U.S.-Pakistan Centers for Advanced Studies in Water

Draft Final Report

Production of drinking water from Indus River through Canal bank filtration for Mehran University Jamshoro: Estimation of yield, pumping requirements, Bio-clogging, and characterization of water quality.

(PROJECT NO.: 27)

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EXECUTIVE SUMMARY

Mehran University of Engineering and Technology (MUET) is withdrawing potable water directly from Kalri Baghar feeder (KB feeder, a canal of the Indus River) through pumping. The canal water is highly turbid (up to 600 NTU) and contains microbial contaminants higher than the permissible range recommended in the guidelines of World Health Organization (WHO). The treatment facility installed for MUET is unable to meet the required safe water quality and treated water remains highly turbid even after addition of coagulants. Despite the presence of Indus River passing 1.5 kilometers apart from MUET, the area has saline groundwater aquifers. Therefore, groundwater extraction for consumption is not an option. MUET is continuously thriving to take progressive steps to ensure provision of safe drinking water for everyone on the campus, but due to continuous extension of staff, students and increase in need, the quality as well as the required quantity of water has not been achieved. Considering this situation, US-Pakistan Center for Advanced Studies in Water (USPCASW) has initiated a project to replace the existing conventional treatment plant and rehabilitation of water distribution infrastructure. Preliminary cost estimates are about PKR 110 million including 10 million for baseline analysis and system's design and 80 million for system's rehabilitation and upgrading. However, the project is still awaiting funds from Government of Sindh. It is necessary to put focus on alternative and cost-effect intervention for provision of safe drinking water for MUET. This report discusses to introduce a natural filtration system, called Canal Bank Filtration, for natural treatment of water without much investment.

Canal bank filtration (CBF) method has been planned to adopt for the supply of naturally filtered water instead of physio-chemical treatment of water. The method has been widely adopted since 1870 in developed countries, for example, Switzerland[1] extracts 80% of its drinking water through canal/riverbank filtration (RBF) method, France using 50%, Finland 48%, Hungary 40%, and Germany 16% drinking water through RBF process. From last 50 years USA is using RBF technique especially in Ohio, Kentucky, Illinois, and Indiana states. The possibility of adoption of CBF system at the KB feeder for extraction of water for drinking purpose at MUET is explored in the current report. The objectives of the study were (i) to predict the well field capacity of CBF system for MUET, (ii) Water quality assessment after CBF in terms of removal of turbidity, microbial, organic contamination, (iii) Bio-clogging assessment of CBF and (iv) Cost-benefit analysis and life cycle assessment of CBF system. The project was executed in three phases. In phase 1, hydrogeological investigations were carried out employing vertical electrical sounding method (VES, using Terameter SAS-4000) and bore-logging on both sides of KB feeder canal. The bore-logs also validated the VES data. On the basis of the hydrogeological assessment CBF site was selected, and pumping tests were conducted with main wells and monitoring wells. In phase 2, construction of vertical wells was completed. As per hydrogeological formation and concept of CBF project the wells were drilled at the depth of 30 feet to collect/intercept the canal seepage. To minimize the cost the primary well diameter was kept as 12 inches while the

[1] Ascott et.al (2016)

monitoring wells have dia of 3 inches. The pumping tests were conducted with different scenarios of availability of water in canal, i.e. flow at 30%, (shortage), at 80% (routine flow), and at 100% (full supply level). The pumping test data was incorporated in AQTESOLV model to estimate soil characteristics and MODFLOW to project the water availability using different canal water level scenarios. On the basis of pumping test results, wellfield capacity was estimated. The phase 3 of the study focused on the establishment of lab column for controlled research, clogging study, chemical analysis to study the removal of microbial, chemical and physical contaminants from CBF and cost-benefit assessment were conducted. The lab column was filled with the original soil extracted during the drilling of the primary well. The water samples were regularly collected from (a) canal, (b) wells and (c) column outlet to record the contaminant removal from (1) wells, and (2) from column outlet and comparing the results with those of source water.

The hydrogeological assessment suggested the best-suited site for CBF as the eastern side of KB feeder (Inspection path aka IP side). The site investigations revealed the surrounding soil of KB feeder with freshwater, with dominant clay lithology. The saturated soil has high seepage of canal water in alluvial zone due to close proximity of KB feeder. Due to heavy clay dominancy in soil (50% clay) the transmissivity was found 3.229 ft^2/m. The discharge rate of 0.3 Liter per seconds (L/s) was observed through pumping test as suitable for extraction of water as the extraction rate suits the recharge rate. Determination of water quality in the CBF system for removal of organics, turbidity, and microbial contamination was recorded as main component of the research. The experimental setup on field and in laboratory revealed the removal of pathogens, microbial and physical contamination up to 90%. The bio-clogging test was conducted by installing pressure gauge to the inlet water pump and monitoring the pressure difference for 190 days. The trend of pressure difference shows a negligible difference in applied pressure. The variation of little pressure was due to variation in turbidity level in canal water. The pressure data confirms the suitability of CBF system for longer times. The results for projected period up to five years using MODFLOW demonstrated that the continuous extraction is possible without any significant decline in water levels in the alluvial zone of the canal.

The cost-benefit analysis of CBF system as compared to the conventional filter system revealed the initial capital costs are associated only for installation of CBF system, while the pumping and disinfection costs will be similar to the current practice. The annual cost of current practice of coagulation and sedimentation process was estimated as PKR 300,000/ annum. While the installation cost of CBF system to convert the same water demand was estimated as PKR 4,500,000. The CBF system will recover the initial capital investment within 15 years. However, the quality of water from CBF will be within the permissible guiding range of W.H.O. for drinking purpose, which is not being achieved from filter plant. It is estimated that approximately 154 bores will be required to meet the water demand of Mehran University of Engineering and Technology and residential area of MUET Society, Jamshoro (4000 m^3/day, estimated in earlier study by USPCASW). These bores should be coupled with the main pump, and the outlet can be connected with the existing pumping station or to the treatment plant. To increase the quantity of water, bore coupling method has been recommended to supply the required quantity of water. The canal bed filtration is a reliable method for safe water supply, minimize the need for water treatment and can be replicable throughout Pakistan for access to safe drinking water to all.

1. INTRODUCTION

Canal or river bank Filtration (CBF) is a traditional approach that extracts water from bore wells, drilled along the banks of a canal or river. During the extraction process, river/canal water passes through the canal bed and bank soil which naturally filtered the water. As the running surface water travels, the seepage occurred from the wetted perimeter of the canal. The seepage water when extracted towards the CBF well, suspended contaminants, as well as pathogens are potentially removed or significantly reduced in numbers resulting from a combination of the physical, chemical and biological processes (Derx et al 2013, Mustafa et al 2016, Jaramillo 2012). The approach was converted into a research proposal to supply safe drinking water to Mehran University of Engineering and Technology (MUET) from the seepage of Kalri Baghar (KB) feeder canal off-taking from Ghulam Mohammad (GM, aka Kotri) Barrage.

Although MUET has taken progressive steps to ensure provision of safe drinking water for everyone on campus, the treatment facility installed at MUET is unable to meet the required demand and quality. MUET is lifting water from KB feeder canal, which is highly turbid and contains a high concentration of suspended solids; pumping it to MUET water filter plant, where coagulation, sedimentation, slow sand filtration, and chlorine disinfection processes make it free from dirt and pathogens (MUET clean water project 2016). The clean water is then supplied to MUET campus and residential areas. The capacity of installed water supply system is about 4,000 cubic meter per day (m^3/d).

The quality of KB feeder water is considered acceptable except bit higher concentration of iron and lead. In a recent study, mean values of iron and lead concentration are found 459.7µg/L and 13.8µg/L, respectively (Gollnitz 2002). The other considerable contaminant in KB feeder water is the presence of suspended solids and can be seen by naked eyes by the users at every water outlet of MUET. Although, a slight reduction in Iron and lead was observed after MUET water treatment plant (Gollnitz 2002) MUET treatment plant is not successful in eliminating suspended solids from KB feed water. Considering this situation, USPCASW initiated a project to replace the existing conventional treatment plant and rehabilitate water distribution infrastructure. Preliminary cost estimates were about PKR 110 million. The project is still awaiting funds from Government of Sindh. As an alternative and low-cost option, establishing a Canalbank Filtration (CBF) system for MUET is proposed as a step forward for providing safe drinking water to MUET community.

Canalbank/Riverbank filtration is widely practiced in many parts of the world due to high potential of safe water production, proximity to users, easiness of extraction, and low cost of operation. A hydraulic gradient can be utilized by extracting water from wells in an alluvial zone in proximity to a river or canal; consequently canal water is traveled through the bank of the canal to the well. Chemical and bacterial contaminants can be eliminated during the flow of surface water to the well through alluvial plain by both chemical and physical process (Jarmillo 2012, Tufenkji 2002, Gibert 1997, Weiss 2002). A distinct biogeochemical condition exists at the interface of surface water and groundwater within alluvial zone of aquifers. This zone is called “hyporheic zone” and responsible of the quality of bank filtrate due to existing physio-chemical conditions such as temperature, pH, oxidation-reduction potential, concentration of oxygen, and organic substrate, [6].

Riverbank filtration can purify water using the following steps:

- Removal of suspended solids and turbidity, eliminating the need for sedimentation,
- Reduction in bacteria, viruses, parasites, the decreasing need for addition of disinfectants,
- Biodegradation of emerging organic, natural organic matters (NOM), and disinfectant by-products (DBPs),
- leveling out fluctuations in temperature and concentration,
- A barrier of peaks and shock loads.

Table-1, different services, and benefits are summarized for using CBF[1].

Services and Benefits	Value
Contaminant removal	Improve public health Long life expectancy Enhanced productivity Capital cost reduction Cancer risk reduction Improved recreational activities Pleasant environment
Less maintenance A reliable source of water supply Organic removal	Reduced operation and maintenance cost Draught management Reduced treatment costs Less regulatory interventions Less monitoring costs
Enhanced Community supply	Enhanced customer satisfaction Lower problems in household plumbing

A series of studies conducted, during 1970-1980, 1994-1995, and in 1999, at Ohio River, Kentucky for extraction of water for drinking purpose using horizontal collector wells (Ray 2002) and significant removal of disinfection byproduct precursors was achieved. Biodegradation and suspended solids removal through filtration were main mechanisms of contaminants removal including natural organic matters (NOM). Moreover, adsorption was also a contributing mechanism for contaminant removal at increased filtration depth. Effective turbidity removal, total coliform, heterotrophic plate count, total aerobic spores, and microscopy particulate removal was demonstrated in the study using RBF (Ray 2002). Along the Ohio, Wabash, and Missouri Rivers, three RBF based water treatment systems were investigated by (Weiss, 2002). Efficient removal of microbial contaminants, TOC, DOC, DBP precursors, and Tri-halo-methane, were demonstrated. The treatment efficiencies for removal of formation potential of total Tri-halo-methane and Halo-acetic acid by RBF and simulated water treatment systems compared and found that removal efficiencies by RBF were almost two times greater than simulated treatment system. It can be inferred that water-quality improvements using RBF can be used to meet strict regulation.

The capacity of a CBF/RBF wellfield depends on canal bank/riverbank conductance, aquifer transmissivity, and dynamics of well screen, considered as yield-limiting factors. Riverbed conductance is considered as a probable factor in reduction of capacity of RBF systems. Nevertheless, there is missing gap of information regarding dependency of extraction yield on canal bank/riverbank conductance. It has been reported that the variation of canal bank/riverbank conductance occurs with time, most likely because of riverbed clogging (Gollnitz 2002). The mechanisms of this clogging can be mechanical entrapment of suspended particles, bacterial growth, or chemical reactions within the interface of aquifer and riverbed.

The CBF method can be explored for extraction of water from KB feeder canal. The current study focused on extraction of water from bank of KB feeder canal, removal of suspended solids, microbial contamination, removal of turbidity through CBF, estimation of CBF capacity to fulfill MUET water demand and other issues such as variation in concentrations of pathogens during and after flood event. The study also used MODFLOW modeling for projection of extraction for a more extended period.

1.1 General description of the research area

The research area falls under the administrative jurisdiction of Jamshoro district of Sindh province as a whole and Irrigation Department, Government of Sindh in particular. The area is semi-arid with rainfall less than 200 mm per year. Mehran University is situated on hilly terrain in Jamshoro town. MUET has established its pumping station at 428021.00 m E and 2808560.00 m N, situated on non-inspection path (NIP) of KB feeder off-taking from Kotri barrage. The Indus River flows 2 km apart with KB feeder parallel on its IP side, while a railway track is running parallel to KB feeder on its NIP side. The research area is an assortment zone between hilly terrain of Khirthar range of Kohistan region and riverine plateau. The MUET filter plant is located 2 kilometers (kms) away on western side of MUET pumping station at the elevation of 15 meters, while the MUET campus is also 2 kms apart from MUET filter plant on northern direction crossing M9 motorway. The canal water is lifted from KB feeder through MUET pumping station, which pump it to MUET filter plant, then filtered water, after treatment, is pumped to MUET campus in three main underground tanks. The stored water then re-supplied to different departments and residential colonies. The CBF site is located on IP side of KB feeder, 1 kms apart on northern side of MUET pumping station. All distances are measured aerially using remote sensing tools.

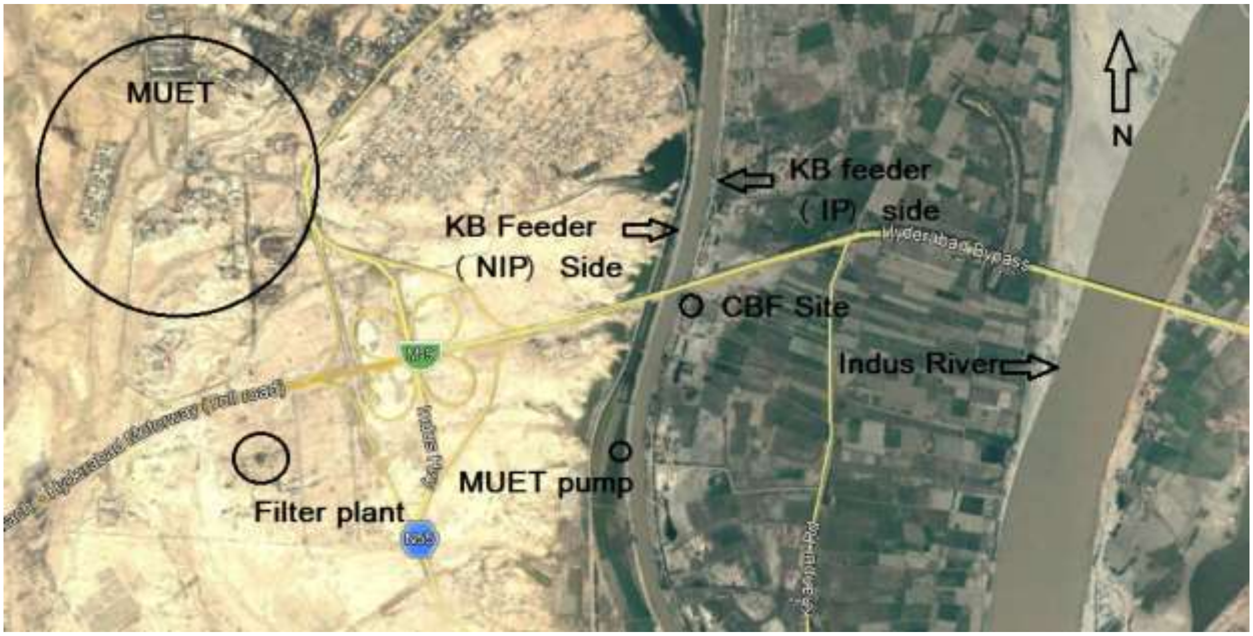

Figure 1 Study area with detail of installation.

1.2 OBJECTIVES

The main objectives of the research were as follows.

1. Prediction of wellfield capacity of CBF system for MUET,
2. Determination of water quality after CBF system in term of organic and turbidity, microbial contamination removal before and during an event (flood/high discharge in river),
3. Assessment of bio-clogging of CBF system,
4. Cost-benefit analysis of CBF system for MUET.

2. METHODOLOGY

The canal bed filtration project is based on the extraction of canal seepage water in the surrounding of the canal area at shallow depth (Fig.2). The seepage of canal water when passes through soil medium, the soil formation acts as a filter material. All the impurities and suspended solids naturally filtered through soil pores and pass the clean water free from dirt, pathogens, and bacteria.

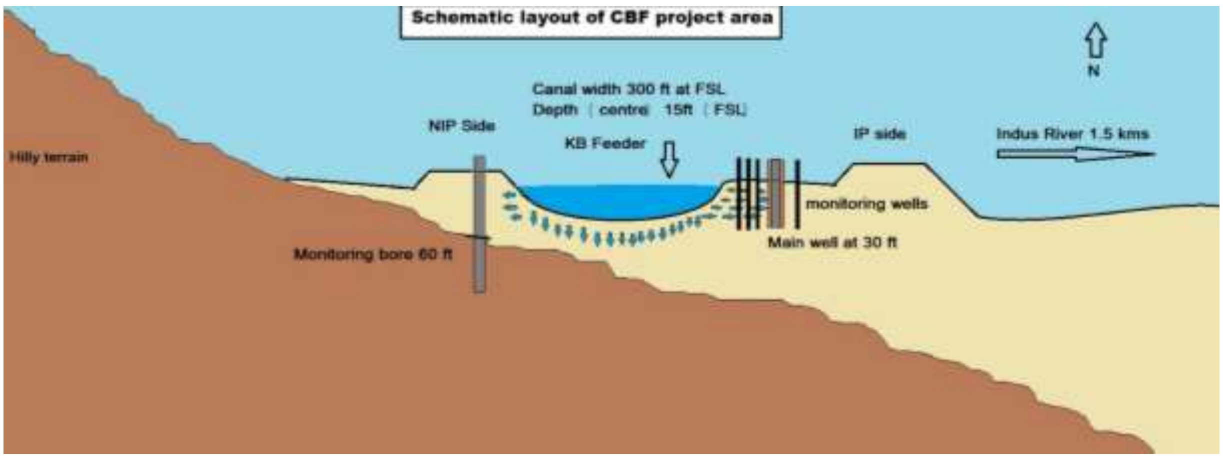

Figure 2 Schematic of CBF area and CBF theme.

The project activities were started from mid-August 2018 and completed until August 2019. The proposed location for CBF site near MUET pumping station was difficult to reach even on motorcycle; however after some earth-filling and leveling the path was made accessible. The project activities were started by geo-technical survey of the area to determine the best-suited location for CBF project surrounding to KB feeder near MUET pumping station. On the basis of geo-technical survey consisting of Vertical Electrical Survey (VES), bore-logging and literature survey the suitable location was identified. After identification of CBF site the installation of experimental setup was established on field as well as in USPCAS-W labs for replicating the experiments in controlled environments with input variations. The step-wise procedure is as follows.

2.1 Vertical Electrical Sounding (VES) analysis for selection of site

Vertical Electrical Sounding (VES) has been employed as a relatively new tool to determine the groundwater quality and to quantify the extent of good water-bearing aquifer. The tool is widely used to predict soil formation on the basis of sounding reflectance of different soil materials including liquids. Every material on earth has its specific signature reflection. The reflectance of electrical sounding is measured in the unit of ohm-meter. The available minerals in water and their relative proportion indicates the quality of groundwater. The range starting from 0.3 ohm-m (highly saline seawater) to 100 ohm-m, which is freshwater (Fig.3). Higher the salt concentration lower the reflectance value. For current study, Terrameter SAS 4000 was employed to determine the suitable location for canal bank filtration project. VES incorporating Schlumberger array method has been selected for determination of groundwater which is recommended for sedimentary and saltwater invasion areas. (ABEM, 2010).

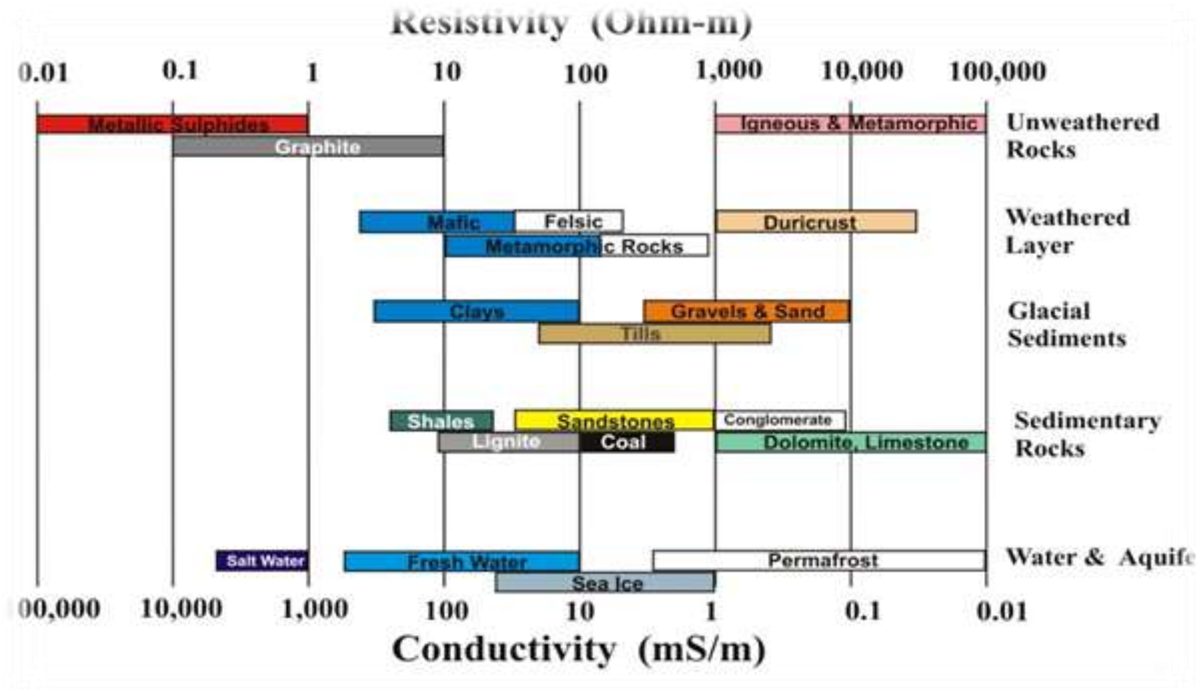

Figure 3 Resistivity ranges of different materials

The sounding depth of SAS-4000 Terra-meter, can penetrate up to 300 meters deep and distinguish between different soil materials, however for current study 180 meter depth was achieved. The reflected VES has been interpreted on the basis of pre-determined ranges of different materials and the soil formation and availability of water, and its quality was evaluated. The geological formation and water quality obtained through VES were validated through bore log data and as stated by (Brohi et al 2012, Ahmed et al 2015).

The VES survey was conducted both on sides of the KB feeder, i.e., left and on right side of KB feeder. Each geographically positioned sounding data was imported, and the layer models have been corrected adopting an iterative procedure. The received reflectance values were interpreted using IX1D and IPI2 Win software. The VES on NIP were conducted along the right bank of KB feeder. The vertical depth has been achieved through spreading the outer electrodes to horizontal length (Fig.4). Same method was applied on IP side (left side) of KB Feeder.

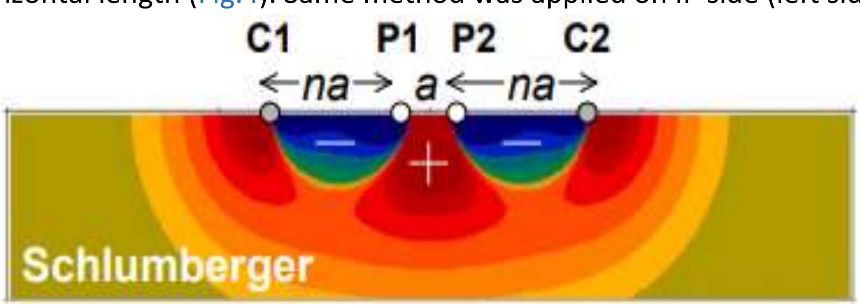

Figure 4 Schematic presentation of VES through with Schlumberger array (ABEM 2010).

2.2 Installation of monitoring and horizontal wells (Field)

As per project design, one main bore with 12 inches of diameter and 4 observation bores with 3 inches of diameter were installed in the research setup along with KB feeder. The main 12” bore is provided with 6” casing. The empty portion between borehole and casing was filled with gravel (Fig.5).

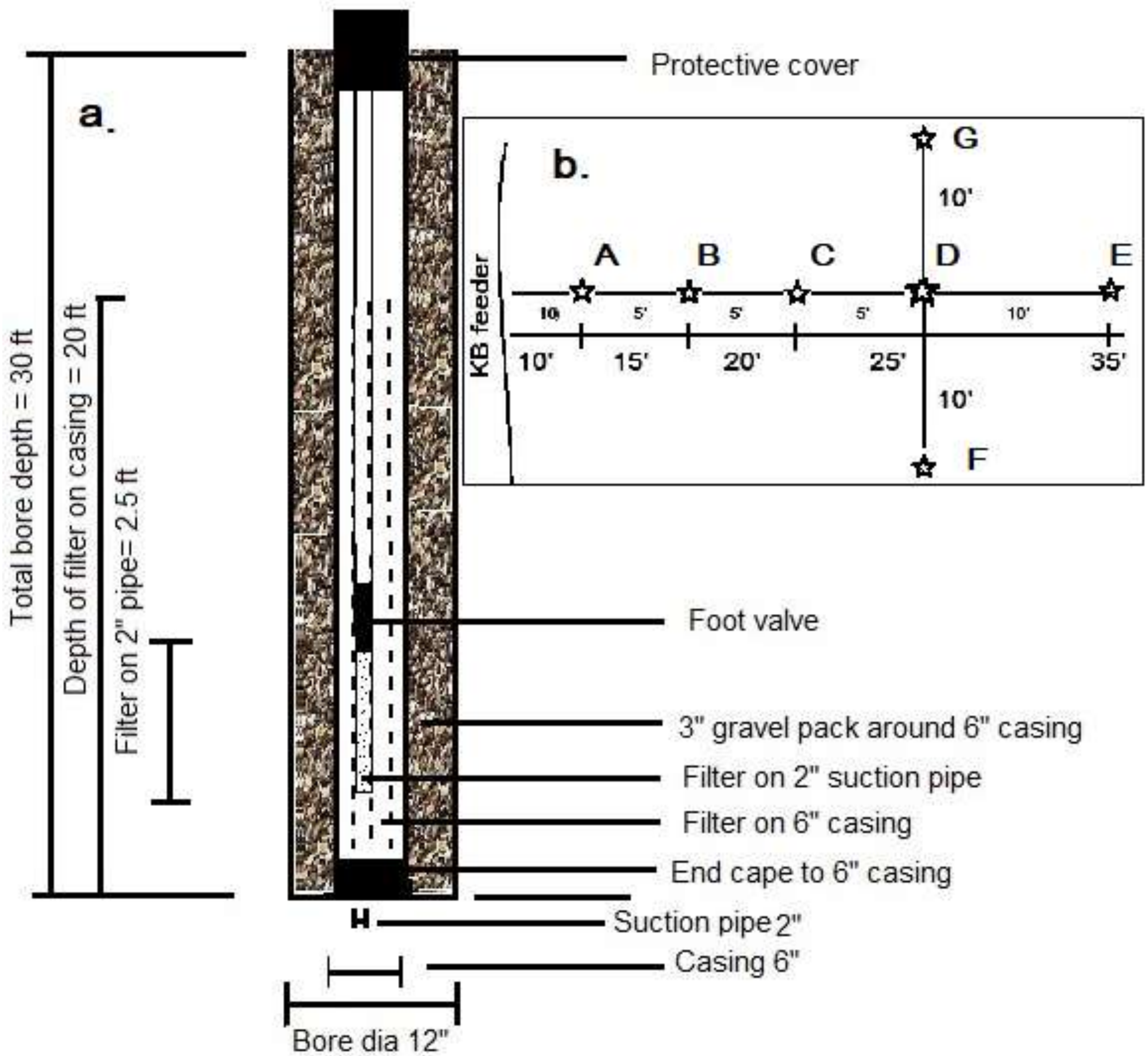

Figure 5 Schematic design of main 12” bore (a) and installation layout (b).

The purpose of main bore was to extract water to conduct yield test for quantification, while the observation bores were used to measure the drawdown in the bore vicinity due to continuous pumping from the main bore and to collect water samples for lab analysis. The water samples have been regularly collected from (i) canal, (ii) well A [which is 10 ft (3m) away from canal], (iii) well B [which is 15 ft (4.57m) away from canal], (iv) well C [which is 20 ft (6m) away from canal] and (v) well D [which is 25 ft (7.62m) away from canal]. The well "D" was drilled as main extraction well to perform pumping test. While the other observation bores were drilled in the circle of 10 ft around the main bore (D). The periodic water samples have been collected from all bores including canal water sample.

2.3 Quantification and Characterization of extracted water

2.3.1 Pumping test to analyze water yield and soil characteristics of the alluvial zone

Pumping test is a practical assessment to determine well yield, well performance and aquifer characteristics (Shende and Chau 2019, Leelaruban and Padmanabhan 2013, Tonder et.al 2002). Multi-bore constant discharge and Recovery pumping tests were conducted at CBF site. The tests were conducted on main wells situated on both NIP and IP sides of the KB feeder. The tests were repeated to calculate the soil characteristics and well yield with different water level scenarios in KB feeder. The variation in the flow depth of KB feeder has been monitored through piezometers as water table depth (Fig. 6).

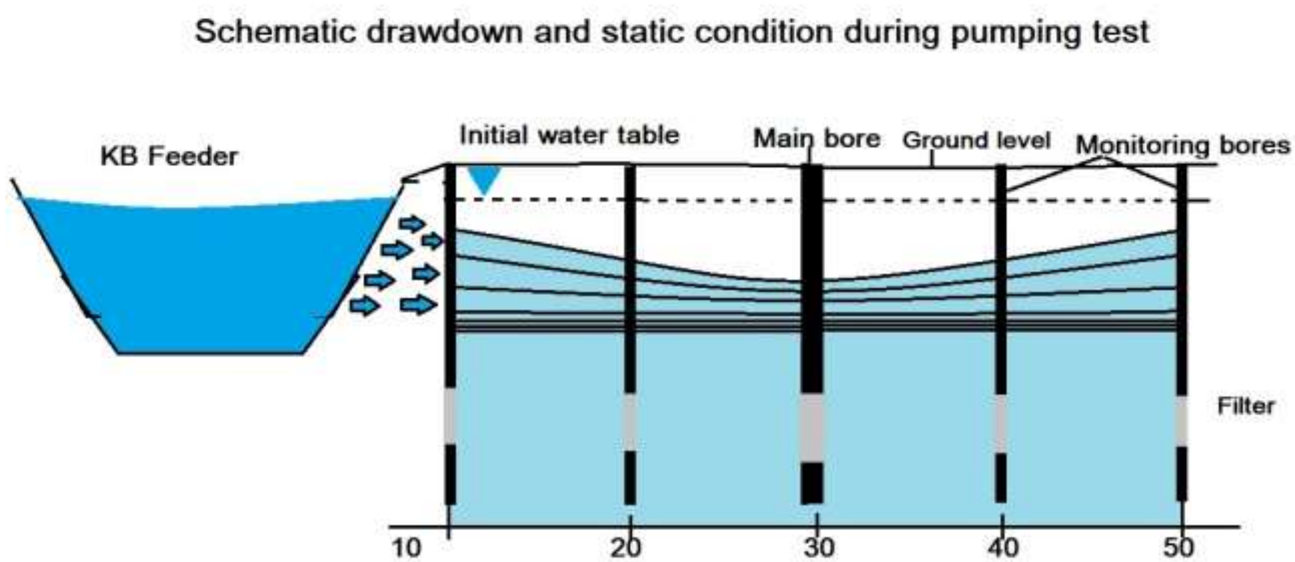

Figure 6 Schematic presentation of pumping test and resulting drawdown in monitoring wells

2.3.2 Scenario based projection on GMS (MODFLOW)

Impact assessment on groundwater levels was performed via groundwater flow model (i.e.MODFLOW 2005) for five year of simulation. Monthly water level fluctuation was quantified. MODFLOW 2005 using continuity equation for water balance (Equation.1) and finite difference scheme to solve it numerically.

$$\frac{\partial}{\partial \mathrm{x}}\left(k_{fx}\frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{x}}\left(k_{fx}\frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{x}}\left(k_{fx}\frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right) = S_o\frac{\partial \mathrm{h}}{\partial \mathrm{t}} + W_o \quad (1)$$

Where, h = hydraulic head; *k = permeability; S_o = storativity; Wo = Source/sink*

KB feeder and Indus River were considered as the river boundary at east and west respectively. Schematic of the model domain is shown in **Error! Reference source not found.**. Aquifer parameters were calculated via pumping test analysis, and incorporated in the model. **Error! Reference source not found.** shows the aquifer parameters used in the model. Model was discretized in 15 m by 15 m cells in x-y direction, and z-direction (depth) model considered two layers. Layer-1 was considered to be10 meter deep, and layer-2 to be 40 m deep. Kb feeder and interceptor drain were considered in layer-1, and river Indus in layer-1 and layer-2. Pumping was simulated in layer-1. Figure 7, shows the discretized area of the model. Head fluctuation in the KB feeder was considered based on the variation in the flow entering the KB feeder. It was considered that the depth in the Kb feeder is directly proportional to the fluctuation in the flow. As due to lack of gauge data this assumption was made. We used flow to capacity ratio for 5 years (i.e. 2010 till 2015) and multiplied it with full supply depth to quantity the head fluctuation in the KB feeder. River Indus was considered to flow at low depth (i.e.14 m from sea surface level), as the head downstream of Kotri nearly remains same and only fluctuates in the flood seasons. On the other hand, the influence of Indus boundary was minimal on the head at the proposed locations of the pumping. Once the data was incorporated in the model. We simulated multiple well arrangements to observe the feasibility of proposed pumping with respect to the water level fluctuations. Model was simulated initially for 10 days in steady state to achieve the equilibrium for levels under no pumping condition, then pumping was simulated continuously for whole simulation period. Each pumping cells was given pumping of 86 m^3/day, and wells were arranged such that we achieve the pumping of 4000 m^3/day.

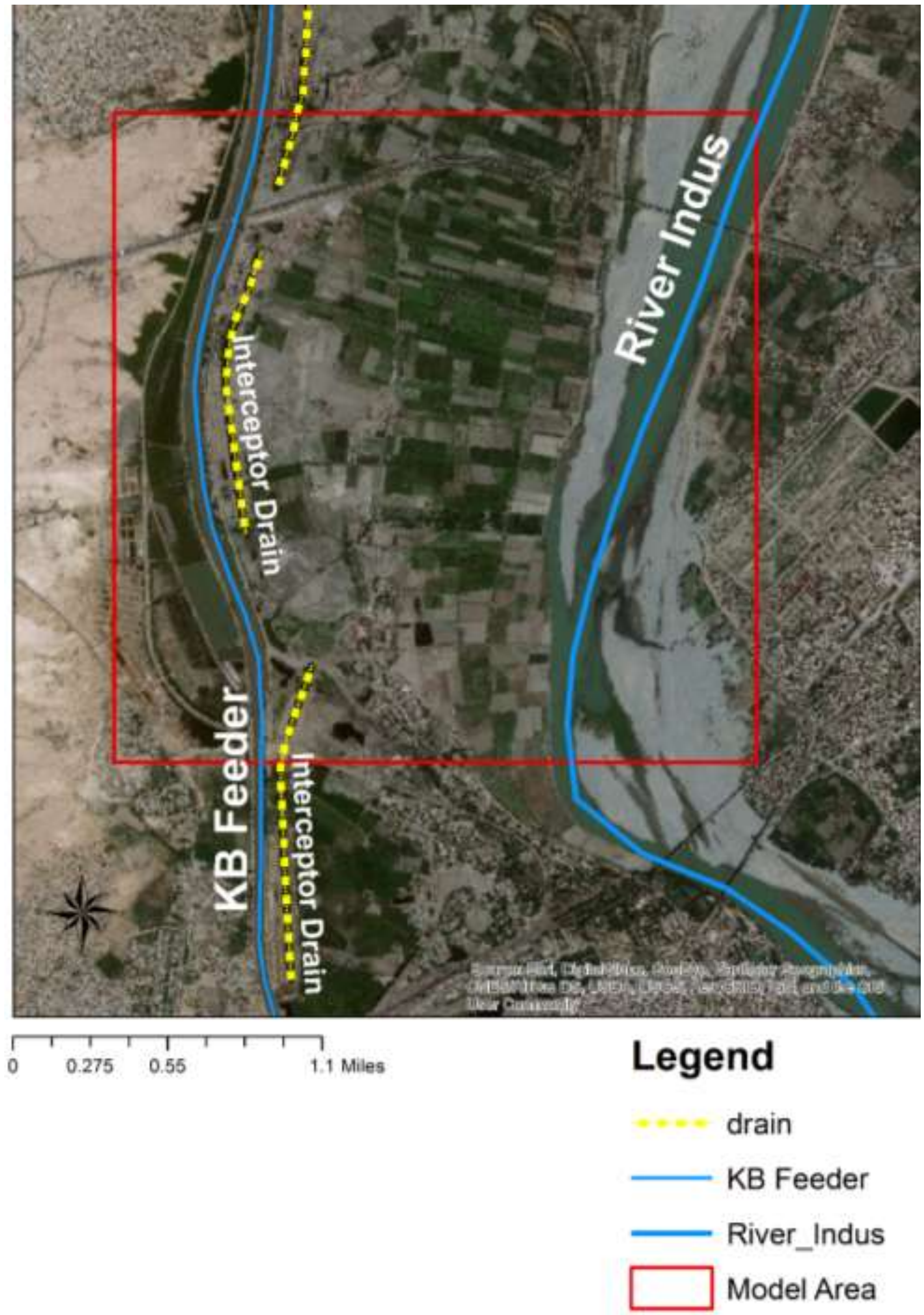

Figure 7 Schematic of study area

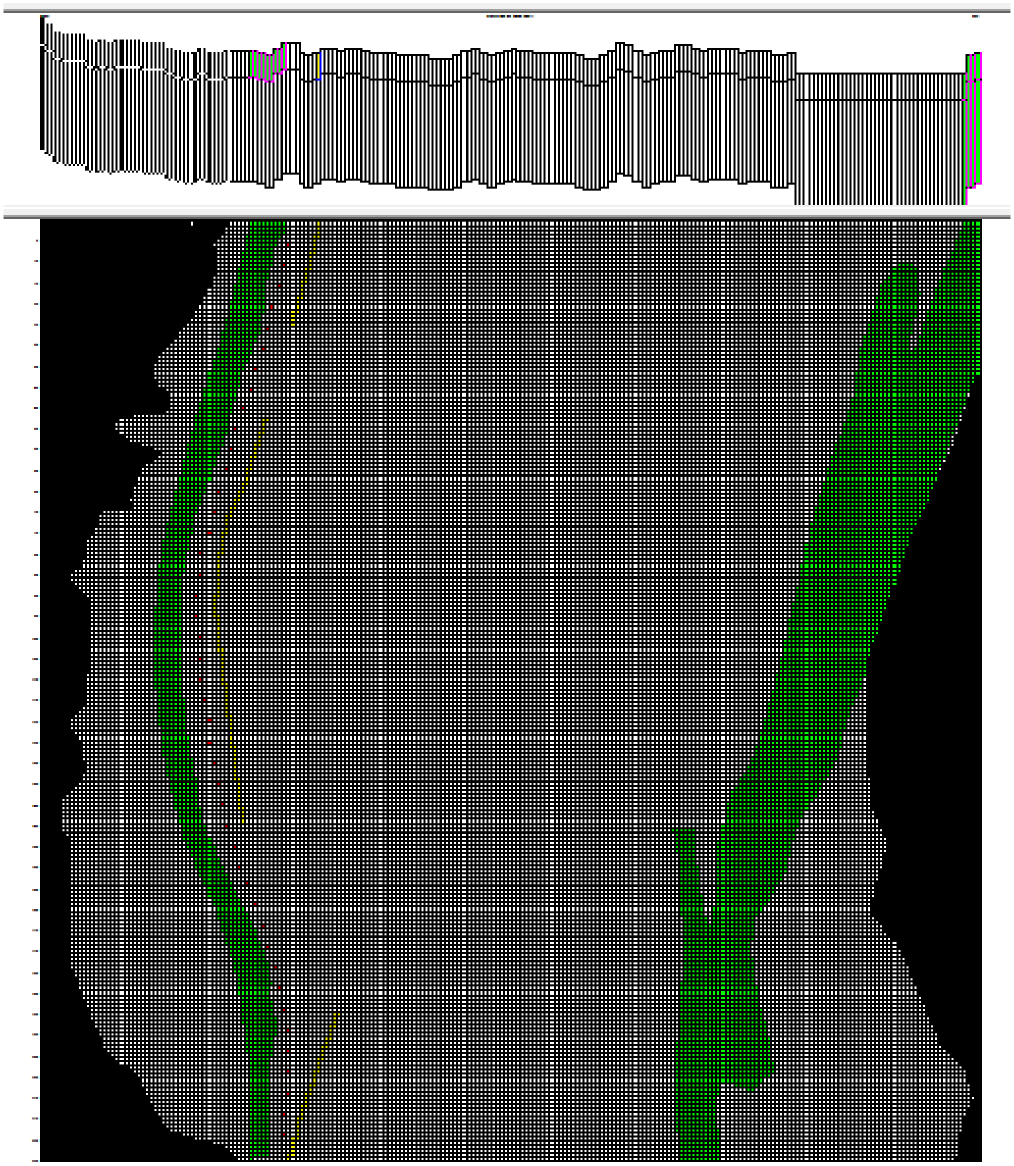

Figure 8 Discretized model

Table 2: Actual Boundary heads and well discharge.

Parameter	Value
Kh	48 m/day
Kv	0.1*Kh
Sy	0.1
Ss	1e-4
K(river)	48 m/d

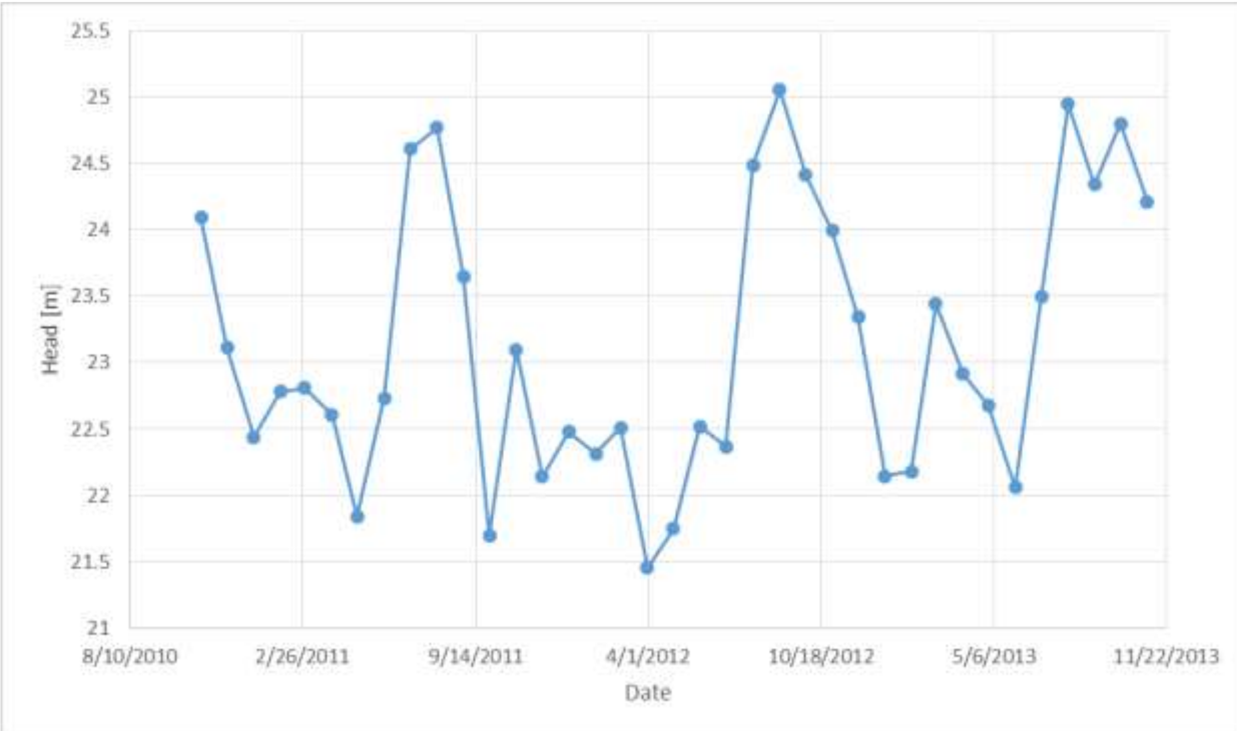

Figure 9 Head fluctuations considered in KB feeder

Table 3: Boundary heads and well discharge. These are repeated every year for whole simulation period

Indus River Head [m]	14
Q [m3/d]	86

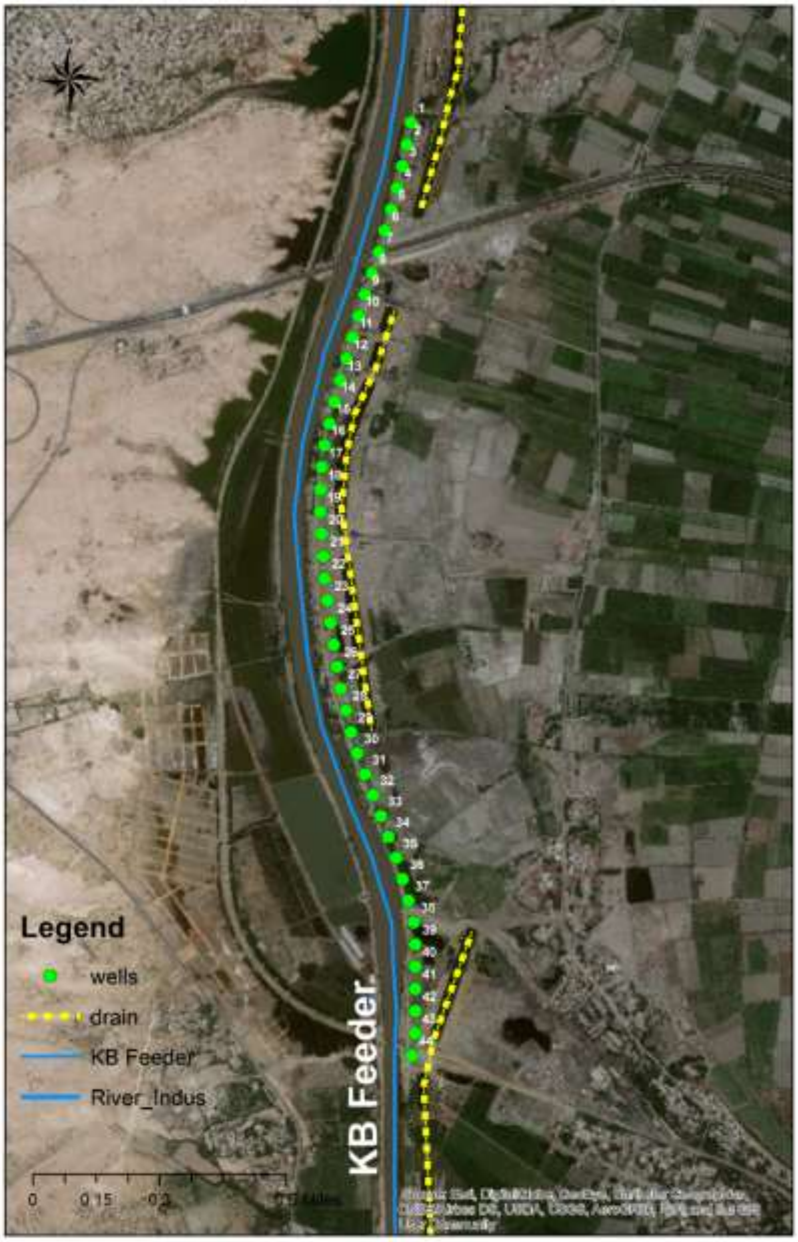

Figure 10 Discretized area showing pumping wells

2.5 Well and monitoring bores water analysis

The regular water samples have been collected from canal, main bore and the monitoring bores. The samples were collected in autoclaved, air tight bottles and brought to USPCASW lab for physio-chemical, microbial, and metal analysis. The physical parameters were also tested on-site using standard field equipment. The water samples were tested for 7 months to monitor the change in contaminates with respect to fluctuation in canal water level. All the samples were analyzed using stand methods. Metals were analyzed using ICP-MS.

2.6 Laboratory column setup and water analysis

In order to determine the results from canal bank filtration process an experimental setup in controlled lab environment has been established. A fiberglass column has been fabricated and placed in the lab, US-Pakistan Center for Advanced Studies in Water (USPCAS-W) established in MUET Jamshoro. The diameter of the column is 5" with inlet at the top and outlet at the bottom. A pressure gauge was placed at the inlet valve to monitor the variation of pressure in the column (Fig. 7). The actual soil extracted from the main bore holes was transported to lab to fill in the column. The column was fed with canal water collected from KB feeder near pumping station.

The textural class of the soil taken from the main bore was determined through sieve analysis method. The water samples of canal as well as water from outlet of the fiberglass column were analyzed for physical, chemical and microbial parameters using standard lab methods (APHA 2017) and equipment. The water samples were continuously collected from the field installations of piezometers, canal and outlet of columns. The EC, and pH, were tested on-site using standard portable equipment; the same were also tested in lab.

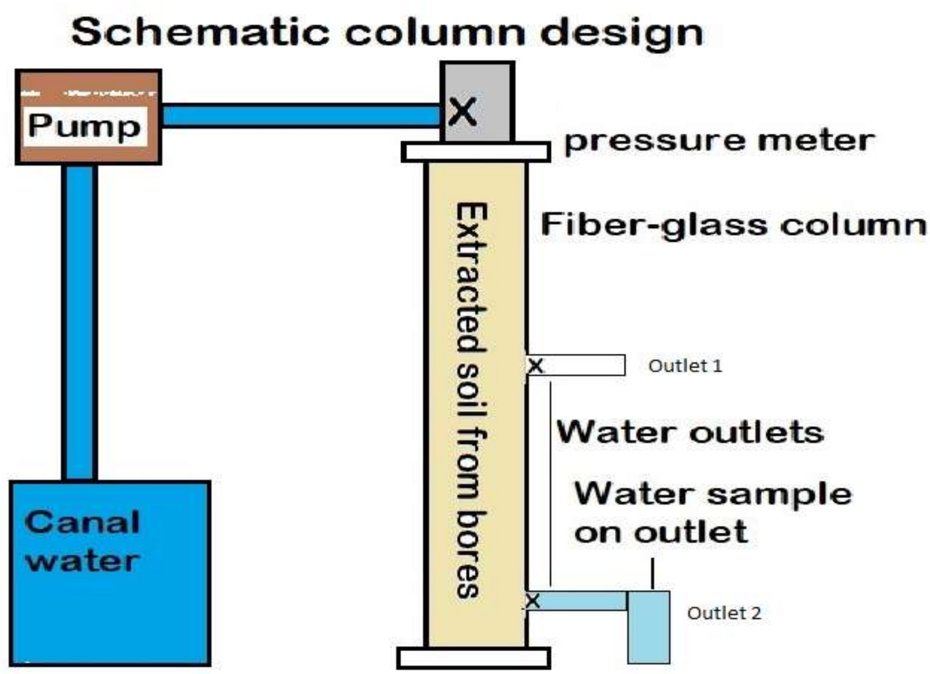

Figure 11 . Experimental column design.

3. RESULTS AND DISCUSSION

3.1 Vertical Electrical Sounding (VES) for groundwater quality assessment

The VES results which were conducted on NIP side near MUET pumping station, indicated the presence of fluvial sandstone in upper 10 meter layer with saline groundwater (Fig.11). The layered model presents the data as mono-layer with negligible variation of resistance. The resistivity data of NIP, reveals the availability of brackish groundwater in the entire surveyed range up to 200 meters in the limestone lithology. The pseudo cross-section indicated the extent of saline groundwater up to the entire depth. The data suggested that there is no impact of canal seepage on NIP side of the RB feeder.

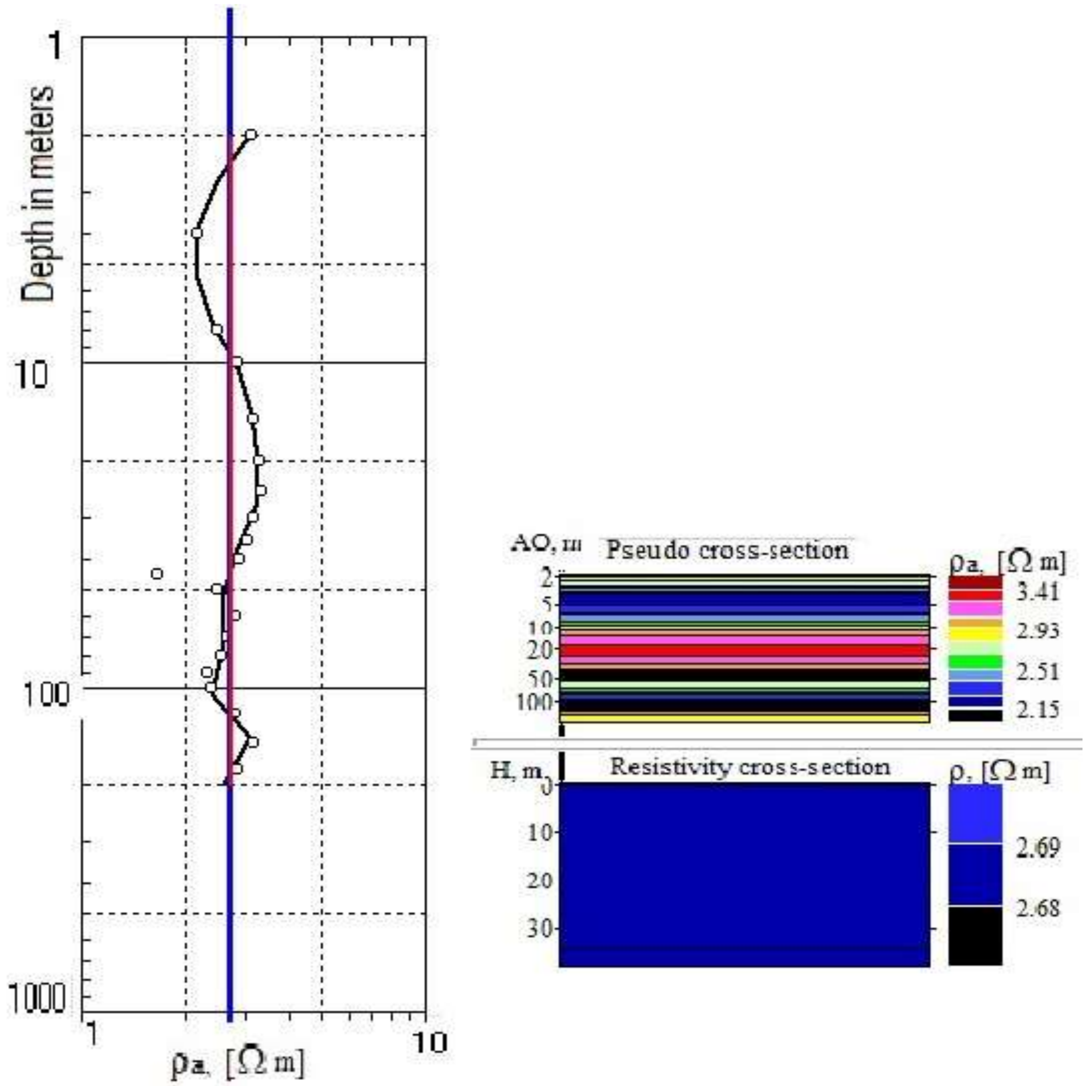

Figure 12: Layered model with Resistivity and Pseudo-cross section on NIP side

The same VES survey was conducted on IP side of the KB feeder. The layered model presenting two resistivity layers. Layer one starting from one meter depth and stretched to the depth of 25 meters, indicating the freshwater in clay bearing lithology. The second layer started from 25 meters and extends to 180 meters indicating the limestone lithology with saline groundwater. The pseudo cross section also shows the gradual decline in water quality and depth wise zoning of different layers with various levels of salinity (Fig. 12).

The VES data of both sides is also in synchronization with the geological formation of the area as Indus River is flowing parallel around 1.5 kms apart with IP side of KB feeder; while the presence of mountainous area on NIP side, deteriorate the water quality in groundwater due to leaching of minerals and mixing with groundwater.

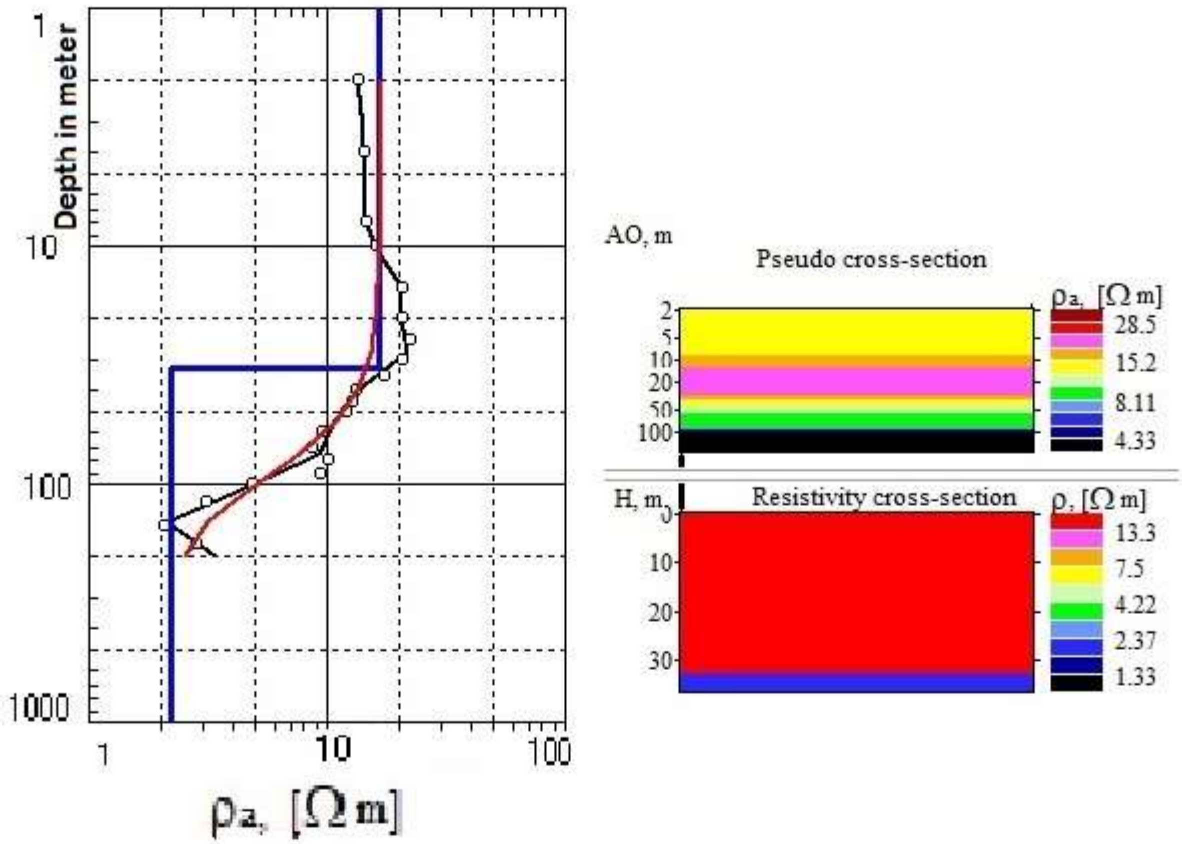

Figure 13. Layered model with Resistivity and Pseudo-cross section on IP side

3.2 Installation of monitoring and horizontal wells (Field)

It is always difficult for hydrologists to determine the suitable location for water bearing bore which permits a good quality and quantity of water. For this purpose test bores were drilled to decide for main bore. Initially the right bank (NIP) of KB feeder was selected to install test bores. The bores were drilled at the depth of 10 to 60 feet.

Table 4: GPS locations of bores and water quality results on NIP side.

Description	GPS location		Depth (ft)	Remarks (EC in dS/cm)
Bore 1	25.392123°	68.284165°	10	High salinity EC 5000
Bore 2	25.392120°	68.283638°	20	Saline GW, EC 4500

Bore 3	25.392232°	68.284373°	60	Installed nested piezometer. GW, EC at 20' = 1200, at 40' = 5000, at 60 = 10000
Bore 4	25.392205°	68.284373°	17	High salinity EC 5000
Bore 5	25.392259°	68.284372°	24	EC 640, insufficient quantity
Bore 6	25.392290°	68.284372°	24	EC 710, insufficient quantity

The GPS locations of the bores, their depth and relative status is described in Table 5. The area on NIP side of KB feeder was officially used as KB feeder canal escape, so normally inundated with canal overflow water or the rainwater as the area has no drain outlet. The inundated water deteriorate the quality of canal seepage water in shallow depth (Fig. 13).

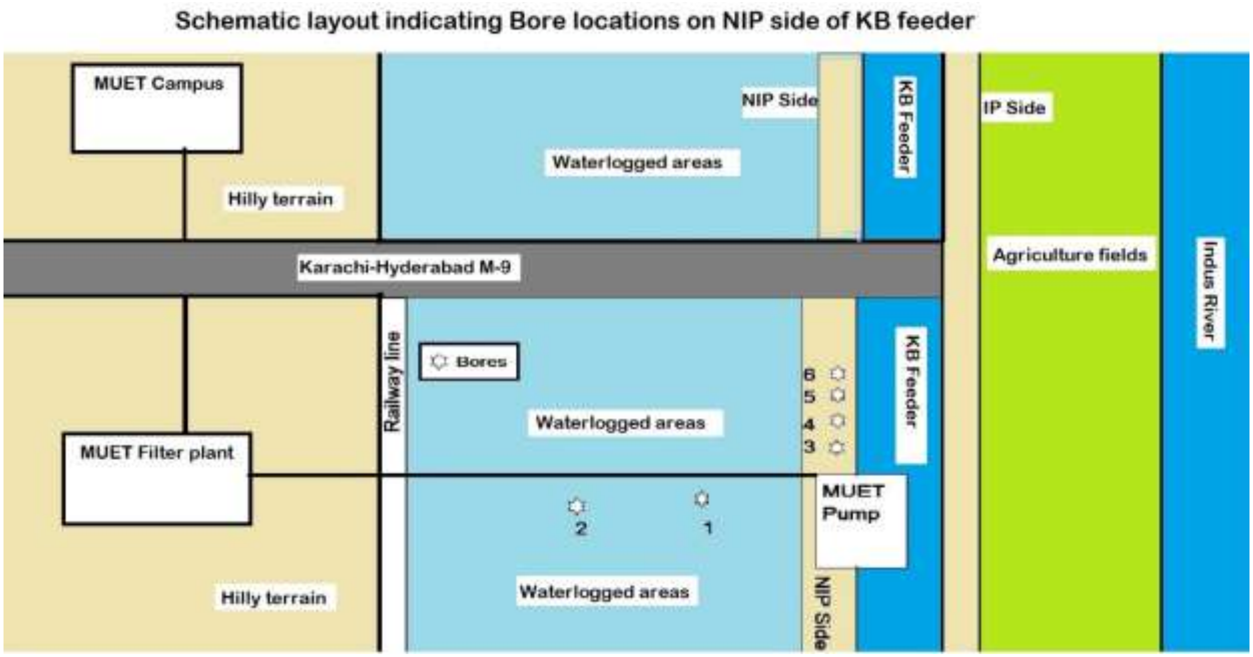

Figure 14. Schematic layout of area indicating bore locations on NIP side of KB feeder.

Bore # 3 was drilled at the depth of 60 feet to check the lithology of soil and groundwater quality at different depths. Nested piezometer was installed in bore #3 at the depth 20', 40' and 60'. The EC of water was recorded on-site through TDS/EC meter and "Reel" (Solinst P2 101 water level meter and TDS/EC meter), which was recorded as started from 1200 dS/cm at 20 feet to 10,000 dS/cm at 60 feet depth. Bore # 5 had a relatively good quality water with EC 640 dS/cm.

After initial results the CBF site was shifted to IP side of canal on the basis of VES and soil lithological information. The similar setup was established on IP side. The bore water quality data (Table: 6) indicates the quality of water on IP side within the permissible range of drinking water quality. All bores were drilled at the depth of 30 ft to collect only the seepage water from canal bank and bad (Fig.14).

Table 5: GPS locations of bores and water quality on IP side

Bore name	Location		Radius	Depth (ft)	EC (dS/cm)
A	25.401526°	68.286954°	3"	30	600
B	25.401526°	68.286975°	3"	30	600
C	25.401524°	68.286996°	3"	30	620
D	25.401527°	68.287012°	12"	30	640
E	25.401527°	68.287046°	3"	30	640
F	25.401560°	68.287013°	3"	30	630
G	25.401494°	68.287013°	3"	30	630
H	25.401456°	68.287020°	12"	30	640
I	25.401589°	68.287012°	12"	30	600

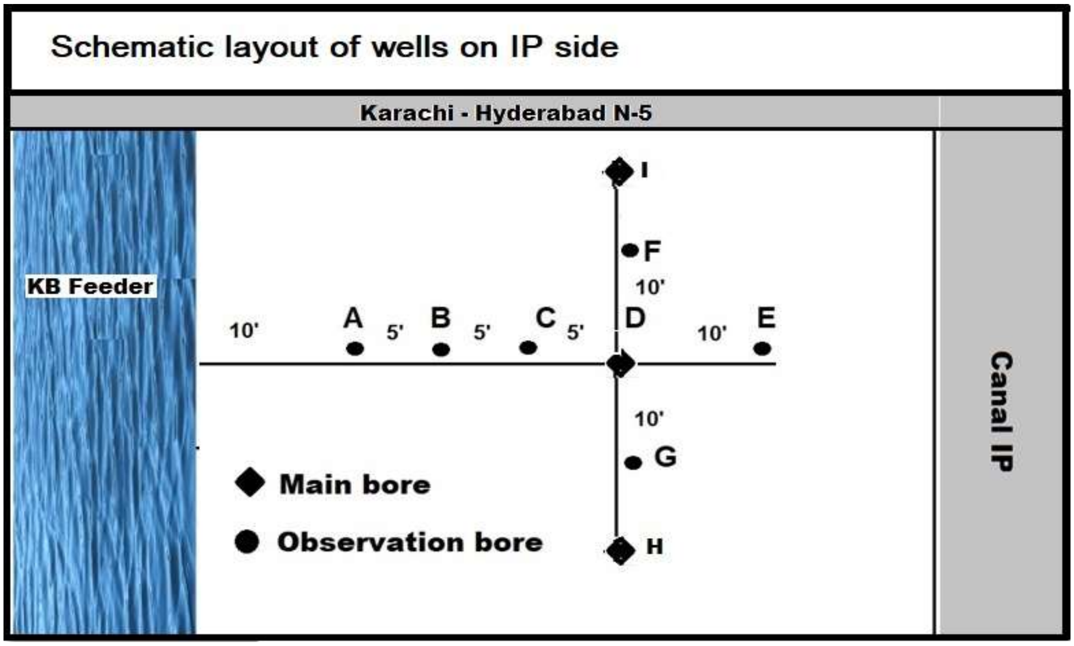

Figure 15 Schematic layout of bore installations at IP side

3.3 Soil Profile and lithology (NIP)

The well bores which were drilled in experimental field area were carefully monitored. The layer-wise soil extracted from the bore depth was kept in buckets to test the texture in the lab. The textural analysis were made on the basis of sieve analysis method. The lithology of bores on right hand side which is Non Inspection Path (NIP) was found sandy clay up to the depth of 12 feet. From 12 to 20 feet, the soil found clayey sand. Beneath that clayey sand there is a silty clay layer which expands further 20 feet down. Below that the hard rock appeared. The upper sandy clay layer is the canal embankment, while the layer from 12 to 20 feet is alluvium layer. Due to dominant clay content the soil permeability is low. The soil below 20 feet has even more impermeable composition with silty clay formation which disallow water movement (Fig. 15).

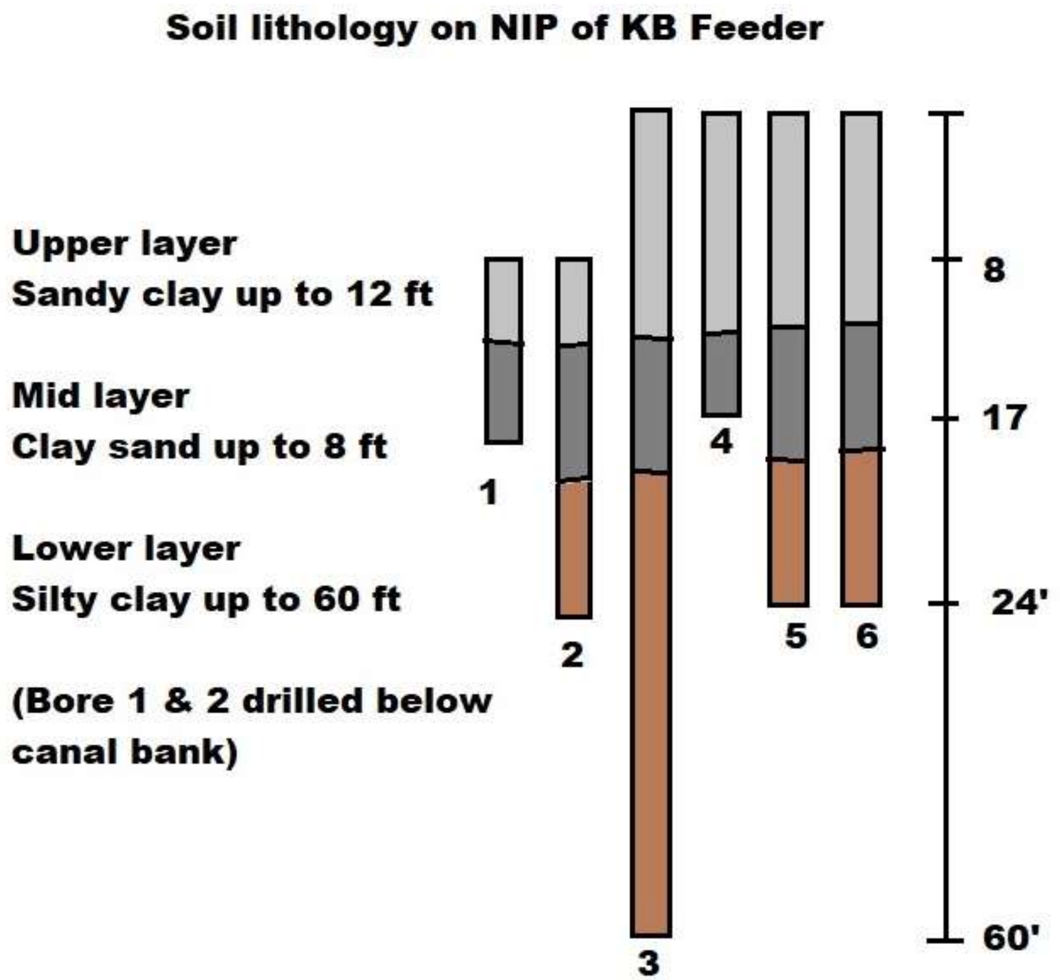

Figure 16 Bore-logs showing soil lithology on NIP side of KB feeder.

The soil lithology of IP side of KB feeder was also determined by keeping the record of extracted soil. The soil samples with layer-wise tagging were brought to lab for sieve analysis method. The bores on IP side were drilled to the depth of 30 feet only (to collect canal seepage water). The lithology of all bores were same with the variation of approximate 1 ft due to soil elevation difference. The soil can be distinguished in two layers with the small variations of clay percentage. The upper 15 ft layer has 45.5% clay while the lower layer below 15 ft has the clay around 50% (Fig: 16).

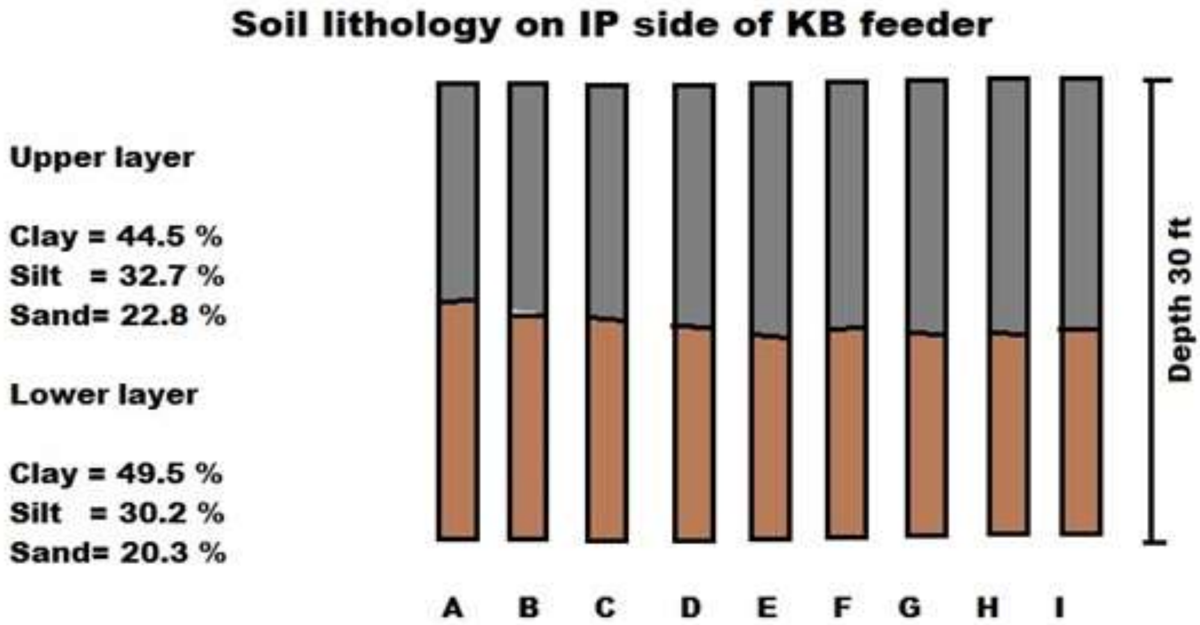

Figure 17. Soil lithology on IP side of KB feeder

3.4 Quantification and Characterization of extracted water

3.4.1 Pumping test to analyze water yield and soil characteristics of alluvial zone (NIP)

The pumping test was conducted on NIP side on Bore #5 to determine whether to select bore # 5 as main bore. The bore is 24 feet deep, with 14 feet water column in 2" dia pipe. The pumping was started with 0.3 liter per second discharge rate. After running for only 4 minutes the pump was stopped due to unavailability of water. The water table was re-gained in 20 minutes to its pre-pumping position. It was observed that due to heavy soils the permeability was very low for pumping the water from the bores. However hand pumps can be installed for local use with operation time of 10 to 15 minutes.

Pumping test to analyze water yield and soil characteristics of alluvial zone (IP)

After sounding and lithological survey the extraction bores were drilled on IP side of the KB feeder. Constant head (discharge) pumping test was conducted on main bore (D) with discharge rate of 0.3 liter per second. Initially the water table was measured in all piezometers which was found at same level. As the aquifer has been defined as unconfined so the water level in the bores, fluctuate with the level of water in the KB feeder. The pumping was started from main well and the resultant decrease in water level in all piezometers was recorded. The initial 5 readings were collected at the time interval of 5 minutes. Later the reading time was expanded to 30 minutes and finally to one hour. Keeping in view the water level impact of KB feeder on groundwater level, three pumping tests were conducted with (i) lower water level (canal closure), (ii) normal flow and (iii) full supply level (fsl). The data of all three pumping tests have been analyzed (Fig.17). Initially in first 40 minutes the water table was decreased to 12 inch, later there was no change in water level even after pumping of six hours. The static water condition was achieved due to continuous seepage from canal bank and bed. The recharge data was also recorded which achieve pre-pumping level within 30 minutes after stopping the pump.

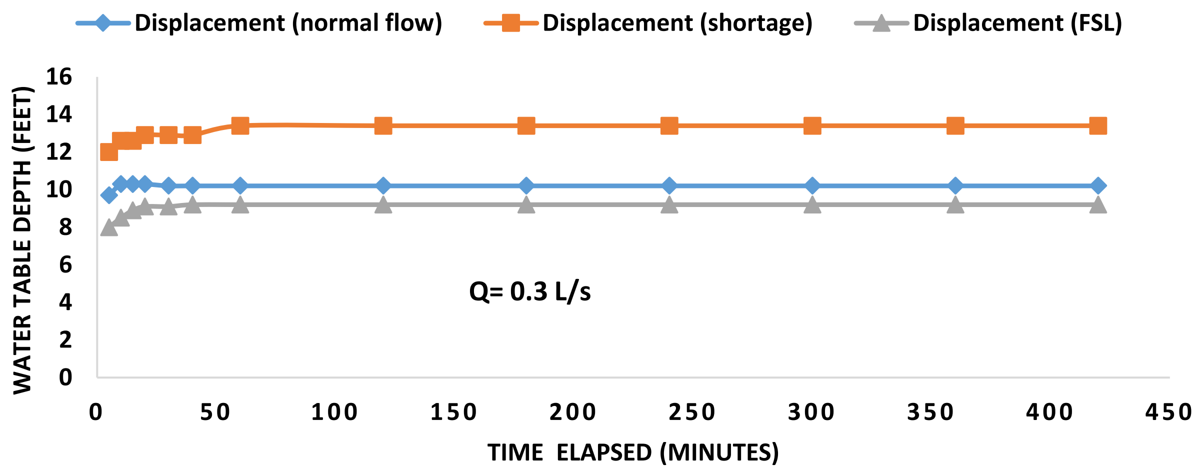

Figure 18 Pumping test analysis curve IP side for three water level scenarios

First test (test-1) was conducted with the routine flow of canal. The water table depth in piezometers was recorded at 9.7 ft. The second test (test-2) was conducted when the canal water level was reduced to 80%. This situation is called canal closure, the 20% water has been released for drinking purpose. The water table depth at that time was 12ft deep. While the 3rd test (test-3) was conducted with full supply level (FSL), the water table raised to 8 ft with canal FSL. However no change was recorded in the drawdown trend of the monitoring bore. The water level become static after around 60 minutes of pumping while the recharge was achieved within 30 minutes.

The pumping data was also plotted on AQTESOLV (demo version by HydroSOLVE, Inc.) for determination of soil parameters. The aquifer was identified as unconfined and soil was assumed as homogeneous. The similar trend of drawdown and static condition were observed with AQTESLOV using Moench 1997 model. The soil characteristics were calculated as:

Table 6. Soil characteristics and values

	Soil characteristics	Values
1.	Transmissivity (T)	3.299 ft^2/min
2.	Hydraulic conductivity (K)	0.11 ft. / min
3	Thickness of aquifer (b)	28 ft
4	Specific yield (Sy)	0.1

3.4.2 Scenario based projection with GMS (MODFLOW)

The system was simulated for 10 days without pumping to equilibrate under river boundary condition. Simulation time was set 37 month (monthly stress period with daily time step). It can be seen in Fig.19 shows fluctuations in the head at the well 1. It can be seen from the result that the groundwater levels are sensitive to the hydraulic response of the water level fluctuation in the KB feeder. The fluctuation in the water level in the KB feeder ranges from 2-4 meter, and this response can also be seen in the pumping cells. Results also indicates that pumping will not have any significant effect on the drawdown of groundwater. A minimal effect of the pumping can be seen in low flow seasons but it recovers quickly as the water levels in the KB feeder rises. Spatially the water levels near the KB feeder are high, which then gradually drops till 9 m, here a water divide can be seen that separates the flow net of KB feeder and river Indus. One assumption that need to be kept in mind is that we have assumed the head in the river Indus at the low flows during this simulation. Water level in the aquifer will response to the flood flows but as per our pumping location that is too close to KB feeder boundary this is not of much importance to look into.

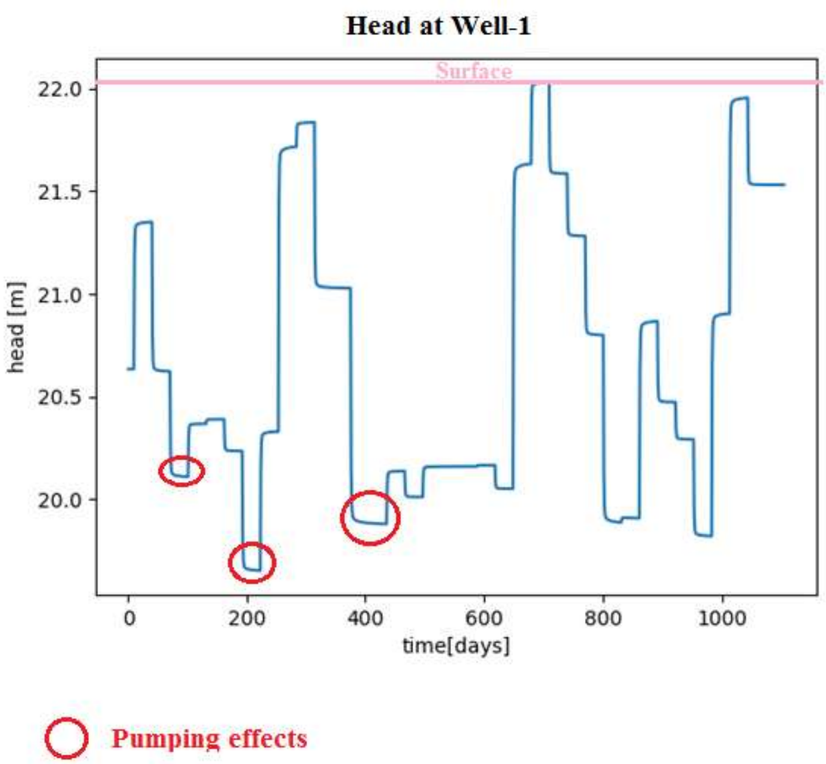

Figure 19 Hydrograph at well-1

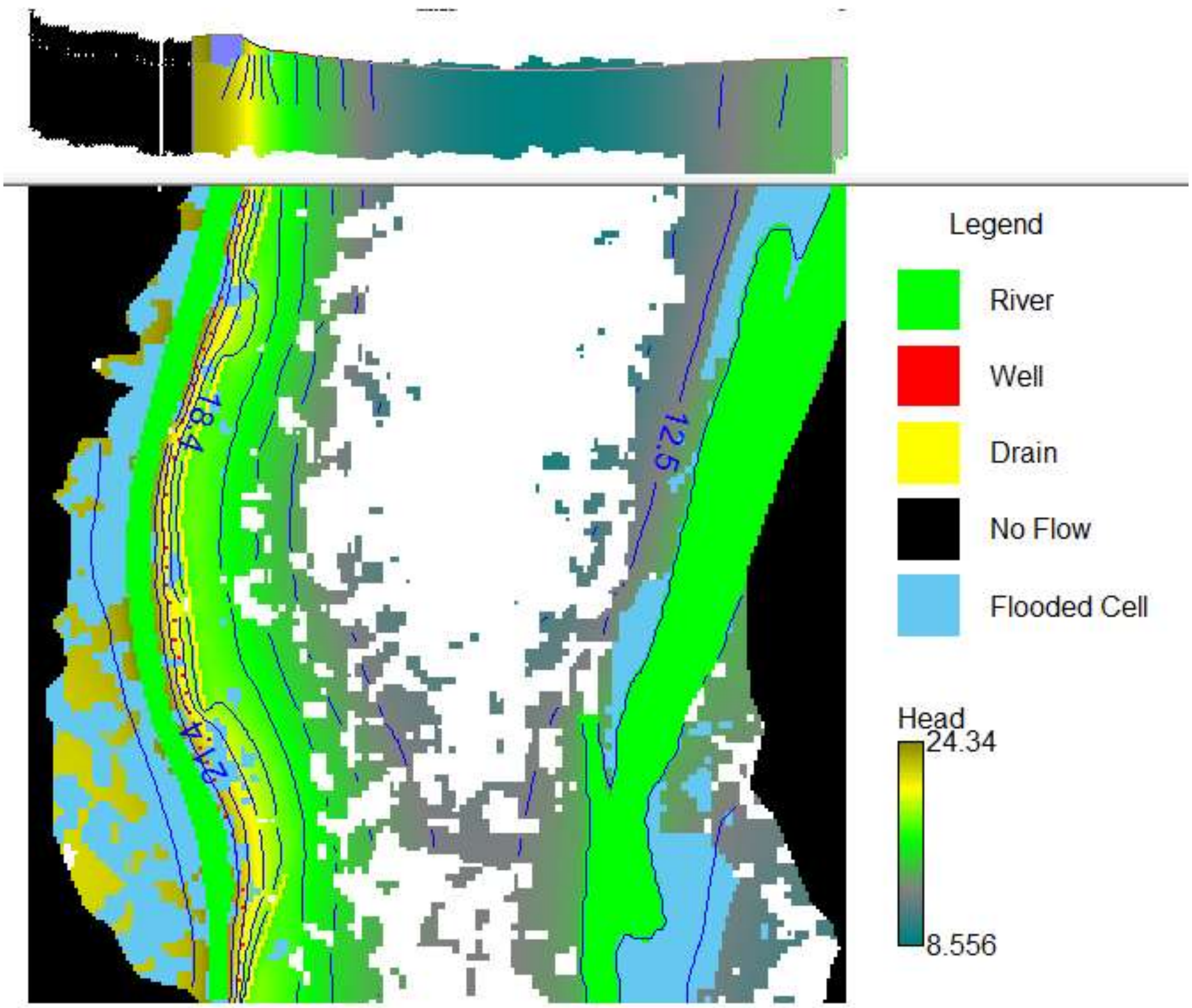

Figure 20 Spatial distribution of heads in layer-1

The projected 5 years scenario of 1st layer (fig 19) showing the canal boundary and river boundary. The flooded cells showing the seepage from canal as well as river. The 1st layer there is low impact of river flooding (seepage) due to low elevation level of river, while the canal cells having seepage (flood) in 1st layer.

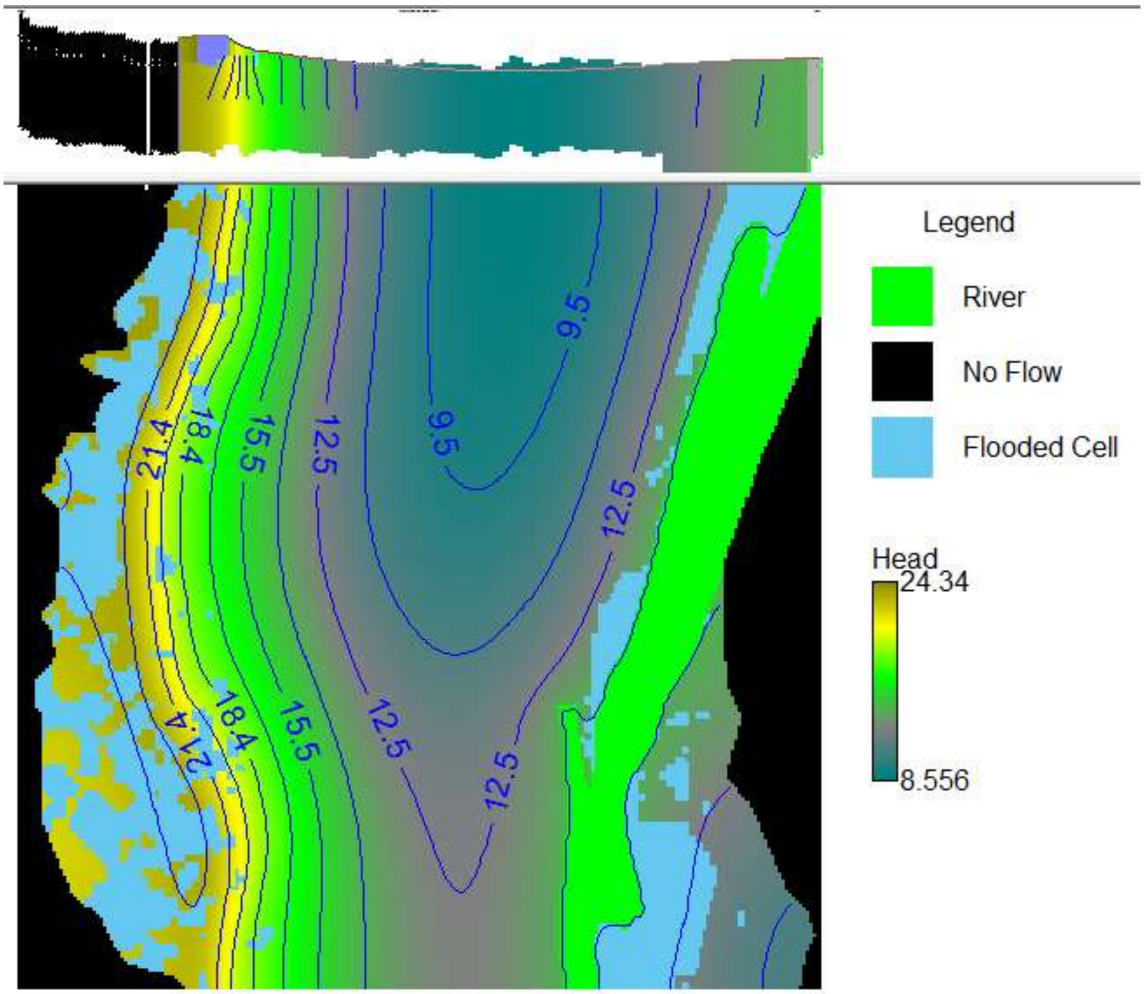

Figure 21 Spatial distribution of heads in layer-2

The model projected layer 2 (fig 20) showing continuous seepage from the river boundary for five years with actual stress periods. The river cells have less impact of flooding due to low flow condition in the river for 11 months.

3.5 Well and monitoring bores water analysis

The regular water samples from well A, B, C and D along with canal water sample analyzed to detect the variation in physical, chemical and biological parameters.

Physical parameters:

Total suspended solids (TSS):

TSS is the dry weight of suspended particles which are not dissolved in the water and can be extracted through filtration process Fig.22

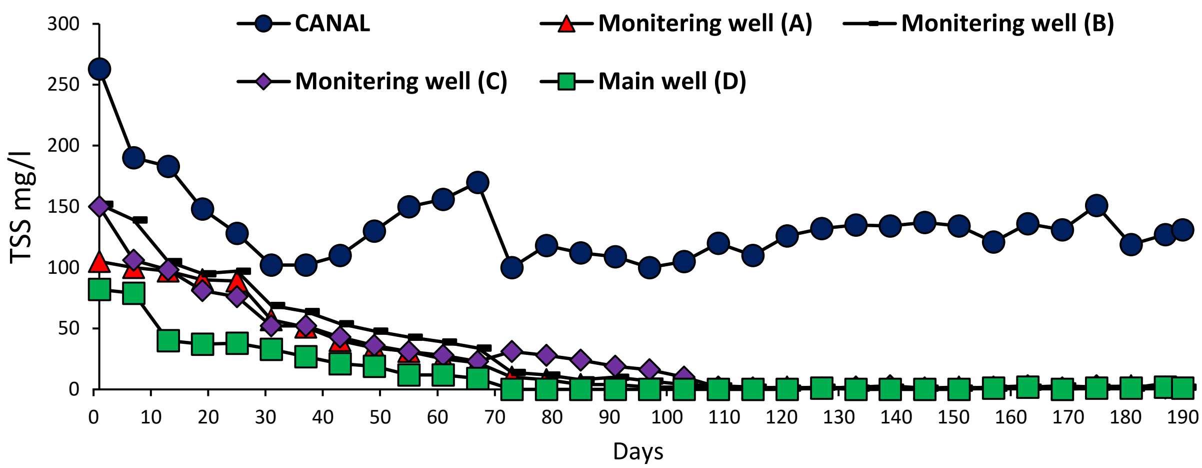

Figure 22 TSS results from main well and monitoring wells (Feb-19 to Aug-19)

Turbidity:

Turbidity was tested using Nephlometer method. The turbidity of water samples from the well was reduced by 78% as compared with canal water samples (Fig.23).

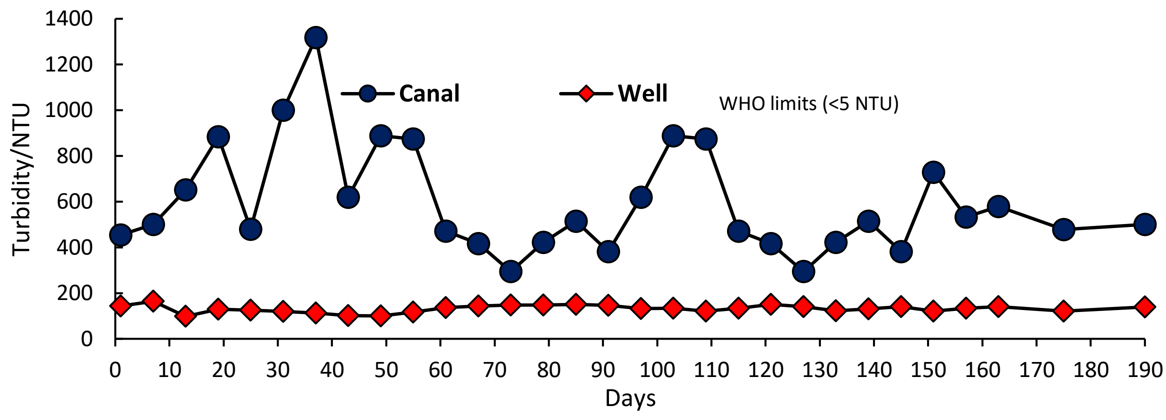

Figure 23 Turbidity analysis of canal and main well (Feb-19 to Aug-19)

Microbial analysis of main well

Escherichia coli (E. coli):

E. coli is a type of fecal coliform bacteria commonly found in the intestines of animals and humans. The presence of *E. coli* in water is a strong indication of recent sewage or animal waste contamination. In canal water highest colony forming unit (CFU) were observed while in main well water sample CFU reduced up to (average value 5.39). *E.coli* contamination was found with variation in canal water (Fig.24), which shows the increase from the month of May to onwards

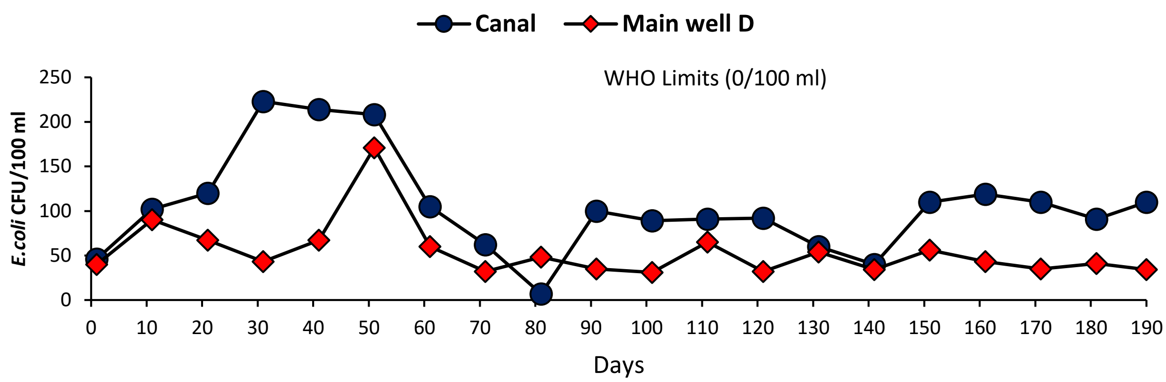

Figure 24 E-Coli reduction in canal and main well (Feb-19 to Aug-19)

Total *Coliform:*

Total coliforms is used as indicator to measure the degree of pollution and sanitary quality of well water, because testing for all known pathogens is a complicated and expensive process. The main source of pathogens in drinking water is through recent contamination from human or animal waste, from improperly treated septic and sewage discharges. In canal water the highest concentration of total coliform group was found 450 CFU/100 mL while in main well water 50-100 CFU/100 ml respectively (Fig. 25).

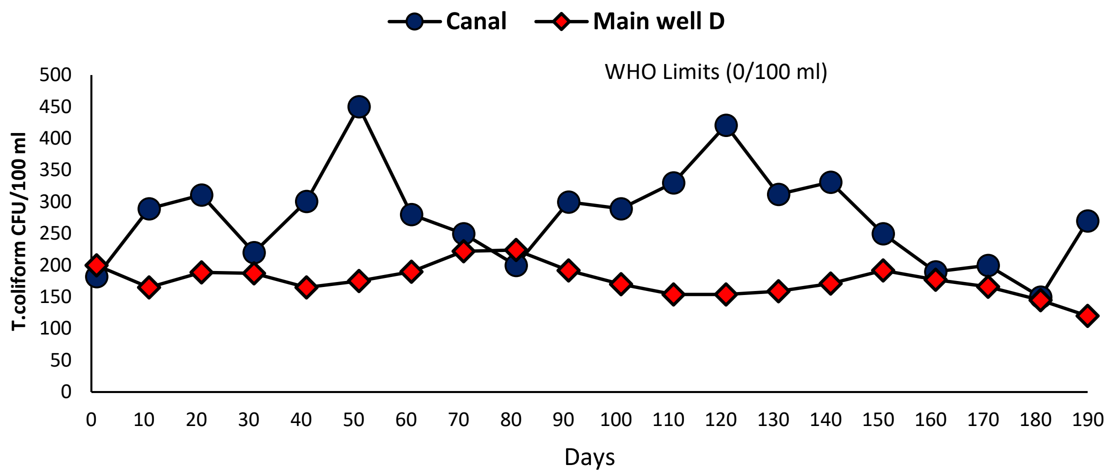

Figure 25 Total Coliform group reduction in canal and main well (from Feb-19 to Aug-19)

***Salmonella Typhi**:*

Salmonella Typhi is one of the leading causes of intestinal illness all over the world as well as the etiological agent of more severe systemic diseases. While water is known to be a common vehicle for the transmission of *Salmonella* servers*.* In canal water initial level of *Salmonella Typhi* was increased up to 50 CFU/100 while in well water reduced to 2-20CFU/100 ml (Fig. 26).

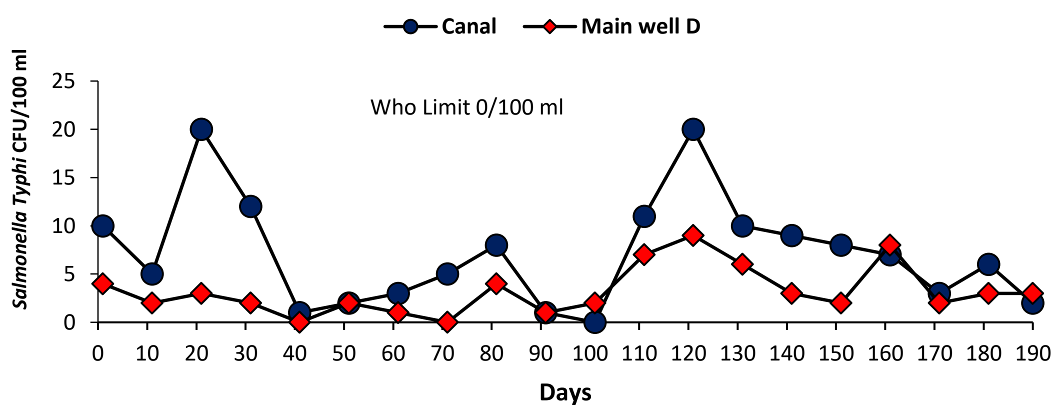

Figure 26 Salmonella Typhi reduction in canal and main well (Feb-19 to Aug-19)

Vibrio cholera:

The highest concentration of *Vibro cholera* was found in inlet water in month of May, while in main well bacterial load decreased. (Fig.27)

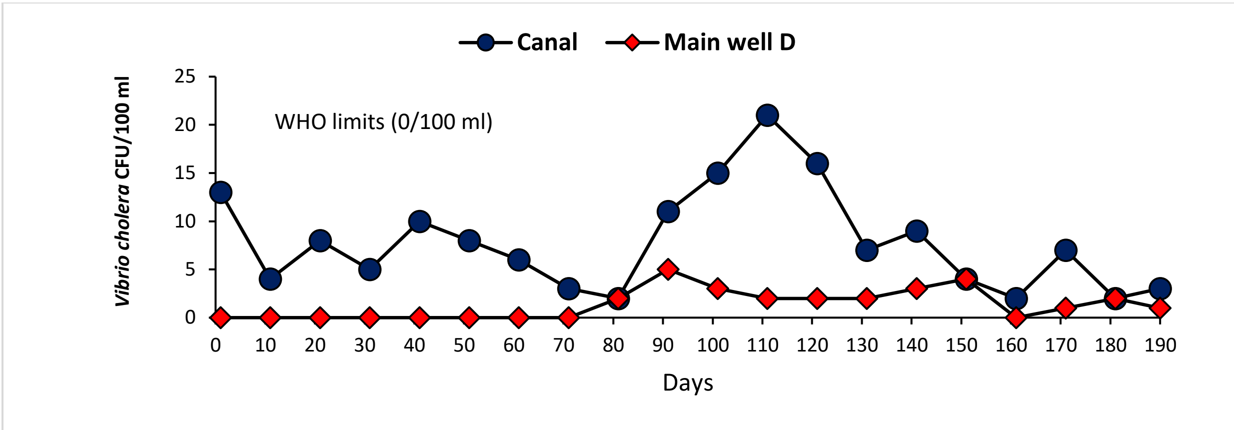

Figure 27 Vibrio cholera reduction in canal and main well (from feb-19 to Aug-19)

Chemical parameters:

Sulphate:

The Sulphate contamination was reduced by 88.7% in the main well on average as compared to the results of canal water (Fig.28)

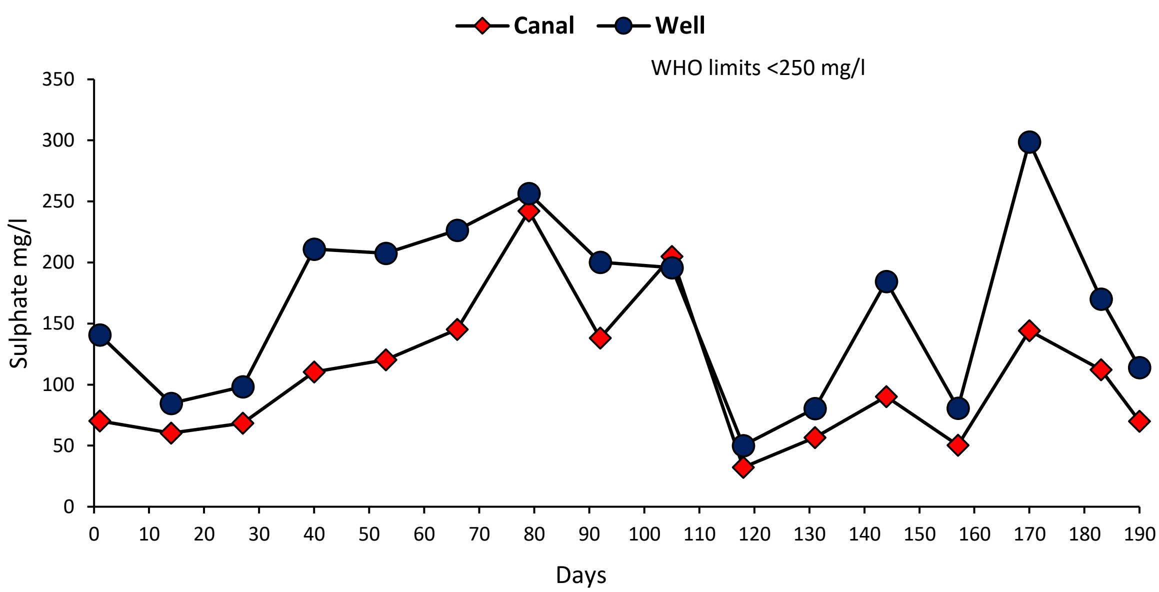

Figure 28 Sulphate contamination of canal and well water (from Feb-19 to Aug-19)

Phosphate:

The phosphate concentration was reduced up to in the water sample collected from main well (Fig.29)

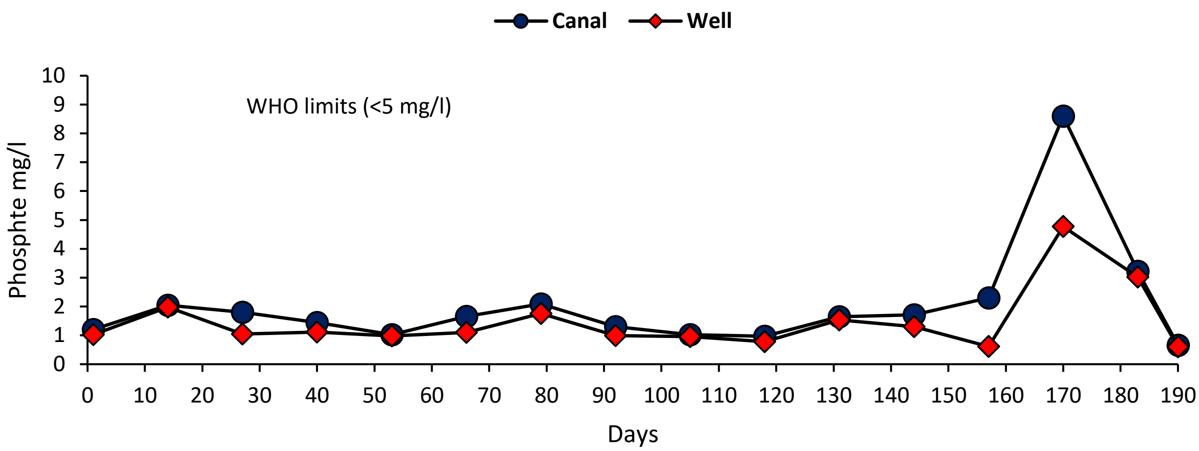

Figure 29 Phosphate contamination of canal and well water (from February to August)

Nitrate:

The nitrate contamination was reduced up to 24% in the water samples collected from main well (Fig.30)

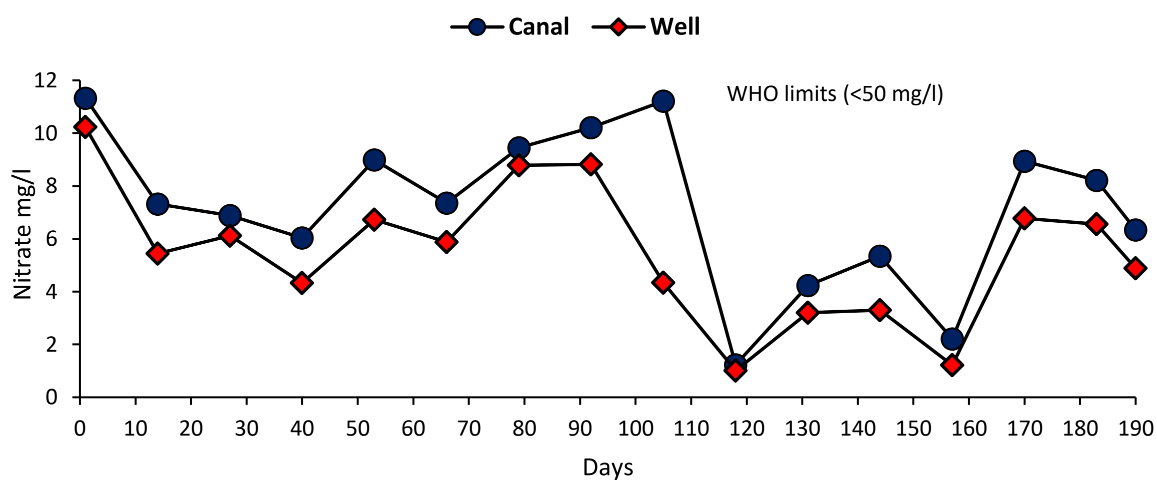

Figure 30 . Nitrate contamination of main well and canal (from February to August)

Fluoride:

The Fluoride contamination was reduced by 8.68 % from the main well samples. The presence of fluoride is due to availability in parent material in the soil (fig.31)

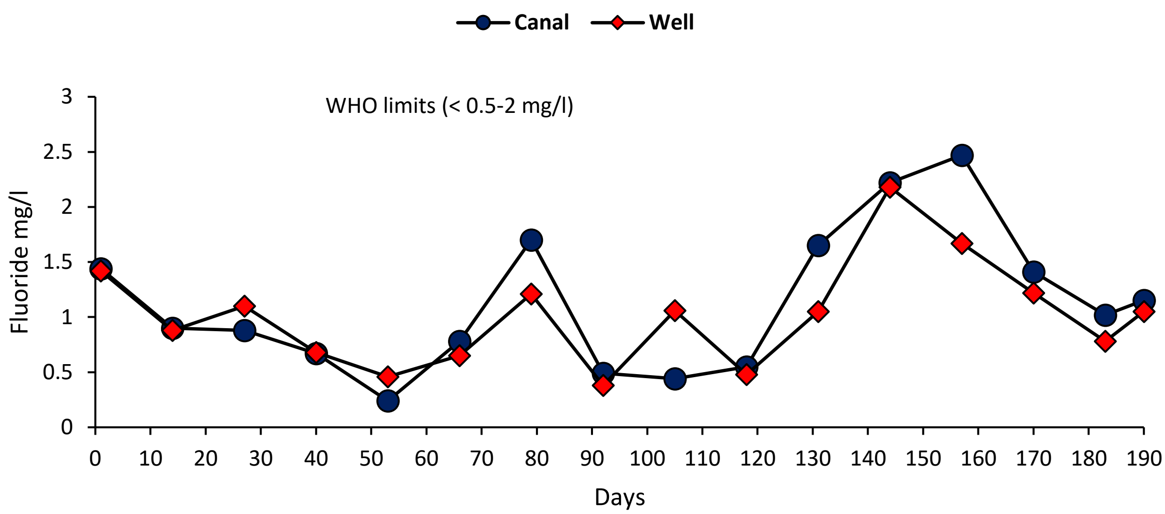

Figure 31 Fluoride reduction from main well (from February to August)

Total nitrogen:

The total nitrogen (TN) concentration were also reduced slightly in the main well. The maximum concentration of TN in the well was 0.6 mg/L.

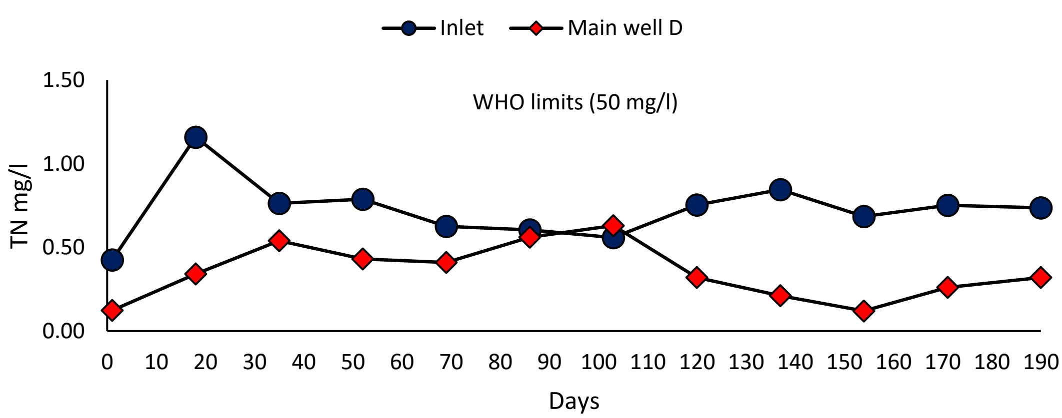

Figure 32 Total Nitrogen (TN) reduction in canal and main well (from February to August)

Total Organic Compounds

The concentration of total organic compounds (TOC) was remained below 3mg/L throughout the monitoring period without much fluctuations. On the other hand, the maximum TOC concentration was up to 9 mg/L in the canal.

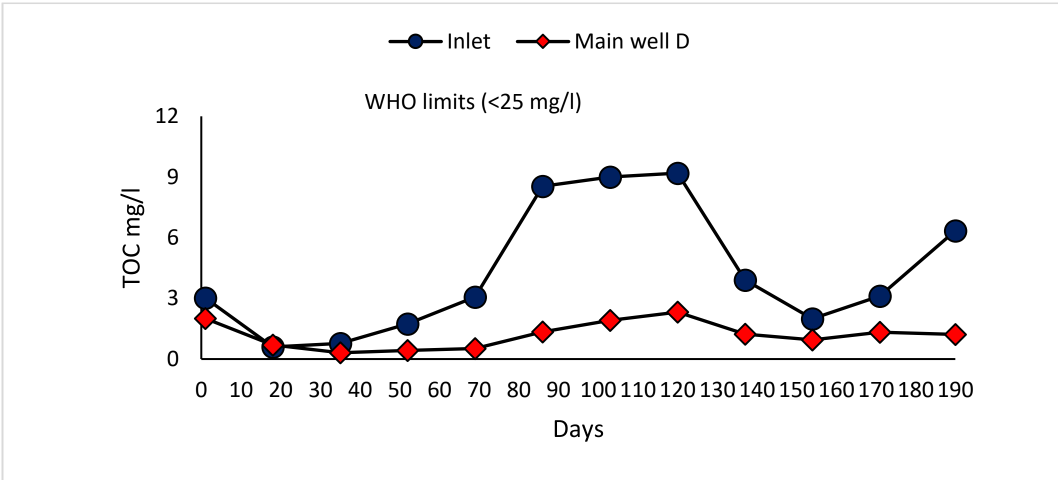

Figure 33 Total organic carbon (TOC) reduction in canal and main well (from February to August)

Sodium (Na):

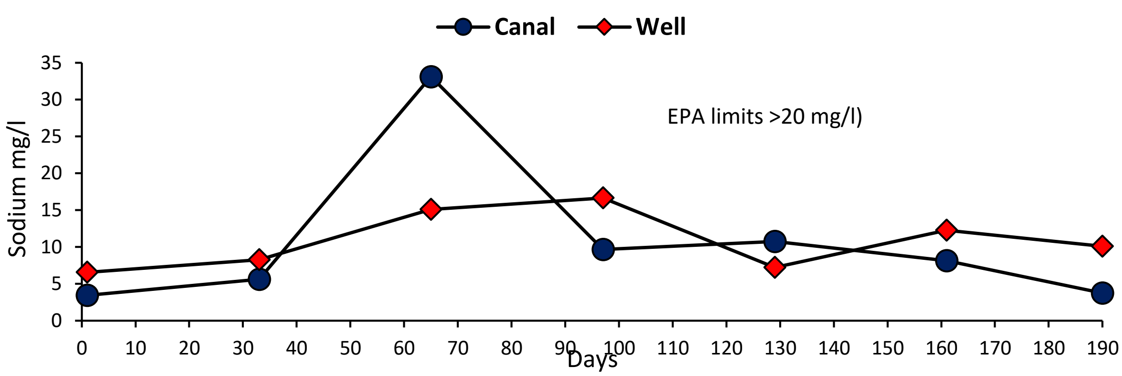

Figure 34 Sodium concentration in canal and well water sample (from February to August)

Potassium:

The potassium concentration was recorded as 2.43 mg/l in canal water samples, while the same day samples from main well indicate a bit increase. This is due to soil composition and leaching of potassium from canal bank soil into the seepage (Fig 35).

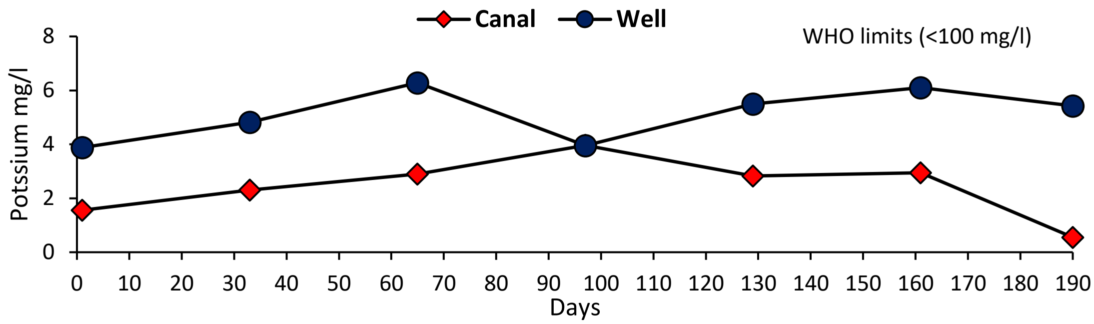

Figure 35 Potassium concentration in canal and well water sample (from February to August)

Magnesium:

The concentration of Magnesium (Mg) was also observed bit higher level in the well water as seen in the case of Potassium. However, in both the case, concentration were much below the limits for drinking water suggested in the guieldlines by WHO.

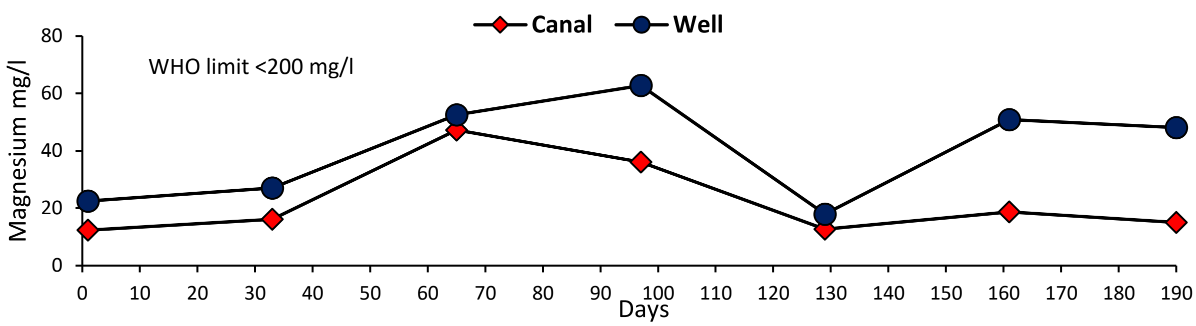

Figure 36 Magnesium concentration in canal and well water sample (from February to August)

Calcium:

In the case of Calcium (Ca), the maximum concentration in the well water was observed 80 mg/, which much below the limit suggested by WHO was.

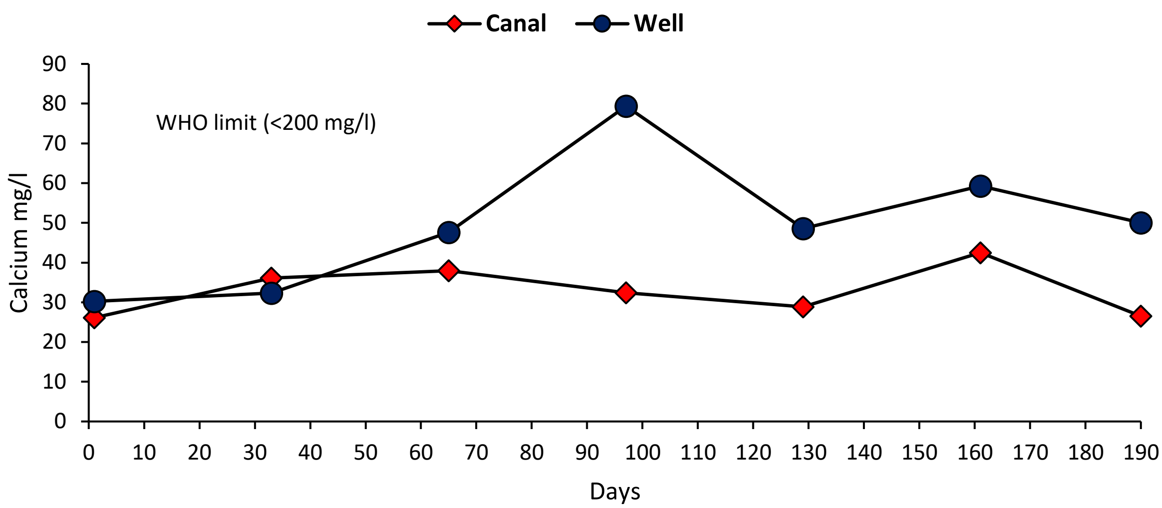

Figure 37 Calcium concentration in canal and well water sample (from February to August)

Metals analysis

All the metals were analyzed using an inductively coupled- Mass spectrometer (ICP-MS) at USPCASW. The metals concentration below detection limits is assumed zero. The detection limits of the ICP-MS is given in the appendix-4

Arsenic (As):

The Arsenic is most toxic form of the element and is found in ground water and surface water. The Arsenic concentration were in the well water were almost the same as compared to those found in the canal water (1-and 2 µg/l) except in one case (6 µg/l), but all the time the concentration remained within recommended limit by WHO guidelines (Fig. 38).

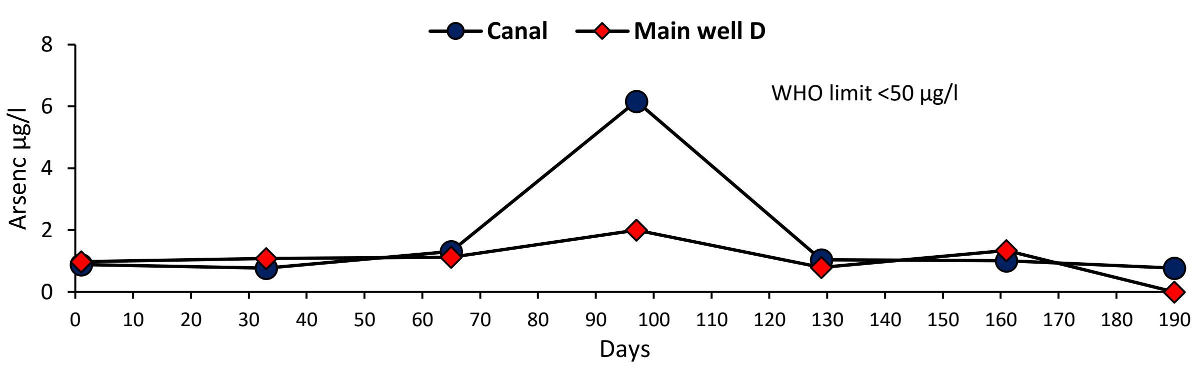

Figure 38 Arsenic concentration in canal and well water sample (from February to August)

Lead (Pb):

Lead contamination poses a serious threat to the safety of drinking water. In the main well the of concentration of Pb was recorded at level 1.5 μg/L . Lead (Pb) value was remained below detection limit of the ICPMS (Fig. 39).

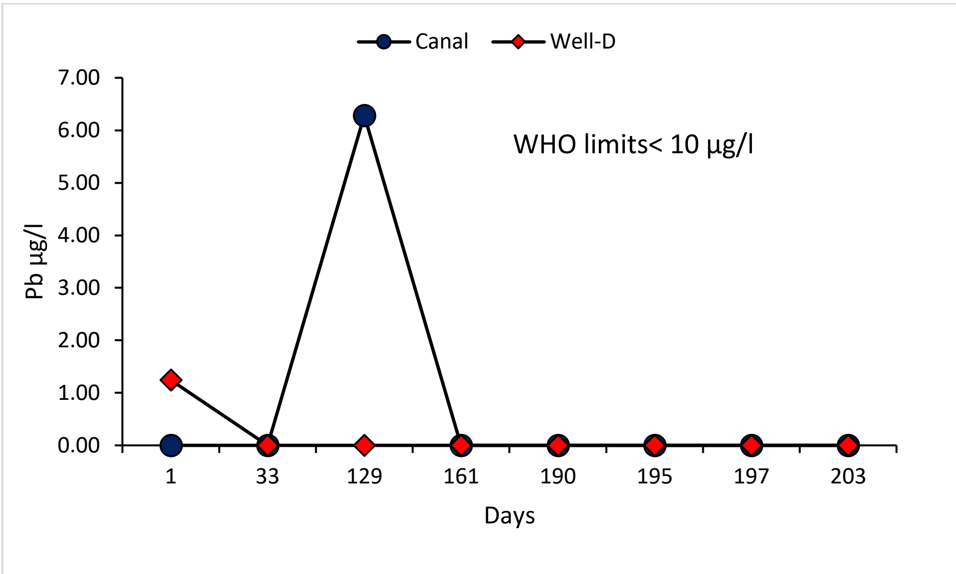

Figure 39 Lead concentration in canal and well water sample (from February to August)

Cobalt (Co):

Cobalt is an element that occurs naturally in the environment in air, water, soil, rocks, plants and animals. It may also enter in surface water through run-off when rainwater runs through soil and rock containing cobalt. In main well water sample, it was observed that maximum concentration of cobalt in main well average value 0.49 μg/L with maximum value of 1 μg/L, much lower than the recommended values in WHO guideline (Fig. 40).

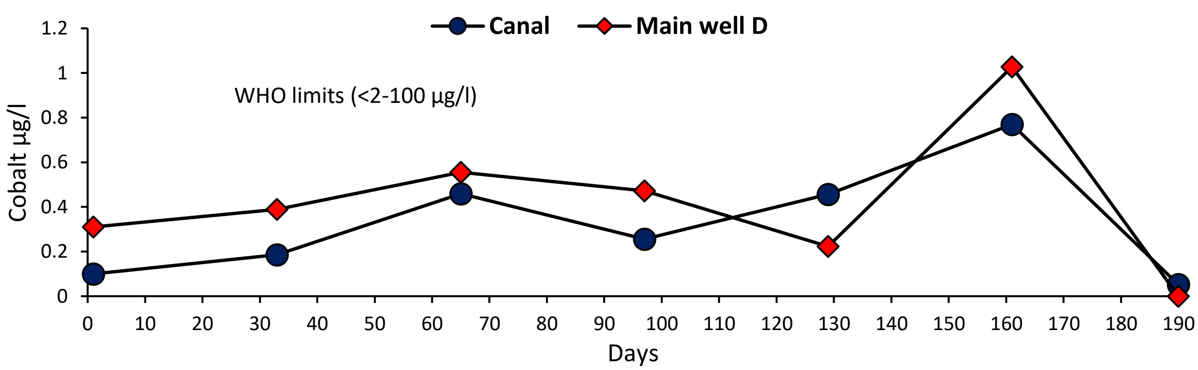

Figure 40 Cobalt concentration in canal and well water sample (from February to August)

Chromium (Cr):

The results revealed that the levels of chromium in extracted water and canal water are below WHO limits. The maximum concentration of chromium was 3µg/L and 5 µg/L in canal and in the main well, respectively (Fig. 41).

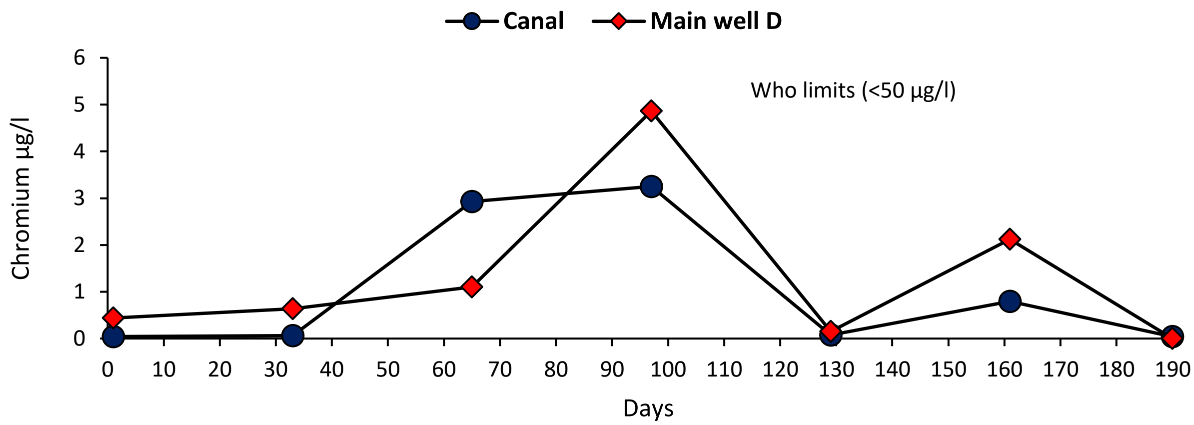

Figure 41 Chromium concentration in canal and well water sample (from February to August)

Copper (Cu):

The concentration of Cu both in the canal and the extracted well water were found below WHO limits (Fig. 42).

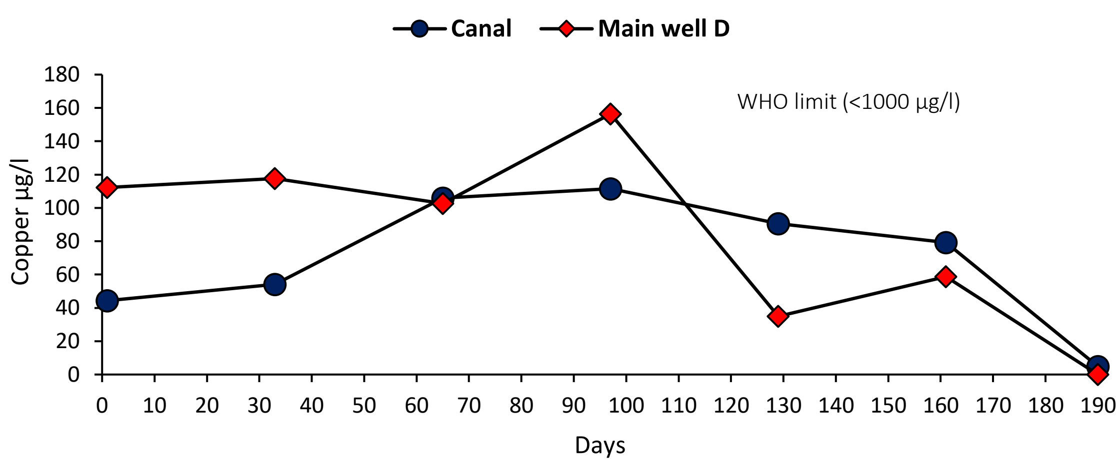

Figure 42 Copper concentration in canal and well water sample (from February to August)

Nickel (Ni):

Nickel concentrations in groundwater depend on the soil use, pH, and depth of sampling. It was observed that highest concentration of Nickel in canal water 30 μg/l while in the main well the maximum concentration was 33 μg/l (Fig. 43).

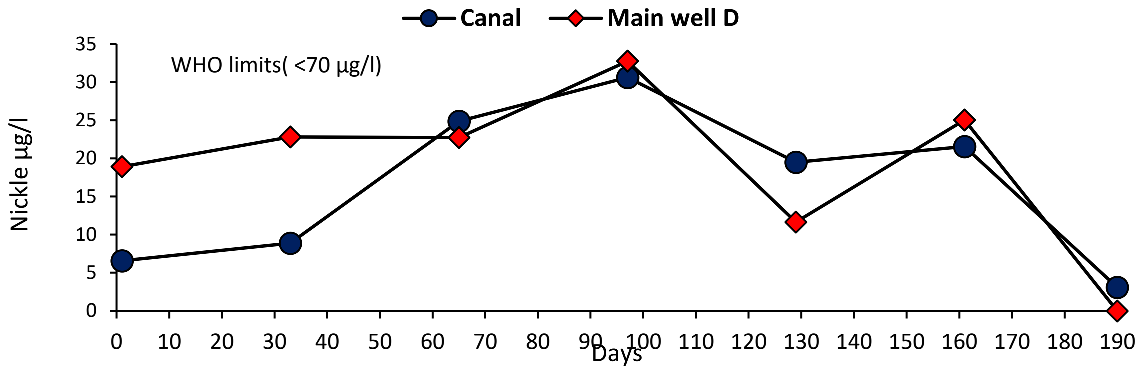

Figure 43 Nickel concentration in canal and well water sample (from February to August)

Manganese (Mn):

Manganese occurs naturally in many surface water and groundwater sources and in soils that may erode into these waters. However, human activities are also responsible for much of the manganese contamination in drinking water. The maximum concentration of water from well was found to be 90 μg/L, below the WHO limits (Fig. 44).

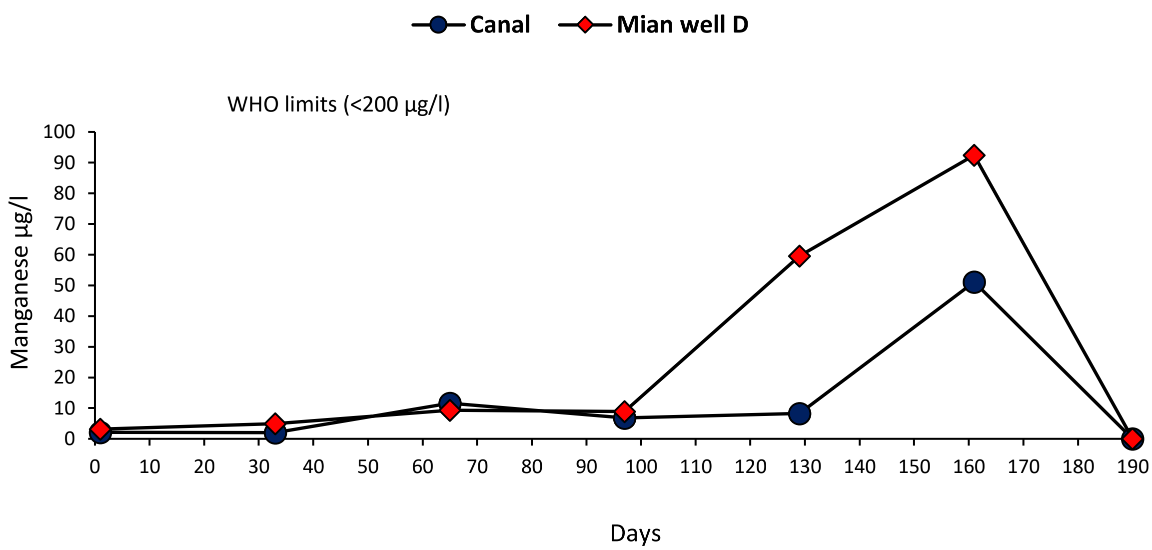

Figure 44 Manganese concentration in canal and well water sample (Feb-19 to Aug-19)

3.6 Laboratory column setup and water analysis

Pressure chart:

Well clogging is inevitable as mentioned by Grischek and Bartak (2016) in their research, but RBF is still a sustainable water supply system. The bio-clogging was monitored in the lab column study by monitoring the input pressure in the column with respect to time. During 190 operation of the column no significant change in input pressure was observed, which indicated that clogging was not occurred in the column (fig.45). The variation in pressure is due to variation in percentage of suspended solids in the input water.

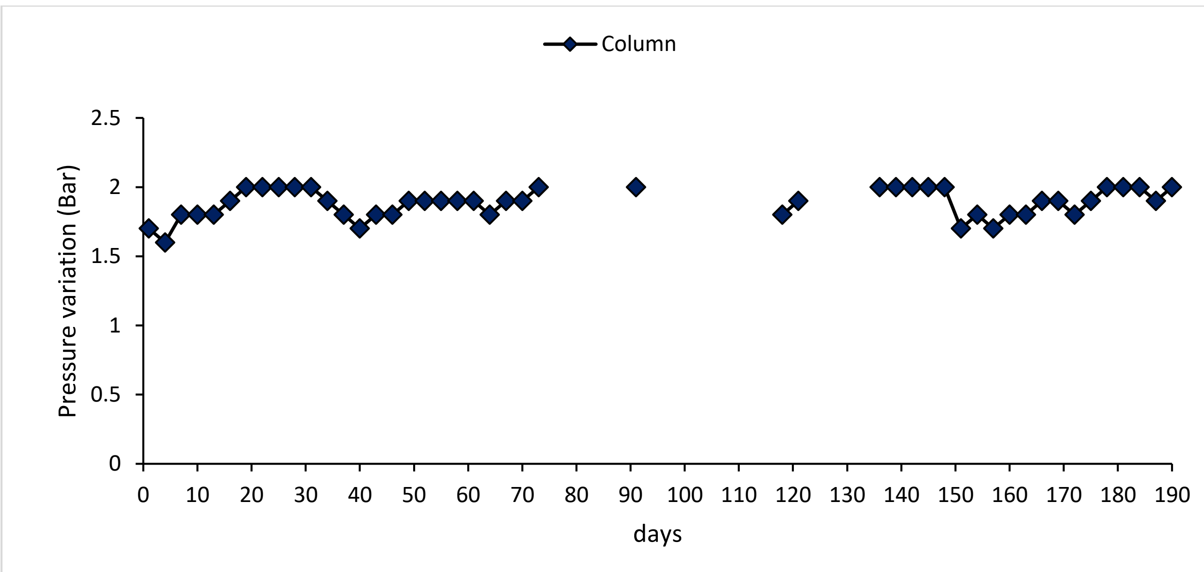

Figure 45 Measurement of pressure in column study (from February to August)

Physical parameters:

Total Suspended Solids:

TSS is the dry weight of suspended particles which are not dissolved in the water and can be extracted through filtration process. The water samples collected from column outlet shows 84.46% reduction in TSS as compared to inlet (canal) water (Fig.46).

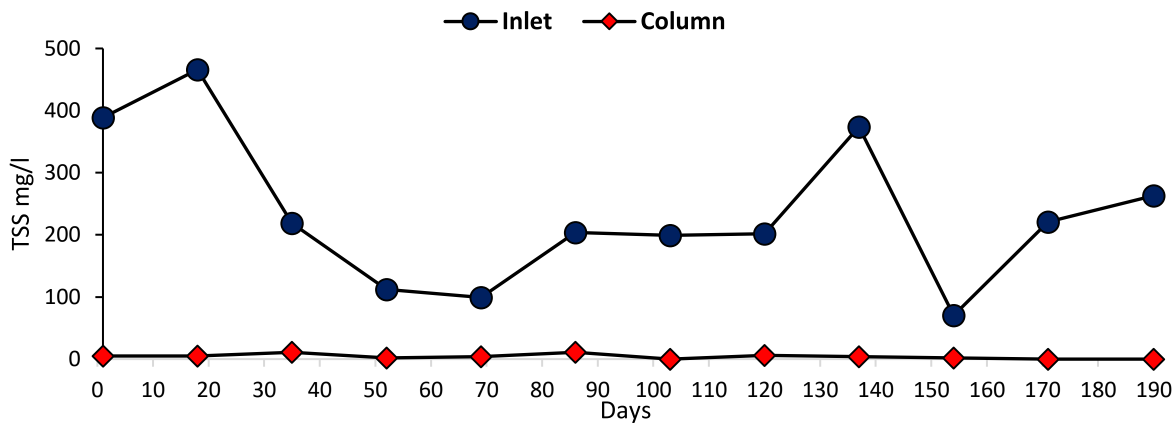

Figure 46 Total suspended solids in column (from February to August)

Turbidity:

The canal water samples were highly turbid. The average turbidity of inlet water was found 600 ppm, while the turbidity of outlet sample was decreased to 99% as the average values found in the range of 1.1 ppm (Fig.47)

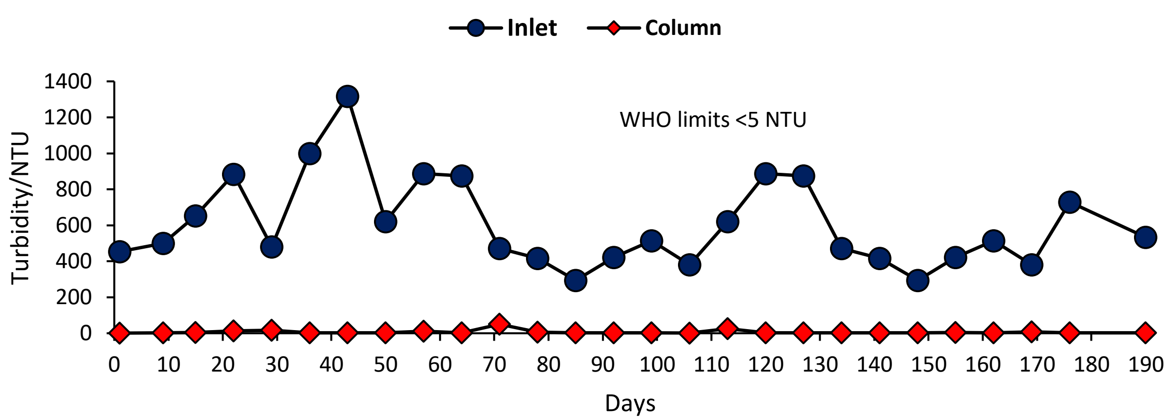

Figure 47 Turbidity reduction in column test (from February to August)

Microbial Analysis:

Escherichia coli (E. coli):

*E-coli co*ntamination was found with variation in inlet water (fig.34), which shows the increase from the month of June to onwards. While the results from column study reflects the consistent reduction up to 90.4 %. (Fig.48)

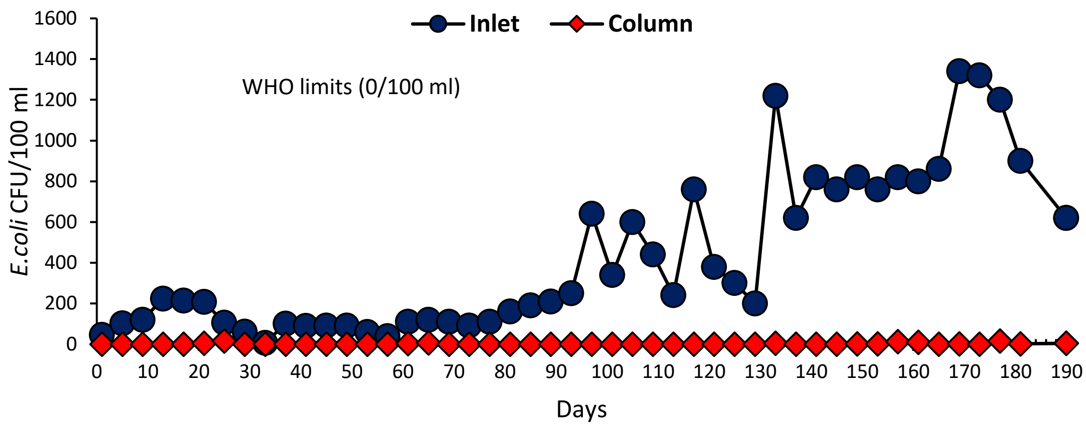

Figure 48 E-Coli contamination reduction in column study (from February to August)

Total *Coliform:*

Total Coliform removal was counted as 90.5% from column study. Again the *T.Colifrom* group count has been increasing from the month May in inlet water (Fig.49).

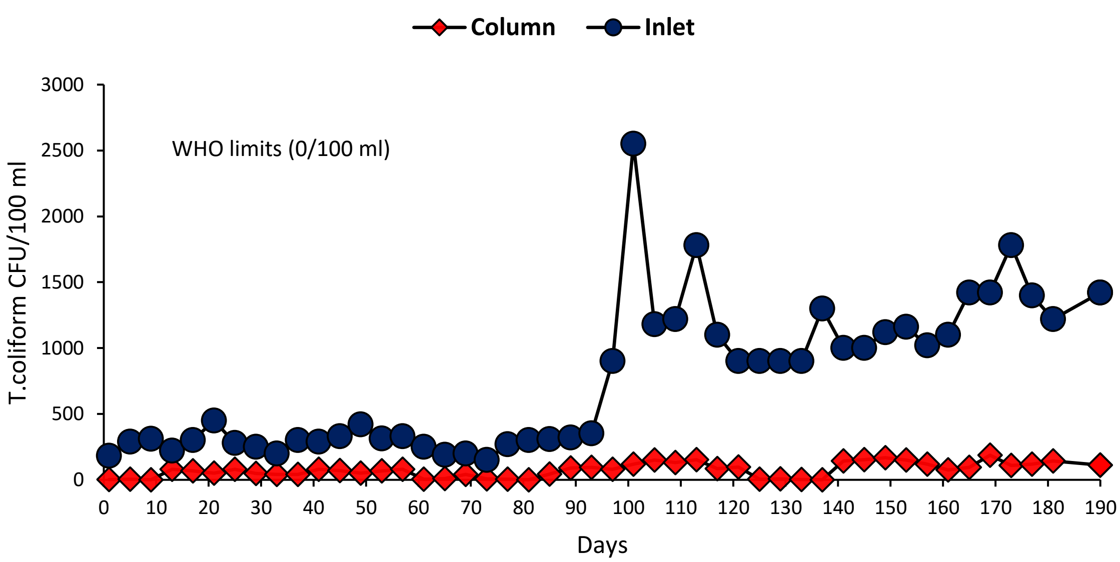

Figure 49 Total Coliform removal through column (from February to August)

Salmonella Typhi:

Salmonella Typhi is group of coliform bacteria. It was observed highest number of *S.Typhi* inlet water in August to September while in column analysis *S.Typhi* was reduced up to 90% removal. (Fig. 50).

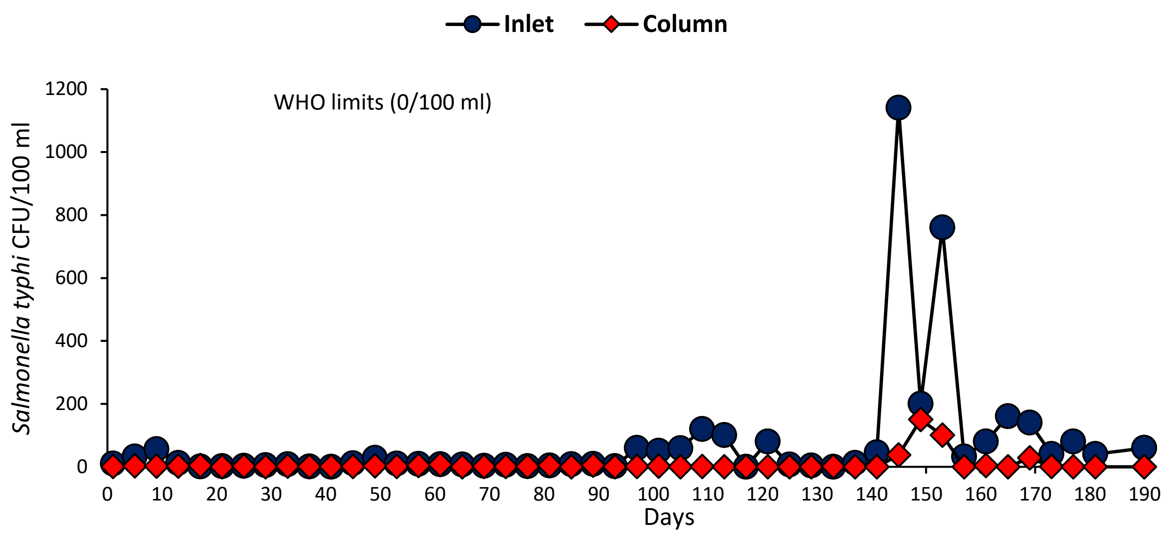

Figure 50 Salmonella Typhi removal through column (from February to August)

Vibrio cholera: The highest concentration of *Vibro cholera* was found in inlet water while in column study bacterial load decreased up to 85%. (Fig. 51)

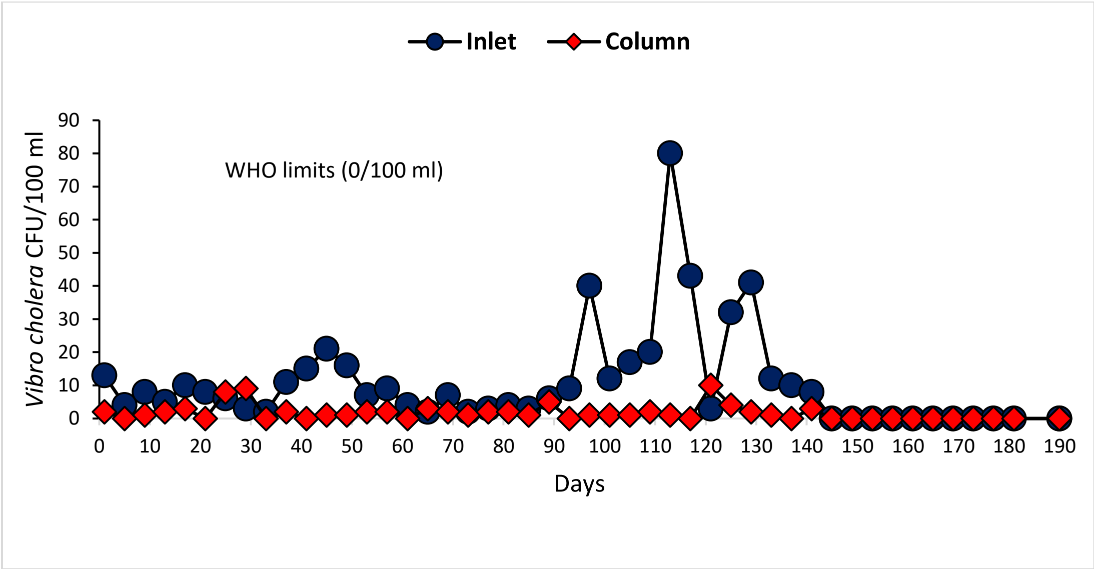

Figure 51 Vibrio Cholera removal through column (from February to August)

Microbial analysis of Soil laboratory columns:

Escherichia coli (E. coli):

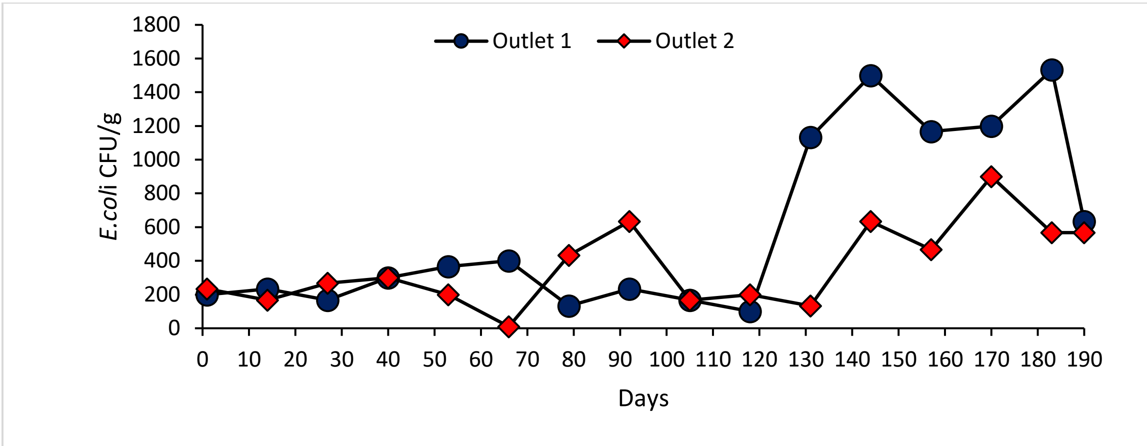

Figure 52 Determination of Soil analysis for E-Coli contamination in column study (from February to August)

Total *Coliform:*

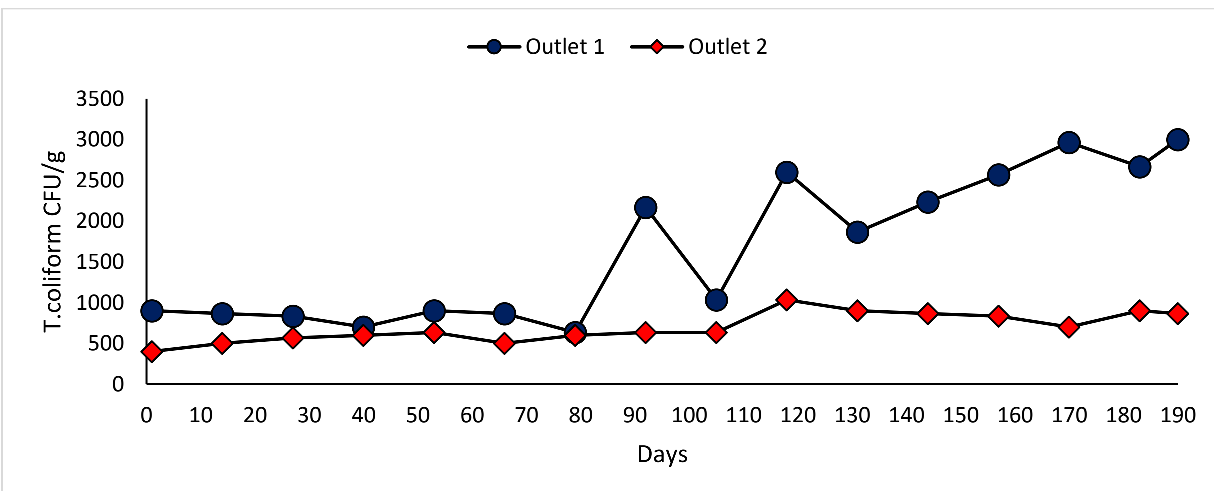

Figure 53 Determination of soil analysis for total coliform concentration in column study (from February to August)

Salmonella Typhi:

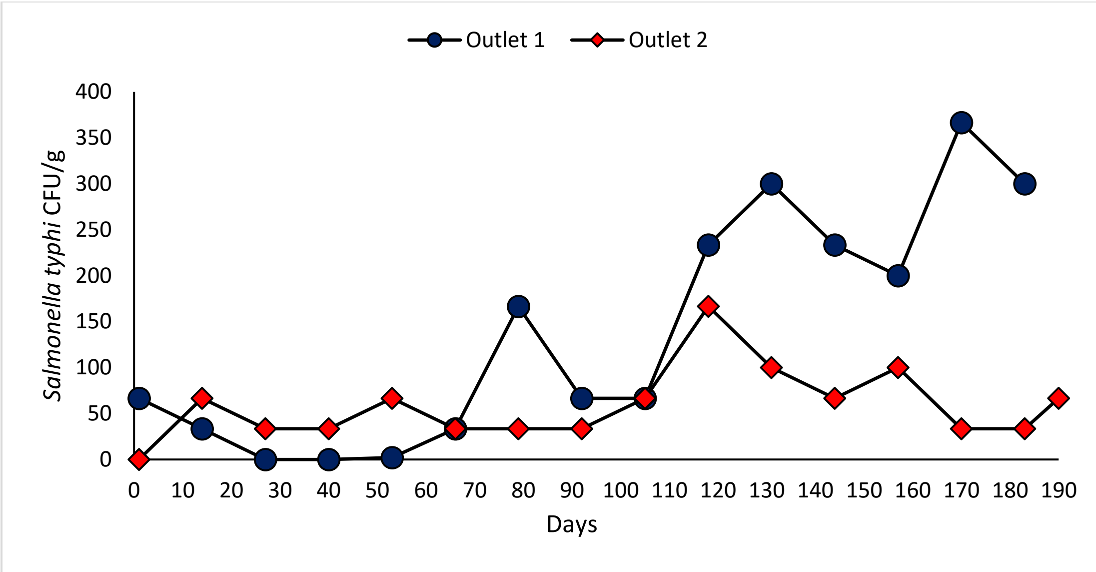

Figure 54 Determination of soil analysis for Salmonella Typhi contamination in column study (from February to August)

Vibrio cholera:

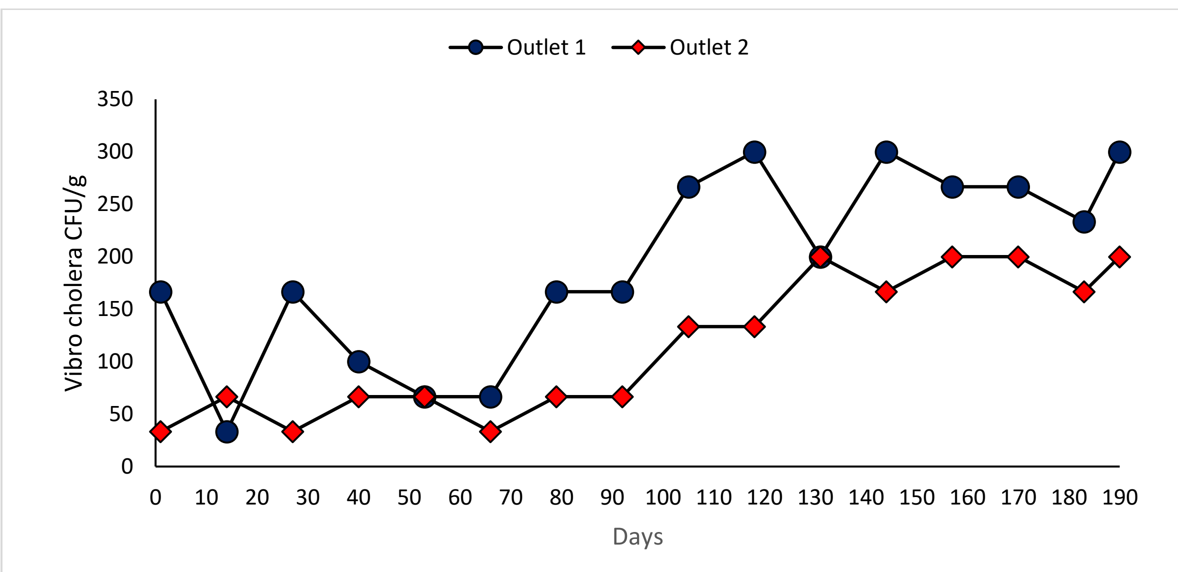

Figure 55 Determination of soil analysis for Vibro cholera in column study (from February to August)

Chemical parameters:

Sulphate:

Sulphate traces was reduced to 11.2% in column study. The trend shows the values parallel to each other (fig.56).

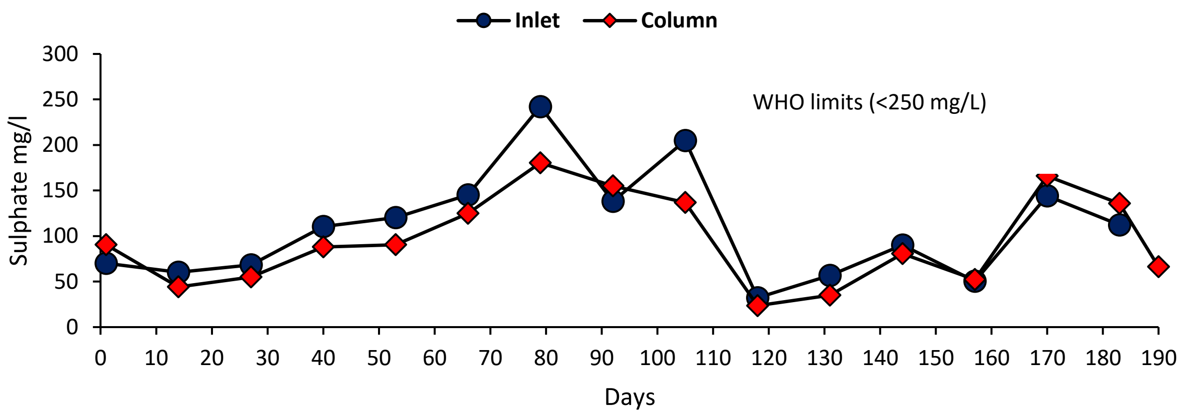

Figure 56 Sulphate analysis in column study (from February to August)

Phosphate:

The phosphate concentration was in traces in the inlet samples, however the column study shows 47% reduction in Phosphate percentage (Fig.57).

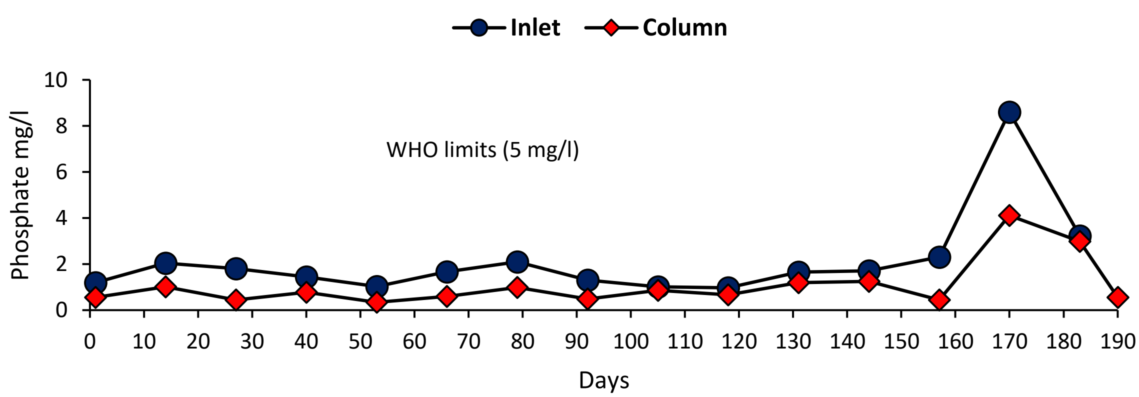

Figure 57 Phosphate concentration and column results (from February to August)

Nitrate:

The Nitrate contamination in column study was reduced from 7.2 to 2.4 ppm. An average 66% reduction was recorded (Fig.58).

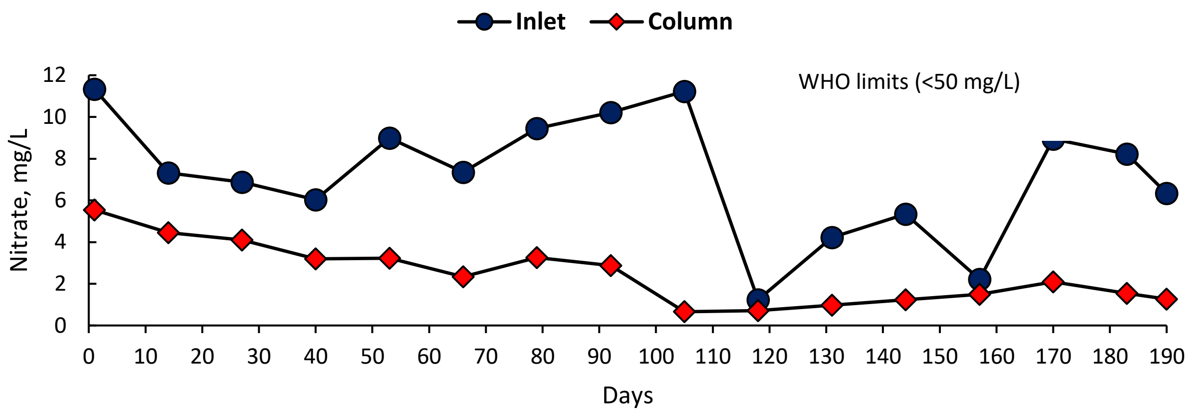

Figure 58 Nitrate contamination and reduction in column study (from February to August)

Fluoride: The Fluoride concentration was found to reduce from 1.16 ppm to 0.8 ppm. An average reduction of 23.70% was found through column study (fig.59).

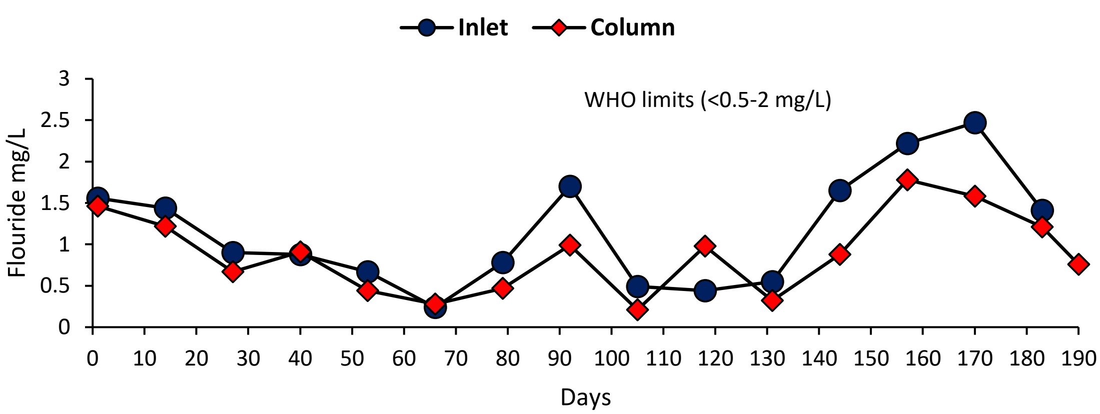

Figure 59 Fluoride contamination and reduction in column study (from February to August)

Total Nitrogen (TN) Total Nitrogen was reduced from 0.7 to 0.6 ppm. An average 14% reduction was recorded through column study (Fig.60).

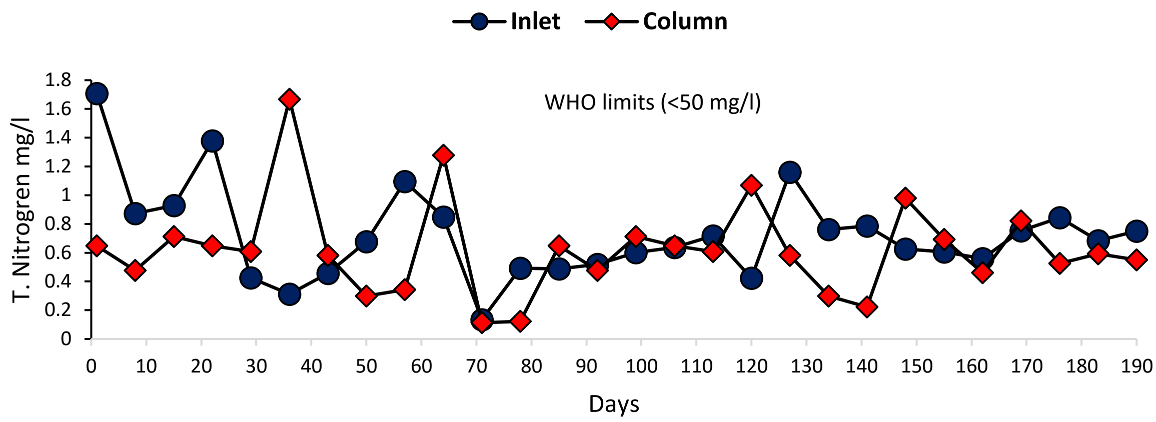

Figure 60 Total Nitrogen (TN) reduction through column study (from February to August)

Total Organic Compound (TOC):

Total Organic Compound was reduced by 28% through column study (Fig.61).

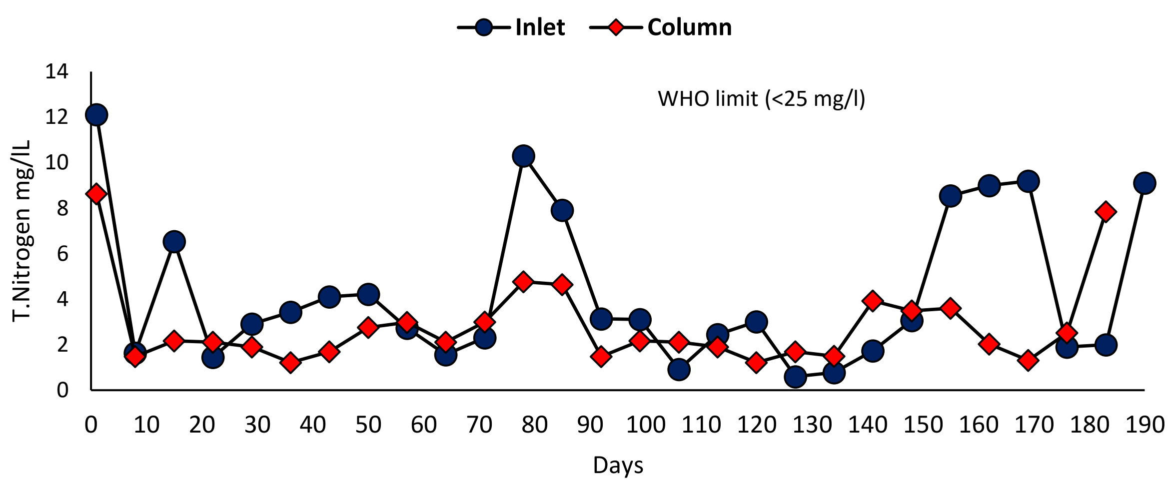

Figure 61 Total Organic Compound reduction through Column study (from February to August)

Mineral Analysis:

Sodium:

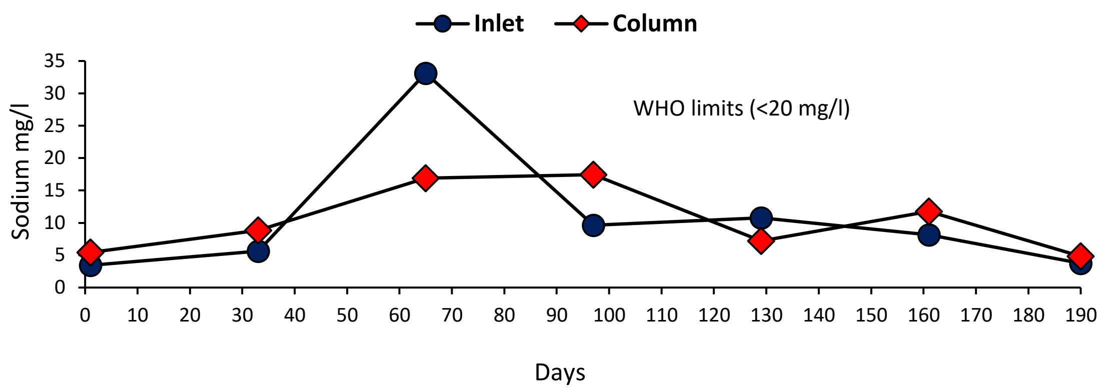

Figure 62 Determination of Sodium ion in column and inlet Water (from February to August)

Potassium:

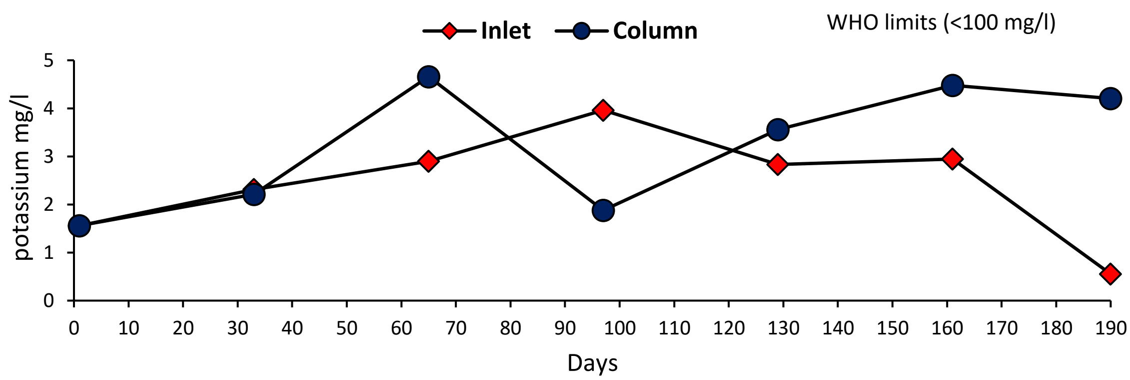

Figure 63 Determination of Potassium in column and inlet water (from February to August)

Magnesium:

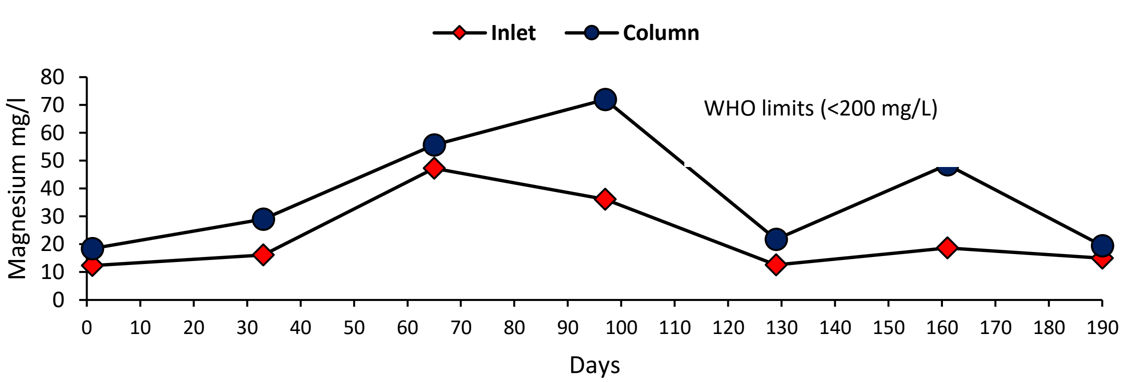

Figure 64 Determination of Magnesium in column and inlet water (from February to August)

Calcium:

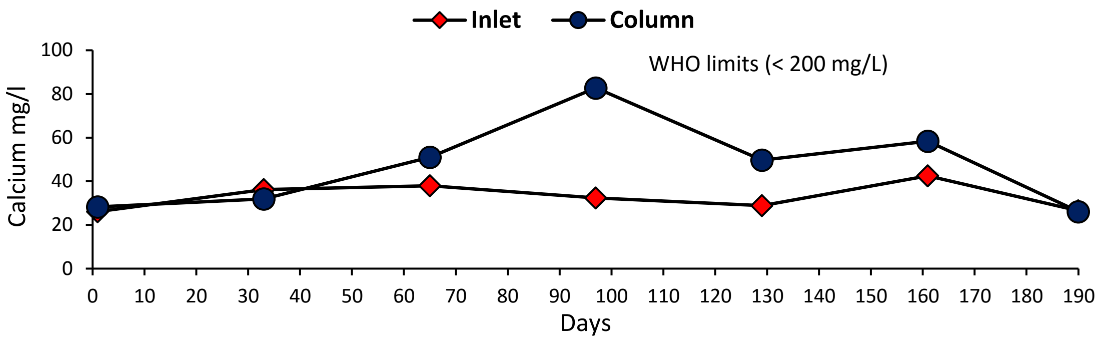

Figure 65 Determination of Calcium in column and inlet water (from February to August)

Metals analysis:

Arsenic (As):

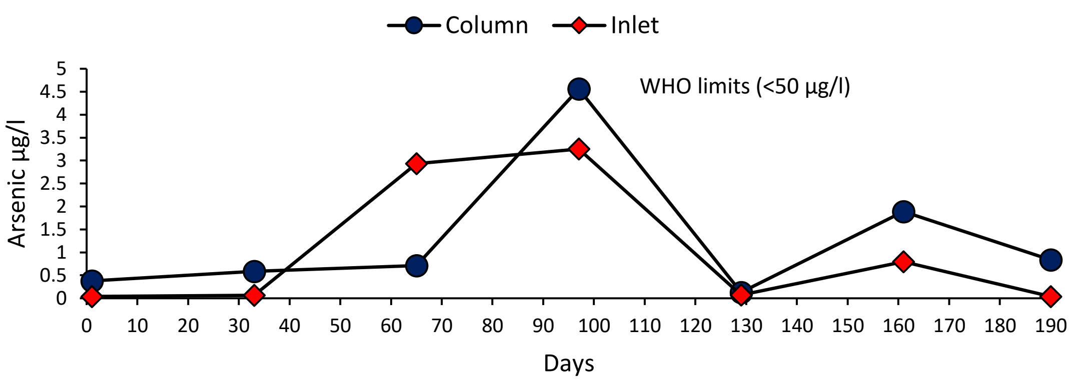

Figure 66 Determination of Arsenic in column and inlet water (from February to August)

Lead (pb):

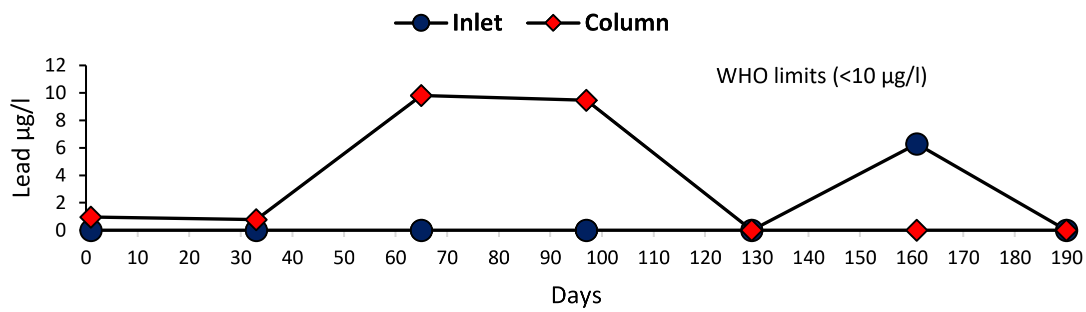

Figure 67 Determination of lead in column and inlet water (from February to August)

Cobalt (Co):

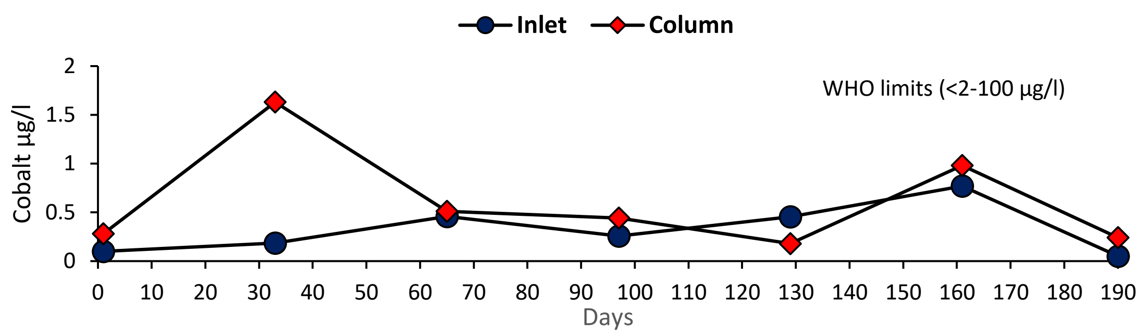

Figure 68 Determination of Cobalt in column and inlet water (from February to August

Chromium (Cr):

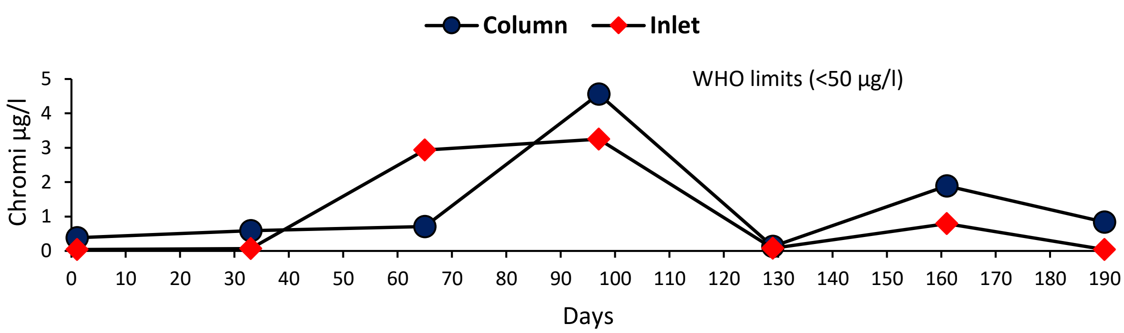

Figure 69 Determination of Chromium in column and inlet water (from February to August)

Copper (Cu):

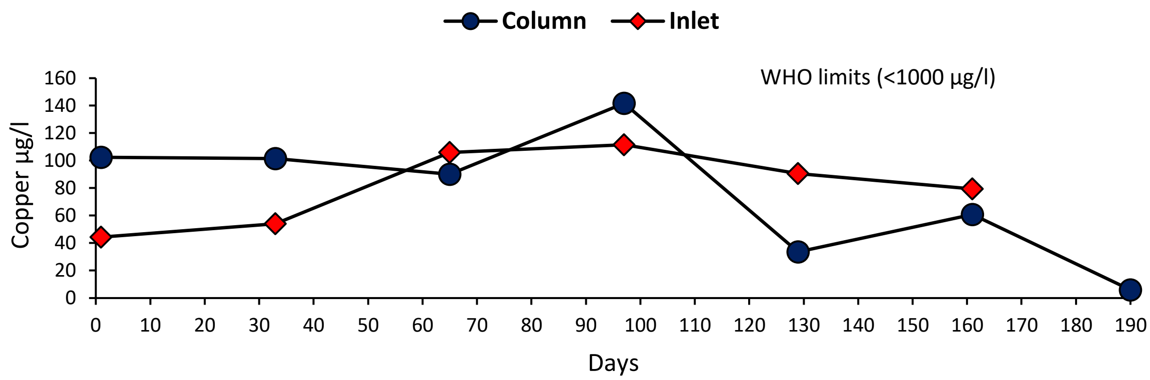

Figure 70 Determination of Copper in column and inlet water (from February to August)

Nickel (Ni):

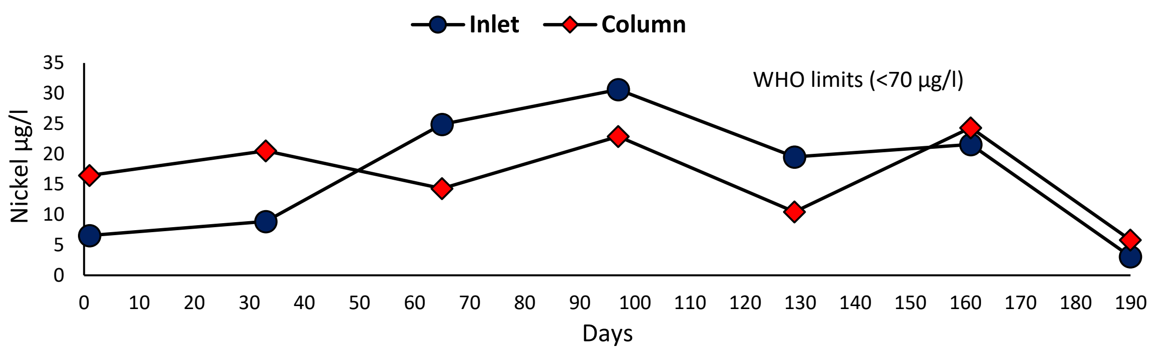

Figure 71 Determination of Nickel in column and inlet water (from February to August)

Manganese (Mn):

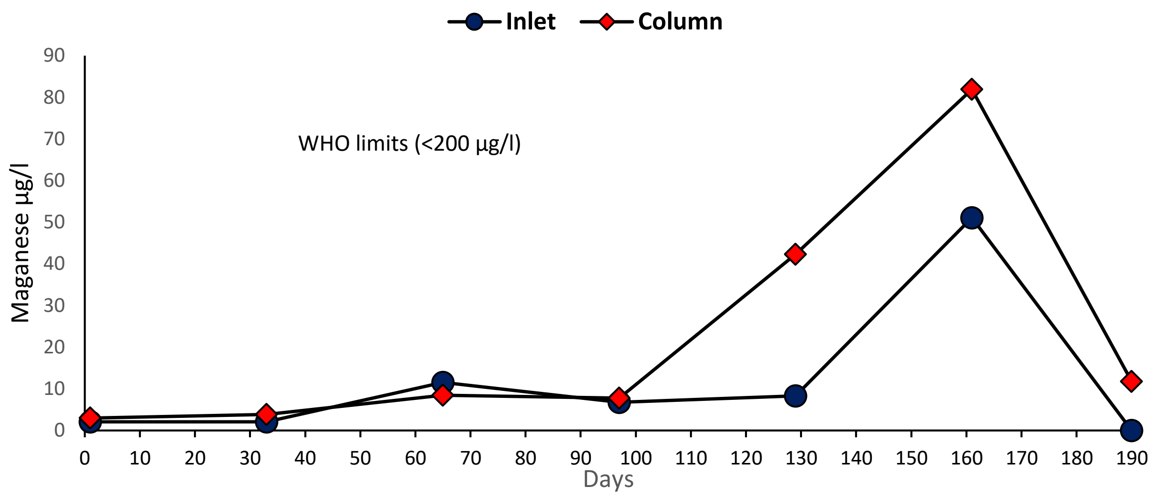

Figure 72 Determination of Manganese in column and inlet water (from February to August)

3.8 Cost benefit analysis

The cost benefit analysis of CBF versus the filter plant expenditures were also conducted to evaluate the benefit of CBF on monetary basis. The total expenditure to filter the 4000 m3 water daily at filter plant using alum (PKR 216,000/ year) and removal of sedimentation (PKR 90,000/annum. The total annual expenditure exceeds to PKR 300,000/ per annum and still the required drinking water quality has not been achieved.

The CBF system to provide the same water quantity and the quality as per WHO guiding limits which costs PKR 4,500,000 for installation, later there is no operational cost. The CBF system will recover its cost within 15 years.

4. CONCLUSION AND RECOMMENDATION

Water withdrawal from highly turbid Canals and Rivers require further physio-chemical treatment for safe production of potable quality water. The treatment of such water needs construction of coagulation/flocculation basins, sedimentation basins and rapid sand filtration. The construction and operation costs of the treatment units are high. These treatment costs can be reduced if extraction of water is carried out through natural filtration called Canal Bed Filtration (CBF). In the current study, investigation were carried out to utilize canal bank filtration on the KB feeder, which is main source of water supply for Mehran University of Engineering and Technology.

The investigations were conducted on both sides of the Canal. However, the most suitable site for extraction of water using canal bed filtration was found to be on the eastern side (left side or Inspection path, aka IP side) of the canal. The data from pumping tests data demonstrated that extraction of water with a constant rate of 25.9 m^3/day from the bore (installed in the first step) of 12 inch in diameter and 30 feet depth can be achieved without any significant drawdown due to equilibrium with seepage from the canal. Further investigation were carried out using two addition bores and the constant discharge rate of 84.6 m^3/day was estimated within the diameter of 40 feet. It has been estimated previously by in a study conducted by researchers of the USPCASW in collaboration of faculty of USPCASW that the current water demand of MUET society (Phase-1, Phase2, and the University) is approximately 1 MGD (3,784 m^3/day). Therefore, the number of wells required (of the above mentioned dimensions) is 134 spreading in the length of 545 meters along the canal bed.

The quality of water extracted from the well located at the canal bed during the project period was also found of excellent quality, free from turbidity, suspended solids, and microbial contamination. The salt concentrations of the extracted water was similar to that of the canal water, i.e. below 600 mg/L. Therefore, the extracted water from the wells can be considered as “fresh water” and safe for potable purpose. The quality of extracted water was remained high even during the low flow (closure period), average flow, and high flow seasons. The column study at the laboratory of USPCASW also confirmed the results and bio-clogging was not observed in the column ever after operation of about 6 months.

The study provide an economical natural filtration method for extraction of drinking water for communities of MUET. The results suggests that the canal/river bed filtration method can be applied for extraction of potable quality water, without any chemical addition, for small, medium and large cities. The application of Canal/River bed filtration will save treatment cost significantly and reliable quality of potable water can be supplied to the communities.

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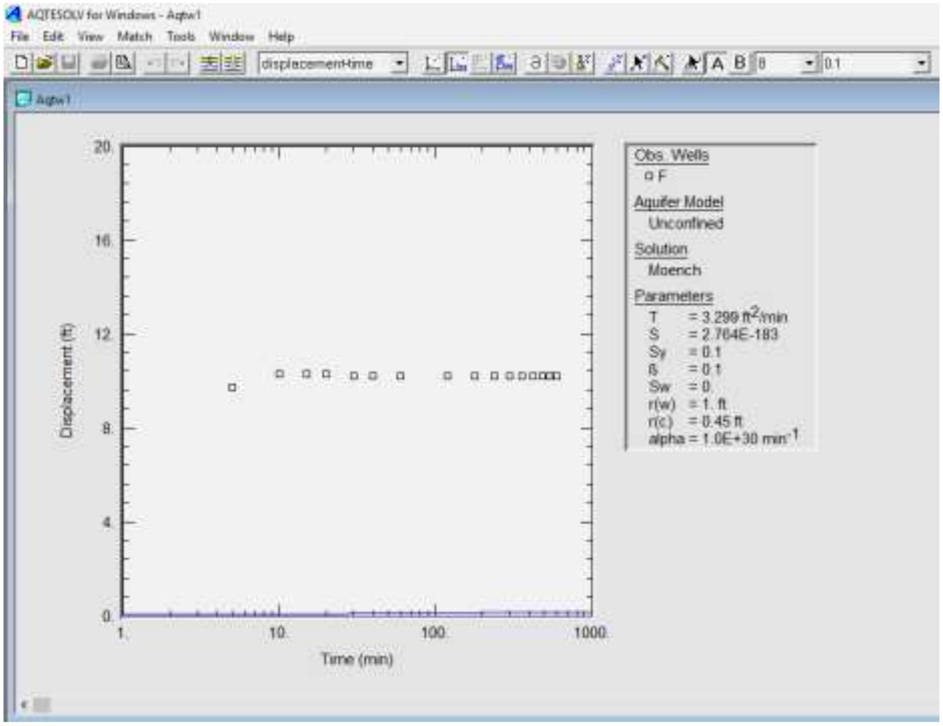
APPENDICES:

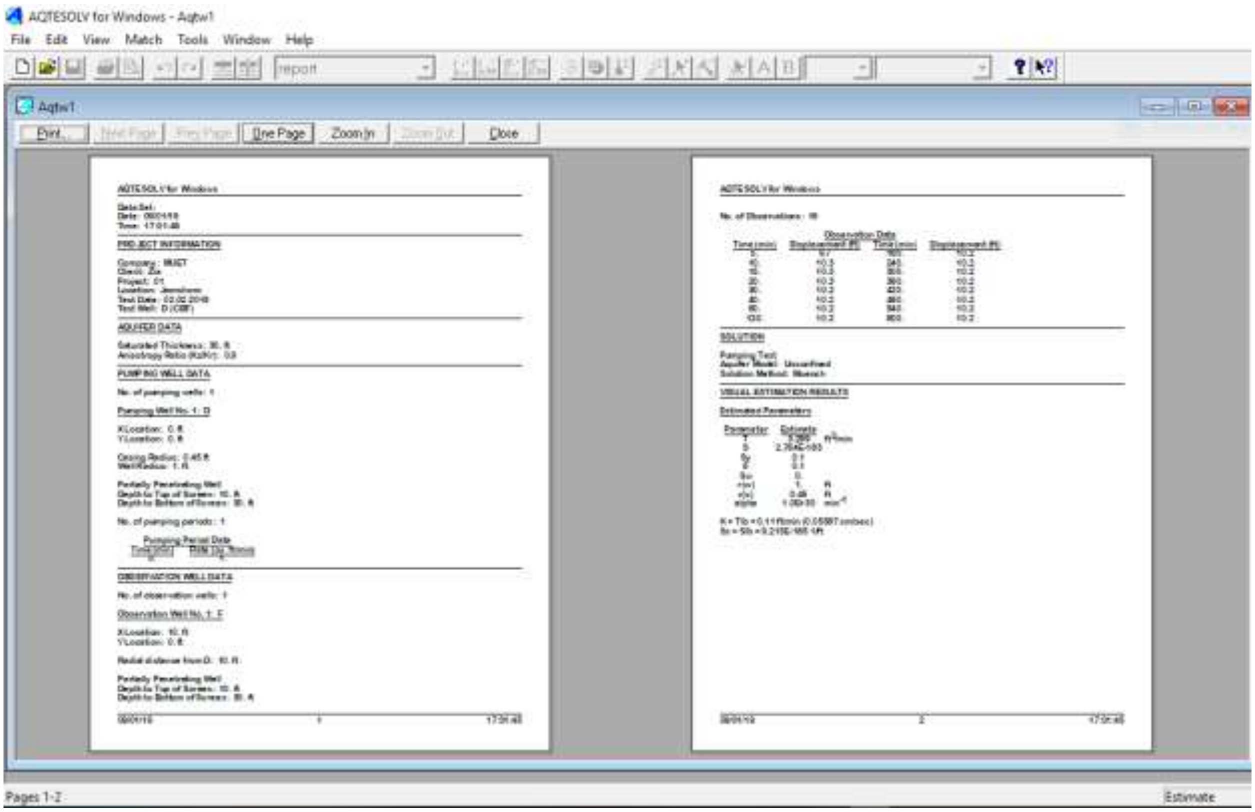
App:1 Pumping test through AQTESLOV model



App:2 Pumping test data sets with variable water level.

No	Time elapsed (minutes)	Displacement (normal flow)	Displacement (shortage)	Displacement (FSL)
1	5	9.7	12	8
2	10	10.3	12.6	8.5
3	15	10.3	12.6	8.9
4	20	10.3	12.9	9.1
5	30	10.2	12.9	9.1
6	40	10.2	12.9	9.2
7	60	10.2	13.4	9.2
8	120	10.2	13.4	9.2
9	180	10.2	13.4	9.2
10	240	10.2	13.4	9.2
11	300	10.2	13.4	9.2
12	360	10.2	13.4	9.2
13	420	10.2	13.4	9.2
14	480	10.2	13.4	9.2
15	540	10.2	13.4	9.2
16	600	10.2	13.4	9.2

App:3.


AQTESOLV for Windows - Aqtw1
File Edit View Match Tools Window Help
Aqtw1
Print... Next Page Prev Page One Page Zoom In Zoom Out Close
Pages 1-2
Estimate

App:4 ICPMS Detection limit

ICPMS:					
Materials/Products tested*	**Types of test/Property Measures**	**Range of measurement**	**Minimum detection limit**	**Uncertainty of Measurement** **RSD (%), n=3**	**Standard specification/Techniques /equipment used**
Arsenic (As) Element/Metal	Lake water, Synthetic water, Surface water	1-5,000 ppb 0.1-0.5-1 ppm	1-10 ppt	±4.9%	Model: PerkinElmer ICP-MS NexION 350-Q Method: Method EPA-200.8 (Determination of trace elements in waters and wastes by ICP-MS) / External standard calibration and sample analyses. Year: 1994 Environmental Monitoring Systems Laboratory Office of R&D U.S. EPA CINCINNATI, OHIO 45268. Authors: J.T. Creed, C.A. Brockhoff, and T.D. Martin.
Copper (Cu) Element/Metal	Lake water, Synthetic water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-

Zinc (Zn) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Lead (Pb) Element/Metal	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Manganese (Mn) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Mercury (Hg) Element/Metal	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Iron (Fe) Element/Metal/Mineral	Lake water, Surface water	1-10,000 ppb 100-250-500 ppb	1-10 ppt	0.9%	-do-

Chromium (Cr) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Nickel (Ni) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Cesium (Ce) Element/Metal	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	<0.1-1 ppt	2.0%	-do-
Cobalt (Co) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Indium (In)	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	<0.1-1 ppt	2.0%	-do-

Element/Metal					
Lithium (Li) Element/Metal	Lake water, Surface water	1-10,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Terbium (Tb) Element/Metal/Mineral	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	<0.1-1 ppt	2.0%	-do-
Calcium (Ca) Mineral	Lake water, Surface water	1-10,000 ppb 1-2-5 ppm	10-100 ppt	1.7%	-do-
Sodium (Na) Mineral	Lake water, Surface water	1-10,000 ppb	1-10 ppt	less than 5%	-do-
Potassium (K) Mineral	Lake water, Surface water	1-10,000 ppb	10-100 ppt	less than 5%	-do-

Magnesium (Mg) Mineral	Lake water, Surface water	1-10,000 ppb 1-2-5 ppm	1-10 ppt	1.7%	-do-
Boron (B) Element/Metal	Lake water, Surface water	1-10,000 ppb	1-10 ppt	less than 5%	-do-
Bismuth (Bi) Element/Metal	Lake water, Surface water	1-10,000 ppb 0.3-0.5-1.4 ppb	<0.1-1 ppt	3.4%	-do-
Cadmium (Cd) Element/Metal	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	1-10 ppt	2.0%	-do-
Molybdenum (Mo) Element/Metal	Lake water, Surface water	1-10,000 ppb 3-6-15 ppb	0.1-1 ppb	2.1%	-do-

Beryllium (Be) Element/Metal	Lake water, Surface water	1-5,000 ppb 5-10-20 ppb	1-10 ppt	less than 5%	-do-
Thallium (Tl) Element/Metal	Lake water, Surface water	1-5,000 ppb 0.3-0.5-1.4 ppb	0.1-1 ppb	3.4%	-do-
Vanadium (V) Element/Metal	Lake water, Surface water	1-5,000 ppb 1.5-3-7 ppb	0.1-1 ppb	2.1%	-do-