USE OF DUAL PUMP SYSTEMS AND INCLINED WELLS TO OPTIMIZE POTABLE WATER RECOVERY AND HYDROCARBON REMEDIATION IN COASTAL AQUIFERS.

J. E. Gale, G.G. Bursey, M.C. Parsons, E. Seok, and G. Keeping, Fracflow Consultants Inc., 154 Major’s Path, St. John’s, NL, Canada, A1A 5A1

ABSTRACT

In aquifers that are characterized by two fluid systems, where there are well defined differences in the fluid densities, optimum recovery of potable water or the remediation of contaminated fluids is best achieved by placing two pumps in each vertical well or inclined well to maximize fluid recovery. If the aquifer contains saline water at depth, the lower pump removes the denser saline water from the bottom of the well and this water is discharged as waste. The upper pump extracts potable water from the less dense freshwater lens, which forms the top of the water column, and this water is added to the water supply system.

In this paper we present the results of long term, dual pump, trials on two well fields that were completed in overburden aquifers. In the first site, the producing wells are underlain at depth by fractured porous bedrock that contains brackish formation water. At the second site, the well field is underlain by silty clay layers and deeper sand layers that contain saline waters. At the first site, the individual well yields are approximately 250 L/min and at the second site, the well yields range from 800 L/min to 1,600 L/min. These long term, dual pump, aquifer tests have demonstrated that pH, fluid conductivity, and chloride levels in the potable water discharge can be maintained at prescribed levels. Demonstration of the effectiveness of the dual pump system has provided the opportunity to restore long term sustainable, potable, water supplies for these two coastal communities, with populations of approximately 1,500 and 7,500, respectively. Prediction of the long term water quality in these two aquifer systems requires the use of variable density, multi-phase, 3D numerical model simulators. Such simulators demonstrate that the use of dual pump systems, in vertical or inclined wells, have the potential to maximize the recovery of a potable water resource and to facilitate the recovery of liquid hydrocarbons in both porous and fractured media.

INTRODUCTION

Many coastal regions obtain potable and industrial water from fractured and or porous media aquifers that are characterized by shallow water tables and thin fresh water lenses. Optimum recovery of potable and industrial water from such aquifer systems is constrained or threatened by the up-coning of intruding
sea water and saline formation waters as well as from anthropogenic contaminants such as liquid or dissolved hydrocarbons. When vertical wells, with a standard pump system, are used to recover water or contaminated fluids, excessive drawdowns result in an unusable mixture of either saline and potable water or contaminated and uncontaminated water, requiring additional treatment of the recovered water or fluids. In many situations, pumping, with a single pump system, at a very low rate, to keep drawdowns in the borehole and in the aquifer to acceptable levels, is not acceptable due to either cost, time or resource demands.

In freshwater/saline water coastal flow systems, an alternative approach is to place two pumps (Figure 1) in each vertical well and/or inclined well to maximize fluid recovery. Where saline water or sea water intrusion is the problem being addressed, in a dual pump system the lower pump removes the denser saline/brackish water from the bottom of the well and this water is discharged as waste. The upper pump extracts potable water from the freshwater lens, which forms at the top of the water column. By extracting the saline/brackish water from the bottom of the well, the lower pump ensures that the salinity concentrations in the upper portion of the water-well fall within prescribed limits. In addition, when inclined wells are used in fractured bedrock aquifers or in fractured porous media aquifers, the wells can be oriented to intersect the most productive water bearing features at angles much less than 90 degrees. As the angle of intersection between the wellbore and the productive zone intersection becomes more oblique, the flow regime changes from purely radial flow to that which approaches linear flow with a corresponding large increase in the production rate per metre of drawdown. This permits one to optimize the drawdown in the well with a corresponding reduction in the volume of upconing waste water produced.

The key to the successful application of a dual pump system, in either vertical or inclined wells, is a clear understanding of the site hydrogeology. In fractured rock aquifers, with their highly variable head and fluid velocity properties, it is important to know how the aquifer transmissivity is distributed over the vertical wellbore column relative to the position of the interface between the two fluids. Also, successful design and operation of a dual pump system is best accomplished through careful 3D, variable density, flow and transport modelling, followed by a period of systematic adjustment of the pumping rate from each pump. This systematic approach allows one to match the relative withdrawal rates of each pump to the hydrogeological characteristics of the site and this permits one to exploit the full potential of the groundwater resource as a sustainable resource. In this paper, we present two examples, from two different hydrogeological settings, of the successful application of dual pump systems to optimize the recovery of a sustainable potable groundwater supply. In addition, we can demonstrate the effectiveness of the same approach (Fetter, 1993) to the recovery of Light Non-Aqueous Phase Liquids (LNAPLs) using inclined wells.

**FINE SAND AQUIFER UNDERLAIN BY FRACTURED POROUS BEDROCK**

The Town of St. George’s, Newfoundland, Eastern Canada, with a population of approximately 1,500
has had a 30 year history of attempts to develop a potable water supply. These attempts have included the construction of an expensive surface impoundment structure, along with the necessary pumping, chlorination, tank storage and pipeline distribution systems. This system, while providing an adequate quantity of water to meet the needs of the Town, has been plagued by high levels of organics which in turn produce high levels of THM’s (TriHaloMethanes) when the water is chlorinated. In addition, the water supply is frequently exposed to sources of bacteria which require the imposition of frequent “boil orders”.

Over the last five to ten years, several attempts were made to develop a potable groundwater supply of approximately 750 to 1000 litres per minute for this community. In the first attempt, seven groundwater wells were developed close to the original surface water reservoir without the benefit of a hydrogeological investigation, before the wells were drilled, and without conducting long term aquifer tests on the first well that was drilled at the site. Within a few days after commissioning the new well field, the wells started to produce salty water and the well field had to be abandoned. The second attempt at developing a potable water supply was also conducted without the benefit of a hydrogeological investigation and the well locations were selected in areas that were readily “accessible” or areas that looked “promising” to the consultant. While the short term well yields were adequate, the most productive wells were located in the local groundwater recharge area and the manganese levels in the water were more than ten times the acceptable levels. After these two expensive and failed attempts to develop a potable groundwater supply, the Town commissioned a study of the hydrogeology of the overall area with emphasis on those areas in which it might be feasible to develop a potable groundwater supply (Fracflow, 2003). Based on a thorough screening of the surface water and groundwater chemistry, within the overburden and bedrock geology framework of this area, followed by 3D flow and transport modelling of the groundwater flow system, two areas were identified as potential areas in which to explore for a potable groundwater supply.

**Geological and Hydrogeological Setting**

The temperature and chemistry of several small streams, located in a broad flat valley near the coastline, suggested that the stream water was strongly influenced by discharging groundwater. Reconnaissance auger drilling, with continuous soil sampling, was completed adjacent to an old railway line. This auger exploration drilling demonstrated that the area was underlain by a laterally extensive fine sand overburden aquifer to a depth of 15 to 20 m. Subsequent diamond drilling determined that fractured porous bedrock was located at approximately 22 metres below ground surface with a thin clay/pug layer on top of the bedrock. Groundwater samples from a piezometer, completed in the bedrock, showed elevated levels of chloride. Analyses of the relative overburden and bedrock permeabilities, from both grain size data and falling head tests in the completed piezometers, suggested that a potable water supply could be developed using a dual pump system. Based on this analysis, a standard, 200 mm diameter, exploratory water well was completed to a depth of 15.24 m, consisting of three, 3 m long., sections of slot 20, 6 5/8 inch ID, 7 5/8 inch OD, stainless steel well screen, followed by a 1.5 m
section of blank casing which in turn was welded to a K-Packer attached to the top of the screen, and with 7 m of surface casing provides an available drawdown of 5 to 6 m. The screened section of the water well was then developed by simultaneous air-lifting and surge blocking to remove the fines from the formation and to develop a natural gravel pack around the well screen.

**Well Yield**

Two submersible water pumps were installed in this well, an upper pump and a lower pump, in an attempt to control chloride levels in the upper portion of the aquifer. A step drawdown aquifer test, followed by a 72-hour aquifer test, was completed on this well and analysis of the aquifer test data gave a hydraulic conductivity of approximately 0.0001 m/s and a specific capacity of approximately 25 USgpm per metre of drawdown. While this well, is capable of producing approximately 150 USgpm based on the 5 to 6 m of available drawdown, water quality concerns required that the long term production from the well be limited to an estimated 60 to 75 USgpm with a corresponding 2.5 to 3 m of drawdown. The static water level in the well is approximately 8 m above mean sea level.

A long term, 30 day, aquifer test was started immediately after the water level changes due to the aquifer tests in the wells had recovered to static levels. Field measurements of pH, conductivity, temperature, and chlorides were conducted four times daily. At least one water sample per day was submitted to the laboratory for chloride analysis. Figure 2 shows the pattern of drawdown in both the pumping well and in the nearby (at a radial distance of 6 metres) observation well during the 30 day aquifer test. The combined flow rate, from both pumps, ranged from 235 L/min to a high of 273 L/min. Drawdown in the pumping well appears to have stabilized at each pumping rate, but the observation well continued to show increases in drawdown at the higher pumping rate indicating that the aquifer had not reached steady state conditions even after 30 days of pumping. At the lower pumping rate, approximately 208 L/min, both wells appear to be approaching steady state hydraulic conditions.

**Water Quality Control Using Dual Pump System**

Field measurements of pH, conductivity, and temperature were conducted throughout the duration of the 30 day aquifer test (Figure 3). Measured pH values ranged from 6.28 to 8.25 in the lower pump and ranged from 5.89 to 7.52 in the upper pump. Conductivity measurements ranged from 788 to 1,395 µS in the lower pump and ranged from 287 to 484 µS in the upper pump (Figure 4). The cumulative volume of water pumped from each pump in the water well is plotted against cumulative hours in each figure. Rainfall data are included on each figure. However, there is no indication of a strong correlation between rainfall and the measured field parameters. Overall, the field values for pH and fluid conductivity show a decreasing trend with time, suggesting that the pumping well is receiving induced recharge from the nearby stream under pumping conditions.
Water samples were collected from the upper and lower pumps and submitted to a laboratory for chloride analysis on a regular basis. Chloride concentrations are plotted against cumulative hours in Figure 5. Chloride concentrations in the upper pump decreased with time and appear to be stabilizing at a concentration of 50 mg/L. The objective for chloride concentrations within Health Canada’s Guidelines for Canadian Drinking Water Quality is 250 mg/L. The final chloride levels in the lower pump appear to have stabilized at approximately 260 mg/L, at the highest flow rate. Since the lower pump discharge was only 27 L/min with a concentration of 260 mg/L and the upper pump discharge was 246 L/min with a concentration of approximately 50 mg/L, and still decreasing, the average concentration for the combined discharge is approximately 70 mg/L, well below the 250 mg/L guideline value for drinking water. Clearly, the dual pump system provides a means of controlling the chloride concentration in this well. Also, both total and dissolved values for manganese and iron in these water samples were well below criteria. However, a slight increase in these metals during the 30 day test is noted in the lower pump discharge water and this is consistent with upward moving bedrock waters since the chemistry of the water from the bedrock piezometer was higher in metals than the water in the overlying sediments.

With a specific capacity of approximately 85 to 95 L/min per metre of drawdown, and a well efficiency of approximately 85 %, at flowrates of approximately 200 L/min, and an available drawdown of approximately 5 m to 6 m, this well is capable of producing approximately 425 L/min with about 5 m of drawdown. Based on the results from the 30 day aquifer test, the Town has decided to construct a well field, consisting of three production wells and one back-up production well, with each well being equipped with a dual pump system, an upper and a lower pump. These three wells will be pumped at the same time for a 30 to 60 day period, to provide an indication of the overall well field production on the aquifer system and the long term water quality. Long term (for a two to three year well field production period) water quality, primarily chloride levels, will be predicted using a 3D variable density, groundwater flow and transport, computer model (TOUGH2; Pruess et al., 1999) based on model calibration with the 30 to 60 day aquifer test data. In is expected that application of the dual pump system in the three production wells will provide a sustainable potable water supply of 750 to 1,000 litres per minute for this community.

**FINE SAND AQUIFER UNDERLAIN BY THICK CLAY LAYERS**

Starting in 1994, the Town of Happy Valley Goose Bay (HVGB) in Labrador, Newfoundland, undertook to develop a potable groundwater supply. A potential well field site was selected, based on accessibility, adjacent to a large river (the Churchill River) and a 200 mm diameter, screened test well, was completed to a depth of approximately 50 m in the fine sand overburden at this site along with several nearby observation wells. Completion of the test well was followed by short term aquifer tests to determine the suitability of the aquifer to meet the water quality and water quantity needs of the Town. Laboratory data showed that the water had elevated levels of manganese and iron which could be removed by existing treatment technologies and that the well yields would supply the total volume required by the Town of HVGB.
**Geological Setting**

The well field is located in an area covered by extensive and thick glaciofluvial deposits, consisting of pro-glacial or ice contact sands and gravels that form fans, deltas, outwash plains, terraces, and kames. The Happy Valley - Goose Bay area is thought to be part of an ancient rift valley where sands have accumulated over marine clays, which in turn have been deposited on red bed sandstones (bedrock). These sandstones are believed to be similar in age and structure to those occurring in western Newfoundland where evaporite deposits such as gypsum, anhydrite and halite are known to exist at depth. Such deposits provide a natural source of high salinity to groundwater that has come into contact with those rock types. Beneath the Churchill River, the surficial materials consist of at least 50 m of sand, silty sand and clayey silt, with near-surface bedrock (gneiss) identified near the south bank of the river. In the area of the Happy Valley - Goose Bay well field, thin layers of clayey silt are present in the river bank and visible in part of the river bed. The presence of these thin clayey silt layers beneath part of the river bed is significant in that they will delay and limit the infiltration of river water into the aquifer as groundwater is being produced at the well field, unless there are ‘windows’ or holes through the clayey silt layers or the thin layers are discontinuous.

**Well Field Development and Operation**

Based on the water quality data and the yield from the initial test well, the Town of HVGB proceeded with the development of a well field at the test well location by completing five large diameter (250 mm diameter) production wells, spaced at 100 to 250 m apart within 20 m of the river bank (Figure 6). Short term (72 hour) aquifer tests were completed on each well to determine the well yields and the groundwater chemistry. One of the wells was pumped for more than 30 days to determine if there would be any short term changes in water chemistry since there were strong indications that old formation waters were present in the discharge water from several of the wells. Overall the five wells showed that the volume of water (5,500 L/min (1,450 US gpm or 1,200 Igpm)) needed by the Town could be provided by these five wells. Once the total yield had been confirmed, the Town proceeded to design and construct a state-of-the-art water treatment plant and a 6 to 7 km long pipeline to connect the treatment plant to the Town's water storage and distribution system at a total cost of approximately $9,000,000. These components of the water system were completed and the well field and treatment systems were commissioned in the Fall of 2002.

**Water Quality Issues**

By mid to late winter of 2003, several of the wells were producing high levels of chloride (approaching 5,000 mg/L) and production from those wells had to be stopped. A preliminary investigation showed that the water at the bottom of all of the wells had elevated chloride levels and in two of the wells (Wells No. 2 and No. 3) this water was adversely impacting the potable water quality. Analysis of the water chemistry, and stable isotope data, suggested that the problem was not related to sea water intrusion but to up-coning or laterally migrating brackish formation waters. Subsequent work showed no evidence that seawater was
migrating up the Churchill River and induced infiltration from this water body was eliminated as a source of the brackish water.

**Hydrogeological Characterization of the Well Field Area**

With such a large capital investment at risk, the Town of HVGB quickly moved to determine the source and extent of the brackish water problem and to investigate possible mitigation steps and solutions. Field work was undertaken to characterize the hydrogeological and hydrogeochemistry setting of the well field area and to determine the well field capture zone, the source of the brackish water and to identify adjacent areas that would be suitable candidates for locating additional production wells to supplement the existing well field production (Fracflow, 2004). This field program included the drilling of an additional exploratory well to 122 m (400 ft) of depth, the installation of three multiple level piezometers in this well, and the drilling and sampling of seven monitoring wells to depths of approximately 60 m. With the additional geological data obtained from this drilling program, a series of cross-sections were constructed through the well field and adjacent areas by extrapolating the known geology between each borehole/well location and assembling these sections into a three-dimensional fence diagram of the site (Figure 7).

The soil samples collected from monitoring wells MW1 through MW6 (Figure 6) identified an upper fine grained silty sand layer that contains thin layers of medium sand containing gneissic pebbles, ranging from approximately 9 m to 45 m thick, which is similar to and contiguous with the overburden layer in which the current production wells have been completed. A clayey silt to silty clay layer, which is approximately 10 to 15 m (35 to 50 feet) thick, was encountered in all of the new boreholes. This low permeability clay layer can be found at depths of 46 m (150 feet) in the eastern portion of the study area near monitoring well MW1, and rises gently to the north-northwest, where it was encountered at a depth of 9 m in monitoring well MW5. Monitoring wells MW1 through MW5 were drilled through this clay layer and completed in the medium sand which underlies the clay layer.

Soil sampling during the drilling of a deep multi-level monitoring well, located immediately north of the Water Treatment Plant (MW8, MW9, and MW10), identified the top of the main upper clay layer at a depth of 51 m (167 feet), having a thickness of 16.1 m (53 feet). Assuming this layer is the same layer as the clay found below or inferred to exist below the existing production wells in the well field and in the monitoring wells, a tabular shaped aquifer can be defined with a gentle dip, starting with a thickness of 9 m at the intersection of the Trans Labrador Highway and Spring Gulch Escarpment (Figures 6 and 7) and thickening towards the well field at the edge of the Churchill River where it reaches a depth of approximately 55 to 60 m in several locations. The bottom of the aquifer is defined by what is referred to here as the upper clay layer. Below the upper clay layer, a high permeability, medium grained, sand was encountered in the deep monitoring well which is similar to that which was found below the upper clay layer in the other monitoring wells. Below this layer of medium grained sand, another clay layer was encountered with a thickness of approximately 2.5 m which overlies a series of thin layers (1.5 to 3 m thick) of alternating fine silty sands, medium sands, and fine grained sands, containing gneissic pebbles, to a depth of 112 m (367 feet). At the
final borehole depth of 122 m (387 ft), abundant gneissic pebbles and cobbles were intermixed with sand. These sequences are assumed to be laterally extensive, based on the hydraulic head measurements and the water chemistry.

Chloride levels are elevated below the clay layers but decrease significantly as one moves towards the recharge area. It is assumed that the source of the brackish water in the well field is by leakage through the low permeability clay layers or through a window in the clay due to the gradients developed by the well field drawdowns. Based on this preliminary hydrogeological assessment, Fracflow proposed that a dual pump system be installed in the two wells that were most impacted to provide both control of the brackish water and to permit part of the well field production to be restored. As an interim step, the pumping rate at each well was reduced. In August, 2003, dual pump systems were installed in the two wells that were most impacted by the brackish water.

**Water Quality Control Using Dual Pump Systems**

Both the Lower and Upper Pumps at Well 2 were started on August 12, 2003. The initial flow rates were in the 945 to 1135 L/min (250 to 300 US gpm or 208 to 250 lpm) range for the Upper Pump and 227 L/min (60 US gpm or 50 lpm) for the Lower Pump (Figure 8). After approximately one month of pumping, the pumping rate in the Upper Pump was decreased weekly in increments of roughly 190 L/min (50 US gpm or 42 lpm). By September 23, the flow from the Upper Pump was down to 378 L/min (100 US gpm or 83 lpm). The flow in the Lower Pump was maintained at 227 L/min (60 US gpm or 50 lpm). The goal was to try and find the optimum pumping ratio between the Upper and Lower pumps whereby the volume of potable water was maximized and the volume of waste water was minimized. However, the electrical conductivity of the discharge water from both pumps at Well 2 did not stabilize and continued to rise. In addition, the electrical conductivity of the production water at Well 3 was also rising. Fracflow concluded that Well 2 would have to be pumped at the maximum flow rate to control the migration of the saline groundwater plume toward Well 3. On November 7, 2003, the valve on the discharge line from the Upper Pump was opened wide, discharging at the rate of about 1,134 L/min (300 US gpm or 250 lpm). That flow rate has remained unchanged since that time. The Lower Pump has continued to discharge water at the rate of 227 L/min (60 US gpm or 50 lpm).

A plot of time versus electrical conductivity for different pumping rates is presented in Figure 8. With increasing time, the difference between the electrical conductivities of the discharge water from the Upper and Lower Pumps increased exponentially. By January and February of 2004, after continuous pumping for approximately 200 days, the electrical conductivity of the water from the Upper Pump (4,000 to 4,500 µS/cm) was four to five times lower, which means four to five times better, than the water from the Lower Pump (18,000 to 19,000 µS/cm). Starting in February, 2004, there is a clear trend of decreasing fluid conductivity in both the upper pump and the lower pump in Well No. 2. This is a clear demonstration of how well the dual-pump system is working.
A plot of time versus chloride concentration is presented in Figure 9. Chloride is used here as a more direct measure of salinity and drinking water quality. The change in chloride with time follows a similar pattern as the change in electrical conductivity, which is not surprising. After more than 200 days of continuous pumping, the chloride concentration in water from the Upper Pump was varying between 1,300 and 1,400 mg/L, which is roughly five times higher than the Maximum Acceptable Concentration (MAC) of chloride in drinking water (250 mg/L). The chloride concentration in the water from the Lower Pump ranged from 7,500 to 8,500 mg/L. These concentrations are being maintained at a pumping ratio of 5 (i.e., 300 US gpm / 60 US gpm). Again, there is clear trend of decreasing chloride levels in both the upper pump and in the lower pump after March, 2004.

The variations in chloride concentration in the water from the Upper Pump, in response to changes in flow rate, indicate that chloride concentrations will likely meet the MAC for drinking water if the flow from the Upper Pump is maintained somewhere between 378 to 567 L/min (100 to 150 US gpm, or 83 to 125 Igpm) and the flow from the Lower Pump remains at 227 L/min (60 US gpm or 50 Igpm) (i.e., pumping ratio of about 2:1). This means that by increasing the flow from the Lower Pump to 378 to 567 L/min (100 to 150 US gpm, or 83 to 125 Igpm), which is probably the maximum possible due to size restrictions in the well, flow from the Upper Pump can be increased to about 756 to 945 L/min (200 to 250 US gpm, or 167 to 208 Igpm).

A dual pump system was also installed in Production Well No. 3. The Lower Pump in Production Well 3 was turned on at 6:30 pm on August 13, 2003. The Upper Pump was started at about 1:35 pm the next day. The initial flow rates were 491 L/min (130 US gpm or 108 Igpm) for the Upper Pump and 113 L/min (30 US gpm or 25 Igpm) for the Lower Pump. A plot of time versus electrical conductivity for different pumping rates is presented in Figure 10. With increasing time, the difference between the electrical conductivities of the discharge water from the Upper and Lower Pumps increased, but not as dramatically as observed at Well 2. After more than 200 days of continuous pumping the electrical conductivity of the water from the Upper Pump in Well 3 (1,000 to 1,100 µS/cm) was nearly ten times lower, which means nearly ten times better, than the water from the Lower Pump (10,000 to 11,000 µS/cm). It is also important to note that the Upper (production) Pump at Well 3 does not run continuously. By March 2004, the lower pump shows a flattening of the fluid conductivity versus time curve with the upper pump showing a somewhat slower flattening of the corresponding curve. The change in chloride with time follows a somewhat different pattern compared with the change in electrical conductivity. After more than 200 days of continuous pumping, the chloride concentration in water from the Upper Pump is varying between 200 and 250 mg/L, which is below the MAC for chloride in drinking water. Chloride in water from the Lower Pump ranged from 3,500 to 4,000 mg/L. These concentrations are being maintained at a pumping ratio of 4.3 (i.e., 130 US gpm / 30 US gpm).

These data clearly demonstrate how effective the dual-pump system is working and, furthermore, show that the pump sizing is almost ideal for this well. However, it must be noted that the conductivity of the water from the Upper Pump is still increasing slowly with time, which means that Lower Pump should be increased in size to accommodate a discharge rate of around 189 L/min (50 US gpm or 42 Igpm). This should allow
the discharge of potable water from the Upper Pump to be increased to roughly 567 L/min (150 US gpm or 125 lgpm).

**SUMMARY**

The installation of two pumps in each well have proven to be effective in controlling upwardly moving brackish/saline waters in two different geological settings. The key to the application of this dual pump approach is to develop a clear understanding of the hydrogeological setting of each well field site. In addition, predicting the long term water quality in the well field requires long term aquifer testing to establish the appropriate pumping rates for each pump and the use of a 3-D numerical model such as TOUGH2 (Pruess et al., 1999) to guide the long term operation of the well fields. The approach described in this paper has demonstrated the potential to produce a sustainable potable water supply for two communities, with populations of approximately 1,500 and 7,500 people, respectively, in areas with complex hydrogeology and hydrogeochemistry, underlain by brackish formation waters. A similar approach, involving the completion of shallow vertical and inclined wells in LNAPL plumes in fractured porous aquifers has proven to be very effective in remediation projects where the impact on a thin fresh water lens has to be minimized.

**REFERENCES**


Fracflow Consultants, 2003. Draft Report, Exploratory Well Drilling Programme Town of St. George’s, NL.


Figure 1  Schematic of dual pump configuration.

Figure 2  Plot of drawdown versus time for the pumping well and the observation well during the 30 day aquifer test.

Upper Pump:
Q = 217 L/min

Lower Pump:
Q = 18 L/min

Upper Pump:
Q = 208 L/min

Lower Pump:
Q = 30 L/min

Upper Pump:
Q = 246 L/min

Lower Pump:
Q = 27 L/min
Figure 3  Plot of pH and the volume of water pumped from the upper and lower pumps in the railway line water well, along with rainfall data.

Figure 4  Fluid conductivities and the volume of water pumped from the upper and lower pumps in the railway line water well, along with rainfall data.
Figure 5  Chloride concentrations and the volume of water pumped from the upper and lower pumps in the railway line water well, along with rainfall data.

Figure 6  Schematic of the hydrogeological study area showing surface water sampling stations, locations of new monitoring wells, and the location of the exploratory production well.
Figure 7  Three dimensional representation of the stratigraphy in the study area.

Figure 8  Binary plot of time versus ground water conductivity for the dual-pumping system at Production Well 2.
Figure 9  Binary plot of time versus chloride for the dual-pumping system at Production Well 2.

Figure 10  Binary plot of time versus ground water conductivity for the dual-pumping system at Production Well 3.