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SUMMARY

Following are the key features and limitations of the developed tool at the moment:

i. The code can include currently maximum 5 wells in different positions and their results can also be extracted and analyzed.
ii. The read function enabled the user to retrieve the data and update and delete options enable the user to do the desired operation to the input data.
iii. The position of the river is currently fixed to the left side of the grid.
iv. If the results of bank filtrate data is required the code is restricted to solve only one well with surface water source.
v. The results stream function and potential head findings can be downloaded as CSV files.
vi. Graphics can be exported and save by the user in high resolution.
vii. The code has been written in such a way that as many pages as feasible may be incorporated to the program in the future without demanding any more adjustments.

USER MANUAL

1. Introduction

Despite the immense amount of water on the earth, decades of ineffective management have resulted in severe water shortages in many areas. Humans use more than half of all renewable and accessible freshwater on the planet, but billions of people still lack access to even the most basic water services. The impact on freshwater habitats is increasing as the world population expands and demand for food and energy rises. Mankind is pumping more water from the ground than they used to in the past and causing scarcity of groundwater. To reduce dependency on groundwater Riverbank Filtration (RBF) method is a good technique, in riverbank filtration is a natural water treatment technology that involves infiltrating surface water into an aquifer and then extracting the water for agricultural or drinking uses. The water that is abstracted is a mix of infiltrating surface water (bank filtrate) and ambient groundwater.

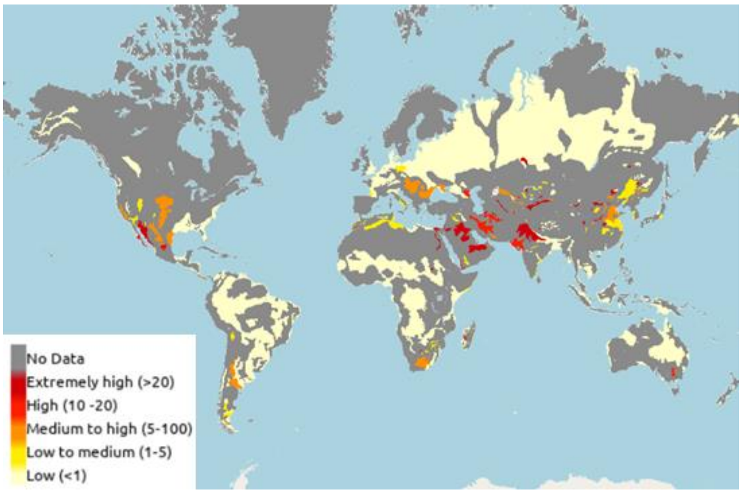

FIGURE 1 WATER SCARCITY AND ADAPTION OF RBF SYSTEM

1.1. Riverbank Filtration

In the last three decades, the riverbank filtration approach is being followed and developed. In this approach, bores are placed next to the river in the aquifer zone. RBF played a key role in Reducing groundwater dependency, and the cost of water treatment is also

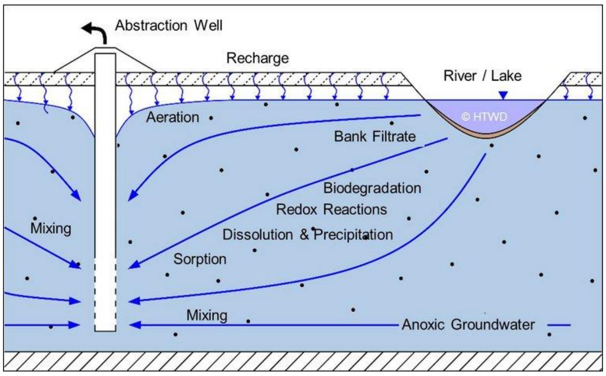

FIGURE 2 ILLUSTRATION OF RBF SYSTEM

reduced as a result of biological, physical, and chemical processes that occur as the water travels from the river to the bore.

1.2. Analytic Element Model (AEM)

Models made on Analytic Element Modelling (AEM) are difficult to build and simple to use. For the solution of partial differential equations, the analytic element method (AEM) is a numerical method. AEM main feature is the use of a harmonic function to describe each aquifer element that influences the flow and thus helping in finding inside information of the groundwater flow. At any location in the flow domain, heads and groundwater flow velocities can be determined. Requirement for defining a model grid is not necessary. One of the many advantages to use AEM is that Method of Images and Principal of Superposition can be integrated in AEM only not in Finite Element Modelling.

1.3. Method of Images

In the case of flow fields with a single straight-line boundary, Method of Images approach provides exact analytical solutions. It's actually a process for passing to an equivalent infinite flow field, where we can apply the well system formulas. Method of images is used to calculate the influence of water levels in a pumping well and to calculate influence of a barrier or an unlimited source of water.

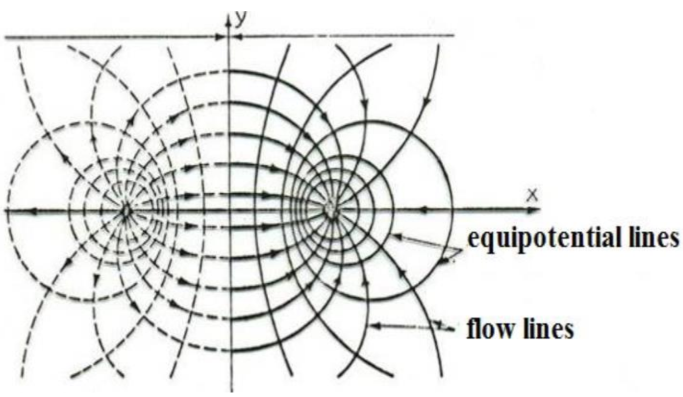

FIGURE 3 IMAGE WELL & DISTRIBUTION

1.4. Principal Of Superposition

Ground-water hydraulics and modeling of ground-water systems both benefit from the notion of superposition, a strong mathematical tool for studying certain types of difficult issues in many fields of science and technology. According to the principle of superposition, problem solutions can be combined to produce composite solutions.

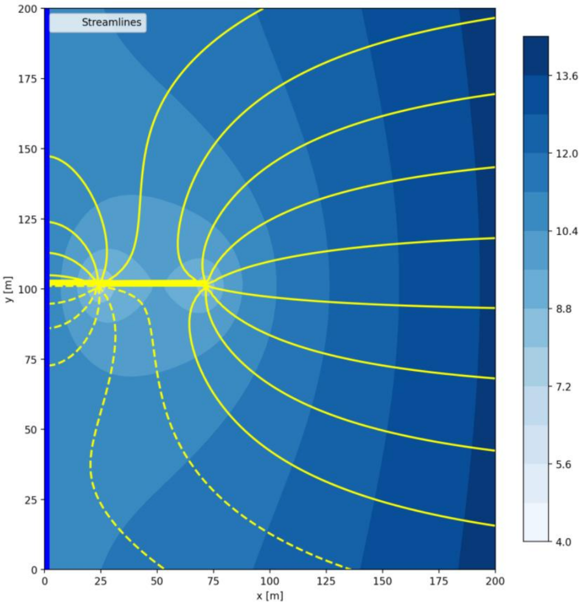

FIGURE 4 MULTIPLE WELLS INCLUSION

This rule applies to linear systems using linear differential equations as their controllers. In our case the principle of superposition is used to add multiple wells in any required domain.

1.5. Darcy Law

Darcy law consider as the basis for groundwater flow it defines the principle which governs how fluid moves in the subsurface. Darcy's law is an equation that describes a fluid's capacity to flow through a porous medium such as rock. It is based on the notion that the quantity of flow between two sites is proportional to the difference in pressure between them, the distance between them, and the interconnectivity of flow routes in the rock between them. Permeability is a measurement of interconnectivity.

1.6. Laplace Equation

The groundwater flow equation is a mathematical relationship that is used in hydrogeology to characterize groundwater flow across an aquifer. A variant of the diffusion equation is used to describe the transient flow of groundwater. A variant of the Laplace equation, which is a type of potential flow with analogs in many areas, is used to describe the steady-state flow of groundwater.

$$\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2} + \frac{\partial^2 \emptyset}{\partial z^2} = 0$$

LAPLACE EQUATION

1.7. Background Mathematics

The analytical element method is being used in the arithmetic operations. As AEM is simple and best for groundwater flow equations. With being in a certain boundary condition such as flow to a pumping well, representation of water flow to a stream segment, or representation of recharge region, etc.

Darcy's equation which was later modified by (Haitjema, 1995) providing the specific discharge (q_z) is used in this work.

$$q_z = -k \frac{d\emptyset}{dz}$$

Laplace equation is used with assumptions such as thickness of aquifer is less than the length of it and the assumptions of Dupuit (1863) that the flowlines are horizontal on the whole. With the assumption of flow being horizontal $q_z = 0$ with this Darcy's law to $\frac{\partial\emptyset}{\partial z} = 0$. Which leads to the continuous groundwater flow equation in the two-dimensional space in the form of Laplace equation turns out to be:

$$\frac{\partial\Phi_x}{\partial x} + \frac{\partial\Phi_y}{\partial y} = 0$$

Where Φ is the discharge potential which is obtained by converting the hydraulic head $\emptyset$ under known boundary conditions. If $\emptyset \leq M$ it defines unconfined conditions, where M is the thickness of aquifer and then the:

$$\Phi = \frac{1}{2} k\emptyset^2$$

Potential head is found according to:

$$\emptyset = \sqrt{\frac{2\Phi}{K}}$$

and if $\emptyset \geq M$ it defines confined conditions and then the:

$$\Phi = KM\emptyset - \frac{1}{2}KM^2$$

And the potential head can be found according to:

$$\emptyset = \frac{\Phi + \frac{1}{2}KM^2}{KM}$$

And for boundary point between confined and unconfined aquifer the discharge potential Φ is given by the Holzbecher (2012):

$$\Phi_{crit} = \frac{1}{2}KM^2 + \Phi_0$$

1.8. Flow Equation for One Well

In the case when the flow is only because of a well alone in the aquifer the flow is radially equal. With the assumption that the $(\boldsymbol{r}, \theta)$ coordinate system is at the center of well the flow is always parallel to radius (r) due to radial equality.

The discharge is calculated from the following the eq:

$$Q = 2\pi r(-Q_r)$$

The discharge potential Φ is calculated from the following the eq:

$$\Phi = \frac{Q}{2\pi} ln\frac{r}{R} + \Phi_0$$

The streamlines which are parallel to the radius emitting from the center of the well its function is calculated by the following eq:

$$\Psi = \frac{Q}{2\pi}\theta$$

The angle θ can also be replaced in the terms x and y:

$$\Psi = \frac{Q}{2\pi} arctan\frac{y}{x}$$

By the application of principal of superposition and linearity of Laplace' equation Φ and Ψ are merged and provides:

$$\Phi = -Q_x + \frac{Q}{2\pi} ln\sqrt{x^2 + y^2} + C \quad and \quad \Psi = -Q_y + \frac{Q}{2\pi} arctan\frac{y}{x}$$

2. Validation

The model is validated with the help of the FloPy Python library. The FloPy package, which comprises of a sequence of Python scripts, may be used to run MODFLOW, MT3D, SEAWAT, and other MODFLOW-related groundwater applications.

The following steps are taken to validate the developed online model:

I. **MODFLOW Model Creation.**
II. **MODFLOW Model Postprocessing.**
III. **AEM Model Calculation.**
IV. **Model Comparison.**

The validity of the developed tool was confirmed and compared using a set of 4 exclusive steps and result comparison.

a) Comparison of Heads

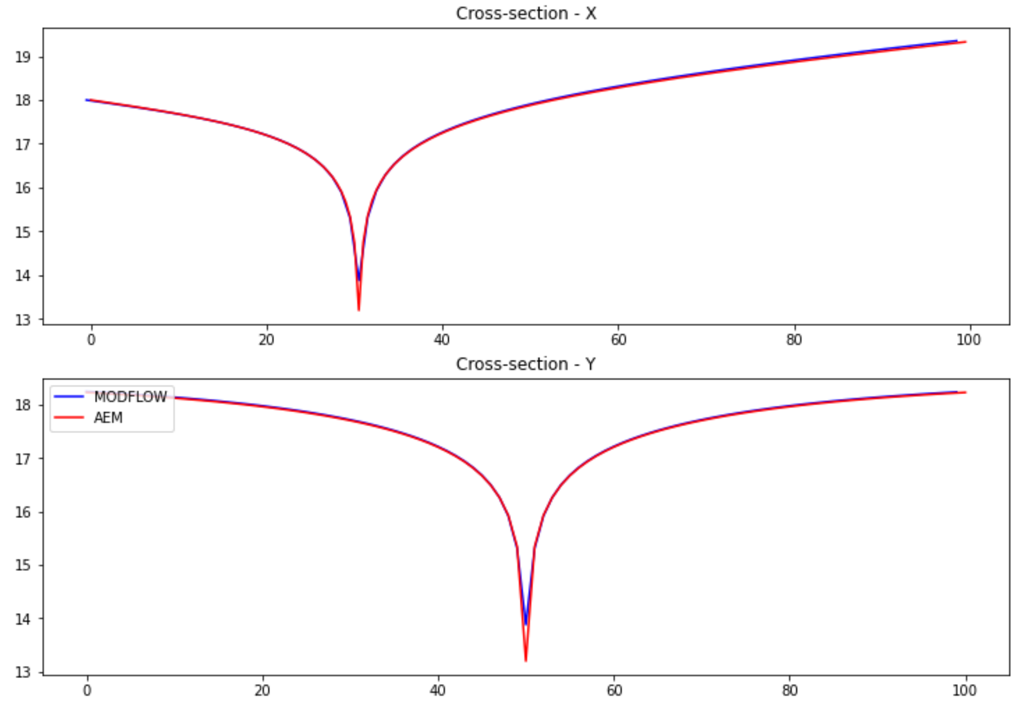

FIGURE 5 HEADS COMPARISON OF AEM AND MODFLOW MODELS

The validity of our model is confirmed by a head-to-head comparison of both models. Figure 5 depicts the cross-section in both x and y directions, with total drawdown under the AEM and MODFLOW models almost matching each other.

b) Comparison of Bank Filtrate Ratio

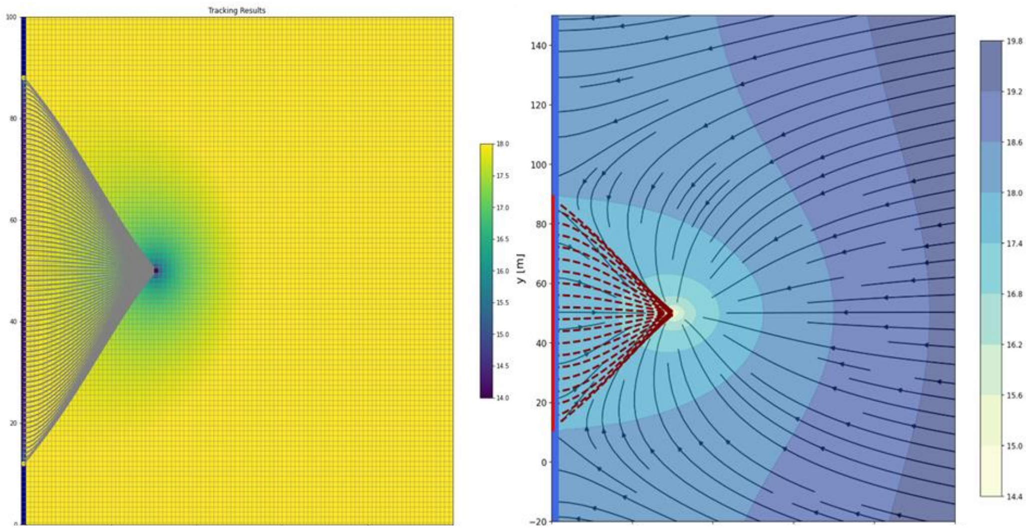

FIGURE 6 COMPARISON OF RESULTS OBTAINED FROM AEM AND MODFLOW MODELS

The bank filtrate ratio obtained from the already developed and trusted software, MODFLOW (Left), is 26% and capture length is 76 m. The AEM based online model, figure 6, produces the almost same results.

c) Comparison of Travel Time

A module named MODPATH is used in conjunction with the FloPy library to compare travel times. The same graphical result, as illustrated in figure 30, is achieved.

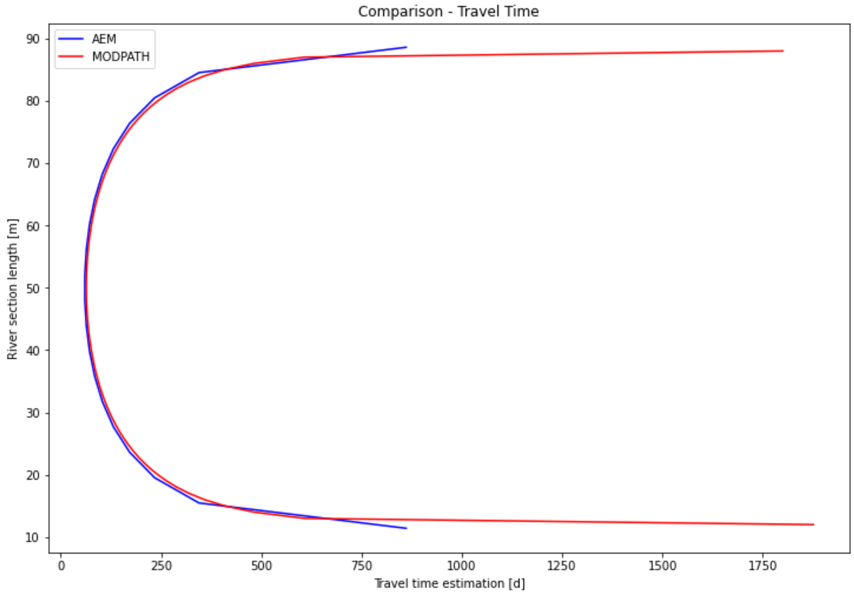

FIGURE 7 THE TRAVEL TIME COMPARISON OF AEM AND MODPATH MODELS

d) Comparison of Clogging Effects on RBF System

Clogging in riverbank filtration system plays an important role and refers to a reduction of riverbed hydraulic conductivity. A comparison of the impact of clogging on RBF is made through MODFLOW and AEM model results. The same approach is used for MODFLOW verification as previously explained using FloPy. The figures (8, 9) shows comparison of result of our tool and MODFLOW model.

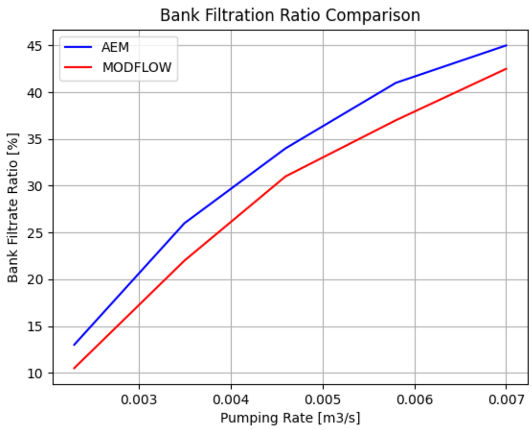

FIGURE 8 COMPARISON OF BANK FILTRATION RATION (AEM AND MODLFOW MODEL)

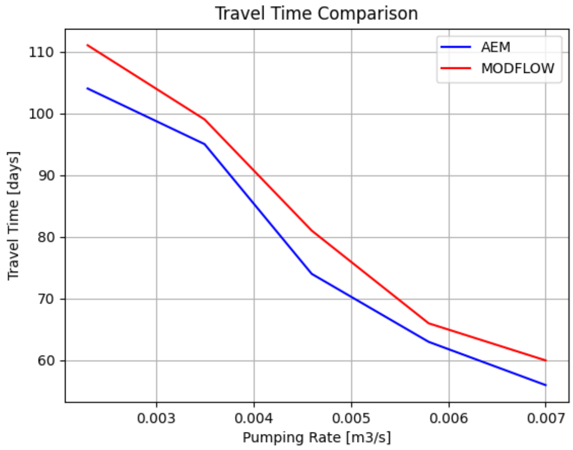

FIGURE 9 COMPARISON OF TRAVEL TIME (AEM AND MODFLOW MODEL)

3. Applied Mathematics in The Application

3.1. Boundary Conditions

The tool is developed with the assumption that our system is static thus making the conditions depended on location not on time. Second boundary condition is kept that the hydrogeological barrier exist at the area's edge. To integrate boundary conditions, the method of images approach can be used in this situation. A fictional source or extraction well with the same coordinate distance from the right boundary of the observed area, in figure 10, is used for this purpose.

If a source well and a (fictitious) extraction well are located opposite each other, the geometry creates an equipotential line, in theory an infinitely long one, with constant hydraulic potential, which is parallel to the y-axis.

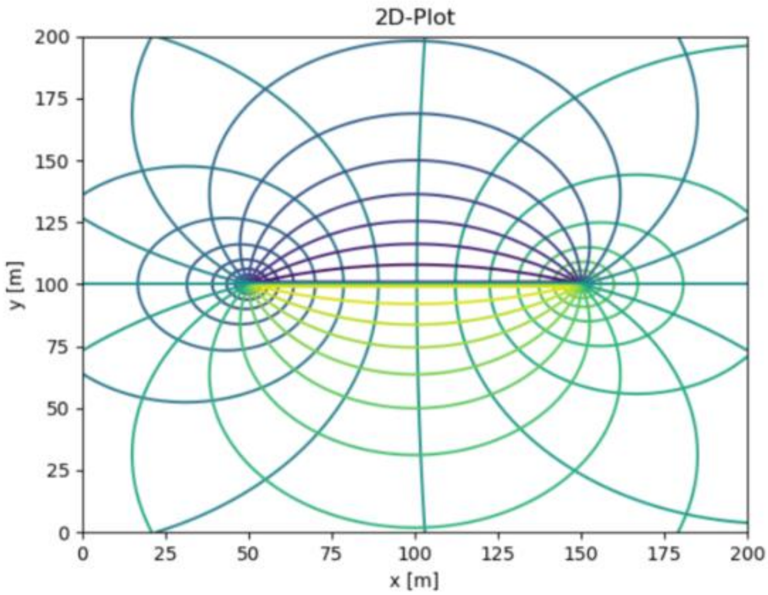

FIGURE 10 SOURCE AND FICTITIOUS EXTRACTION WELL

3.2. Single Well

For calculating the flow for a single well the app is incorporated with the same equation as described in the section 1.8. The Discharge, discharge potential Φ and streamline function are calculated by the following equation:

$$Q = 2\pi r(-Q_r)$$

$$\Phi = -Q_x + \frac{Q}{2\pi} ln\sqrt{x^2 + y^2} + C$$

$$\Psi = -Q_y + \frac{Q}{2\pi} arctan\frac{y}{x}$$

3.3. Multiple Well (Amalgamation of Method Images and Principal of Super Position)

The computation of multiple wells is based on the idea of superposition, which is detailed in section 1.4. The second type of boundary condition, a river on one border of the territory, was likewise incorporated into the model using the image approach (see figure 11). The following equations are used to obtain results for several wells.

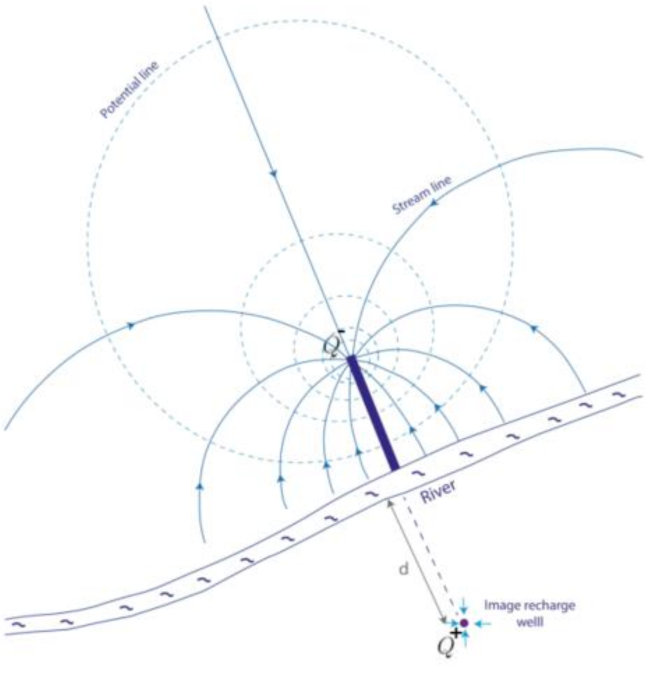

FIGURE 11 METHOD OF IMAGES

To calculate the Potential Function and Stream Function the mathematical equation which are used for getting result are the following:

$$\Phi = -Q_0 x + \frac{Q}{2\pi} \ln\frac{(x+d)^2 + y^2}{(x-d)^2 + y^2} + \Phi_0$$

$$\Psi = -Q_0 y + \frac{Q}{2\pi} [\arctan\left(\frac{y}{x+d}\right) - \arctan\left(\frac{y}{x-d}\right)]$$

3.4. Contribution Ratio

The water entering from the surface is represented as bank filtrate (river in this case). The total amount of water collected from the well is a combination of surface and groundwater. A bank filtration system is designed to deliver a certain value of bank filtration share, or the percentage of bank filtrate in total pumped water. The remaining portion of groundwater extraction is pure aquifer groundwater. The bank filtrate ratio is affected by a number of factors, the most important of which are the well's distance from the river's edge and the rate at which it is pumped.

The equation used to calculate the bank filtrate involves the calculation for the stagnation point (Fig 12) by the following equation:

$$y_{stag}^2 = -d^2 + \frac{d}{\pi}\frac{Q}{Q_x 0}$$

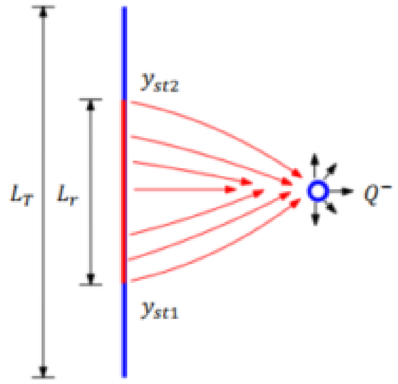

FIGURE 12 REPRESENTATION OF BANK FILTRATE

The total amount of bank filtrate Q_{bf} is then given by the difference between stream function values at two stagnation points:

$$Q_{bf} = \Psi(y_{stag}) - \Psi(-y_{stag}) + Q$$

River capture length is calculated by:

$$L_r = y_{stag1} - y_{stag2}$$

Bank filtrate ratio is a ratio of Q_{bf}, calculated:

$$Q_{contrib} = \frac{Q_{bf}}{Q}$$

3.5. Travel Time

The term travel time indicate that the time required for water to travel from its origin to its current position (Fig 13). It should also be kept in consideration that long travel time are guarantor that the contamination levels in the water will be substantially low as compared to less travel time.

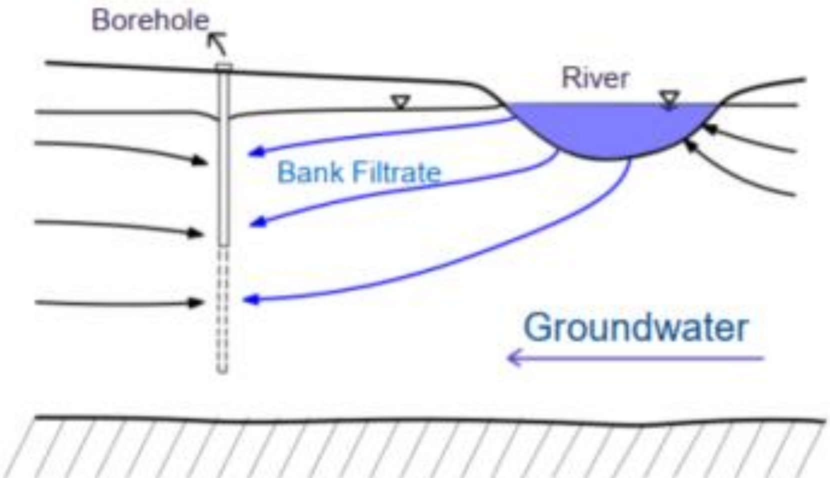

FIGURE 13 SCHEMATIC FOR TRAVEL TIME

Travel Time calculation involves the following set of procedures:

A. Calculation of specific discharge carried out at particle location by using following equation:

$$Q_x = -\frac{\partial \Phi}{\partial x} \; and \; Q_y = -\frac{\partial \Phi}{\partial y}$$

Specific discharge (q) in x and y direction as:

$$q = \frac{Q}{\emptyset}$$

B. Velocity (v) at particle location:

$$v = \frac{q}{n_e}$$

Where, n_e represents effective porosity.

C. Projecting the next point, see figure 13, from velocity vector with small distance spacing Δs.

$$x_2 = x_1 + \Delta s \frac{v_x}{v}$$

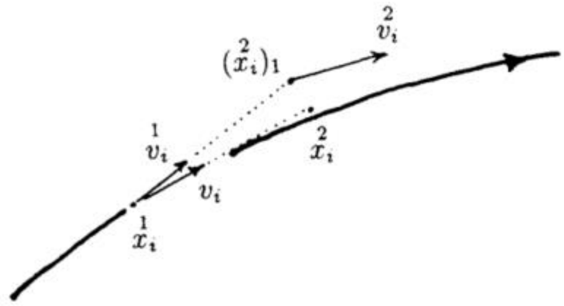

FIGURE 14 PREDICTOR-CORRECTOR METHOD FOR INTEGRATING THE VELOCITY VECTOR ALONG A STREAMLINE

D. Correction of the trajectory, using predictor-corrector method shown in figure 14, with the stream function and iteration will be carried out until particle reaches the well.

E. Calculation of travel time (t) by using base equation:

$$t = \sum \frac{\Delta s(x,y)}{v(x,y)}$$

3.6. Clogging

When suspended solids accumulates from recharge water the process is referred as clogging. Due to clogging at riverbed a thin layer is formed, comprises of different size particles (Figure 15). Colmation layer can eventually leads to an RBF system failure as it can cause reduction of contribution ratio and accession of travel time.

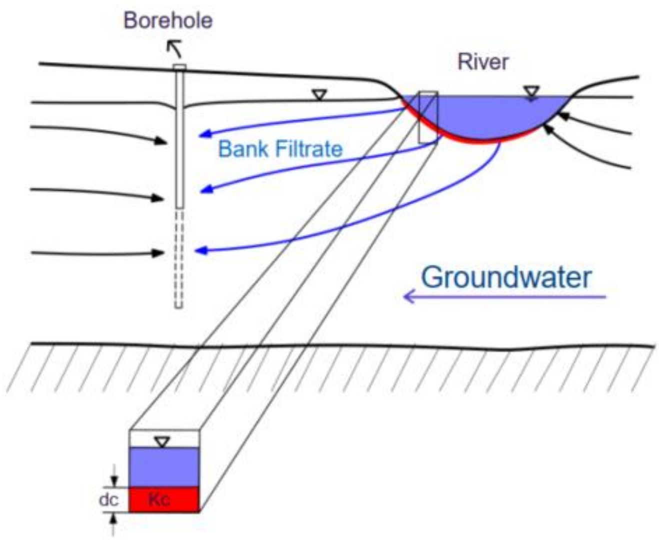

FIGURE 15 SCHEMATIC FOR CLOGGING IN RBF SYSTEM

Colmation layer calculation involves the following set of procedures:

A. The under mentioned equation is used to calculate the value of clogging parameter p.

$$p = \frac{K}{K_d} \times d$$

B. This clogging parameter is added to model to recalculate the values of potential function, stream function, and head

C. According to new numerical values of potential function, stream function and head, the bank filtrate ratio and travel time calculation carried out.

4. Introduction of The Application

The aim of this **program is** to give an alternative to previously created software by providing a simple solution to Riverbank Filtration challenges and a solution for homogeneous, isotropic aquifers under static environment. The tool is based exclusively on Python, an open-source and widely available programming language. Python 3.8 is the core language used with Streamlit as the primary framework.

Streamlit, at its root, converts data scripts into shareable web applications that may then be connected to a GitHub repository. Streamlit generates web applications by converting data scripts straight into web apps, eliminating the need for callbacks because widgets are handled as variables. Multiple Python libraries are used to support the mathematical equations such as, Scipy, Sympy, Numpy, Pandas, Matplotlib and Sqlite3.

Being open source, it can be later modified or supplemented with other additional RBF or Groundwater related problems.

5. Setting up

This tool does not require setting up or any installation procedures and it is develop keeping the user friendliness in mind. The tool can be use independent of any operating system as well as independent of any devices such as Computer, Smart Phones or Tablets. It can be used through any internet browser (internet connection required) such as, Safari, Microsoft Edge, Google Chrome, Firefox etc.

6. Operation

The application provides applicable functionalities the interface of the program is

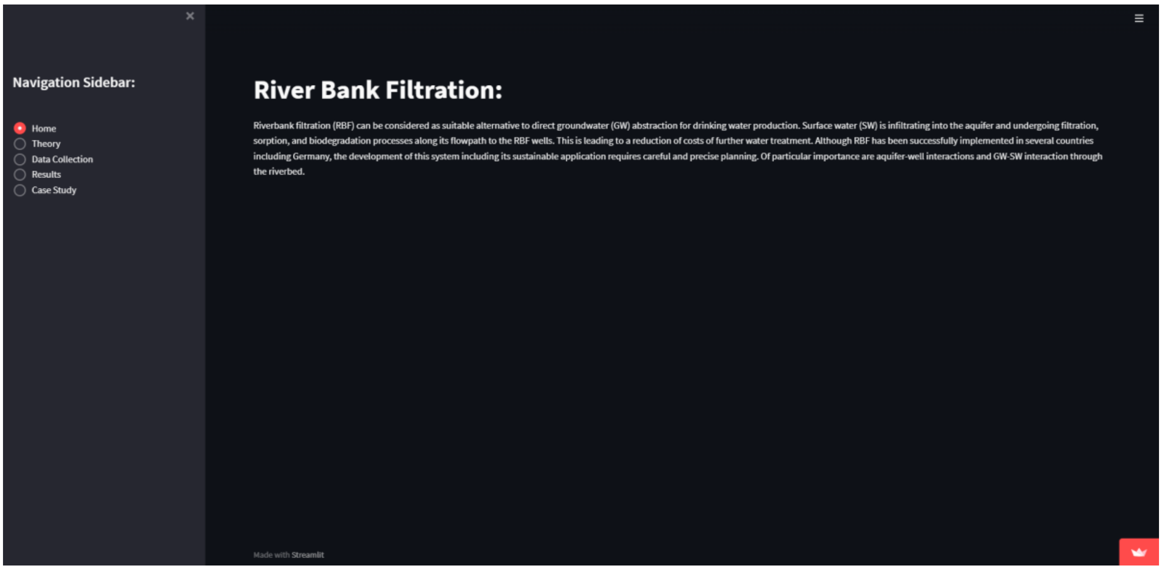

FIGURE 16 APP HOME AT A GLANCE

simple, elegant and provide controlled functionalities. With the navigation Bar On the left providing with the options of brief introduction to the RBF at the Home as illustrated in (Fig 16) and the Theory option providing the background of theory involved.

The second option is data collection which is the input section of the app where the user has to provide with the parameters such as data of Aquifer and Well with the sub option either to Create a new or Update or View or Delete the previously defined data

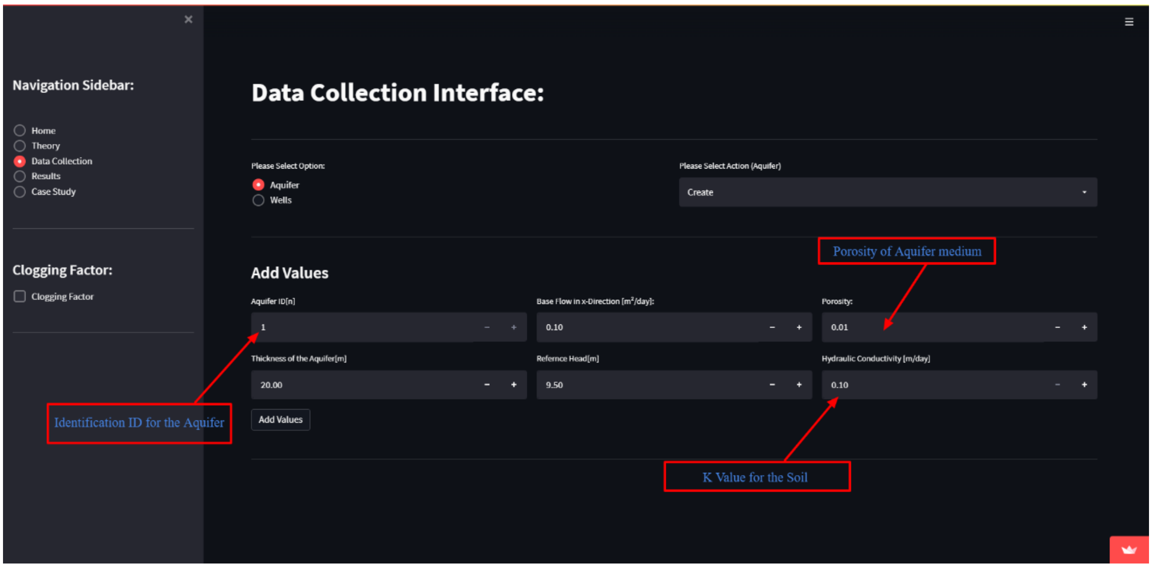

FIGURE 17 DATA COLLECTION FOR AQUIFER

for Aquifer and Well as depicted in (Fig 17 and Fig 18). At the Aquifer and Well Window the user has to provide the data as follows:

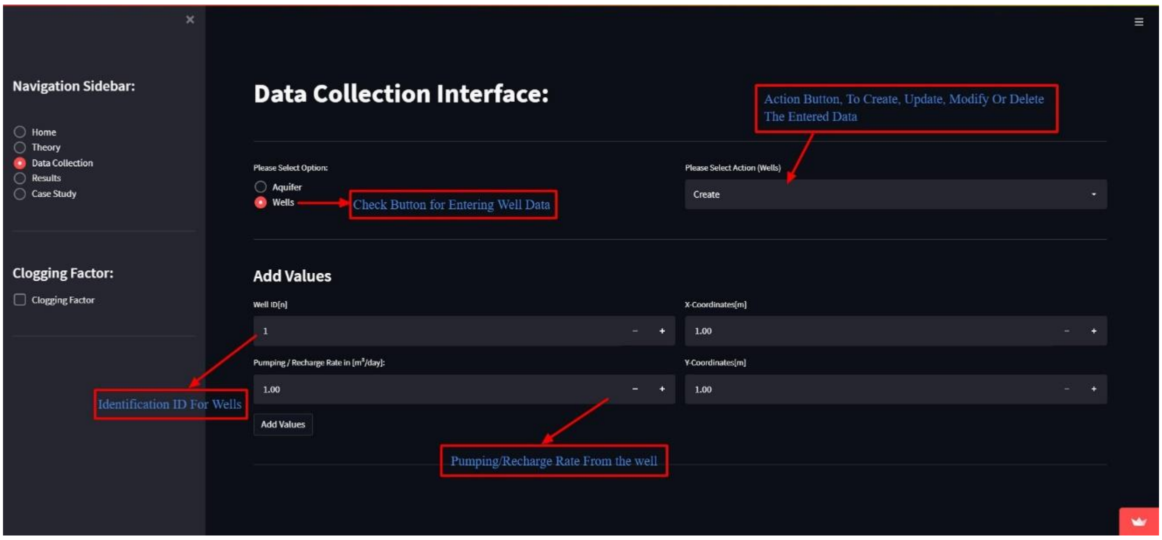

FIGURE 18 DATA COLLECTION FOR WELL

	Parameters	Unit
Aquifer	Base Flow	[m2/day]
	Porosity	[n]
	Thickness	[m]
	Ref. Head	[m]
	Hyd. Cond.	[m/day]
Well	Pump Rate	[m3/day]
	X-Coord.	[m]
	Y-Coord.	[m]

TABLE 1 USER INPUT FOR WELL & AQUIFER

The checkbox (Clogging Factor) visible at the data collection windows enable the user and opens a dropdown field to input the data for Colmation Layer as described in (Fig 19) which is to calculate the clogging effect, the application also portrays result if the button for Colmation Factor is unchecked without the clogging effects. With the button being checked user has the option to Create a new or Update or View or Delete the colmation

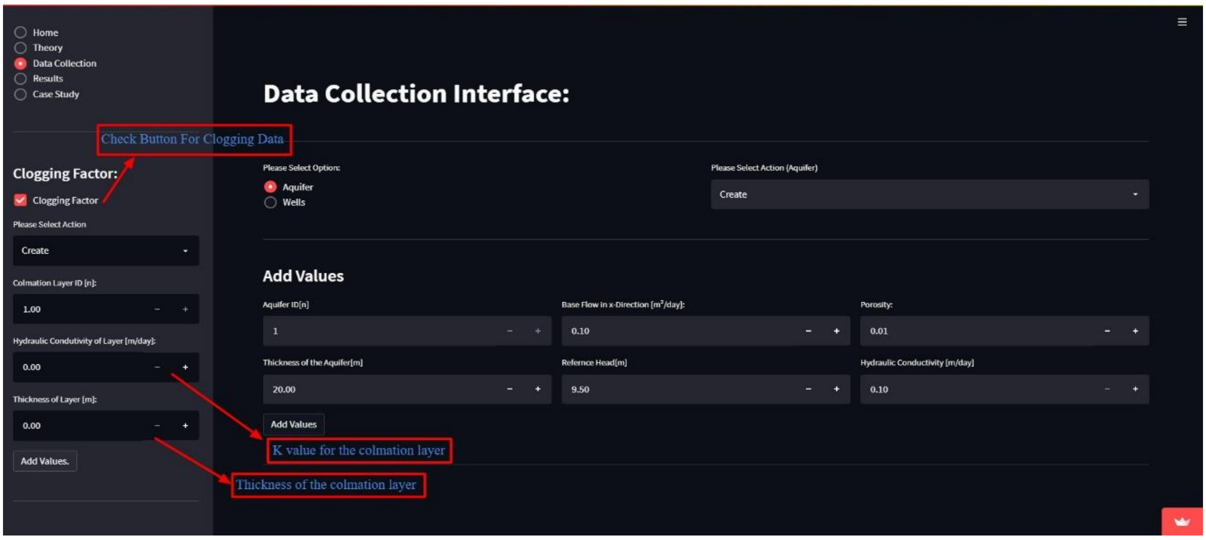

FIGURE 19 DATA COLLECTION FOR CLOGGING FACTOR

layer data and the user has to provide the specific data related with colmation layer as illustrated in Table 2 once the user has provided the data the button for Add Values should be clicked in order to show result with the clogging effects.

	Hyd. Conductivity (kd)	**Thickness of Layer (d)**
Colmation Layer	[m/day]	[m]

TABLE 2 COLMATION LAYER INPUT PARAMETERS

By clicking on the result button, the application will show the results for the entered data. But if the user needs to modify or edit the entered data it can be done by going back to the Data Collection and selecting the update option from the dropdown menu of, Please Select Action. Using the download buttons, you may download the corresponding stream function and potential function values as "csv" files (Fig 20).

If none of the button at the result window is unchecked the application displays the illustration only at the right side of window demonstrating the contribution of water

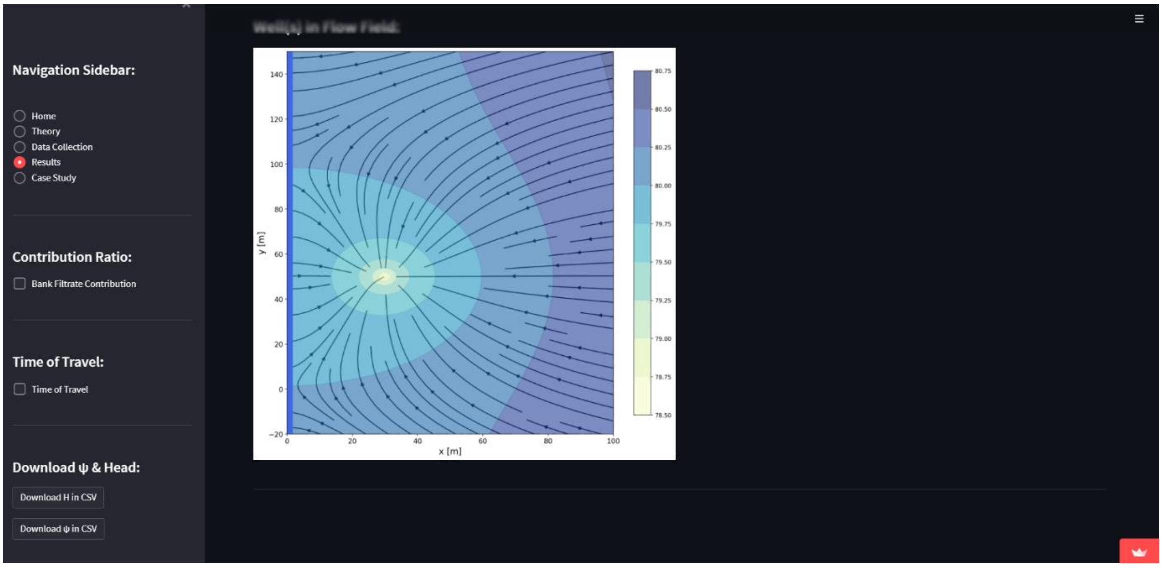

FIGURE 20 DEPICTION OF RESULT WINDOW

to the well from the Aquifer and River source in the form of streamlines (Fig 6).

If the button for the Contribution Ratio and Time of Travel button are checked the result page displays a visualization on the right side of the window and numerical results on the left also the additional visualization appears on the right side shows the effective region of the river involved in water contribution for the well "Bank Filtrate" (Fig 6).

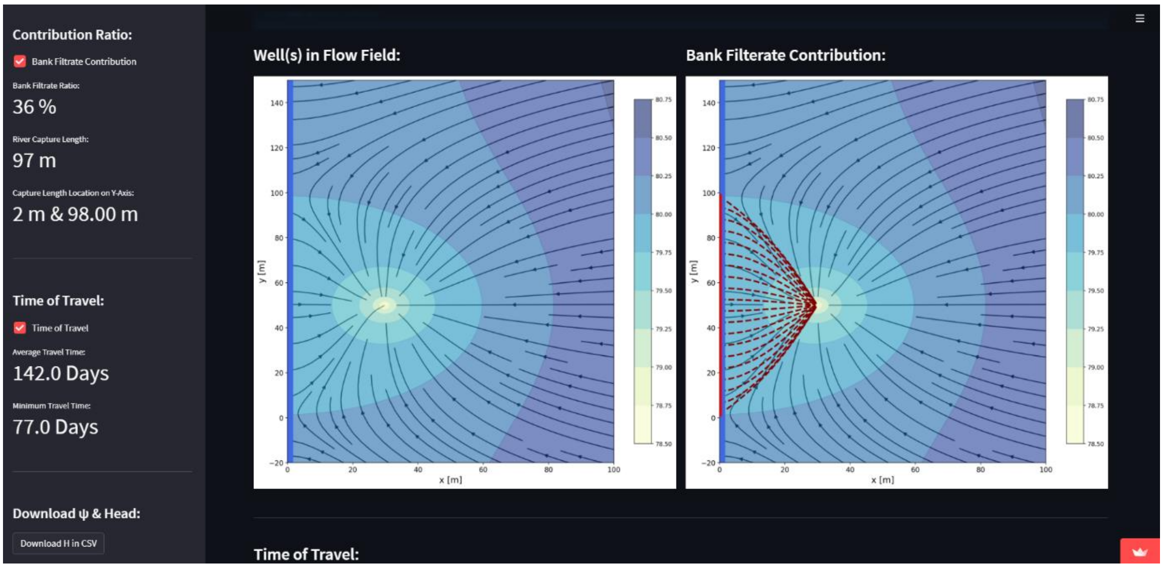

FIGURE 21 BANK FILTRATE CONTRIBUTION FOR WELL

7. Online Deployment

The tool is currently deployed on Streamlit cloud platform, where currently 3 users can use the tool at once, with the possibility to further upgrade the functionality to multiple users using the app at once. Currently the app can be access by clicking here.

8. Organization Involved in Development

The app is developed under joint research program of Technical University Dresden and University of Applied Sciences Dresden (HTW Dresden).

TECHNISCHE UNIVERSITÄT DRESDEN

Hochschule für Technik und Wirtschaft Dresden
University of Applied Sciences