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Chapter 7

ENHANCED BIOREMEDIATION PILOT STUDY OF A CR(VI)-IMPACTED OVERBURDEN GROUNDWATER SYSTEM IN KANPUR, UTTAR PRADESH, INDIA

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ABSTRACT

Pilot-scale electron donor injection enhances hexavalent chromium, Cr(VI), biochemical reduction to trivalent chromium, Cr(III), in an overburden groundwater system impacted by Cr(VI) disposal in Kanpur, Uttar Pradesh, India . The study area is located in the Indo-Gangetic alluvial plain, and is characterized by overburden stratigraphy consisting of up to about 50 meters of generally fine to medium sand interbedded with silty clay, which is underlain by about 100 meters of laterally continuous clay. The clay is underlain by interbedded fine to medium sand and clay to a depth of about 500 meters, which overlies granitic bedrock. Cr(VI) has been detected for about 20 years at concentration up to 16 milligrams per liter in groundwater samples collected from the shallower fine to medium sand unit. The source is believed to be indiscriminate dumping of wastes resulting from production of Basic Chrome Sulfate ($Cr(OH)_2SO_4$, BCS) and other reagents used by local leather tanneries. Approximately 540 kilograms of a carbohydrate-based remedial additive were injected into two wells screened in the fine to medium sand unit using about 40,000 liters of groundwater. Treatment solution make-up water was obtained from a downgradient extraction well located within the Cr(VI) plume, amended with remedial additive, and then injected into the upgradient wells to establish hydraulic control on the injection and minimize dilution. Performance monitoring included five rounds of groundwater sampling for Cr(VI), total chromium, and certain indicator parameters, including total organic carbon (TOC) as an electron donor surrogate. Pilot study results suggest that remedial additive amendment resulted in an up to 99.9% reduction in Cr(VI) concentration; an up to 97% reduction in total chromium; and up to an order of magnitude increase in TOC concentration over the four month study.

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1. BACKGROUND

Appreciating the gravity of the alarming status of contaminated groundwater resources on the Indian subcontinent and the local reliance upon these resources for potable water, the Government of India is developing a concerted effort to preserve and protect India's groundwater. In light of the technological advancements in the field of groundwater remediation, India has sought to employ an innovative remedial approach to address a Cr(VI) contaminant condition in overburden groundwater in Kanpur, Uttar Pradesh. In fact, the work reported herein was carried out in 2006 and represents, to the author's knowledge, the first reported field-scale groundwater remediation project on the Indian subcontinent.

Kanpur, a major industrial city in north Indian state of Uttar Pradesh (U.P), where the study was undertaken, includes a municipal area of about 260 square kilometers (KMC, 2006). Bordered in the north by river Ganga and in the south by the river Pandu, the city lies between latitudes of about 26021'0'' and 26030'0'' north and longitudes of about 80010'0'' and 80030'0'' east, included in the Survey of India topographic Sheet Nos. 63B/3 and B/7. Previous studies have indicated that the process of urbanization in the city is associated with higher concentration of heavy metals in river sediments (Singh et al, 1999), low lying lands, and groundwater. The chromium concentration in groundwater and the pattern of land use in the city are interrelated (CPCB, 1997).

Groundwater samples collected from potable water supply wells in Nauriakhera, the present area of the investigation, contain Cr(VI) at concentrations ranging from about 0.008 to 16.00 milligrams per liter (mg/l), owing to indiscriminate disposal practices of waste sludge (5-10% Cr2O3 by weight) generated from industrial production of BCS, an important reagent used by local tanneries. Such industries, existing in the general vicinity of the Study Area up to about the late 1980s, have been either closed or moved to more rural areas.

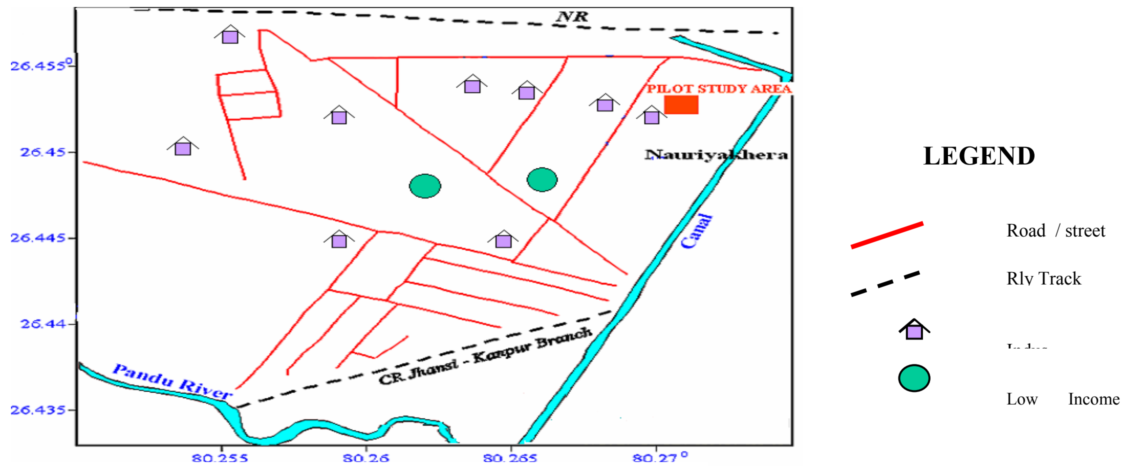
Cr(VI) in the waste sludge is leachable and has ultimately reached overburden groundwater. The Cr(VI) plume has impacted sensitive receptors such as shallow drinking water wells.

The Study Area is part of Indo-Gangetic alluvial plane, exhibiting more or less flat topographic relief, with the major slope running from northwest to southeast and subsurface stratigraphy predominated by medium sand and gravel inter-bedded with silty clay (CGWB, 2000). The micaceous sandy horizons have Himalayan provenance (Singh and Bajpai, 1989). Based on borehole data (CGWB, 2000), granitic bedrock underlies overburden soils at a depth of about 500 meters in the general Study Area.

2. METHODS

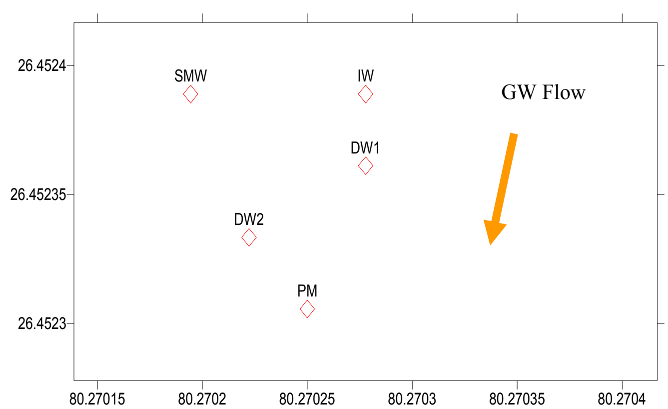
To evaluate an in-situ bioremediation approach for addressing the Cr(VI) contamination in overburden groundwater, the following work was completed:

- Macro-level investigation of groundwater quality, in a quasi grid of 40 productive water supply wells screened in the shallow groundwater system, was carried out to assess the spatial distribution of Cr(VI) and other associated ions and also to locate highest Cr(IV) impacted area in which to carry out the remedial pilot study. Please refer to the Pilot Study Location Plan for the approximate location of the pilot study within the Study Area.



Pilot Study Location Plan

- Installation of a well field comprised of four new injection/monitoring wells (IW, SMW, DW-1, DW-2) as well as an existing piezometer (PM), with well screens intersecting the same laterally-continuous Cr(VI)-impacted hydrostratigraphic unit consisting of sand lenses, inter-layered between clay and/or clayey caliche. The drilling program was carried out using water rotary drilling technique to advance each borehole to its termination depth of about 47.2 meters below ground surface (bgs). Refer to the Well Field Location Plan for exploration locations relative to the general direction of groundwater flow.



Legend: IW: Injection Well; ... itoring Wells, PM: Piezometer

Well Field Location Plan

- The baseline monitoring program was executed using a modified low-flow sampling technique. The purpose was to establish baseline groundwater quality conditions for the pilot study from which performance could be evaluated. The scope of baseline monitoring included 10 metals and 7 indicator parameters. Results are appended in the Data Summary Table.

- The remedial additive injection program, using a groundwater recirculation approach, was executed by achieving steady state pumping conditions, with a recirculation rate of about 22 liter per minute (LPM) through split injection into two wells (IW & SMW).

- Remedial additive injection into the IW and SMW was carried out for about 43.5 hours at about 15 LPM mean flow rate (4 to 21 LPM range), for a total injection load of about 540 kilograms of EDC-M (Electron Donor Compound-Metals, manufactured by EcoCycle Corporation of Toyama, Japan) dissolved in about 40,000 liters of re-circulated groundwater. Note that EDC-M is formulated with two components, EDC-M1 and EDC-M2, each of which is packaged separately and injected sequentially (*i.e.*, EDC-M1 before EDC-M2). For the pilot study injection, about 210 kilograms of EDC-M1 were injected first, diluted in about 12,000 liters of re-circulated groundwater, followed by about 330 kilograms of EDC-M2, diluted in about 28,000 liters of groundwater, in consideration of the manufacturer's recommendations. Refer to the Remedial Pilot Study Process Diagram for additional information on the recirculation/injection program.

- Five rounds of (post-injection) performance monitoring were performed (same wells and parameters) using similar sampling technique, as for baseline sampling. Post-injection groundwater sampling results are also summarized in the Data Summary table.

3. RESULTS

3.1 Hydrostratigraphy

Based on the results of the drilling program carried out to install the pilot test well field as well as those of previous work performed in the Study Area, the overburden hydrostratigraphy includes two notable groundwater flow systems, each of which can be classified as an overburden aquifer given is used for water supply:

- A deep regional flow system occurring in stratified sand at a depth greater than about 300 meters bgs; and
- Local/intermediate flow systems occurring in sand lenses at shallower depth intervals.

The regional flow system within the deep overburden is hydraulically confined and characterized by an approximately 100-meter thick laterally continuous and generally transmissive stratified sand unit overlying granitic bedrock likely of the Archaean-age Bundelkhand complex. The regional flow system occurs at a depth of about 300 to 500 meters bgs.

The subordinate local and intermediate flow systems in the shallow overburden are generally at least partially hydraulically confined and characterized, at least at the scale of the pilot study, by relatively continuous transmissive sand lenses, interlayered clay and/or clayey caliche, to a depth of up to about 300 meters bgs.

Water supply wells are installed in both the shallow local/intermediate groundwater flow systems serving residential or small community users and the deep regional flow system serving industrial, municipal, or large community users in the Study Area, and both represent potential sensitive receptors owing to the current Cr(VI) condition.

3.2 Spatial Impact of Cr(VI)

With respect to Cr(VI) contamination in Study Area overburden groundwater, the highest detected concentrations are typically for samples collected from the local and intermediate groundwater flow systems in the shallow overburden at depths ranging from about 20 to 50 meters bgs. While the deep regional groundwater flow system has reportedly not yet been impacted by Cr(VI) contamination from the shallow flow systems, there is the potential for downward advection of Cr(VI), driven by downward vertical hydraulic gradients, to deleteriously impact groundwater quality of the deep flow system. Therefore, it is imperative that Cr(VI) contamination in the shallow groundwater flow systems be addressed before it impacts the deep flow system, notwithstanding the current unacceptable risk Cr(VI) poses to identified sensitive receptors of shallow overburden groundwater in the Study Area.

3.3 Remedial Pilot Study Performance Data

Baseline and post-injection performance monitoring results for the parameters identified in the Remedial Pilot Study are summarized in the attached Data Summary Table. Specific observations regarding Chromium, the critical parameters of interest, are summarized below.

3.3.1 Hexavalent Chromium, Cr(VI)

As shown on the Data Summary Table, baseline Cr(VI) concentrations ranged from 8.16 mg/L to 12.55 mg/L (arithmetic mean: 10.74 mg/L1) for groundwater samples collected from all five wells, whereas post-injection concentrations for the same well locations ranged from non-detectable above the analytical reporting limit (RL) of 0.03 mg/L to 4.17 mg/L (geometric mean: 0.71 mg/L) over the pilot study duration, which is consistent with an overall 93 percent reduction (%Reduction) in Cr(VI) concentration. The magnitude of the overall %Reduction is consistent with the biochemical transformation of Cr(VI) to Cr(III), driven by electron donor amendment.

Post-injection Cr(VI) results are summarized below on a round-specific basis:

- For the first post-injection sampling round, detected Cr(VI) concentrations ranged from 0.23 to 4.17 mg/L, reflecting an up to two orders of magnitude decrease in Cr(VI) concentrations within about 2 weeks of the injection program;

[1] Our statistical approach for estimating means as well as or percent reductions assumes a value of 0.01 mg/L for non detects above the analytical RL of 0.03 mg/L.

- For the second post-injection round, Cr(VI) concentrations ranged from non-detectable above analytical RLs to 0.32 mg/L Cr(VI), reflecting an up to three orders of magnitude decrease in Cr(VI) concentrations within about 4 weeks of the injection program;
- For the third post-injection sampling round, Cr(VI) concentrations were non-detectable above analytical RLs, reflecting a three orders of magnitude decrease in Cr(VI) concentrations within about 10 weeks of the injection program;
- For the fourth post-injection sampling round, Cr(VI) concentrations were non-detectable above analytical RLs, reflecting a three orders of magnitude decrease in Cr(VI) concentrations within about 13 weeks of the injection program; and
- For the fifth post-injection round, Cr(VI) concentrations ranged from non-detectable above analytical RLs to 0.67 mg/L Cr(VI), reflecting an up to three orders of magnitude decrease in Cr(VI) concentrations within about 17 weeks of the injection program.

A notable rebound in the Cr(VI) concentration for the groundwater sample collected from DW-2, the well with the highest baseline Cr(VI) concentration, was detected during the fifth post-injection sampling round. This apparent rebound may either represent analytical variability or possibly Cr(VI) advection to the well DW-2 location, and not to chemical oxidation of Cr(III) to Cr(VI) given there was no significant (order of magnitude or greater) increase in total chromium concentration for this well location that would be consistent with that transformation pathway as discussed in the following section.

3.3.2 Total Chromium, T-Cr

Based on the Data Summary Table, baseline T-Cr concentrations ranged from 12.88 to 19.49 mg/L (arithmetic mean: 15.80 mg/L) for groundwater samples collected from all five wells, whereas post-injection concentrations for the same well locations ranged from 0.4 mg/L to 10.66 mg/L (geometric mean: 1.21 mg/L), which is consistent with an overall $92\%_{\text{Reduction}}$ in T-Cr concentration. The magnitude of this overall $\%_{\text{Reduction}}$ is the same as the overall reduction observed for Cr(VI), and is consistent with the biochemical transformation of more mobile Cr(VI) to immobile Cr(III), driven by electron donor amendment.

T-Cr results on a round-specific basis are summarized as follows for the five rounds of post-injection monitoring:

- For the first post-injection sampling round, detected T-Cr concentrations ranged from 9.09 to 10.66 mg/L (arithmetic mean: 9.97 mg/L), reflecting a 37% decrease in mean T-Cr concentrations within about 2 weeks of the injection program;
- For the second post-injection sampling round, T-Cr concentrations ranged from 0.46 to 7.79 mg/L Total Cr (geometric mean: 2.02 mg/L), reflecting an 87% decrease in T-Cr concentrations within about 4 weeks of the injection program;
- For the third post-injection sampling round, T-Cr concentrations ranged from 0.19 to 7.78 mg/L (geometric mean: 1.27 mg/L), reflecting a 92% decrease in T-Cr concentration within about 10 weeks of the injection program;
- For the fourth post-injection sampling round, T-Cr concentrations ranged from 0.08 to 2.71 mg/L (geometric mean: 0.84 mg/L), reflecting a 95% decrease in T-Cr concentrations within about 13 weeks of the injection program; and

- For the fifth post-injection sampling round, T-Cr concentrations ranged from 0.12 to 2.87 mg/L (geometric mean: 0.41 mg/L), reflecting a 97% decrease in T-Cr concentrations within about 17 weeks of the injection program.

3.3.3 Biological transformation Indicator Parameters

To evaluate the sequential development of anaerobic, chemically reducing conditions stimulated by electron donor amendment, seven criteria parameters including dissolved oxygen (DO), Redox Potential (Eh), sulfate, nitrate, dissolved iron, dissolved manganese, and TOC were identified. The trend of these parameters as depicted in Data Summary table is consistent with the biologically-mediated transformation of Cr(VI) to Cr(III).

4. DISCUSSIONS

4.1 Groundwater Quality

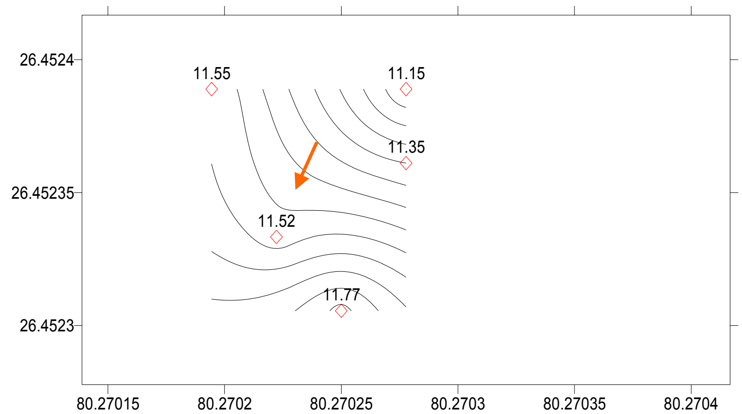
- Based on the Data Summary Table, the indicator parameters each exhibited a decreasing trend with time, relative to baseline conditions, over the pilot study duration (*i.e.,* DO, up to 77% reduction; ORP, up to 271% reduction; sulfate, up to 74% reduction; and nitrate, up to 83% reduction). This trend is directly consistent with the development of anaerobic, chemically reducing conditions stimulated by electron donor amendment. The reduction in DO, sulfate, and nitrate concentrations are respectively consistent with the microbial metabolic processes of aerobic mineralization, sulfate reduction, and nitrate reduction, respectively. The reduction in ORP values with time is consistent with the development of chemically reducing conditions owing to electron donor amendment perturbing the groundwater system by scavenging terminal electron acceptors DO, nitrate, oxidized metals, and sulfate;
- The indicator parameter, sulfide, was also analyzed as part of performance monitoring. Sulfide was not detected above analytical RLs during baseline groundwater sampling, but was detected at concentrations ranging from 0.5 mg/L to 34.2 mg/l during post-injection sampling. The increased sulfide concentration with time, in response to electron donor amendment, represents a secondary line of evidence that sulfate reduction was stimulated by electron donor amendment, and is consistent with the generally depressed sulfate concentrations, in response to the pilot study injection, as discussed above;
- The indicator parameters dissolved iron, dissolved manganese, and TOC exhibited a generally increasing trend over the pilot study duration consistent with the typical response of groundwater systems to electron donor amendment. With respect to these metals, the increased dissolved iron concentration is consistent with the enhanced biochemical reduction of insoluble ferric iron (III) to soluble ferrous iron (II), mediated by iron-reducing bacteria. The increased dissolved manganese concentration is consistent with the enhanced biochemical reduction of insoluble manganese (IV) to soluble manganese (II), mediated by manganese-reducing bacteria. In the case of both iron and manganese oxide reduction, transformation was stimulated by electron donor amendment, which provided the organic carbon driving biochemical reduction;

- The liberated ferrous iron (II) and manganese (II) are expected to be respectively oxidized to ferric iron (III) and manganese (IV), and then re-sorbed onto the formation matrix once they migrate beyond the anaerobic, chemically reducing treatment zone effected by electron donor amendment into the initially aerobic, chemically oxidizing shallow overburden groundwater system (Brömssen, M.V., 1999). With respect to TOC, the increased concentration is consistent with EDC-M amendment, as TOC is a suitable surrogate measurement for that remedial additive;
- pH values, in standard log units, for baseline groundwater samples ranged from about 6.7 (IW) to 7.0 (DW-1 and DW-2), whereas values for post-injection samples ranged from about 4.6 (IW) to 7.5 (existing Piezometer). Post-injection values for groundwater samples collected from wells IW, SMW, DW-1, and DW-2 were typically lower than the baseline values approaching neutrality for these same locations, likely reflecting organic acid fermentation products of the remedial additive as well as biogenic production of carbon dioxide from remedial additive mineralization to yield carbonic acid. Despite the general post-injection decrease in pH for the groundwater samples collected from these wells, the values generally remained within the pH range considered conducive for microbial activity and did not appear to become inhibitory. Subsurface soils in the site vicinity are believed to contain significant bulk fraction of calcium carbonate, which serves as a natural buffering agent to maintain pH near baseline values. The baseline pH value for the groundwater sample collected from the existing piezometer was generally similar to the post-injection pH values for the same well, likely reflecting its respective location within the well field (*i.e.,* the most downgradient well); and
- Specific conductivity values, in microsiemens per centimeter (*u*s/cm), for baseline groundwater samples ranged from about 865 (IW) to 1,450 (existing piezometer) *u*s/cm, whereas values for post-injection samples ranged from about 962 (SMW) to 10,160 (IW) *u*s/cm. Post-injection specific conductivity values for groundwater samples collected from the IW, SMW, DW-1, and DW-2 were typically lower than baseline values, likely reflecting the total dissolved solid contribution to groundwater from remedial additive amendment. The baseline specific conductivity value for the groundwater sample collected from the existing piezometer was generally similar to the post-injection specific conductivity values for the same well, likely reflecting its respective location within the well field (*i.e.,* the most downgradient well).

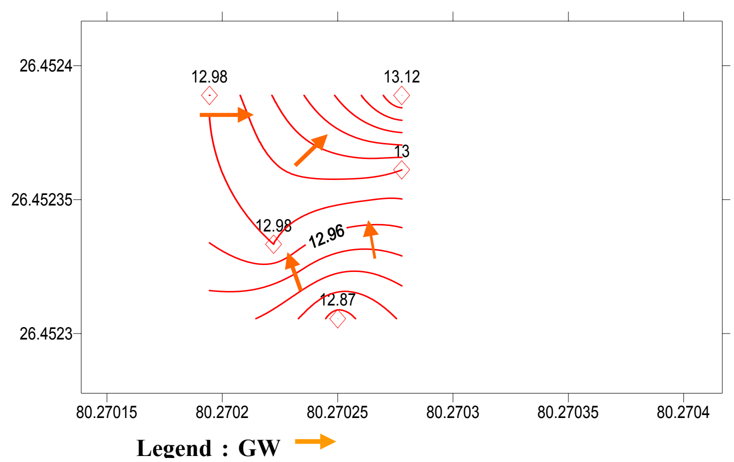
4.2 Groundwater Elevation Data

As depicted in Baseline and Post-Injection Groundwater Elevation Contour Plans included below, baseline groundwater flow was generally toward the south to southwest, trending roughly parallel with the canal to the east. As shown in the Post-Injection Groundwater Elevation Contour Plans, the groundwater flow net initially reflected a groundwater depression in the general vicinity of the extraction well (DW-2), owing to groundwater pumping during re-circulation, followed by variable flow directions that ultimately, resulted in a general flow reversal from the baseline direction of south to southwest, to the final apparent post-injection direction of north to northeast. Groundwater flow nets, following remedial injection programs, typically equilibrate to baseline conditions within a few weeks based on our experience. Therefore, the baseline and post-injection groundwater elevation contour plan sets are more consistent with conditions unrelated to the Remedial Pilot Study, such as the pumping of nearby shallow wells to meet potable/process water demand, irrigation associated with local agriculture, or variation in canal or other surface water stage.

Pre-Injection Groundwater Elevation Contour Scenario



Post-Injection Groundwater Elevation Contour Scenario



Note : Contours plotted using depth to groundwater level (DWL) in meters below ground surface (bgs)

5. CONCLUSIONS

The pertinent conclusions of the Remedial Pilot Study are as follows:

- Cr(VI) contamination in the local and intermediate groundwater flow systems poses unacceptable risk to:

  - Potential sensitive receptors for shallow overburden groundwater owing to its presence at concentrations exceeding the Indian Standard for Drinking Water Quality, and
  - The deep, regional groundwater flow system owing to potential for vertical migration from the shallow Cr(VI)-impacted groundwater flow system driven by the generally downward hydraulic gradient;
- Electron donor amendment stimulated the biologically-mediated transformation of up to about 99.9% of mobile and toxic Cr(VI) mass to immobile and nontoxic Cr(III) during the 17-week pilot study. In fact, laboratory analysis (Clesceri, *et al* 2005) of groundwater samples collected from four of five well field locations during the last post-injection sampling round did not detect Cr(VI) at concentrations exceeding Indian Standard for Drinking Water Quality. Indicator parameter data were consistent with Cr(VI) transformation to Cr(III) owing to microbially-mediated processes in accordance with the Remedial Pilot Study technical approach; and
- Based on the range of pH and Eh values for overburden groundwater in the Study Area, it is unlikely that the Cr(III) can undergo reversal to Cr(VI) following treatment. Even so, given the shallow groundwater system is used as a drinking water source in the Study Area, long term groundwater monitoring would be prudent to protect sensitive receptors.

Based on the positive results of the Remedial Pilot Study and the preliminary Conceptual Site Model developed as part of this work, the authors recommend implementing a full-scale remedial program in the Study Area including a data gap investigation as expeditiously as practical to advance it toward closure.

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DATA SUMMARY TABLE

Location : Injection Well (IW)

Date	SWL	PH	DO	Eh	Cond	S2-	SO4 2-	NO3	TOC	Cr +6	T-Cr	Fe	Mn	Ni	Cu	Co	Zn	Hg	As
26.01	11.2	6.91	4.1	118	865	ND	139	3.52	34.46	10.01	12.9	0.17	0.06	0	0.01	0	0.08	ND	ND
9.02	11.8	Sampling was not possible due to excessive foaming																	
24.02	12	4.6	0.9	-25	10160	**	270	**	34.22	**	6.42	351.7	71	0.34	0.53	0.5	2.13	**	**
10.04	12	6.96	1.7	-	3870	5.96	35.18	0.92	420.2	ND	0.19	40.45	15.1	ND	1.58	ND	1.16	0.04	ND
28.04	12.4	6.71	1.6		2290	24.2	28.94	0.25	72.89	ND	0.08	9.94	2.98	ND	0.15	ND	0.96	ND	0.06
26.05	13.1	6.45	1	-110	1140	3.3	61	0.23	82.39	ND	0.12	7.16	1.9	ND	0.06	ND	0.03	ND	0.08

Location : Side Gradient Monitoring Well (SMW)

Date	SWL	pH	DO	Eh	Cond	S2-	SO4	NO3	TOC	Cr	T-	Fe	Mn	Ni	Cu	Co	Zn	Hg	As
26.01	11.6	6.94	4.8	115	1014	ND	263	5.45	52.14	8.16	16.4	0.31	0.06	0	0.03	0	0.07	ND	ND
9.02	11.9	Sampling was not possible due to excessive foaming																	
24.02	12.6	6.06	1.8	-93	3290	1	140	1.73	46.23	0.56	0.86	67.95	11.1	0.05	0.2	0	0.14	**	**
10.04	12	6.55	1	-70	1535	3.73	60.41	1.03	211.7	ND	0.47	14.68	2.91	ND	0.94	ND	0.17	0.06	ND
28.04	12.6	6.74	1.8		1019	1.2	77.38	0.55	30.38	ND	0.87	7.03	3.33	ND	0.08	ND	0.33	ND	0.05
26.05	13	6.62	1.4	-234	962	6.2	161	1.4	39.23	ND	0.57	5.03	0.74	ND	0.05	ND	0.03	ND	0.04

Location : Down-gradient Well No. 1 (DW-1)

Date	SWL	pH	DO	Eh	Cond	S2-	SO4	NO3	TOC	Cr	T-	Fe	Mn	Ni	Cu	Co	Zn	Hg	As
26.01	11.4	7.04	4.6	105	1120	ND	214	2.2	52.02	11.2	15.3	0.27	0.03	0.02	0.4	0	0.23	ND	ND
9.02	12.2	5.83	3.7	-18	2250	2.24	337	1.46	51.35	0.34	10.2	37.13	11.8	0.05	0.08	0	0.28	ND	ND
24.02	12.4	6.39	2.9	-49	1657	0.6	142	1.05	51.64	0.06	1.68	19.78	7.95	0	0.04	0	0.25	0.05	ND
10.04	12.2	6.44	0.8	-70	2380	10.2	58.57	0.52	446.8	ND	7.78	100.6	11	ND	0.6	ND	0.22	0.08	ND
28.04	12.8	6.52	1.3	-	1309	6.8	31.32	0.52	128.4	ND	0.4	17.94	3.83	ND	0.12	ND	0.32	ND	0.08
26.05	13	6.24	1.2	-128	1216	92	76	1.3	98.3	ND	0.2	13.71	2.51	ND	ND	ND	0.19	ND	0.1

Location : Down-gradient Well No. 2 (DW-2)

Date	SWL	pH	DO	Eh	Cond	S2-	SO4	NO3	TOC	Cr	T-	Fe	Mn	Ni	Cu	Co	Zn	Hg	As
26.01	11.5	7.02	4.9	112	1256	ND	289	4.89	46.04	12.55	19.5	5.2	0.3	0.01	0.07	0	0.19	ND	ND
9.02	12.1	6.15	3.4	-15	1838	12.2	352	2.09	47.33	0.23	9.09	16.82	8.82	0.01	0.03	0	0.18	ND	ND
24.02	12.4	6.42	2.7	-24	2080	0.5	236	1.33	50.28	ND	7.79	24.45	7	0.03	0.01	0	0.09	0.06	ND
10.04	12	6.58	0.8	-43	1454	4.26	92.98	1.4	225.9	ND	3.3	17.17	4.26	ND	0.09	ND	0.19	0.09	ND
28.04	12.5	6.78	1.2	-	968	8.24	96.09	1.27	41.6	ND	2.71	5.99	1.71	ND	0.08	ND	1.09	ND	0.05
26.05	13	6.48	0.8	-1	1039	ND	93	2.15	61.6	0.67	2.87	4.03	0.87	ND	0.02	ND	0.02	ND	0.07

Location : Piezometer (PM)

Date	SWL	pH	DO	Eh	Cond	S2-	SO4 2-	NO3	TOC	Cr +6	T-Cr	Fe	Mn	Ni	Cu	Co	Zn	Hg	As
26.01	11.8	6.73	3.2	105	1450	ND	394	9.79	37.57	11.8	14.9	0.66	0.15	0.04	0.08	0	0.12	ND	ND
9.02	10.8	6.74	3.8	-12	1330	0.85	183	6.09	38.21	4.17	10.7	28.36	2.42	0.11	1.8	0	1.01	ND	ND
24.02	11.8	7.16	3	-13	1563	ND	235	1.34	39.2	0.32	0.46	4.7	1.68	0.04	0.1	0	0.11	0.01	ND
10.04	11.9	6.75	0.8	-36	1376	3.98	95.33	1.31	208.2	ND	1.44	6.7	2.63	ND	0.87	ND	0.23	0.02	ND
28.04	12.2	7.51	1.3	-88	1438	7.7	148.9	1.73	56.92	ND	0.9	54.27	4.91	ND	0.84	ND	0.65	ND	0.1
26.05	12.9	7.4	1.5	- 156	1372	2.7	55	0.35	66.86	ND	0.28	27.12	2.36	0.05	1.06	ND	0.29	ND	0.05

Notes:

1. Results for heavy metals, except Cr(VI), are reported as total dissolved metals, analyzed using atomic absorption spectroscopy in the flame mode.
2. SWL: Static water level in meters below ground surface (bgs).
3. Eh in mV.
4. Conductivity in µS /cm.
5. All others except pH in mg/l. pH is in standard units.
6. ND: Not detectable above analytical reporting limits.
7. ** : could not be completed due to excessive turbidity.
8. Date of Injection: February 8, 2006.
9. Dates are in day/month format. Note that 26.01 refers to a baseline sampling round; other dates refer to Post Injection sampling rounds.