Feasibility Study of Scavenging Approach to Stop Saltwater Toward Water Wells

Basic Information

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Publications

1. Frank Tsai, 2011, Multimodel Uncertainty Analysis for Chance-Constrained Saltwater Intrusion Management, Louisiana Water Resources Research Institute, Louisiana State University, Baton Rouge, Louisiana, 10 pages. (USGS 104B)
2. Tsai, F. T.-C., and A.S. Elshall. (2011). A Hierarchical Bayesian Model Averaging Approach to Cope With Sources of Uncertainty in Conceptual Ground Water Models, World Water & Environmental Resources Congress, Palm Springs, CA, May 22-26, 2011.
3. Tsai, F. T.-C. (2011). Development of Scavenger Well Operation Model To Stop Saltwater Intrusion Toward Water Wells In The “1,500-Foot” Sand of The Baton Rouge Area, Louisiana, World Water & Environmental Resources Congress, Palm Springs, CA, May 22-26, 2011.
4. Tsai, F. T.-C. (2011). Scavenger Wells Stop Saltwater Intrusion in Baton Rouge, Louisiana, MODFLOW and More 2011, Golden, CO, June 5-8, 2011
5. Elshall, A. S., F. T.-C. Tsai, and J. S. Hanor. (2011). Uncertainty and Characterization of the Baton Rouge Fault System in a Bayesian Framework, 2011 American Geophyiscal Union Fall Meeting, December 5-9, 2011, San Francisco, CA.
6. Chitsazan, N., and F. T.-C. Tsai. (2011). A Chance-Constrained Multimodel Approach to Design a Saltwater Intrusion Mitigation Plan, 2011 American Geophysical Union Fall Meeting, December 5-9, 2011, San Francisco, CA.
7. Hanor, J. S., E. L., Chamberlain, and F. T.-C. Tsai. (2011). Evolution of the Permeability Architecture of the Baton Rouge Fault Zone, Louisiana Gulf Coastal Plain, 2011 American Geophyiscal Union Fall Meeting, December 5-9, 2011, San Francisco, CA.

SYNOPSIS

Title: Feasibility Study of Scavenging Approach to Stop Saltwater Toward Water Wells
Project Number:
Start Date: 3/1/2011
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Primary PI: Frank T.-C. Tsai

Problem and Research Objectives

Due to excessive groundwater withdrawal, many Louisiana freshwater aquifers are being contaminated by saltwater intrusion. The major aquifer systems affected include the Chicot aquifer system of southwestern Louisiana, the Sparta aquifer system of northern Louisiana, and the Southern Hills aquifer system in the Baton Rouge Capital Area.

The project focuses on saltwater intrusion mitigation in the Southern Hills aquifer system in the Baton Rouge area. The aquifer system consists of a sequence of aquifers and aquicludes, which extends to a depth of about 3,000 feet. Prior to heavy pumping, freshwater was effectively isolated from saltwater to the south by the low permeable Baton Rouge fault. Recent USGS monitoring wells (EB-917 and EB-918 for the "1,500-foot" sand, EB-630, EB-1028, and EB-1150 for the "2,000-foot" sand), reveal progressive saltwater intrusion toward public and industrial water wells in the "1,500-foot" sand and "2,000-foot" sand (Lovelace, 2009). Water wells may be forced to reduce withdrawal rates or cease pumping altogether if saltwater encroachment cannot be stopped. Insufficient groundwater will critically hamper economic development in the Capital Area.

The goal of the project is to develop a scavenger well operation (SWOP) model to halt saltwater movement in the "1,500-foot" sand toward the water wells at Lula pump station operated by the Baton Rouge Water Company. The study area is shown in Figure 1. On October 28, 2009, chloride concentration of 182 mg/L was measured at the water well EB-658 (Lula-19). This poses a concern that a high chloride front may have come near the Lula wells. To better understand the current situation of saltwater intrusion and to resolve this urgent issue, the SWOP model aims to utilize scavenger wells to prevent high chloride concentration from reaching Lula wells. Scavenger wells are small extraction wells to be placed at a certain distance in front of water wells to capture and intercept saltwater. The decision variables in the SWOP model are the number, location, and extraction rate of scavenger wells.

Specific objectives are to:
(1) Understand the past, current, and future saltwater intrusion patterns
(2) Estimate the flux of groundwater flow across the Baton Rouge fault
(3) Estimate the flux of chloride concentration across the Baton Rouge fault

(4) Determine the number, location, and extraction rate of scavenger wells that can effectively stop saltwater intrusion to EB-658
(5) Evaluate the impact of scavenger wells on increasing saltwater intrusion across the fault

Figure 1: Study area. The base map is created by Louisiana GIS Digital Map 2007. The Baton Rouge Fault line is obtained from McCulloh and Heinrich (2012).

Methodology - Saltwater intrusion model development and calibration

The entire modeling period was divided into a model calibration period and a model prediction period. Model calibration period was from 1/1/1945 to 12/31/2009, a 65-year period. In the calibration period, groundwater head data and chloride data were used to estimate model parameters. Simulated groundwater head and chloride concentration distributions at the end of 12/31/2009 were used as initial conditions (beginning of 1/1/2010) for the model prediction period. Model prediction period was a 50-year period from 1/1/2010 to 12/31/2059. Twelve (12) scenarios of scavenger well operations were tested in the model prediction period.

In the report, modeling results at the beginnings of three specific dates (1/1/2010, 1/1/2035, and 1/1/2060) were particularly discussed. These three dates served as the check points to evaluate groundwater heads and chloride concentrations at the current situation and situations after 25 and 50 years. It is noted that the information at the beginning of 1/1/2010 was that at the end of 12/31/2009, the information at the beginning of 1/1/2035 was that at the end of 12/31/2034, and the information at the beginning of 1/1/2060 was that at the end of 12/31/2059.

The "1,500-foot" sand saltwater intrusion model was developed using MODFLOW (Harbaugh et al., 2000) and MT3DMS (Zheng and Wang, 1999) under Groundwater Modeling System (GMS) (AQUAVEO^{TM}). The terrain of the study area covers the Baton Rouge metropolitan area. The eastern boundary of the study area extended to the Amite River, the western boundary was along the Mississippi River, the northern boundary intersected the north end of I-110 freeway, and the southern boundary was around 600 meters south of the Baton Rouge fault. It covered an area of around 300 km^2. The area was discretized into 188 rows, 195 columns, and 1 layer. Coarse computational cells of 200 m by 200 m were given at the northeastern area, where saltwater intrusion was not a concern. Finer computational cells of around 50 m by 50 m were given to the area of ongoing saltwater intrusion. The aquifer thickness was determined from the prior studies (Tsai and Li, 2008; Li and Tsai, 2009).

It was understood that saltwater intrusion is a density-dependent flow process. Flow process should be coupled with mass transport process at each time step to reveal encroachment of denser saltwater near the bottom of an aquifer. Since this modeling study served for the planning purpose and only considered one vertical layer to the "1,500-foot" sand in order to reduce computation complexity, density effect was not simulated. This means that MODFLOW and MT3DMS were decoupled. MODFLOW was run first to obtain groundwater levels. Then, MT3DMS was run using MODFLOW solutions to simulate intrusion of chloride concentration. In the future work, density effect can be simulated by discretizing the aquifer thickness into multiple layers.

In order to better predict the history of saltwater intrusion in the "1,500-foot" sand, the starting date of modeling was 1/1/1945. This was determined according to the timeline of installation of the BRWC water wells in the "1,500-foot" sand. The first BRWC water well EB-413 was installed in 1946 at the Government pump station. From USGS studies (Meyer and Turcan, 1955), saltwater intrusion in the study area was not reported prior to 1946. In this study, the period prior to 1946 is denoted as the pre-anthropogenic pumping period. Detailed initial groundwater head and chloride concentration at 1/1/1945 and boundary condition from 1/1/1945 to 12/31/2009 were given in Tsai (2011)

(1) Water wells

Sixteen (16) water wells were installed in the study area during the period 1/1/1945-12/31/2009. Pumpage data was obtained from the Capital Area Ground Water Conservation Commission (CAGWCC) and BRWC. EB-504 was a BRWC water well, which was completed in 1949 and was out of service in 1979. EB-1295C (Stumberg-02) screened both the "1,500-foot" and "1,700-foot" sands. CAGWCC assigned EB-1295C pumpage record to the "1,500-foot" sand. This study included EB-1295C water well.

There was no pumpage data for EB-371B and EB-773 prior to 1975. EB-371B was completed in 1941 (Meyer and Turcan, 1955). Monthly pumpages for 1945-1974 at EB-371B and for 1964-1974 at EB-773 were determined by their 5-year monthly pumpage averages (1975-1979).

BRWC had lump sum pumpage data at water wells EB-413 and EB-504 for 1953-1962. To split EB-413 from EB-504 for this period, weighting coefficients for EB-413 were determined using the ratios of three-year monthly pumpage averages (1975-1977) to lump sum pumpages: EB-413 pumpages/(EB-413+EB-504 pumpages). BRWC also had lump sum pumpage data of water wells EB-413, EB-504, and EB-771 for 1963-1974. The same approach of deriving weighting coefficients was applied to splitting the lump sum pumpages for this period.

BRWC had lump sum pumpage data of water wells EB-510, EB-657, EB-658, EB-726, EB-938, and EB-939 for 1953-1974. For splitting the pumpages, weighting coefficients were obtained using the ratios of five-year monthly averages (1975-1979) of their individual pumpages to the lump sum pumpages in this 5-year period.

Finally, the monthly pumpages for 1946-1952 at EB-413 were determined by 5-year monthly pumpage averages (1953-1957). The monthly pumpages for 1949-1952 at EB-504 were determined by 5-year monthly pumpage averages (1953-1957).

(2) The "Connector" Well

The connector well, EB-1293, started in April 1999. Since the recorded groundwater data at EB-1293 did not represent head in the "1,500-foot" sand, the head data could not be used to assign a constant head boundary condition, or could not be used to compare to simulated water levels at EB-1293. Instead, recorded flow rate was used to represent EB-1293 as an injection well in the model. According to January 2009 CAGWCC Newsletter, the average injection rate was 475 gallons per minute or 2,589 m^3/day (or 0.684 mgd).

Principal Findings and Significance

(1) Saltwater intrusion analysis for 1/1/1945-12/31/2009

Homogeneous hydraulic conductivity of 55 m/day was used in the groundwater model. A homogeneous fault hydraulic characteristic (fault hydraulic conductivity per unit fault width) (Hsieh and Freckleton, 1993) was estimated 8.0×10^{-4} day^{-1} for a segment from the west boundary to the intersection of Wards Creek and Corporate Boulevard. The other segment of the fault had a relatively low hydraulic characteristic value of 3.5×10^{-4} day^{-1}. Although not shown here due to page limit, simulated groundwater levels compare well to the observed data for different time periods at several USGS observation wells. According to water level in EB-917, groundwater level declined at a rate of 1.31 m/year (4.3 ft/year) before 1980, 0.40 m/year (1.3 ft/year) in the 1980s and 1990s, and 1.16 m/year (3.8 ft/year) after 2000. According to the simulated groundwater head distribution, a cone of depression centered at Lula pump station is evident.

Pore water pressure differences and groundwater flow velocity (Darcy velocity) across the Baton Rouge fault were estimated at a single point using simulated groundwater heads at EB-782B and at its adjacent computational cell (134, 71) south of the fault. Using the harmonic mean approach, equivalent hydraulic conductivity for this calculation was obtained 0.081 m/day. The results are shown in Figure 2. Negative water pressure difference and negative flow velocity occurred at the beginning of a few years of simulation because of southward flow across the fault. Figure 2 shows a trend of increasing pressure difference and flow velocity in the last 10 years (2000-2009). Pressure difference on 1/1/2010 was estimated at 43 psi (pounds per square inch). The flow velocity was estimated at 4.84×10^{-2} m/day on 1/1/2010.

The maximum head pressure difference on 1/1/2010 occurred around 100 m west of the intersection of Dalrymple Drive and the fault line. The computational cell (137, 39) south of the fault had groundwater head of -7.957 m and the computational cell (136, 39) north of the fault had groundwater head -38.852 m. This resulted in head difference 44 psi and flow velocity m/day on 1/1/2010. The maximum pressure difference was only one psi higher than that at EB-782B.

Porosity was estimated 27%, longitudinal dispersivity was estimated 180 m, and transverse dispersivity was estimated 0.36 m. The same homogeneous porosity, longitudinal dispersivity, and transverse dispersivity were used for both “1,200-foot” sand and “1,500-foot” sand. It was observed that major chloride concentration at EB-917 and EB-918 might be the result of lateral-flow-driven chloride transport along the fault from the east side. Therefore, a high ratio of longitudinal dispersivity to transverse dispersivity was obtained to reveal faster chloride transport to EB-807A and EB-658, but slower chloride transport to EB-917 and EB-918.

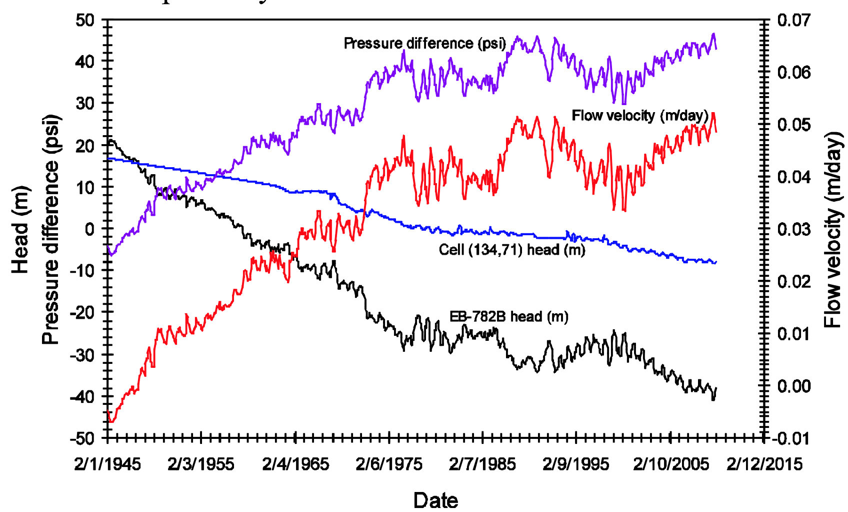


Figure 2: Simulated groundwater heads at EB-782B and at its adjacent computational cell (134, 71) south of the fault, pressure difference (psi), and flow velocity (m/day).

Simulated chloride breakthroughs were compared to chloride data. Simulated chloride concentrations showed up earlier compared to lower chloride data at EB-807A, but were similar to high chloride data. Simulated chloride concentrations showed good agreement to the chloride data at EB-807A after 1981, and to the chloride data at EB-917 and EB-658 after 2000. Simulated chloride concentrations were underestimated at EB-918 after 2000. This indicates that chloride transport simulation along the fault from the eastern side needs more study. However, the lateral-flow-driven chloride concentration showed less impact on EB-658 and EB-807A.

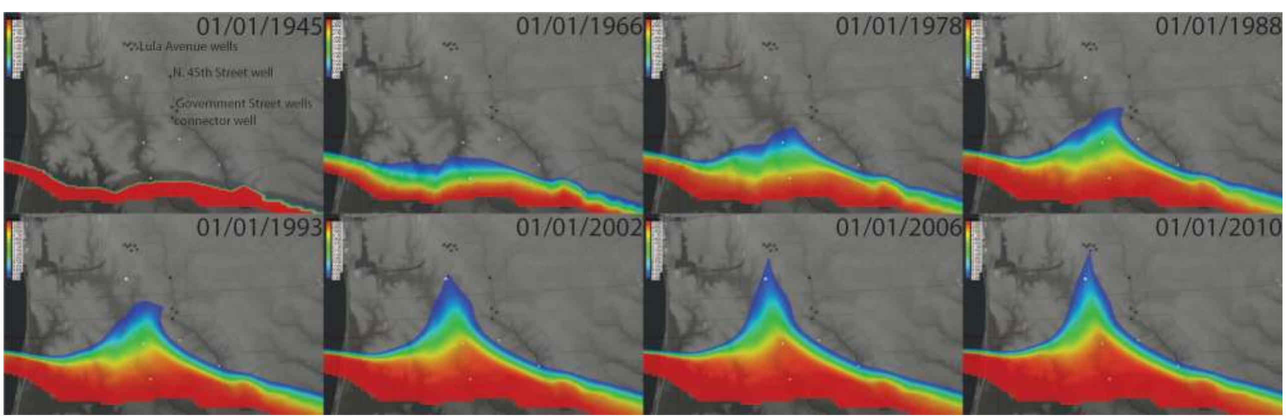


Figure 3: Saltwater intrusion pattern. Front line represents chloride concentration of 250 mg/L.

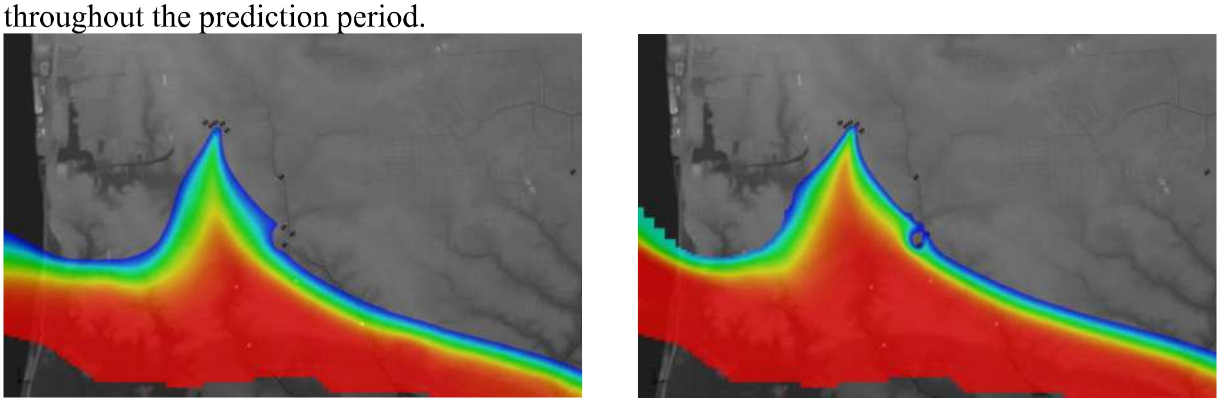
The 65-year simulation in Figure 3 shows a unique movement of the saltwater intrusion front. From 1945 to 1987, a single chloride front was developed and moved toward EB-771 (Government-06). From 1987 to 2001, the front started to retreat and a new front started to develop and move toward the Lula wells. From 2001 to 2009, a single front moved toward EB-658 (Lula-19). This unique movement of chloride concentrations was revealed by the “up-downup" chloride data at EB-917. The unique intrusion pattern is the combined effect of the low permeable Baton Rouge fault and dynamic anthropogenic pumping.

Chloride mass flux was estimated at a single point using simulated groundwater flow velocity simulated chloride concentrations at EB-782B and its adjacent computational cell (134, 71) south of the fault. The magnitudes of advective mass flux and dispersive mass flux were similar prior to 1957. After 1957, advective mass flux dominated dispersive mass flux due to high groundwater flow velocity. Dispersive mass flux was strong in 1955-1980. The total mass flux on 1/1/2010 was estimated 0.98 kg/day-m^2.

(2) Saltwater intrusion prediction-"No-action" scenario (no scavenger wells)

The saltwater intrusion model was run for 50 years from 1/1/2010 to 12/31/2059 without scavenger wells. Predicted breakthrough curves in EB-658 and other observation wells were used as baseline information to evaluate the stopping efficiency of various scenarios through using scavenger wells as presented in the following section.

To extend the saltwater intrusion model to predict chloride concentrations in the period 1/1/2010-12/31/2059, time-varied boundary values of groundwater head were estimated using the linear trend of head declination in the last 5 years, 1/1/2005-12/31/2009. The monthly pumpages of water wells were estimated based on 5-year (2005-2009) averaged pumpages. The total withdrawal rate at Government pump station (two water wells) was 2.53 mgd, at Lula pump station (six water wells) was 7.07 mgd, and at N. 45th pump station (one water well) was 1.69 mgd. The total pumpage of water wells was 12.45 mgd. The injection rate of the connector well remains 0.684 mgd, and chloride concentration at the southern boundary remains 5,500 mg/L throughout the prediction period.



(a) 1/1/2035 (b) 1/1/2060

Figure 4: Chloride concentration distribution on (a) 1/1/2035, and (b) 1/1/2060 for the no-action scenario. The front line is 250 mg/L.

Chloride concentrations increase at EB-658, EB-807A, EB-917, and EB-918 in the period 1/1/1945-12/31/2059. Chloride concentration in EB-658 was predicted to 754 mg/L on 1/1/2035 and 1,540 mg/L on 1/1/2060. Figure 4 shows the concentration distributions on 1/1/2035 and 1/1/2060. Chloride concentrations in EB-807A, EB-917, and EB-918 were predicted to be thousands mg/L on 1/1/2035 and almost reach the maximum concentration 5,500 mg/L on 1/1/2060. Chloride concentrations in EB-413, EB-771, and EB-1293 were predicted tens mg/L on 1/1/2035, but would reach hundreds mg/L on 1/1/2060. Estimated chloride concentrations at N. 45th well, EB-927, were very low throughout the prediction period.

(3) Scenarios of stopping saltwater intrusion to EB-658 using scavenger wells

Twelve (12) scenarios listed in Table 1 were designed to reduce chloride concentration at EB-658. The starting date of using scavenger wells was assigned to 1/1/2011. The first four scenarios used one scavenger well with a constant extraction rate throughout the prediction period 1/1/2010-12/31/2059. Extraction rates with a 0.25 mgd (million gallons per day) increment increase were tested from 0.25 mgd to 1.00 mgd in scenario 1 to scenario 4, respectively. Scenarios 5-7 and scenario 9 used two concurrent scavenger wells, scenario 8 used three concurrent scavenger wells, and scenario 10 used four concurrent scavenger wells. Concurrent scavenger wells mean that scavenger wells were active from the beginning to the end of the prediction period. Scenarios 11 and 12 considered two sequential scavenger wells. The first scavenger well was active with an extraction rate of 0.50 mgd entirely throughout the prediction period. However, the second scavenger well was only active between 1/1/2036 and 12/31/2059.

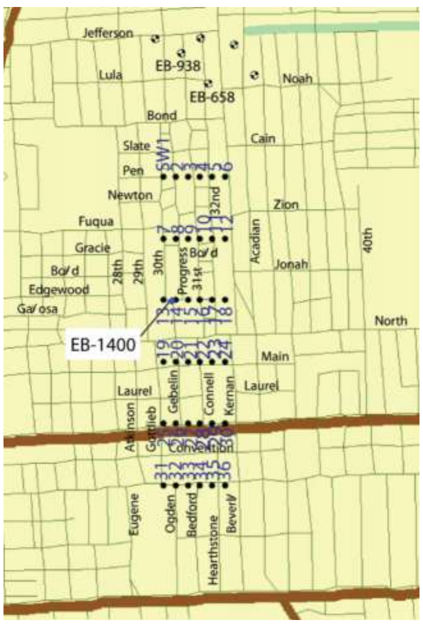


Figure 5: 36 potential locations of scavenger wells.

Table 1: Simulated chloride concentrations at EB-658 using the best solutions in individual scenarios.

Scenario	Scavenger well	Concentration (mg/L) 1/1/2035	1/1/2060
No action	-	754	1540
1	SW21 (0.25 mgd)	385	903
2	SW20 (0.50 mgd)	143	412
3	SW20 (0.75 mgd)	40	122
4	SW13 (1.00 mgd)	10	17
5	SW21, SW19 (2×0.25 mgd)	147	399
6	SW21, SW13 (0.25 mgd and 0.50 mgd)	35	114
7	SW20, SW19 (0.50 mgd and 0.25 mgd)	39	115
8	SW21, SW19, SW13 (3×0.25 mgd)	33	110
9	SW20, SW13 (2×0.50 mgd)	9	15
10	SW21, SW19, SW13, SW7 (4×0.25 mgd)	7	16
11	SW20, SW13 (0.50 mgd and 0.25 mgd)	143	116
12	SW20, SW13 (0.50 mgd and 0.50 mgd)	143	19

A total of 36 potential locations of scavenger wells, named from SW1 to SW36, were predetermined in Figure 5. The best locations of scavenger wells in the searching order and the simulated chloride concentrations in EB-658 on 1/1/2035 and 1/1/2060 are listed in Table 1. Scenarios 1, 2 and 5 are not feasible solutions for the period 1/1/2036-1/1/2060. Scenarios 6-12 were all feasible solutions to keep low chloride concentrations at EB-658 throughout the entire prediction period. We found that

(1) If scavenger wells were placed too close to the Lula wells, high chloride concentration would be dragged near the Lula wells. EB-658 would pump high chloride concentration in later time.

(2) If scavenger wells were placed far away from the Lula wells in a high chloride concentration zone, high chloride concentrations north of the scavenger well could not be caught. High chloride concentrations would eventually arrive at EB-658.

(3) Scavenger wells had a tendency to locate at the first three columns since the chloride concentration was slowly leaning to the west due to the impermeable zone at the west side.

(4) Using high extraction rate, there were many feasible locations to install scavenger wells, in addition to the best location. Scavenger wells at the best location give the lowest concentration at EB-658.

As shown in Figure 6, it was found that breakthrough curves at EB-658 using one single scavenger well and using multiple scavenger wells were similar for the same total extraction rates. For example, scenarios 3, 6, 7, and 8 used a total of 0.75 mgd, but different numbers of scavenger wells. The breakthrough curves were similar. Scenarios 4, 9, and 10 used a total of 1.00 mgd, but different numbers of scavenger wells. The breakthrough curves were similar. This result provides many options with the same total extraction rates.

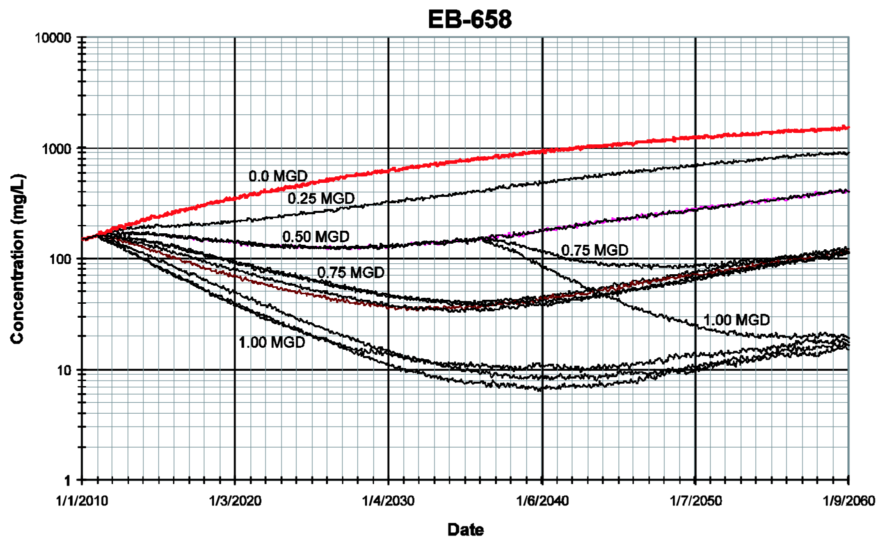
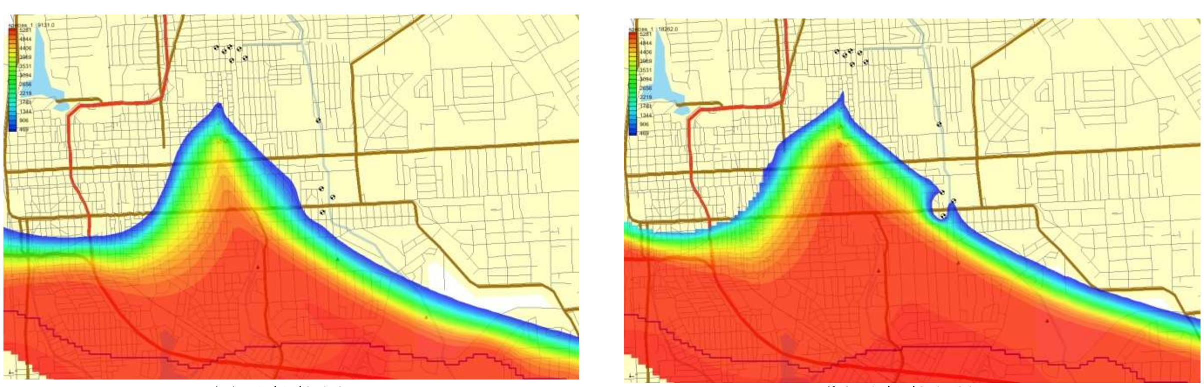


Figure 6: Predicted chloride concentration at EB-658 under different scenarios.

The impact of scenario 10 on the groundwater flow across the fault at EB-782B is not significant comparing to the current condition. Without scavengers, the pressure difference linearly increased from 43 psi on 1/1/2010 to 82 psi on 1/1/2060. The groundwater flow linearly increased from 4.84×10^{-2} m/ day on 1/1/2010 to 9.19×10^{-2} m/day on 1/1/2060. The total mass flux increased from 0.98 kg/day-m^2 on 1/1/2010 to 1.87 kg/day-m^2 on 1/1/2060. Those values showed a 90% increase in 2060 with respect to the values on 1/1/2010.



(a) 1/1/2035 (b) 1/1/2060

Figure 7: Chloride concentration distribution on (a) 1/1/2035 and (b) 1/1/2060 under scenario 10 (4 scavenger wells). The front line is 250 mg/L.

As shown in Figure 7, scenario 10 keeps the 250 mg/L front line away from the Lula wells for the next 50 years. However, the water wells at Government pump station would encounter high chloride concentration in 50 years. Using scenario 10, a total of one-mgd extraction rate caused additional drawdown of 0.02 m south of the fault and additional drawdown of 1.66 m north of the fault compared to the no-action scenario. This resulted in an additional 2.33 psi pressure difference and 2.62×10^{-3} m/day groundwater flow velocity. The total mass flux increased by 0.051 kg/day-m^2. Those values counted for less than 6% increase with respect to the values on 1/1/2010.

Scenarios with 1 mgd extraction rate indicate that SW13 (UTM-NAD83 X=676779 m, Y=3370623 m) at Progress Park is the best location for installing a scavenger well. A new observation well, EB-1400 (N 30’ 27.285, W 91’ 09.509) at Progress Park between SW13 and SW14 was completed in 2011 by Layne. It can be converted to a scavenger well if permitted.

Three scenarios using 1-mgd interceptor wells (scavenger wells) were suggested by Layne Hydro (Layne Hydro 2012). Using the current model, Figure 8 shows that scenario 4 (one scavenger well at Progress Park) from this study outperforms Layne’s three scenarios. This is because the location of scavenger wells was optimized in this study.

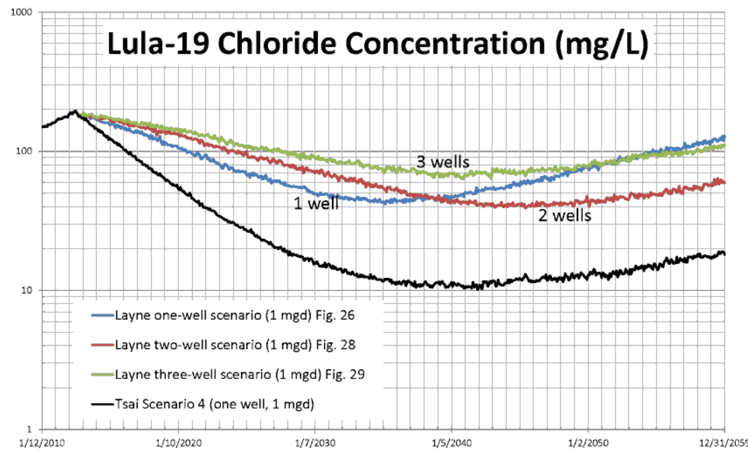


Figure 8: Comparison of scenario 4 with Layne’s three scenarios.

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