose zone having 80-20% Soil Moisture at 30 & 10-degree) temp)

BIOPLUME III Modeling
(to estimate biodegradation rate of dissolved LNAPL in saturated zone)

HYDRUS 3D Modeling
(using randomly generated recharge & extraction rate)

Data set training and testing of ELM

Trained ELM

Evaluating the fitness function using Particle Swarm Optimization (PSO)

Stop criteria met?

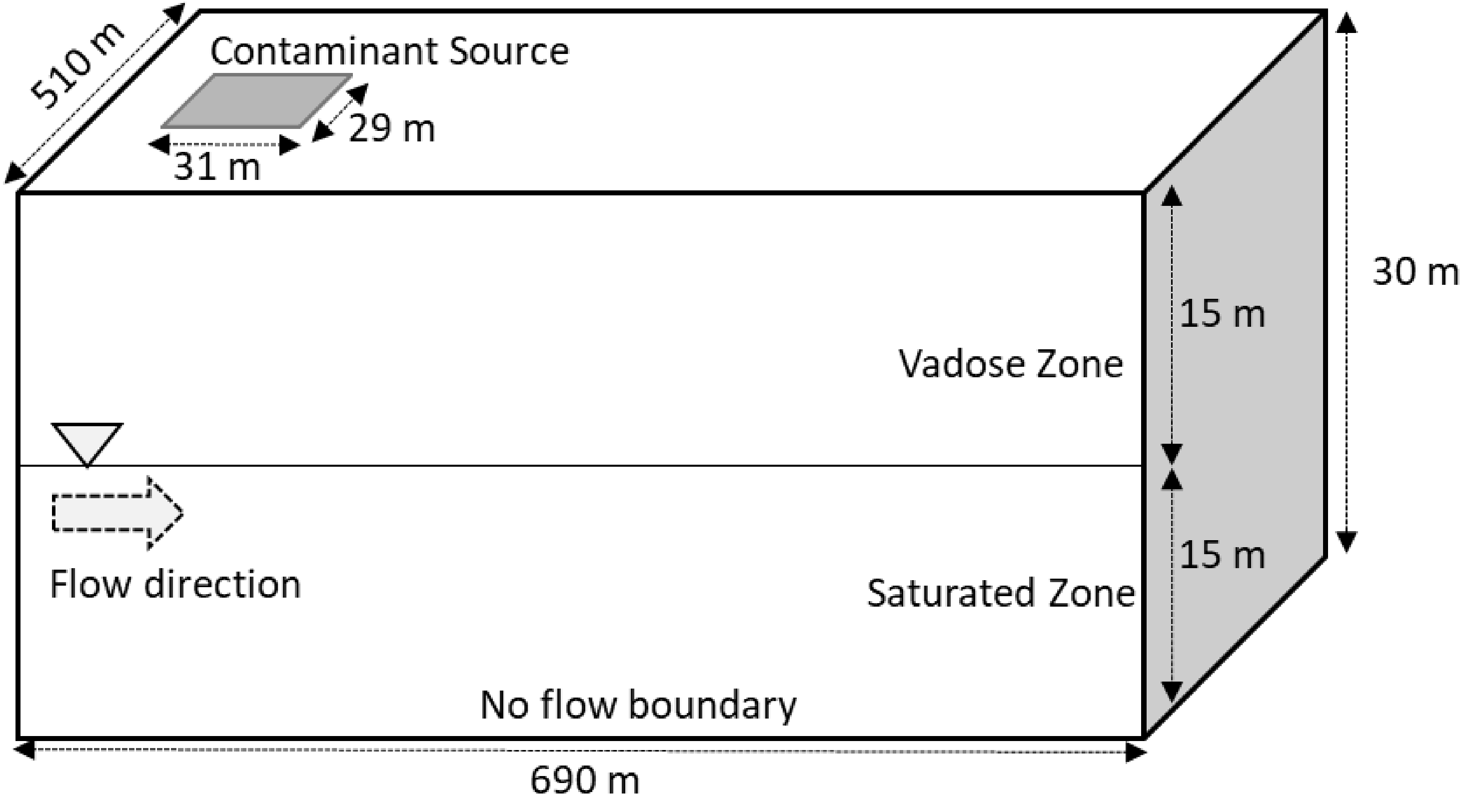
Is optimal solution achieved?

Output

High moisture-High temperature combination gives the minimum remediation time and cost

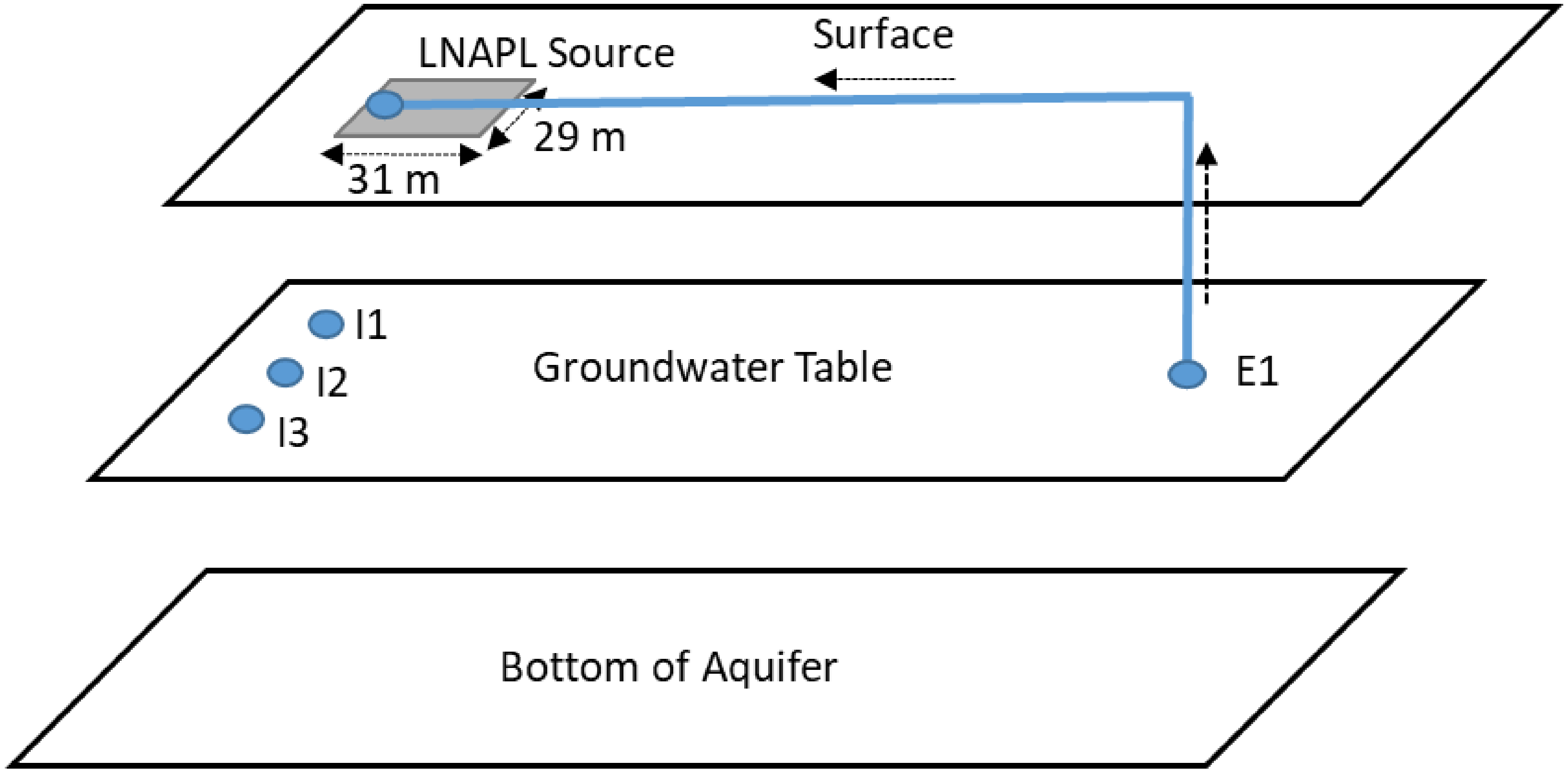
Gupta, P. K., Yadav, B., Yadav, B. K., Sushkova, S., & Basu, S. (2021). Engineered Bioremediation of NAPL Polluted Sites: Experimental and Simulation-Optimization Approach under Heterogeneous Moisture and Temperature Conditions. Journal of Environmental Engineering, 147(8), 04021023.)

Study Domain- partially saturated and saturated zones

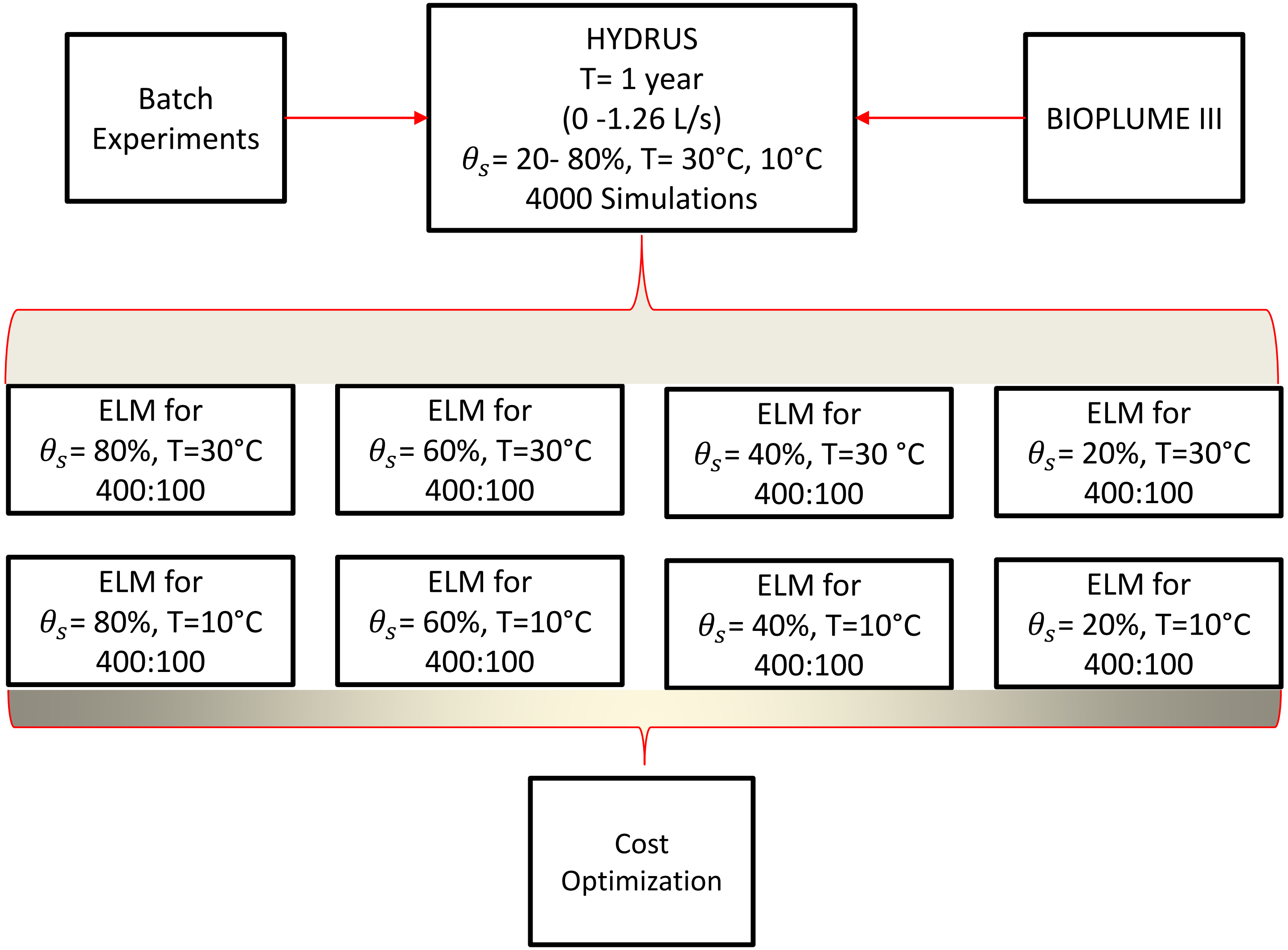


- The steady state condition was considered throughout the simulation.
- Homogeneously distributed sand was considered as porous media.
- Constant pumping rates were taken

Injection/Extraction well and Recharge flux location



Trained surrogate simulator to replace HYDRUS 2D/3D



Batch Experiments

HYDRUS
T= 1 year
(0 -1.26 L/s)
θ_s= 20- 80%, T= 30°C, 10°C
4000 Simulations

BIOPLUME III

ELM for
θ_s= 80%, T=30°C
400:100

ELM for
θ_s= 60%, T=30°C
400:100

ELM for
θ_s= 40%, T=30 °C
400:100

ELM for
θ_s= 20%, T=30°C
400:100

ELM for
θ_s= 80%, T=10°C
400:100

ELM for
θ_s= 60%, T=10°C
400:100

ELM for
θ_s= 40%, T=10°C
400:100

ELM for
θ_s= 20%, T=10°C
400:100

Cost Optimization

Objective function for constant pumping rates

Minimize $$F = W_F \sum_{e=1}^{Nw} C_{p_e} \cdot p_e + \sum_{e=1}^{Nw} C_{Ip_e} \cdot Ip_e + D\left[\sum_{e=1}^{N_i} p_e\right] + E\left[\sum_{e=1}^{N_e} p_e\right]$$

$$W_F = \left[(1+i_r)^T - 1\right] / \left[i_r (1+i_r)^T\right]$$

Minimize Concentration = C_{max}

Subject to:-

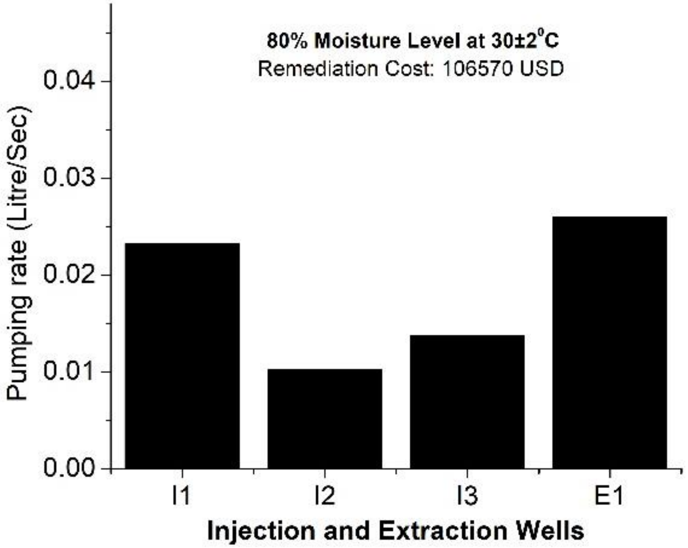
$$0 \le C_{ow} \le C_{st} \qquad Ow = 1,2 \ldots N_o$$

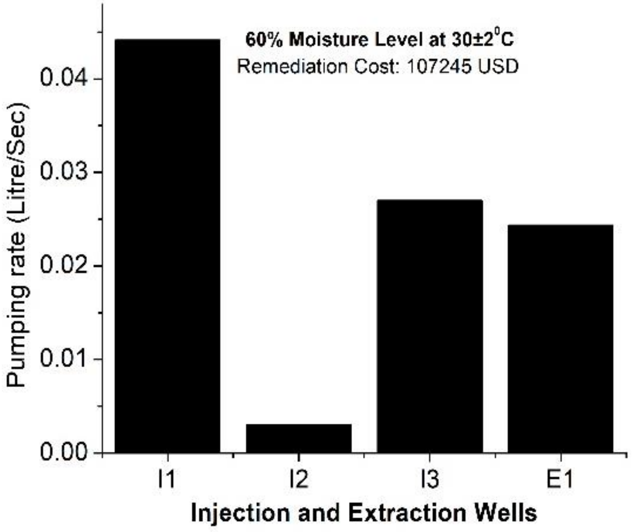
$$H_{i\min} \le H_e \le H_{i\max} \qquad e = 1,2 \ldots N_i$$

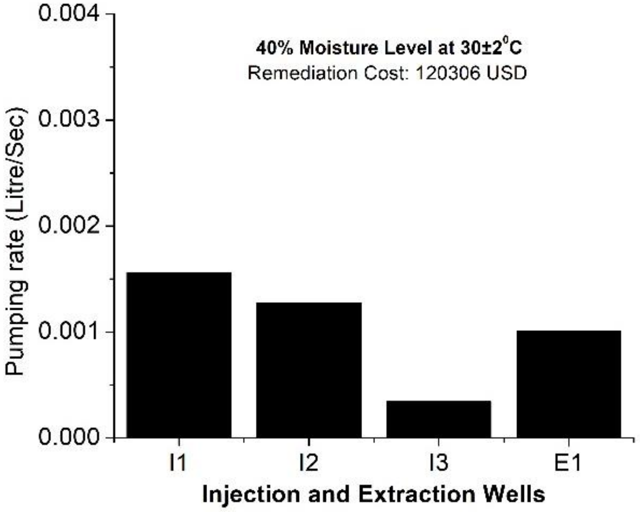
$$H_{e\min} \le H_e \le H_{e\max} \qquad e = 1,2 \ldots N_e$$

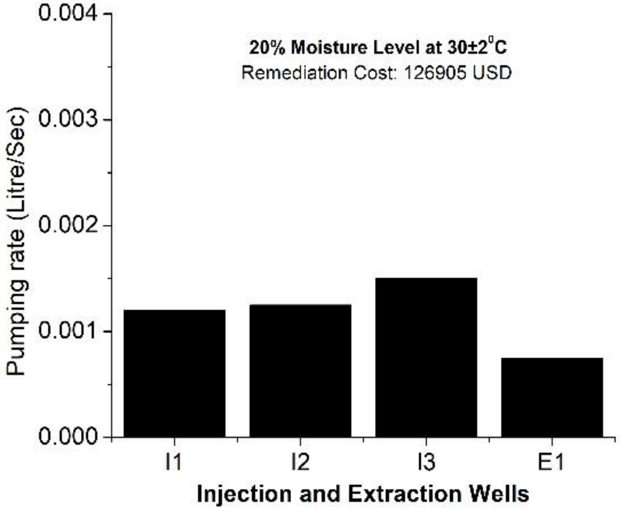
$$p_{\min} \le p_e \le p_{\max} \qquad e = 1,2 \ldots Nw$$

Optimized injection and extraction rates at 30 °C

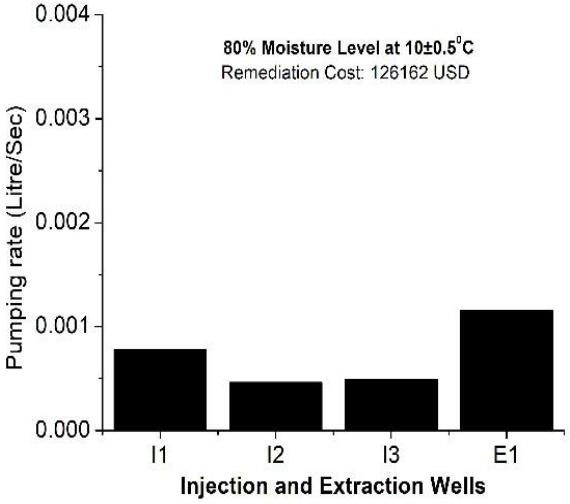

80% Moisture Level at 30±2°C
Remediation Cost: 106570 USD

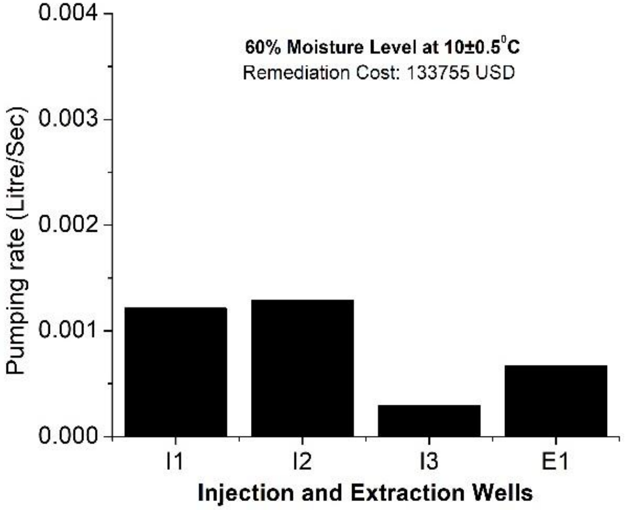

60% Moisture Level at 30±2°C
Remediation Cost: 107245 USD

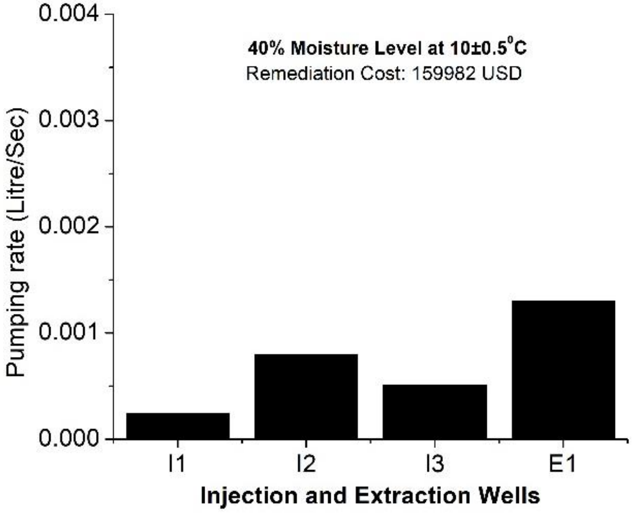

40% Moisture Level at 30±2°C
Remediation Cost: 120306 USD

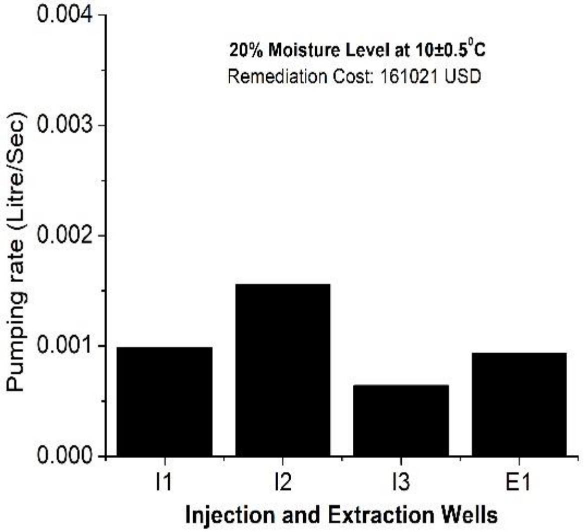

20% Moisture Level at 30±2°C
Remediation Cost: 126905 USD

Optimized injection and extraction rates at 10 °C



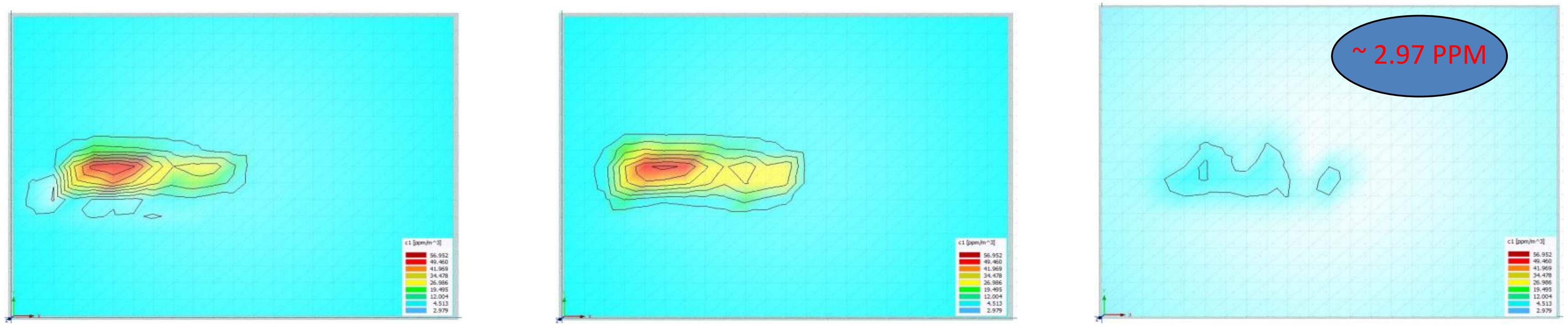




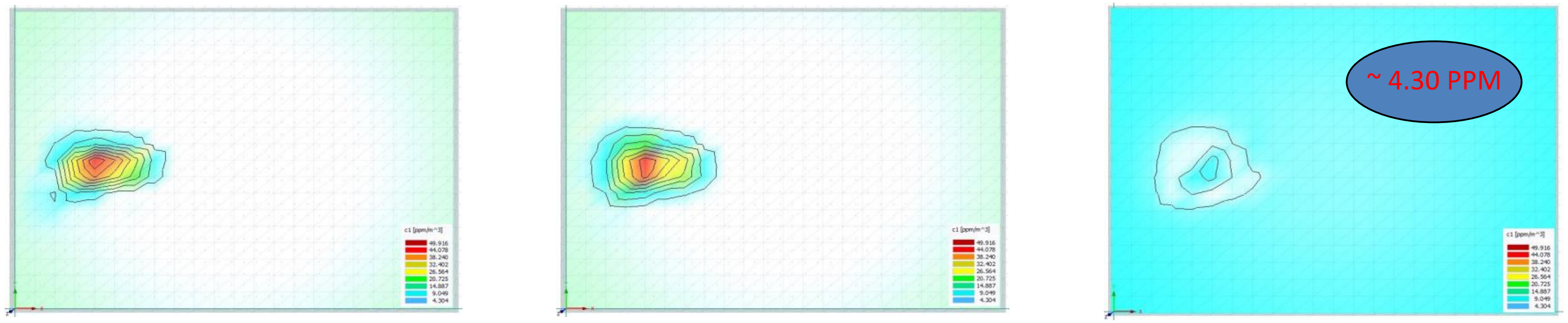


Validation of the optimized injection and extraction rates at 30 °C

80% and temperature 30°C



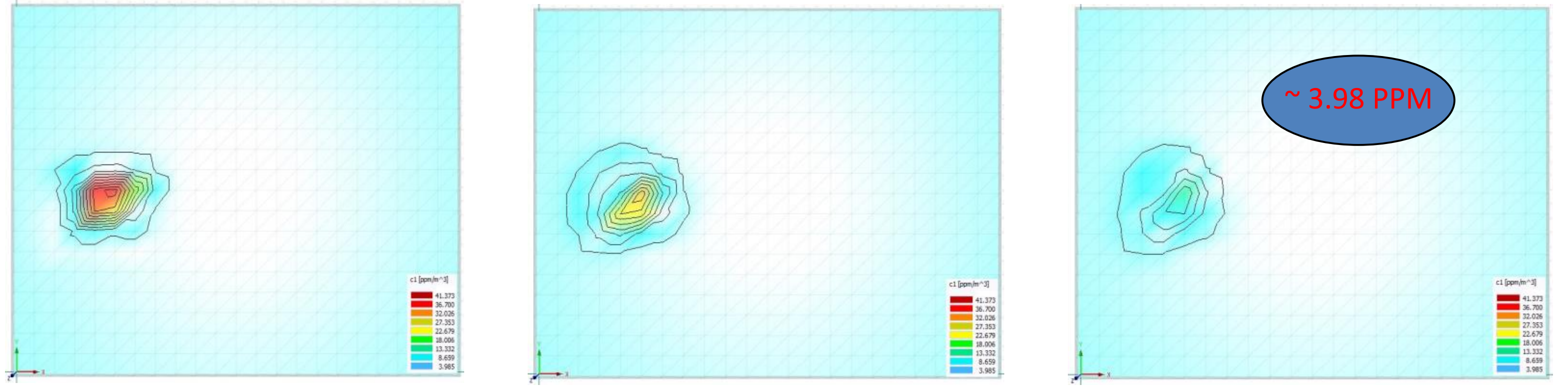
60% and temperature 30°C



5 days 180 days 365 days

Validation of the optimized injection and extraction rates at 30 °C

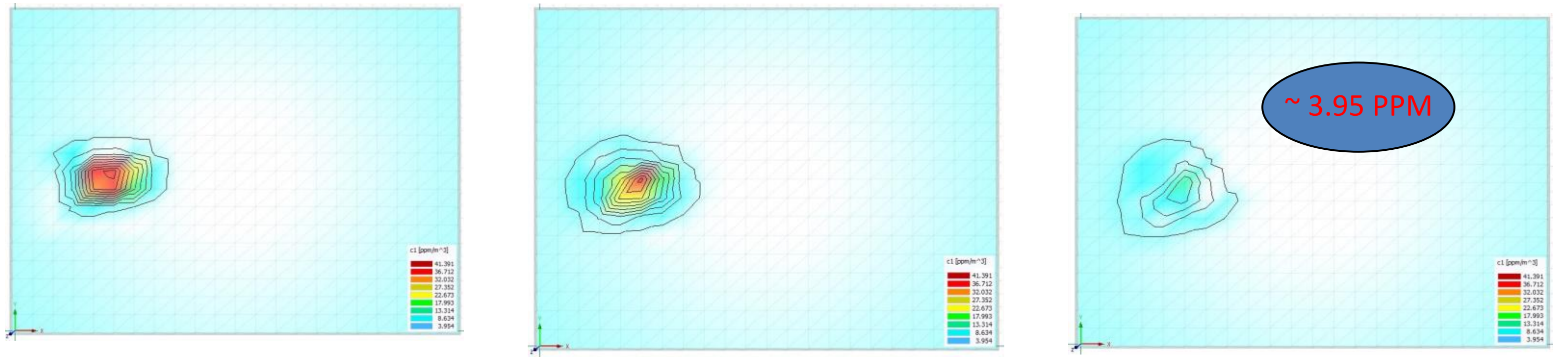
40% and temperature 30°C



~ 3.98 PPM

5 days 365 days 455 days

20% and temperature 30°C

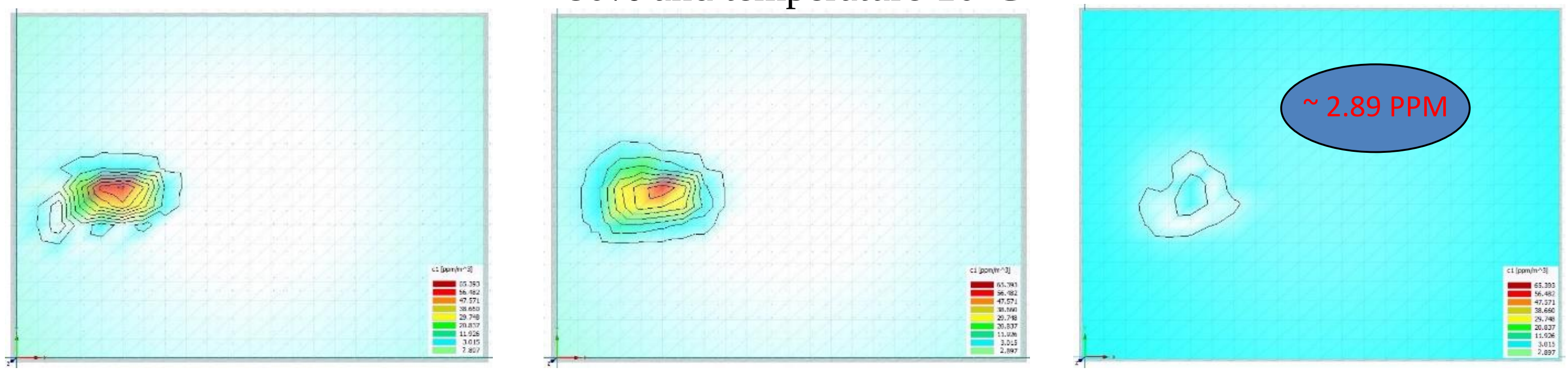


~ 3.95 PPM

5 days 455 days 545 days

Validation of the optimized injection and extraction rates at 10 °C

80% and temperature 10°C



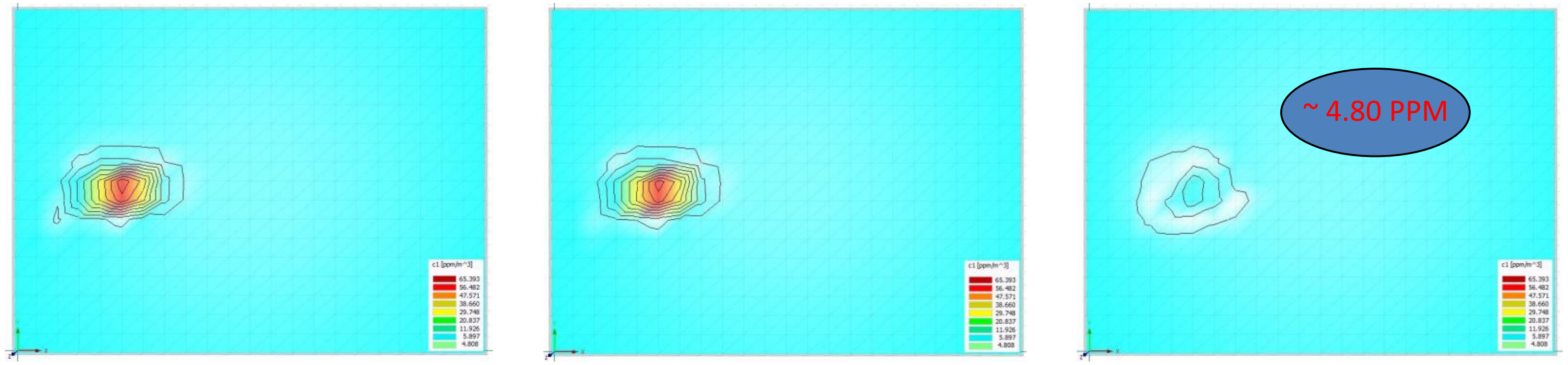
~ 2.89 PPM

5 days

455 days

545 days

60% and temperature 10°C



~ 4.80 PPM

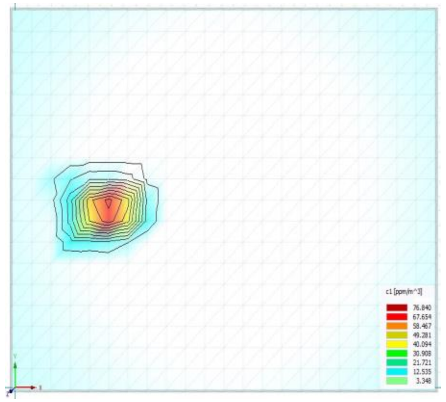
5 days

455 days

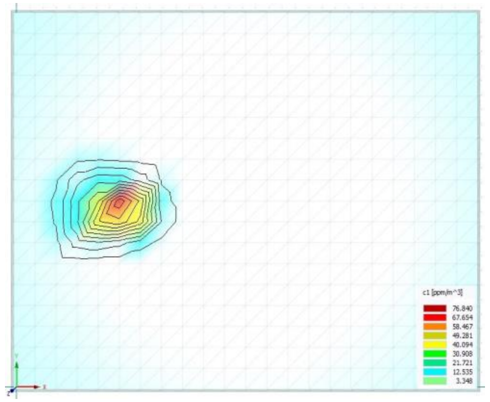
730 days

Validation of the optimized injection and extraction rates at 10 °C

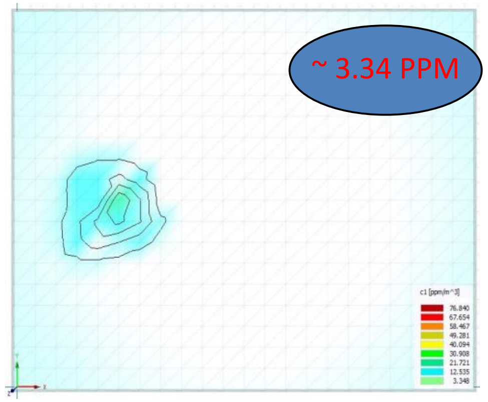
40% and temperature 10°C



5 days

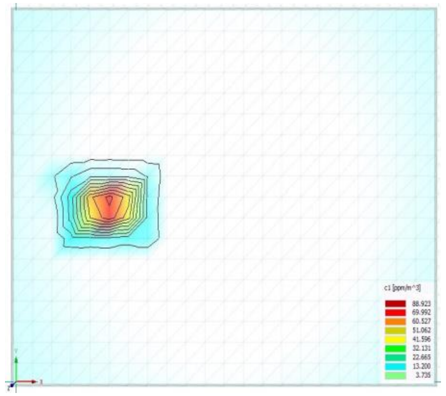


455 days

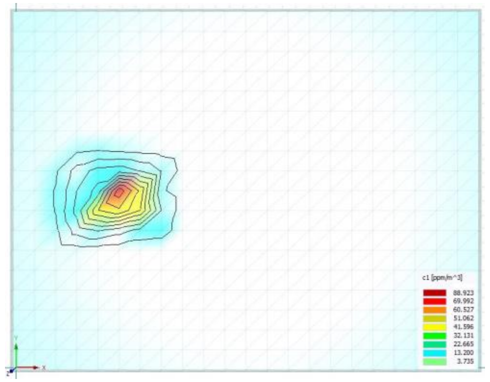

~ 3.34 PPM

545 days

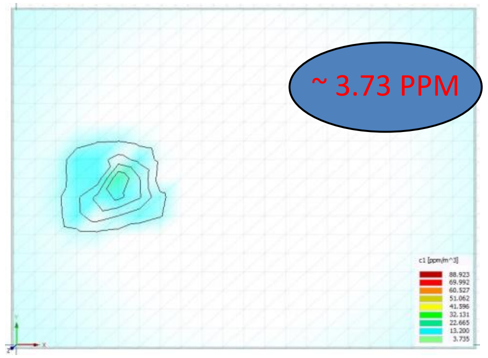
20% and temperature 10°C



5 days

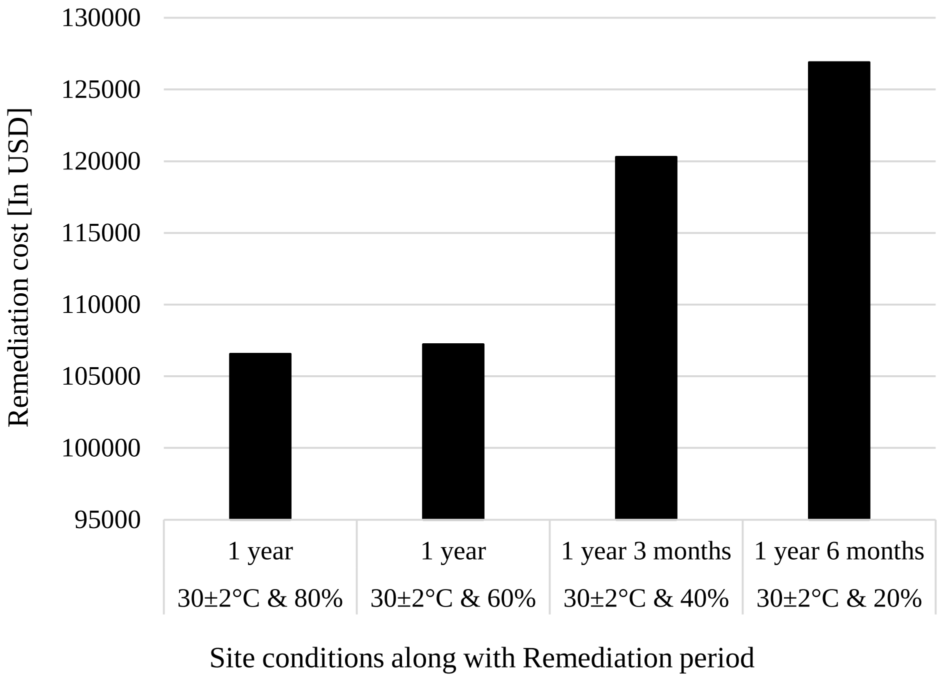


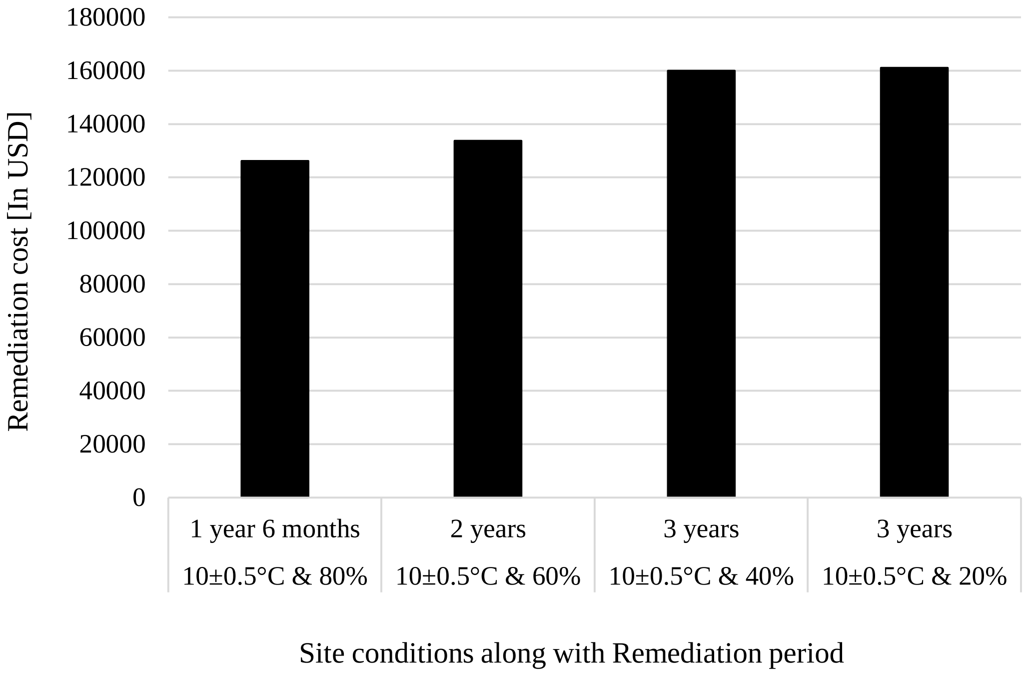
455 days


~ 3.73 PPM

730 days

Optimized remediation system cost





High moisture-
High temperature
combination gives
the minimum cost

Gupta, P. K., Yadav, B., Yadav, B. K., Sushkova, S., & Basu, S. (2021). Engineered Bioremediation of NAPL Polluted Sites: Experimental and Simulation-Optimization Approach under Heterogeneous Moisture and Temperature Conditions. Journal of Environmental Engineering, 147(8), 04021023.)

Summary

- In-situ bioremediation is the effective strategy for remediation of water contaminated with the petroleum hydrocarbons causing least site disturbance and minimum cost.

- The simulation optimization approach can solve the management problem. The approach of data based modeling can be very useful in hybrid simulation-optimization formulation.

- The developed approach can be generalized in case the remediation time changes, site constraints changes etc.

- The study also suggest that the more realistic and feasible design can be formulated by extending the optimization scope (well cleaning)
- The integrated approach of experimental, numerical and data based modeling gives the flexibility to characterise the site condition more effectively and accurately

- The similar approach can be extended to study the impact of other hydrological and hydrogeological variables on fate and transport of contaminants

- The scope and accuracy of data based modeling can be extended using various data mining techniques.

References

1. Yadav, B., Mathur, S., Ch, S., & Yadav, B. K. Simulation-Optimization approach for the consideration of well clogging during cost estimation of in situ bioremediation system. Journal of Hydrologic Engineering, 23(3), 04018001, (2018).
2. Yadav, B*., Ch, S., Mathur, S., & Adamowski, J. Estimation of in-situ bioremediation system cost using a hybrid Extreme Learning Machine (ELM)-particle swarm optimization approach. Journal of Hydrology, 543, 373-385, (2016).
3. Gupta, P. K., Yadav, B., & Yadav, B. K. Assessment of LNAPL in subsurface under fluctuating groundwater table using 2D sand tank experiments. Journal of Environmental Engineering, 145(9), 04019048, (2019).
4. Gupta, P. K., Yadav, B., Yadav, B. K., Sushkova, S., & Basu, S. (2021). Engineered Bioremediation of NAPL Polluted Sites: Experimental and Simulation-Optimization Approach under Heterogeneous Moisture and Temperature Conditions. Journal of Environmental Engineering, 147(8), 04021023.)

Thank You