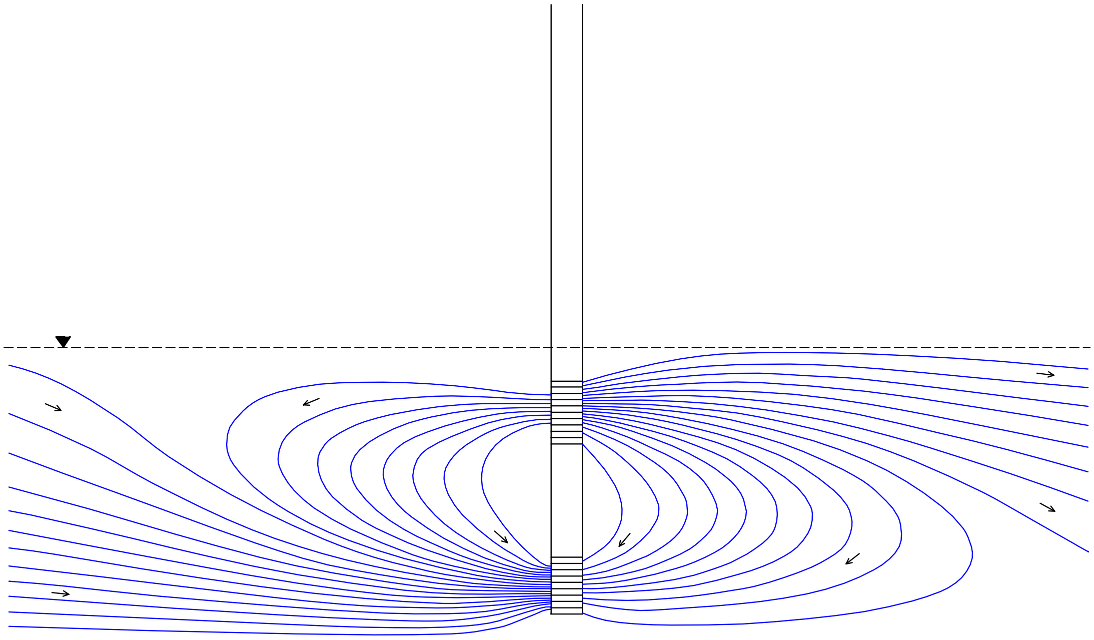
ADVANCED GROUNDWATER REMEDIATION SYSTEMS



Steve Wilhelm & Associates, Inc.

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Steve Wilhelm & Associates was formed in 1997 to offer cost-effective groundwater remediation systems using in-situ remediation technologies.

We work primarily with re-circulating well technologies, which remove contaminants within wells. With such technologies, the water is never brought aboveground, but remains in the aquifer.

Six technologies are used to remove the contaminants from the water:

- With Density Driven Convection (DDC) technology, the contaminants are stripped from the water by air sparging within the well; the water is pumped through the well by air-lift pumping.
- With In-Situ Groundwater Remediation (ISGR) technology, the contaminants are removed by adsorption onto granular activated carbon or other adsorptive treatment medium, or by treatment with a reactive medium.
- With Floating Product Removal (FPR) technology, a skimmer pump is incorporated in a specially designed ISGR well to remove the floating product at the same time the groundwater is treated for dissolved contaminants.
- With Blowerless Air Sparging (BAS) technology, air is forced out of a recirculating well into the aquifer, as in traditional air sparging. BAS technology uses a recirculating well and no blower, compressor, or air pump in moving the air down the well and out into the aquifer.
- With Blowerless In-Well Stripping (BIWS) technology, the water is stripped of contaminants as it passes through a recirculating well, as with traditional in-well stripping technology. BIWS technology uses no blower, compressor, or air pump in stripping the water within the well.
- With Dissolved Oxygen Enhancement (DOE) technology, the water is saturated with dissolved oxygen as it passes through a recirculating well. As with BAS and BIWS technologies, DOE technology uses no blower, compressor, or air pump in saturating the water with oxygen within the well.

DDC technology and ISGR technology are patented. FPR, BAS, BIWS, and DOE technologies are patent-pending.

There are many advantages to recirculating well technologies; the advantages are provided elsewhere on this web page.

Contaminants treated include:

- Petroleum hydrocarbons, including MTBE and TBA
- Floating products, such as fuels

- Halogenated hydrocarbons, such as the solvents TCE, PCE, and vinyl chloride
- Other solvents and volatile organic compounds
- Semi-volatile organic compounds
- Any compound that is effectively removed from water by carbon adsorption
- Many metals, such as lead, uranium, and mercury
- Arsenic and other inorganic contaminants that can be either adsorbed or removed by a reactive medium (e.g., ion-exchange resin)

Given an aquifer, confined or unconfined, that produces at least one tenth gallon per minute, a recirculating well treatment system can generally be developed for a site. However, no technology solves every problem, and there are limitations that must be borne in mind when applying these technologies.

We can provide complete systems, including all drilling, mechanical systems, air pollution abatement (if required), and controls. Typically, we assume all responsibility for successful installation and provide a turnkey system. Mechanical systems, including blower systems, down-well components, and controls are provided on a direct sale or lease basis.

If you would like to consider recirculating well technology for a site, just fill in the Design Data Form and fax or mail it to us, or fill out the form on line and e-mail it to us. It is not necessary to have all of the information requested on the form; some information can be estimated, or replaced with an assumed value. We will provide a conceptual design and budget-level cost estimate, typically within one week.

Steve Wilhelm & Associates is incorporated in the state of Oregon. We have completed projects ranging from just over $100,000 to $1,500,000. Our insurance limits are up to $1,000,000 per occurrence. We have bonded projects up to $1,500,000. Our Dunn & Bradstreet number is 00-818-5725.

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CONTAMINANTS TREATED WITH RECIRCULATING WELLS

A wide variety of contaminants can be treated with the six recirculating well technologies we use. Volatile organic contaminants, such as solvents and gasoline. Semi-volatile contaminants, such as MTBE and some diesel constituents. Inorganic contaminants, such as chromium and arsenic. Floating substances (LNAPLs), such as gasoline and lubricating oils.

A contaminant can be removed from groundwater with one of our technologies if:

- It is volatile or semi-volatile,
- It can be treated with granular activated carbon,
- It can be treated with an ion exchange resin or other exchange medium,
- There is an adsorptive or reactive medium for treating it as a water contaminant,
- It is aerobically or anaerobically biodegradable, *or*
- It is a floating product (LNAPL).

The entire range of contaminants exemplified below can be treated with our patented and patent-pending recirculating well technologies, without pumping the water to the surface and with no aboveground treatment. Example contaminants that can be removed:

Chlorinated Hydrocarbons:

TCE, PCE, DCE, DCA, chlorobenzene, dichlorobenzene, chloromethane, chloroethane, carbon tetrachloride, chloroform, methylene chloride, 1,1,1-trichloroethane, vinyl chloride

Fuel Spills:

Gasoline, diesel, Jet A, other fuels, benzene, ethyl benzene, toluene, xylenes, methyl-*tert*-butyl ether (MTBE), *tertiary*-butyl alcohol (TBA)

LNAPLs:

Lubricating oils, cutting oils, food-grade oils, LNAPL components of crude oil, paint solvents, non-polar solvents, gasoline, diesel, Jet A

FGMP Contamination (Coal Tar):

Benzene, ethylbenzene, toluene, xylenes, naphthalene

Other Volatile and Semi-Volatile Organic Contaminants:

Methyl-ethyl ketone, creosote

Other Organics:

Some explosives, some pesticides, PCBs

Metals:

Lead, chromium, uranium and other radioactive species, mercury, cadmium, copper, nickel

Inorganic Contaminants:

Nitrates, sulfates, perchlorates, arsenic

THE SIX TECHNOLOGIES WE USE

Steve Wilhelm & Associates uses six recirculating well technologies:

- Density-Driven Convection, a patented in-well stripping technology developed by others and licensed by *Steve Wilhelm & Associates.*

  This technology uses stripping within the well to remove volatile and many semi-volatile contaminants from the groundwater as it passes through the well. It was developed by Wasatch Environmental, Inc. and patented under US Patent 5,426,598. We have used this technology since 1997, refining and further developing the patented concept. It is an excellent technology for removing dissolved volatile and many semi-volatile contaminants from groundwater.

- In-Situ Groundwater Remediation, a patented technology (US Patent 6,921,477) developed by *Steve Wilhelm & Associates.*

  This technology uses an adsorptive or reactive medium to remove dissolved contaminants from the ground water within the well. We developed this technology to expand the range of contaminants we can address using recirculating wells beyond the volatile and semi-volatile contaminants that can be stripped from groundwater. With this technology, we can remove volatile, semi-volatile, and many non-volatile contaminants, including ionic species such as chromium and arsenic.

- Floating Product Removal, a patent-applied-for technology developed by *Steve Wilhelm & Associates.*

  This technology uses an In-Situ Groundwater Remediation type well to both treat the groundwater for dissolved constituents of the floating product and to create a depression (drawdown) around the well that induces floating contaminants to flow toward the well for removal by a skimmer pump or other means. Greatly increased removal rates for floating contaminants can be achieved without extracting groundwater from the aquifer.

- Blower-Less Air Sparging, a patent-applied-for technology developed by *Steve Wilhelm & Associates*

  In this recirculating well technology, air (or other sparging fluid) is forced out of the well into the aquifer, as with traditional air sparging. The difference is the means of compressing the air and delivering it to a point below groundwater where it can be forced out of the well. The technology uses no blower, compressor, or air pump of any kind; it uses no aboveground equipment other than a control panel. Power consumption is a small fraction of the power consumption of traditional air sparging. Taking advantage of the large radius of influence of a recirculating well, the sparging air is carried much farther from the well than in traditional air sparging, greatly increasing well spacing over traditional air sparing.

- Blower-Less In-Well Stripping, a patent-applied-for technology developed by *Steve Wilhelm & Associates*

  This technology operates very similarly to blower-less air sparging, except that the air (or other sparging fluid) drawn into the well is returned to the surface after it strips contaminants from the water and saturates the water with oxygen, instead of being forced out into the aquifer. The sparging fluid, bearing the stripped contaminants, can be released to the atmosphere, or treated at the surface if required. The technology uses no blower, compressor, or air pump of any kind. Unless the off-gas requires treatment, it uses no aboveground equipment, other than a control panel. Power consumption is a small fraction of the power consumption of traditional in-well stripping.

- Dissolved Oxygen Enhancement, a patent-applied-for technology developed by *Steve Wilhelm & Associates*

  This technology is almost identical to blower-less in-well stripping, except for the amount of air (or other aerating fluid) used. If the only objective is raising the dissolved oxygen level of the water, possibly to full saturation or even greater, with no need to strip contaminants out of the water, very little air is required. An air to water ratio of 1:25 will provide enough oxygen for saturation to 10.5 mg/L. Excess air is used to increase the efficiency of the aeration process, the excess being returned to the surface. Dissolved oxygen enhancement can also be used to add other gases to the aquifer, such as hydrogen.

These technologies differ in the method of removing contaminants from the groundwater as it passes through the recirculating well.

FREQUENTLY ASKED QUESTIONS

1. Can recirculation be demonstrated?

This question often comes up because density-driven convection (DDC) technology relies on multiple treatment steps (multiple passes through the well) to achieve a high degree of treatment. For example, at the 10th Street Site in Columbus, Nebraska, the theoretically calculated recirculation ratio was 3.10. That is, a typical water molecule entering the treatment zone of the well from upgradient would pass through the well and the treatment zone 3.10 times (on average) before escaping downgradient.

Since the stripping efficiency in the well was 75% (measured twice, at 74.6% and 75.3%) recirculation was critical to achieve a higher overall removal efficiency. Monitoring results from a well-designed system of monitoring wells indicated that the overall removal efficiency actually achieved across the treatment zone (upgradient concentrations of TCE versus downgradient concentrations) was 90.1%. The only way to get an overall reduction greater than the single-pass stripping efficiency is for the water to pass through the well, on average, more than once. These reduction rates indicate an average of 3.02 trips (versus the 3.10 predicted from theoretical calculations) through the DDC well for each water molecule entering the treatment zone. Thus, a typical water molecule would enter the treatment zone and pass through the DDC well, and then return to the DDC well twice before escaping downgradient. These data demonstrate recirculation in the 10th Street Site DDC system.

For most projects, demonstration of recirculation is hampered by lack of a sufficient monitoring system. Only pilot studies have sufficient wells in a well-designed configuration to allow demonstration of recirculation. *Steve Wilhelm & Associates* has performed three pilot studies with adequate monitoring systems. The three pilot studies were at the Former Naval Ammunition Depot (NAD) in Hastings, Nebraska, at the 57th & N. Broadway Site in Wichita, Kansas, and at the 10th Street site mentioned above. In all three cases, recirculation was demonstrated. At the NAD and the 57th & N. Broadway sites, dye tracer studies were used to demonstrate recirculation.

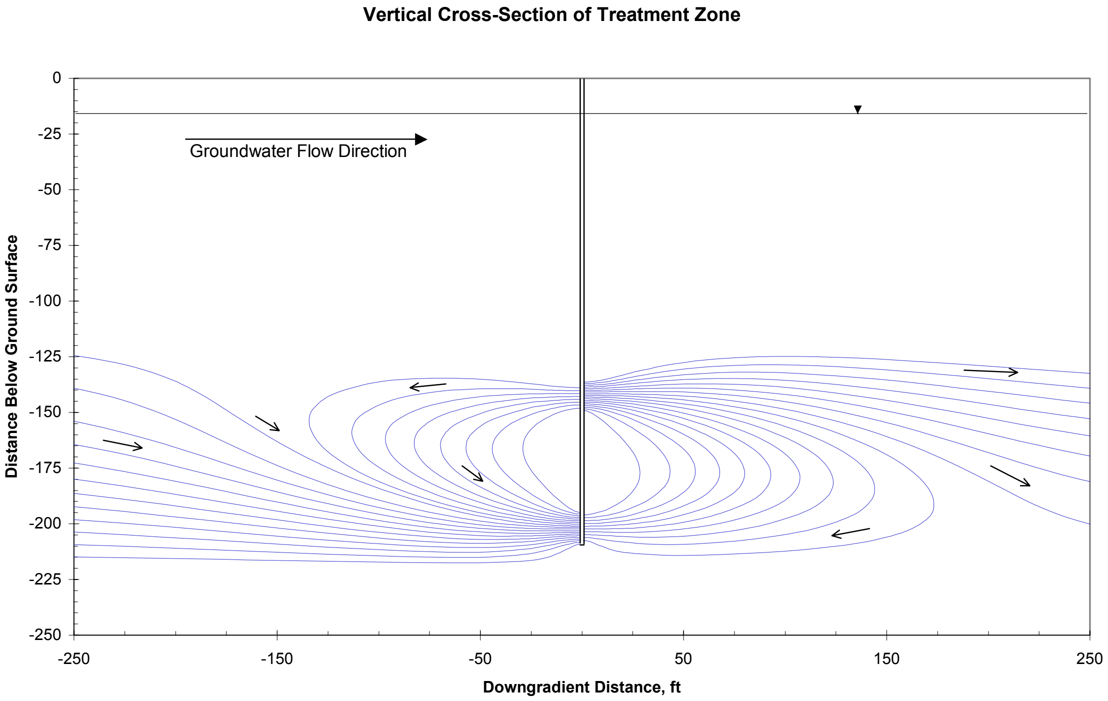
DDC, Blowerless Air Sparging, and Blowerless In-Well Stripping, and Dissolved Oxygen Enhancement technologies utilize the several passes the water makes through a recirculating well to increase overall effectiveness. DOE technology generally adds sufficient oxygen to the water on a single pass to support complete mineralization of the contaminants (up to 3.5 ppm hydrocarbons) to CO_2 and H_2O, but can saturate the water with oxygen on each of the several passes through the well.

In-Situ Groundwater Remediation, Floating Product Removal technologies do not rely on recirculation to achieve adequate removal of dissolved contaminants. For ISGR and FPR systems using granular activated carbon treatment, for example, removal of the contaminants typically is complete (to non-detect levels) in a single pass through the well.

2. Since a recirculating well establishes a closed-loop zone of circulation around the well, how can water approaching the treatment zone from upgradient enter the well? Why doesn't the water from upgradient simply go around the recirculating well's zone of circulation?

This question comes up because flowlines do not cross, and it would seem that the three-dimensional pattern of flow lines established around a recirculation well would effectively bar the flow of "new" water from upgradient entering the treatment zone of a recirculation well.

The answer lies in understanding the upgradient/downgradient flow regime around a recirculating well. The figure below is a plot of the results of modeling efforts for the Massachusetts Military Reserve site on Cape Cod. This was a near sand-box aquifer at the location modeled.



The water exiting the upper screen flows outward in all directions from the recirculating well, including upgradient. The resultant obstruction to flow at the upper level of the aquifer can be seen in the plot on the left. The water approaching and entering the treatment zone from upgradient cannot flow through the recirculating zone; but, it can flow under it, as it is pulled toward the well by the low pressure induced at the inlet screen. This is the manner in which the "new" water enters the treatment zone, is mixed with other (recirculating) water in the well, and begins its recirculation.

3. Is rebound a problem with recirculating well technologies?

Rebound happens when a remediation technology fails to remove or degrade all of the contamination, as when a reagent such as potassium permanganate, or a biological agent such as a particular strain of bacterium, or a nutrient such as molasses, or a physical removal method such as air sparging, fails to reach all parts of an aquifer. Residual contamination then diffuses out of un-remediated zones once the remediation technology is turned off or ceases to function. Any technology that leaves residual contamination in the aquifer is likely to suffer rebound. Also, any site in which there are continuing sources of contaminants, either in source areas upgradient, in the vadose zone, in low-flow zones within the aquifer, or in LNAPL or DNAPL layers or zones within the aquifer, will experience rising concentrations once a remediation system is turned off or is no longer functioning (e.g., exhaustion of a nutrient).

At most sites where we have installed recirculating well systems, it was not the role of the systems to deal with concentrated source areas. Rather, our projects have tended to be in downgradient portions of the plume, dealing exclusively with dissolved contamination. In this “gate-keeper” function, a remediation system can only remediate the contamination that reaches it. As long as contaminants continue to arrive at the recirculating well system from upgradient, the system will still be needed and will have to be operated continuously. If the system is shut off with contaminants still moving into the area from upgradient, concentrations are going to rise.

In cases where there is residual contamination in the vadose zone that is still leaching downward into the groundwater, no amount of remediation of the groundwater (removal of dissolved constituents from the groundwater) is going to remove the source in the vadose zone. Until the source is addressed, by soil vapor extraction, excavation, soil heating, or other means, the continuing release of contaminants to the groundwater will necessitate continuing operation of the recirculating well system.

In cases where there is LNAPL or DNAPL contamination, groundwater remediation will have to continue until the LNAPL or DNAPL is removed. Floating Product Removal (FPR) technology can be used to remove floating product and other floating contaminants, while treating the groundwater to non-detect levels. However, if an FPR system is shut off before all the floating product is removed, rebound is quite likely.

Many sites have contaminants that are trapped in silt layers, clay layers, and other low-flow regimes within the aquifer. The contaminants entered those zones perhaps years before, when contamination levels were higher, and are slowly diffusing out of those zones into the higher flow regions that are now at lower concentrations. One of the difficulties with pump-and-treat systems and air-sparging systems is that they tend to treat water only from those layers and zones of the aquifer that yield water most readily, the higher conductivity zones. Yet the higher conductivity zones are often the least contaminated. Removing water from the lower-flow, more stagnant zones of the aquifer would be preferable, once the permeable pathways have been cleaned, but there is no way to redirect flows with pump-and-treat or air sparging technologies.

Pump-and-treat systems, in effect, preferentially remove water from the least contaminated zones of an aquifer and continue to do so even after those zones have been cleaned. These systems rely primarily on diffusion to remove contaminants from the more stagnant zones in the aquifer. While diffusion eventually will move the contaminants to the higher conductivity zones, where pumping can remove them, diffusion processes are very slow when compared to convective flow processes. While waiting on diffusion, it is necessary to pump and treat and release enormous quantities of water, at very low contamination levels, over many years. This problem is exacerbated for contaminated slit and clay layers that are relatively thick.

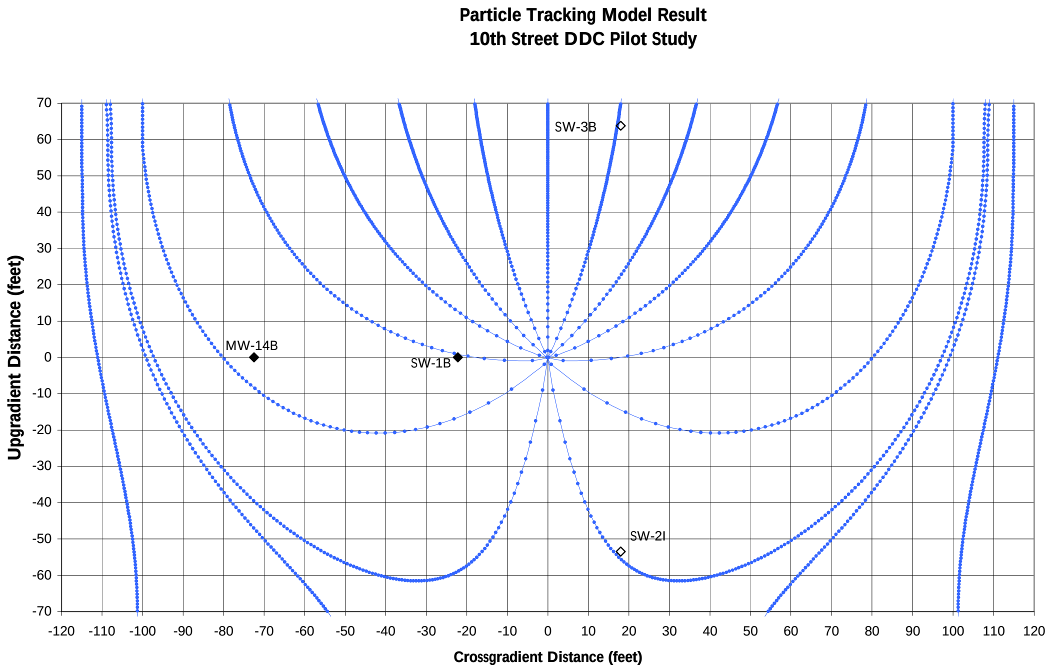
Recirculating well systems circulate water through all zones of the aquifer by inducing vertical gradients and flows over a large treatment area. By removing water from one level of the aquifer and releasing it to another level of the same aquifer, recirculating wells induce vertical gradients. The vertical gradients induce vertical flows through the more stagnant parts of the aquifer and flush contaminants into higher flow zones. By pushing water through the more stagnant zones of the aquifer, recirculating wells do not rely on diffusion alone to move trapped contaminants. Convection moves contaminants faster than diffusion, often orders of magnitude faster.

Because recirculating well technologies move all of the water in an aquifer, they can remove contaminants that pump-and-treat and air sparging systems must trust to diffusion to move. In this way, recirculating well technologies can more rapidly remove these trapped contaminants that will, if not removed, lead to rebound when the remediation is ended.

4. How was the projected capture width or radius of influence calculated for my site? Has this theory ever been demonstrated in the field?

The calculations are performed according to a method developed several years ago, and that is commonly used with recirculating wells. The calculations require about three hours to perform with a pencil and calculator.

At the 10th Street Site in Columbus, Nebraska, a transducer study was performed to measure the actual capture width of the pilot well, so it could be compared to the predicted capture width. The theoretical calculations indicated an expected capture width of 192 feet. The transducer study results were used to determine the gradient imposed by the pumping of the recirculating well. The imposed gradient and the natural gradient, were entered into a proprietary particle-tracking model developed by *Steve Wilhelm & Associates* to permit modeling using actual aquifer pressures generated by a recirculating well system. The results of the particle-tracking model are presented in the figure below. The result was that the capture width of the recirculating well, was 216 feet.



DENSITY DRIVEN CONVECTION

In-Well Stripping With Re-Circulating Wells

Density-Driven Convection (DDC) is a simple patented technology that removes volatile and many semi-volatile contaminants from groundwater *within the well*. It does not pump the water to the surface or otherwise remove it from the aquifer. The groundwater is pumped more vigorously than in a pump-and-treat approach, circulated several times through a treatment zone established around the treatment well, and stripped of contaminants during each of several passes through the well.

While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used. Figure 1 shows the basic configuration.

- The well penetrates to the maximum depth of the contamination, with a normal inlet screen across the lower several feet of the contaminated thickness.
- The well incorporates a second screen, an outlet screen, usually at or near the normal water table.
- The functions of the two screens can be reversed, with the upper screen serving as the inlet screen and the lower screen serving as the outlet screen.
- An air line is located in the center of the well and extends to some distance below the normal water table. The depth of the air line below the water table is called the submergence.
- The air line is connected, generally via underground piping, to a pressure blower.
- Air is forced down the air line. The water is pumped by air-lift pumping to a level above the water table. The air-lift pumping both pumps the water through the well and strips the volatile and semi-volatile contaminants from the water.
- The treated (stripped) water exits through the upper screen and flows back into the aquifer through the sand pack and the aquifer materials.
- At the water table, a mound is formed, resulting in higher head values near the well.
- The treated water flows outward from the well and downward under the influence of the vertical gradients created by the extraction process at the bottom of the well and the mounding at the water table. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be more outward than downward.
- A torroidal-shaped treatment zone is created that typically returns the majority of the treated water to the lower screen. The shape and size of the treatment

zone are largely determined by the treated thickness, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate.

- The water cycles through the treatment zone several times, on average, before escaping downgradient. The stripping process does not have to achieve final cleanup levels in a single pass, since the water will return to the well for additional treatment. The process is rather like having several stripping towers in series, each achieving good stripping efficiency. Five passes through the well, even at only 85% removal on each pass, easily exceeds 97% removal.
- The air travels up the well to the surface. At the surface, it can be treated for contaminant removal (e.g., carbon adsorption) or released directly to the atmosphere. If it is treated, it is typically recycled to the pressure blower and reused in a closed-loop mode for additional stripping.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing density-driven convection systems. Well diameter, optimal pumping rate and air-water ratio, number of wells and well placement, length of the outlet screen, special development procedures, blowers versus compressors, controls and instrumentation, calcite precipitation potential, pipe sizes, air flow velocities, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations, infiltration galleries, higher air-water ratios, and multiple rows of wells.

The major advantages of DDC technology are listed below. The specific advantages of DDC over air sparging and pump-and-treat are presented separately in this brochure.

ADVANTAGES OF DENSITY-DRIVEN CONVECTION OVER PUMP & TREAT

In-well stripping is frequently compared to pump-and-treat systems because both involve pumping the contaminated groundwater through a treatment step, and because pump-and-treat systems often use air stripping-based treatment. The two technologies are actually more different than similar.

In-situ versus ex-situ. DDC is an in-situ treatment process that does not involve pumping the groundwater to the surface. Pump-and-treat is an ex-situ treatment process.

Water Discharge Problems. Because DDC does not involve pumping groundwater to the surface, there is no treated water to release. Pump-and-treat systems create a large volume of water that must be released, typically through an NPDES permit or to a municipal treatment plant. Such releases must be monitored, with periodic reporting. In some settings, it would not be possible to release the water, often because the local streams or the treatment plant could not handle the increased flows. A polishing step, often with aqueous phase carbon, is sometimes required after stripping to meet the discharge requirements. Release is especially problematic if there are other contaminants or natural components of the groundwater (e.g., salt, radioactive constituents) that could not be released, either to streams or to a treatment plant. It is often desirable to remove volatile contaminants through in-well stripping and leave the groundwater with all of its other constituents in the aquifer.

Point of Stripping. DDC accomplishes the stripping within the well and then releases the stripped water to the aquifer to recirculate and bring more contaminants back to the treatment well.

Pump-and-treat systems accomplish the stripping step (or other treatment step) outside the well, usually in an aboveground treatment system specially designed for the site. For volatile compounds, the initial treatment step often is air stripping in a stripping tower or tray stripper. To avoid damage during the winter, the above-ground treatment system must be protected from freezing.

Pumping and groundwater circulation. DDC pumps water through the well, drawing water from one level of the aquifer, treating it, and releasing it to another level of the same aquifer. Because the water moves vertically as well as horizontally through the aquifer, under the influence of strong vertical gradients induced by the draw down and mounding created by the pumping and release, the water moves outward from the well and then back in a torroidal circulation pattern. The torroidal treatment zone has a radius of influence that is similar to pump-and-treat capture zones. The radius of influence has to be determined for each site, but often is 2 to 5 times the distance between the inlet screen and the outlet screen. For a 50-foot depth of contamination, well spacings of 300 to 500 feet are theoretically possible, though more conservative designs (200+ feet) would typically be used.

Pump-and-treat systems remove the water from the aquifer by drawing it into a pumped well and conveying it to the surface. Extraction preferentially removes water from those layers and zones of the aquifer that yield water most readily, the higher conductivity zones. Yet the higher conductivity zones are often the least contaminated. Removing water from the lower-flow, more stagnant zones of the aquifer would be preferable, once the permeable pathways have been cleaned, but there is no way to redirect flows. Pump-and-treat systems, in effect, preferentially remove water from the least contaminated zones of an aquifer and continue to do so even after those zones have been cleaned.

More vigorous remediation. DDC circulates water through all zones of the aquifer by inducing vertical gradients and flows over a large treatment area.

By removing water from one level of the aquifer and releasing it to another level of the same aquifer through a recharge screen, in-well stripping induces vertical gradients and flows. The vertical gradients induce flows through the more stagnant parts of the aquifer and flush contaminants to higher flow zones. By pushing water through the more stagnant zones of the aquifer, DDC does not rely on diffusion to move trapped contaminants. Convection moves contaminants faster than diffusion, often orders of magnitude faster.

Pump-and-treat approaches rely primarily on diffusion to remove contaminants from the more stagnant zones in the aquifer. While diffusion eventually will move the contaminants to the higher conductivity zones, where pumping can remove them, diffusion processes are very slow when compared to convective flow processes. While waiting on diffusion, it is necessary to pump *and treat* enormous quantities of water over many years. This problem is exacerbated for contaminated lower conductivity zones that are relatively thick.

Faster. Pump-and-treat and DDC operate on different principles: pump-and-treat passively draws to its extraction wells whatever water will flow most easily under the horizontal gradients induced by the pumping, and relies on diffusion to remove contaminants from lower permeability zones; while DDC, through strong vertical gradients, vigorously circulates and treats all of the water within the treatment zone. Because DDC operates on this different principle, it can be relatively quicker in remediating a site. At a site in Wichita, Kansas, cleanup to the remediation goal was achieved in most of the DDC wells in less than one year.

Cheaper. DDC systems are built using standard, off-the-shelf well components. Capital expenditures for aboveground equipment are slightly less than pump-and-treat, since no stripping tower is necessary. In-well stripping avoids the need for an NPDES permit or discharge to a treatment plant and the attendant monitoring and reporting costs.

During its life cycle, any remediation system requires oversight, monitoring, maintenance, and periodic reporting. With life cycles extending to decades, pump-and-treat approaches incur large costs for continuing these efforts throughout a remediation.

Thus, Density-Driven Convection technology is less expensive to install, cheaper to operate each month, and completes the remediation in a fraction of the time. All of this adds up to much lower costs than pump-and-treat.

ADVANTAGES OF DENSITY-DRIVEN CONVECTION OVER AIR SPARGING

In-well stripping is frequently compared to air sparging because both remove contaminants via air stripping without bringing the groundwater to the surface. However, the two technologies are actually more dissimilar than similar.

Point of stripping. In-well stripping accomplishes the stripping step within the well and then releases the water to the aquifer to recirculate and bring additional contaminants back to the treatment well. The air stream with the contaminants remains within the well, from which it is easily recovered for treatment.

Air sparging performs the stripping step outside of the well. The injected air and the stripped water do not move in any predictable patterns, and the nature and effectiveness of the interaction between the sparging air and the groundwater is largely unknown. The air, with the stripped contaminants, is allowed to drift upward to the vadose zone, where recapture is uncertain and typically incomplete.

Pumping and groundwater circulation. In-well stripping pumps water through the well, drawing water from one level of the aquifer, treating it, and releasing it to another level of the same aquifer. The result is that the water moves outward from the well in a torroidal circulation pattern. The water moves both horizontally and vertically through the aquifer under the influence of strong vertical gradients induced by the drawdown and mounding created by the pumping and release. The torroidal treatment zone has a much greater radius of influence than air sparging can create. The radius of influence has to be determined for each site, but often is 2 to 5 times the distance between the inlet and outlet screens. For a 50-foot thickness of contamination, well spacings of 300 to 500 feet are theoretically possible, though conservative designs (200+ feet) are typically used. A typical maximum radius of influence cited in the literature for sparging wells is 20 feet.

Air sparging does not circulate the groundwater effectively. Consequently, the zone of influence of an air sparging well is restricted to the area near the well, through which the air moves upward. Flows, if any, created by the upward drift of air through the aquifer are impossible to predict. Various patterns are envisioned for the zone of influence of an air sparging well; most commonly, it is envisioned as a fractious pattern of air paths from which the water has been excluded. The radius of influence is generally thought to decrease with depth, allowing untreated water to flow between adjacent wells and escape treatment. To counter this, very close well spacings are required, often on the order of 25 feet, and many more wells are required than for in-well stripping systems.

Fewer wells. For the reasons given immediately above, DDC systems require fewer wells than air sparging systems.

And DDC wells are typically not expensive. They have an extra section of screen and an air line down the center. Other than that, they are similar to air sparging wells and are constructed of off-the-shelf, typically PVC, components.

More flexible well placement. Because fewer wells are required and the distances between wells can be so much larger than for air sparging, there is greater flexibility in placing wells. DDC systems are not as sensitive to where the wells are placed. This allows locating wells out of the way of surface obstructions, utilities, roadways, residences, etc.

Lower pressures. Direct sparging works best when it is possible to inject air into the formation at the full depth of the contamination. There is necessarily a high pressure in the well, if the contamination extends very far below the water table. With no resistance in the aquifer, such as a large gravel and cobble aquifer might approximate, there is a pressure of approximately 0.43-psi per foot below static groundwater level. Given an additional pressure requirement due to flow resistance in the aquifer, the pressures in a direct sparging system can be quite high. For a 50-foot depth of contamination below the water table, the required air pressure can easily be 35 to 50 psi. This results in a need for expensive compressors and ultimately results in large energy costs, significant noise problems, and large quantities of heat that must be handled.

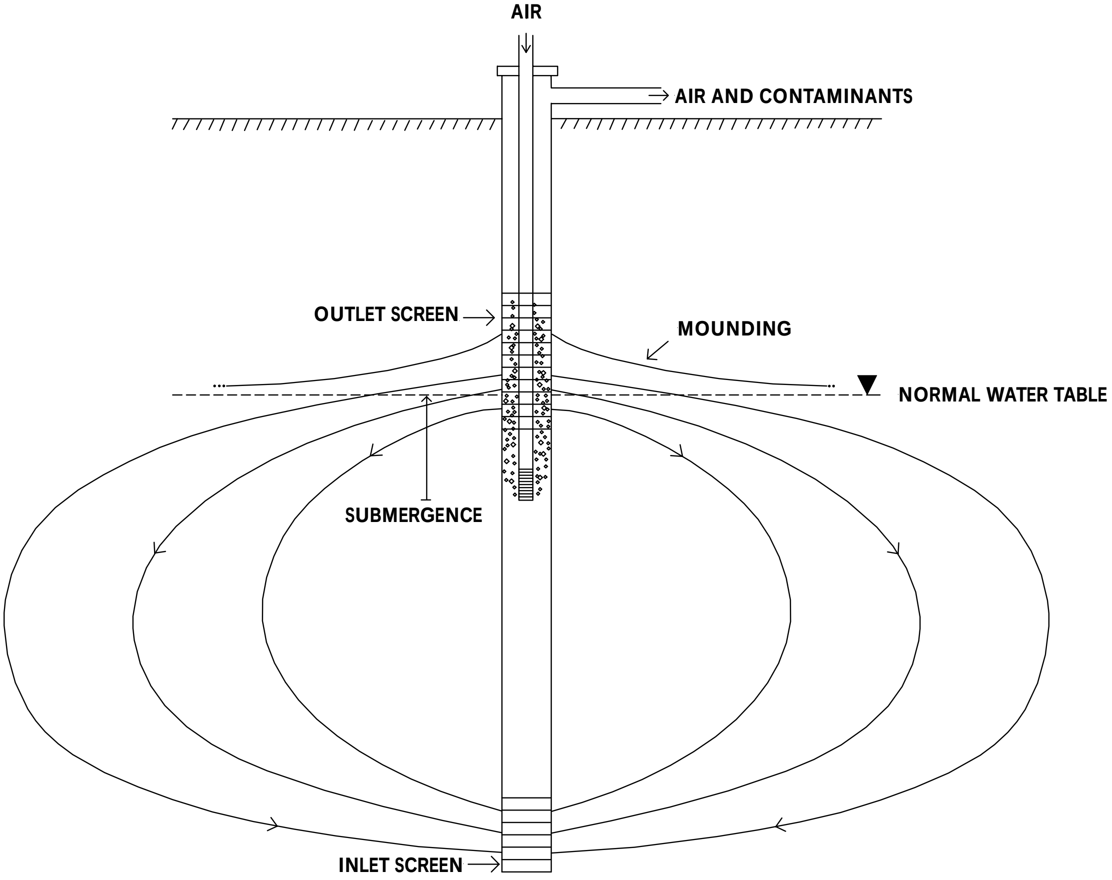
In-well stripping works at low pressures. It is only necessary to inject air a few feet below the water table, just far enough to facilitate creating a stripping zone in the well of ten to fifteen feet of bubbles. And, there is no need to push air against any resistance in the formation; all flows (air and water) occur in the smooth, open well casing. Thus, in-well stripping systems typically run at 3 – 7 psi. Electrically driven blowers are used instead of compressors, keeping energy costs and noise to reasonable minimums, and eliminating smoke from diesel-driven compressors.

More targeted remediation. DDC systems can treat just the portion of the aquifer that is contaminated. If the contamination does not extend to the surface of the groundwater, the upper screen can be placed below the water table, and only the water that is contaminated is treated.

Air sparging systems must inject air at the full depth of the contamination, even if the contamination is restricted to a limited zone deep in the aquifer. As an example, the hydrostatic pressure at the maximum depth of contamination at a site in Massachusetts would have been 100 psi, although the plume thickness was only 120 feet thick (52 psi). The energy cost for air sparging would be quite large. DDC systems treat only the contaminated portion of the aquifer and the energy costs reflect that. An in-well stripping system at MMR ran at approximately 4 psi.

Capturing the stripped contaminants is easier and less uncertain. When stripping volatile contaminants in the formation using air sparging, the flow patterns of the air are not well known, even in theory. This results in reduced ability to capture the stripped contaminants. To the extent that capture fails, contaminants are only moved from the groundwater the vadose zone and the atmosphere.

DDC treats the contaminants in the well, where they are stripped from the water. The contaminant-laden air is not allowed to disperse beyond the well. By confining the stripping process to the well, the contaminants are readily available for capture and treatment.



Schematic DDC Well

Figure 1

MAJOR ADVANTAGES OF DENSITY-DRIVEN CONVECTION WITH RE-CIRCULATING WELLS

FASTER

- Faster than pump and treat or air sparging. Much less than the 30 to 50 years commonly estimated for pump-and-treat.
- More vigorous than pump-and-treat approaches. Pump-and-treat is passive in nature, extracting the water that is easiest to extract and waiting for contaminants to diffuse from lower permeability zones. Re-circulating wells induce vertical gradients to vigorously circulate and treat *all of the water in the aquifer* multiple times.

CHEAPER

- Lower initial capital costs, lower maintenance costs, and faster cleanups result in lower life-cycle costs.
- Fewer wells than air sparging. Well spacing typically 2 to 5 times the depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.
- Lower pressures than air sparging systems, typically only 3 to 7 psi. Equipment and energy costs are lower than for air sparging.

MORE FLEXIBLE

- Large well spacings allow great flexibility in placing wells.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers, re-circulation patterns are enhanced by these typical real-world features.
- Pumping rate and air/water ratio, the two essential system variables, can be independently adjusted after installation to match actual aquifer response. Even well diameter and screen placement can be modified to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or specific parts of a plume can be targeted.
- Enhances bioremediation of biodegradable contaminants. Saturates the treated water with dissolved oxygen. Facilitates natural attenuation.
- Can be used to distribute nutrients in the groundwater to enhance bioremediation.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels. No re-injection problems. Eliminates the need for water treatment at the surface.
- No air emissions. Re-circulating wells can be operated in a closed loop mode, with zero discharge.

IN-SITU GROUNDWATER REMEDIATION

Contaminant Removal to Non-Detect With Re-Circulating Wells

In-Situ Groundwater Remediation is a simple patented technology that removes contaminants from groundwater *within the well*. It does not pump the water to the surface or otherwise remove it from the aquifer. The groundwater is pumped more vigorously than in a pump-and-treat or air sparging approach, circulated several times through a treatment zone established around the ISGR well, and treated for removal of contaminants during each of several passes through the well.

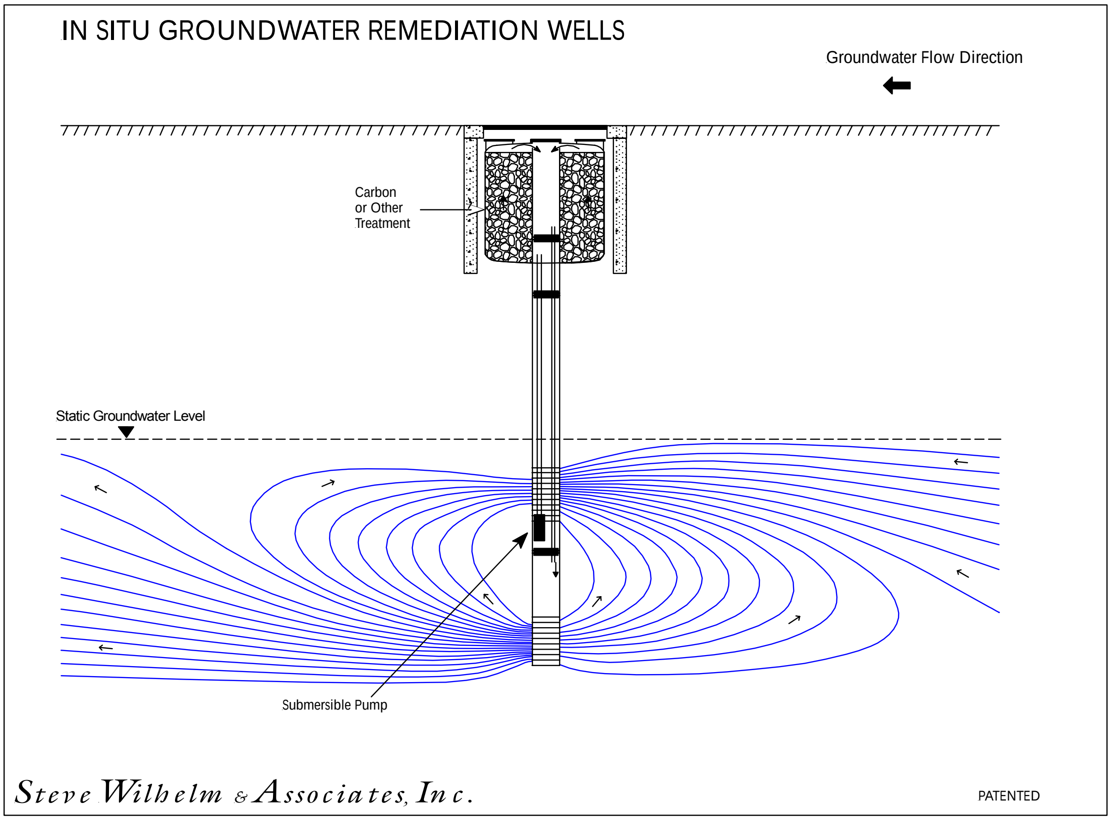
While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used. Figure 1 shows the basic configuration.

- The well penetrates to the maximum depth of the contamination, with a normal inlet screen across the lower several feet of the contaminated thickness.
- The well incorporates a second screen, an outlet screen, usually at or near the normal water table.
- The functions of the two screens can be reversed, with the upper screen serving as the inlet screen and the lower screen serving as the outlet screen.
- The inlet portion of the well is separated from the outlet portion by a packer.
- The size of the well casing increases just below ground surface to a diameter of a few feet, to accommodate placement of an adsorptive or reactive treatment medium in the well. A central pipe is located in this larger-diameter portion of the well. The central pipe serves to collect the water after treatment and convey it back to the lower, smaller-diameter portion of the well.
- The water is pumped by a submersible pump to the larger-diameter portion of the well, where it is pumped through the treatment medium.
- The treated water exits the treatment medium and is conveyed by the central pipe back to the smaller-diameter portion of the well. From this point, the water is conveyed through the smaller-diameter portion of the well to the exit screen. The water then flows, under gravity and/or applied pressure, through the outlet screen and flows back into the aquifer through the sand pack and the aquifer materials.
- At the exit screen, higher than normal pressures are formed, resulting in higher head values near the well.
- The treated water flows outward from the well and downward under the influence of the vertical gradients created by the extraction process at the bottom of the well and the mounding at the water table. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be more outward than downward.
- A recirculation zone is created that typically returns the majority of the treated water to the inlet screen. The shape and size of the treatment zone are largely determined by the treated thickness, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate.

- The water cycles through the treatment zone several times, on average, before escaping down gradient. The treatment process does not have to achieve final cleanup levels in a single pass, since the water will return for additional treatment. Five passes through the well, at 85% removal on each pass, easily exceeds 97% removal. Using activated carbon as an adsorptive medium, treatment is usually 100% in a single pass through the well.
- There are no above-ground systems or equipment. Typically, the only above-ground appearance of an ISGR system is a manhole with an adjacent power pole that has a utility meter and a control panel.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing In-Situ Groundwater Remediation systems. Well diameter, optimal pumping rate, number of wells and well placement, length of the outlet screen, special development procedures, controls and instrumentation, in-well plumbing configuration, constructability, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations and multiple rows of wells.

The general advantages of ISGR and specifically the advantages of ISGR over air sparging and pump-and-treat technologies are listed below



MAJOR ADVANTAGES OF IN-SITU GROUNDWATER REMEDIATION WITH RE-CIRCULATING WELLS

NO SURFACE EQUIPMENT

- Constructed entirely below ground, ISGR systems take up no aboveground space.
- Silent operation.

FASTER

- Faster than pump and treat or air sparging. Much less than the 30 to 50 years commonly estimated for pump-and-treat systems.
- More vigorous than pump-and-treat approaches. Pump-and-treat is passive in nature, extracting the water that is easiest to extract and waiting for contaminants to diffuse from lower permeability zones. Re-circulating wells induce vertical gradients to vigorously circulate and treat *all of the water in the aquifer* multiple times.

CHEAPER

- Lower initial capital costs, lower maintenance costs, and faster cleanups result in lower life-cycle costs.
- Fewer wells. Well spacing typically 2 to 5 times depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.
- Lower pressures than air sparging systems, typically just the pressure required to pump the water to near ground surface. Pumping an incompressible fluid (water instead of air), energy costs are lower than for air sparging.

MORE FLEXIBLE

- Large well spacings at many sites allow great flexibility in placing wells.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers, re-circulation patterns are enhanced by these typical real-world features.
- Pumping rate can be adjusted after installation to match actual aquifer response. Pumping rate and even screen placement can be modified to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or parts of a plume can be targeted.
- Can be used to distribute nutrients in the groundwater to enhance bioremediation.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels. No re-injection problems. Eliminates the need for water treatment at the surface.
- No air emissions. Re-circulating wells can be operated with zero discharge.

ADVANTAGES OF
IN-SITU GROUNDWATER REMEDIATION TECHNOLOGY

In-Situ Groundwater Remediation (ISGR) technology offers several advantages over other groundwater remediation technologies, especially pump-and-treat and air sparging.

In-situ versus ex-situ. ISGR is an in-situ treatment process that does not involve pumping the groundwater above the surface. The water remains within the well and the aquifer at all times, never penetrating the plane of the ground surface.

No Water Discharge Problems. Because ISGR does not involve pumping groundwater above the ground surface, there is no treated water to release and no loss of use of the water for other purposes. Pump-and-treat systems create large volumes of water that must be treated and released, typically through an NPDES permit or to a municipal treatment plant. Such releases must be monitored, with periodic reporting. A polishing step, often with aqueous phase carbon, is sometimes required after treatment by stripping, to meet discharge requirements. In some settings, it is not possible to release the water, because the local streams or the treatment plant could not handle the increased flows. Release is especially problematic if there are other contaminants or natural components of the groundwater (e.g., salt, radioactive constituents) that could not be released, either to streams or to a treatment plant. It is often desirable to remove specific contaminants through recirculating wells and leave the groundwater, with all of its other constituents, in the aquifer. It is usually undesirable to remove the water from the aquifer and thus lose the water to other beneficial uses.

No Aboveground Systems. ISGR has a very limited aboveground expression. A manhole, which is typically not even noticed by an urban dweller, and an adjacent power pole, also essentially unnoticeable, are the only aboveground indications of an ISGR system. The power pole has a typical electric power meter and a control panel. A small pilot light can be incorporated in the control panel to indicate that the system is operating normally. Other than these features, there is nothing to indicate that a groundwater remediation system is present and operating. With this limited surface expression, access, aesthetics, and security problems are all but eliminated.

No Noise. ISGR systems are silent in operation. With only one moving part, the impellers of an ordinary submersible pump operating in the well below normal groundwater level, the systems emit no detectable noise.

Lower Energy Consumption. ISGR works at low pressures, pumping an essentially incompressible fluid, water. This greatly reduces energy costs. Instead of air sparging, with blowers or compressors working at tens of horsepower, ISGR wells operate with ordinary submersible well pumps, typically at less than one horsepower per well.

In some settings, air sparging works best when it is possible to inject air into the formation at the full depth of the contamination. There is necessarily a high pressure in the well, if the contamination extends very far below the water table. With no resistance in the aquifer, such as a large gravel and cobble aquifer might approximate, there is a pressure of approximately 0.43 psig per foot of depth below the static groundwater level. Given an additional pressure requirement due to flow resistance in a more typical sand and silt aquifer, the pressures in a direct sparging system can be quite high. For a 50-foot depth of contamination below the water table, the required pressure can easily be 35 to 50 psi. This results in a need for expensive compressors and ultimately results in large energy costs, significant noise problems, and large quantities of heat that must be managed.

Less Expensive. ISGR technology eliminates all aboveground systems, substituting a common submersible pump and a below-ground quantity of an adsorptive or reactive medium to remove the contaminants from the groundwater. The entire mechanical system consists of the wellhead, a pump, and internal plumbing in the well. A variable frequency drive can be incorporated to alter the flow rate, but that is the only mechanical complexity that can be introduced into the technology.

Operation and maintenance costs of ISGR systems are quite low. There are no adjustments to make, and there are only two consumables to change out: filters and the carbon or other treatment medium. Carbon usage per pound of contaminant is higher with aqueous-phase carbon than it is for vapor-phase carbon. However, the increased carbon usage over a stripping system is made up for in the reduced capital costs, power consumption, and operation and maintenance labor. Carbon changeout can be accomplished in one and a half hours per well.

ISGR avoids the need for and the attendant monitoring and reporting costs of an NPDES permit or discharge to a treatment plant.

During its life cycle, any remediation system requires oversight, monitoring, maintenance, and periodic reporting. With life cycles extending to decades, pump-and-treat and air sparging approaches incur large costs for continuing these efforts.

ISGR is less expensive to install, cheaper to operate each month, and completes remediation in a fraction of the time required by pump-and-treat, air sparging, and most other methods. All of this adds up to much lower life-cycle costs.

Pumping and groundwater circulation. ISGR pumps water through the well, drawing water from one level of the aquifer, treating it, and releasing it to another level of the same aquifer. The water moves outward from the well and then back in a recirculating pattern. The water also moves vertically through the aquifer under the influence of strong vertical gradients induced by the draw down and mounding created by the pumping and release. The treatment zone has a capture width that is similar to pump-and-treat capture zones. The radius of influence has to be determined for each site, but often is 2 to 5 times the distance between the inlet screen and the outlet screen. For example, for a 50-foot thickness of contamination, well spacings (twice the radius of influence) of 300 to 500 feet are theoretically possible, though more conservative designs (200 +/- feet) would typically be used.

Pump-and-treat systems remove the water from the aquifer by drawing it into a pumped well and conveying it to the surface. Extraction preferentially removes water from those layers and zones of the aquifer that yield water most readily, the higher conductivity zones. Yet the higher conductivity zones are often the least contaminated. Removing water from the lower-flow, more stagnant zones of the aquifer would be preferable, once the permeable pathways have been cleaned, but there is no way to concentrate the pumping on these portions of the aquifer. Pump-and-treat systems, in effect, preferentially remove water from the least contaminated zones of an aquifer and continue to do so even after those zones have been cleaned.

Air sparging most often does not circulate the groundwater effectively. Consequently, the zone of influence of an air sparging well is restricted to the area near the well, through which the air moves upward. Flows, if any, created by the upward drift of air through the aquifer are difficult to predict. Various patterns are envisioned for the zone of influence of an air sparging well; most commonly, it is envisioned as a fractious pattern of air pathways from which the water has been excluded. The radius of influence is generally thought to decrease with depth, allowing untreated water to flow past the wells and escape treatment. To counter this, very close well spacings are required, often on the order of 25 feet, and many more wells are therefore required than for ISGR systems.

More vigorous remediation. ISGR circulates water through all zones of the aquifer by inducing vertical gradients and flows over a large treatment area.

By removing water from one level of the aquifer and releasing it to another level of the same aquifer, ISGR induces vertical gradients and flows. The vertical gradients induce flows through the more stagnant parts of the aquifer and flush contaminants to higher flow zones. By pushing water through the more stagnant zones of the aquifer, ISGR does not rely on diffusion to move trapped contaminants. Convection moves contaminants faster than diffusion, often orders of magnitude faster.

Pump-and-treat approaches rely primarily on diffusion to remove contaminants from the more stagnant zones in the aquifer. While diffusion eventually will move the contaminants to the higher conductivity zones, where pumping can remove them, diffusion processes are very slow when compared to convective flow processes. This problem is exacerbated for lower conductivity zones that are relatively thick. This is why pump-and-treat systems are often predicted to require 30+ years to achieve remediation goals. And during the entire 30+ years, enormous quantities of water have to be pumped and treated and monitored and released under permit.

Point of Treatment. ISGR accomplishes the treatment within the well and then releases the treated water to the aquifer to re-circulate and bring more contaminants back to the treatment well.

Pump-and-treat systems accomplish the treatment step outside the well, usually in an aboveground treatment system specially designed for the site. Aboveground systems have several disadvantages, including aesthetic considerations, noise, space requirements, weatherization requirements, access limitations, security, and others.

Air sparging performs the treatment step outside of the well. The stripped water does not move in a definitely predictable pattern. The air stream, with the stripped contaminants, drifts upward to the vadose zone, where recapture is uncertain and in some cases incomplete. When recapture is incomplete, air sparging simply moves the contaminants from one medium (groundwater) to two others (the vadose zone and the atmosphere).

More targeted remediation. ISGR systems can treat just the portion of the aquifer that is contaminated. If the contamination does not extend to the surface of the groundwater, the upper screen can be placed below the water table, and only the water that is contaminated is treated. Or, if the contamination does not extend to the bottom of the aquifer, the lower screen can be placed only to the depth of the contamination. If the contamination is in a confined aquifer, ISGR well screens can be placed to circulate and treat the water below the aquitard.

Air sparging systems must inject air at the full depth of the contamination, even if the contamination is restricted to a limited zone deep in the aquifer. As an example, the hydrostatic pressure at the maximum depth of contamination at a site in Massachusetts would have been 100 psi, although the plume thickness was only 120 feet (52 psi). The energy cost for air sparging at such a site would be quite large. Further, air sparging generally cannot be used in a confined aquifer.

More flexible well placement. Because fewer wells are required and the distances between wells can be so much larger with ISGR than with air sparging, there is greater flexibility in placing the treatment wells. ISGR systems are not as sensitive to where the wells are placed. This allows locating wells out of the way of surface obstructions, utilities, roadways, residences, etc.

FLOATING PRODUCT REMOVAL

Two-Pump LNAPL Removal With Re-Circulating Wells

Floating Product Removal (FPR) is a simple patent-pending technology that removes LNAPL contaminants from groundwater using a two-pump approach, but without removing groundwater from the aquifer. High efficiency removal of the floating product and treatment of the groundwater for dissolved contamination are accomplished in a single borehole. FPR uses In-Situ Groundwater Remediation (ISGR) wells to depress the groundwater surface around each well, resulting in greatly increased flow of the floating product to the well for removal by a skimmer pump.

Dissolved contaminants (e.g., BTEX, MTBE) are removed by carbon adsorption or other suitable adsorptive or reactive medium. The groundwater is pumped more vigorously than in a pump-and-treat or air sparging approach, circulated several times through a treatment zone established around the FPR well, and treated for removal of contaminants during each of several passes through the well.

The entire process is completed below ground, with the only aboveground expression of the system being a manhole cover and a power pole with a power meter and a control panel. FPR systems can be located virtually anywhere a drill rig can drill a hole, even in an active driveway or the middle of a busy street.

While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used. The figure shows the basic configuration.

- The ISGR well penetrates to the maximum depth of the dissolved contamination, or to a depth chosen to achieve a desired capture width. An inlet screen is set at or near the top of the groundwater.
- The ISGR well incorporates a second screen, an outlet screen, usually at or near the bottom of the well.
- The inlet portion of the well is separated from the outlet portion by a packer.
- The size of the well casing increases just below ground surface to a diameter of a few feet, to accommodate placement of an adsorptive or reactive treatment medium in the well. A central pipe is located in this larger-diameter portion of the well. The central pipe serves to collect the water after treatment and convey it back to the lower, smaller-diameter portion of the well.
- The water is pumped by the submersible pump to the larger-diameter portion of the well where it is pumped through the treatment medium.
- The treated water exits the treatment medium and is conveyed by the central pipe back to the smaller-diameter portion of the well. From this point, the water is conveyed through the smaller-diameter portion of the well to the exit screen. The water then flows, under gravity and/or applied pressure, through the outlet screen

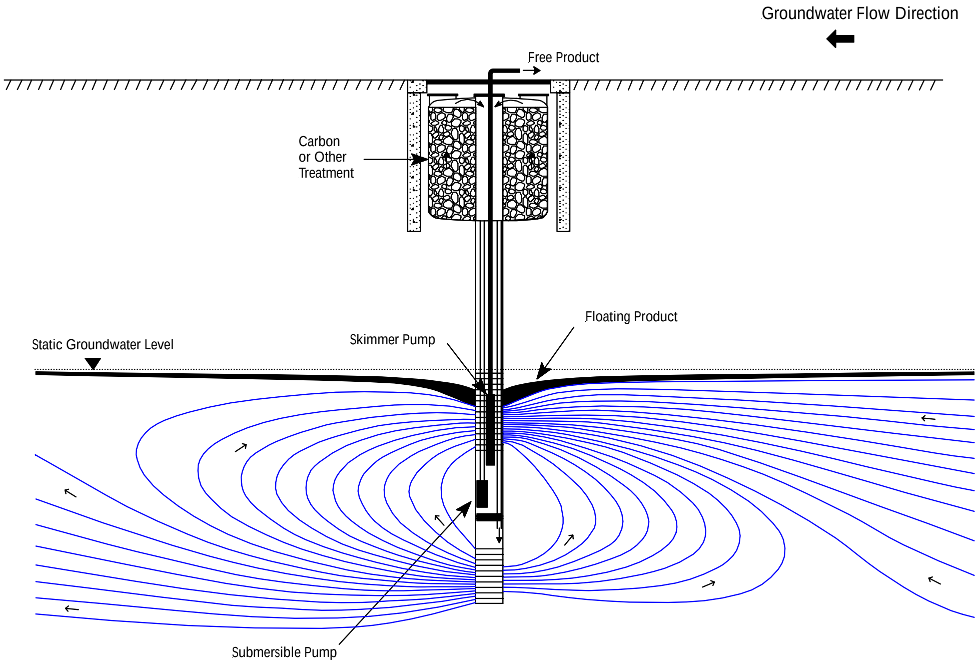
and then flows back into the aquifer through the sand pack and the aquifer materials.

- At the exit screen, higher than normal pressures are formed, resulting in higher head values near the well.
- The treated water flows outward from the well and upward under the influence of the vertical gradients created by the extraction process at the top of the well and the increased pressure at the outlet screen. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be more outward than upward.
- A recirculation zone is created that typically returns the majority of the treated water to the inlet screen. The shape and size of the treatment zone are largely determined by the treated thickness, the hydraulic gradient, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate.
- The water cycles through the treatment zone several times, on average, before escaping downgradient. The treatment process does not have to achieve final cleanup levels in a single pass, since the water will return for additional treatment. However, using activated carbon as an adsorptive medium, treatment is usually 100% in a single pass through the well.
- A skimmer pump is incorporated in the ISGR well, in an adjacent well in the same borehole, or in a nearby borehole.
- The ISGR treatment for dissolved contaminants and the skimmer pump for floating product removal can be operated independently or simultaneously at any time.
- There are no above-ground systems or equipment. Typically, the only above-ground appearance of an FPR system is a manhole with an adjacent power pole that has a utility meter and a control panel. A drum or tank to collect the recovered product can be located any convenient distance from the well.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing Floating Product Removal (FPR) systems. Well diameter, optimal pumping rate, number of wells and well placement, length of the inlet and outlet screens, special development procedures, controls and instrumentation, in-well plumbing configuration, constructability, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations and multiple rows of wells.

The major advantages of Floating Product Removal technology are discussed below. More detailed discussion of the advantages of FPR over air sparging and pump-and-treat technologies is provided.

FLOATING PRODUCT REMOVAL WELLS



Steve Wilhelm & Associates, Inc.

PATENT PENDING

MAJOR ADVANTAGES OF FLOATING PRODUCT REMOVAL WITH RECIRCULATING WELLS

NO SURFACE EQUIPMENT

- Constructed entirely below ground, ISGR systems take up no aboveground space. The only above ground equipment is a drum or other container for the free product.
- Silent operation.

FASTER

- Faster than a simple skimmer pump approach. The drawdown induced by the recirculating well results in much faster and more complete flow of the floating product to the FPR well, where it pools at an increased thickness for faster and more complete removal by the skimmer pump.
- Faster treatment for dissolved contaminants than pump and treat or air sparging. Much less than the 30 to 50 years commonly estimated for pump-and-treat systems. With floating product, pump-and-treat or air sparging/soil vapor extraction systems can run for decades before cleanup is completed.
- More vigorous than pump-and-treat or air sparging approaches. Pump-and-treat is passive in nature, extracting the water that is easiest to extract and waiting for contaminants to diffuse from lower permeability zones. Air sparging flows air through paths of least resistance, often treating only a portion of the water that flows through the treatment zone. However, re-circulating wells induce vertical gradients to vigorously circulate and treat *all of the water in the aquifer* multiple times.

CHEAPER

- Lower initial capital costs, lower maintenance costs, and faster cleanups result in lower life-cycle costs.
- Fewer wells. Well spacing typically 2 to 5 times depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.
- Lower pressures than air sparging systems, typically just the pressure required to pump the water to near ground surface. Because FPR involves pumping an incompressible fluid (water instead of air), energy costs are lower than for air sparging.

MORE FLEXIBLE

- Large well spacings at many sites allow great flexibility in placing wells. Placing wells at a gas station site, for example, can be quite flexible.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers, re-circulation patterns are enhanced by these typical real-world features.

- Pumping rates (skimmer pump and submersible pump) can be adjusted after installation to match actual aquifer response. Pumping rate and even screen placement can be modified to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or parts of a plume can be targeted.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels beyond the immediate vicinity of the wells. No re-injection problems. Eliminates the need for water treatment at the surface, with the attendant routine monitoring and reporting.
- No air emissions. Recirculating wells can be operated with zero discharge.

ADVANTAGES OF FLOATING PRODUCT REMOVAL TECHNOLOGY

Rapid Removal of Floating Product. Floating Product Removal technology uses a re-circulating well to create a large cone of depression around the borehole. The groundwater is usually depressed by several feet, creating a curved surface, rather like a funnel, that the floating product moves along as it flows toward the well. Unlike use of a skimmer pump without a depressed groundwater surface, the floating product can form and maintain a layer of several inches thickness at the skimmer pump, greatly increasing the rate of product removal. Removal of free product is by far the most direct and effective way to remediate a site with floating product. Transference of the free product to the dissolved phase (pump-and-treat) and transference to the vapor phase (air sparging/soil vapor extraction) are vastly less efficient means of removing the product. Pump-and-treat and air sparging/soil vapor extraction systems can run for years at floating product sites without significant removal of a thick floating layer. Pumping the product out in its free form is orders of magnitude more efficient. Floating Product Removal technology permits rapid removal of the floating layer. Complete cleanup can be achieved rapidly compared to pump-and-treat and air sparging/soil vapor extraction.

In-situ versus ex-situ. FPR is an in-situ treatment process that does not involve pumping the groundwater to the surface. The water remains within the well at all times, never penetrating the plane of the ground surface.

No Water Discharge Problems. Because FPR does not involve pumping groundwater to the surface, there is no treated water to release. Two-pump skimmer systems create large volumes of water that must be released, typically through an NPDES permit or to a municipal treatment plant. Such releases must be monitored, with periodic reporting. In some settings, it would not be possible to release the water, often because the local streams or the treatment plant could not handle the increased flows. At small sites, such as many gas stations, there is no room to handle the large quantities of water that would have to be treated and released. A polishing step, often with aqueous phase carbon, is sometimes required after stripping to meet the discharge requirements. Release is especially problematic if there are other contaminants or natural components of the groundwater (e.g., salt, radioactive components) that could not be released, either to streams or to a treatment plant. It is sometimes desirable to remove floating product and its dissolved constituents, and yet leave the groundwater with its other constituents in the aquifer, as can be done through FPR.

Point of Treatment. FPR technology accomplishes the treatment for dissolved contaminants within the well and then releases the treated water to the aquifer to re-circulate and bring more contaminants back to the treatment well.

Pump-and-treat systems accomplish the treatment step outside the well, usually in an aboveground treatment system specially designed for the site. Aboveground systems have several disadvantages, including aesthetic considerations, noise, space requirements, weatherization requirements, access limitations, and others.

Pumping and groundwater circulation. FPR technology pumps groundwater through the well, drawing water from the top of the aquifer, treating it, and releasing it to a lower level of the aquifer. The result is that the water moves outward from the well and then back in a torroidal circulation pattern. The water moves vertically through the aquifer under the influence of strong vertical gradients induced by the draw down and mounding created by the pumping and release. The treatment zone has a capture width that is similar to pump-and-treat capture zones. The capture width has to be determined for each site, but often is 2 to 5 times the distance between the inlet screen and the outlet screen. For a 50-foot depth of contamination, well spacings of 300 to 500 feet are theoretically possible, though more conservative designs (200 +/- feet) are typically used.

Pump-and-treat systems remove the water from the aquifer by drawing it into a pumped well and conveying it to the surface. Extraction preferentially removes water from those layers and zones of the aquifer that yield water most readily, the higher conductivity zones. Yet the higher conductivity zones are often the least contaminated. Removing water from the lower-flow, more stagnant zones of the aquifer would be preferable, once the permeable conduits have been cleaned, but there is no way to concentrate the pumping on those portions of the aquifer. Pump-and-treat systems, in effect, preferentially remove water from the least contaminated zones of an aquifer and continue to do so even after those zones have been cleaned.

More vigorous remediation. FPR technology circulates water through all zones of the aquifer by inducing vertical gradients and flows over a large treatment area.

By removing water from one level of the aquifer and releasing it to another level of the same aquifer, FPR induces vertical gradients and flows. The vertical gradients induce flows through the more stagnant parts of the aquifer and flush contaminants to higher flow zones. By pushing water through the more stagnant zones of the aquifer, FPR does not rely on diffusion to move trapped contaminants. Convection moves contaminants faster than diffusion, often orders of magnitude faster.

Pump-and-treat approaches rely primarily on diffusion to remove contaminants from the more stagnant zones in the aquifer. While diffusion eventually will move the contaminants to the higher conductivity zones, where pumping can remove them, diffusion processes are very slow when compared to convective flow processes. This problem is exacerbated for lower conductivity zones that are relatively thick. This is why pump-and-treat systems are often predicted to require 30+ years to achieve remediation goals. And during the entire 30+ years, enormous quantities of water have to be pumped and treated and monitored and released under permit.

Cheaper. FPR technology eliminates all aboveground systems, substituting a common submersible pump and a quantity of an adsorptive or reactive medium to remove the dissolved contaminants from the groundwater, and a skimmer pump to remove the floating product. FPR avoids the need for and the attendant costs of an NPDES permit or discharge to a treatment plant.

During its life cycle, any remediation system requires oversight, monitoring, maintenance, and periodic reporting. With life cycles extending to decades, pump-and-treat and air-sparging/soil-vapor-extraction approaches incur large costs for continuing these efforts.

Easier Placement. FPR systems can be placed nearly anywhere a drill rig can bore a hole. Because there is no aboveground equipment, except a drum or other container for the removed free product, the well can be placed even in high traffic areas, such as in an active driveway of a gas station. Vehicles of any kind can drive over and even park on the system without harm. FPR does not take up valuable parking or traffic space.

Thus, FPR is less expensive to install, cheaper to operate each month, and completes the remediation in a fraction of the time. All of this adds up to much lower costs than pump-and-treat or other approaches.

BLOWERLESS AIR SPARGING

Air Sparging With No Aboveground Blower System

Blowerless Air Sparging (BAS) is a simple patent-pending technology that sparges the aquifer with air (or other sparging fluid) as in traditional air sparging. BAS uses recirculating wells to accomplish the compression of the air and to deliver the air to the sparging depth. Recirculating wells enable BAS to treat large capture widths.

There are several differences between BAS and traditional air sparging:

- No blower system or other aboveground equipment. BAS uses no blower, compressor, or air pump of any kind; it uses no aboveground equipment other than a control panel.
- Power consumption is a small fraction of the power consumption of traditional air sparging. In a typical positive displacement blower system operating at 15 psig, more than 75% of the energy used is wasted, largely in generation of useless heat. In BAS, compression of the air is isothermal, eliminating the generation of waste heat.
- Sparging is possible at much greater depths. In traditional air sparging, sparging is limited to perhaps 20 feet below groundwater surface. With Blowerless Air Sparging, sparging depths of 100 feet below groundwater surface are possible, depending on depth to groundwater.
- Greater radius of influence. The radius of influence of sparging wells is difficult to establish in the field, but experiments tend to indicate 20 feet as the maximum in typical settings. Taking advantage of the large radius of influence of recirculating wells, with Blowerless Air Sparging, the sparging air is carried much farther from the well, greatly increasing well spacing over traditional air sparging. Far fewer wells are required.
- More effective stripping and aeration of the water. In traditional air sparging, the nature and effectiveness of the interaction of the water and the air are unknown because the interaction happens in the aquifer under unknown conditions. With Blowerless Air Sparging, the water and air are initially brought together in the well, where they are mixed under extremely vigorous conditions. Stripping and aeration of the water by the air are both highly effective.
- Less disruption of the aquifer. In traditional air sparging, large quantities of air are forced out into the aquifer, where the air displaces the water from some fraction of the porosity of the aquifer, thus reducing the available flow paths for the water. The air and water occupy different spaces in the aquifer. After a brief period of operation, it is often necessary to turn off the sparging air and allow the water to return to the flow paths from which it has been displaced (cycling). With Blowerless Air Sparging, much less air can be used ad still achieve the same level of effectiveness in stripping contaminants from the water and adding oxygen to the water. This also reduces the need to capture the sparging air with soil vapor extraction.

Dissolved contaminants (e.g., BTEX, MTBE) are removed from the groundwater by the stripping action of the air, which occurs both inside the well and in the aquifer. The groundwater is pumped more vigorously than in a traditional air sparging approach, circulated several times through a large treatment zone established around the BAS well, and treated for removal of contaminants and saturation of the water with oxygen during each of several passes through the well.

The entire process is completed below ground, with the only aboveground expression of the system being a small manhole cover and a power pole with a power meter and a small control panel. BAS systems can be located virtually anywhere a drill rig can drill a well, even in an active driveway or the middle of a busy street.

While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used. Figure 1 shows the basic configuration.

- The BAS well penetrates to the maximum depth of the dissolved contamination, or to a depth chosen to achieve a desired capture width. An inlet screen is set at or near the top of the groundwater.
- The BAS well incorporates a second screen, an outlet screen, usually at or near the bottom of the well.
- The inlet portion of the well is separated from the outlet portion by a packer.
- The water is pumped by a submersible pump (or other means) to a point above the static groundwater level, where its direction reverses and it begins to travel back down the well toward the outlet screen.
- As the water flows downward, a partial vacuum is formed in the down pipe.
- At a point along the downward path, a metered amount of air is admitted to the down pipe, where it mixes vigorously and thoroughly with the water.
- The water and air (bubble) mixture travel downward to the outlet portion of the well. As the water and air (bubble) mixture descend in the down pipe, the pressure increases to above atmospheric pressure, which increases the saturation concentration of oxygen in water, resulting in the water being oversaturated with oxygen when it reaches the outlet screen.
- The water and air (bubble) mixture flows through the outlet screen and into the aquifer through the sand pack and the aquifer materials.
- At the exit screen, higher than normal pressures are formed, resulting in higher head values near the well.
- The treated water, containing the dissolved oxygen (and other components of air), flows outward from the well and upward under the influence of the vertical gradients created by the extraction process at the top of the well. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be even more outward than upward.

- A recirculation zone is created that typically returns the majority of the treated water to the inlet screen. The treated depth, the hydraulic gradient, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate largely determine the shape and size of the treatment zone.
- As the water circulates upward through the aquifer, the pressure decreases. The excess air dissolved in the water due to the higher pressures in the lower region of the well effuses out of the water, turning the water a milky-white color. It is by this mechanism that sparging is effected at distances much greater than the 20 feet maximum typical of traditional air sparging wells.
- The water cycles through the treatment zone and the well several times, on average, before escaping down gradient.
- There are no above-ground systems or equipment. Typically, the only above-ground expression of a BAS system is a manhole with an adjacent power pole that has a utility meter and a small control panel.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing Blowerless Air Sparging (BAS) systems. Well diameter, optimal pumping rate, number of wells and well placement, length of the inlet and outlet screens, special development procedures, controls and instrumentation, in-well plumbing configuration, other pumping methods, constructability, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations and multiple rows of wells.

The major advantages of Blowerless Air Sparging technology are discussed below.

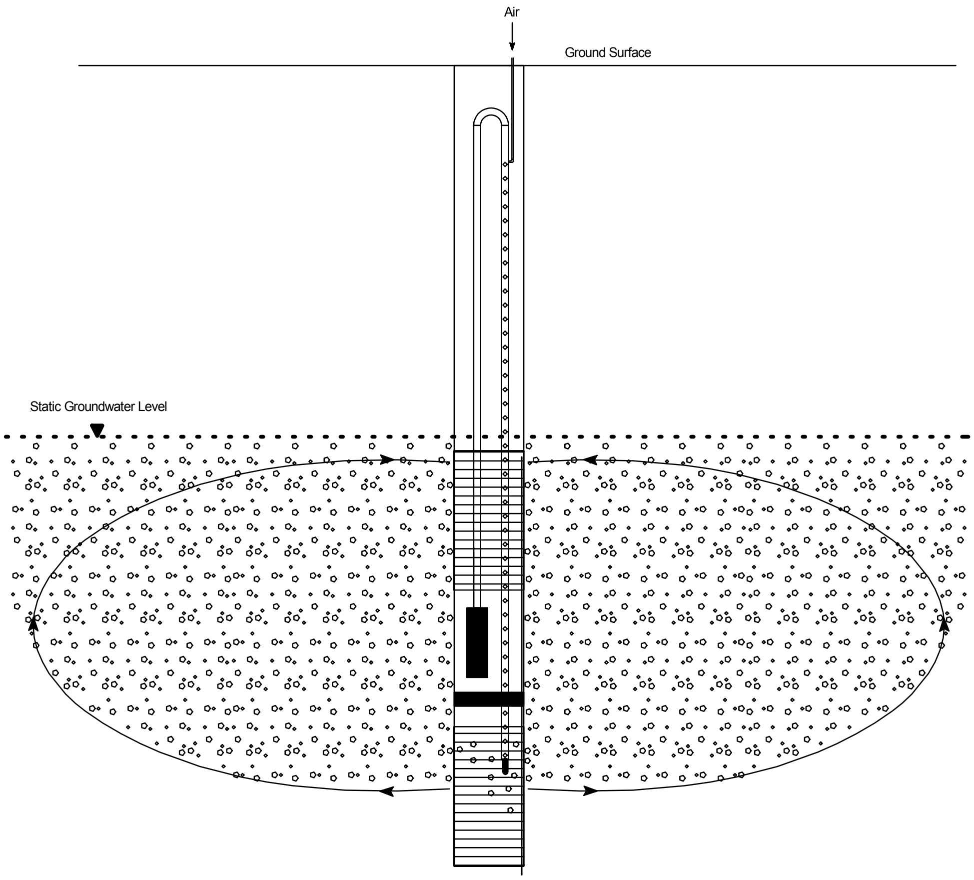


Figure 1 - Blowerless Air Sparging

PATENT PENDING

MAJOR ADVANTAGES OF BLOWERLESS AIR SPARGING WITH RECIRCULATING WELLS

NO SURFACE EQUIPMENT

- Constructed entirely belowground, BAS systems take up no aboveground space. The only aboveground equipment is a small control panel that operates the submersible pump.
- Silent operation.

FASTER

- Faster than traditional air sparging. Pumping the water in an established treatment cell around the well and treating it on several passes through the well is much more thorough than the largely unknowable treatment process of an air sparging well.
- More vigorous than traditional air sparging approaches. Air sparging flows air through paths of least resistance, often treating only a portion of the water that flows through the treatment zone. However, re-circulating wells induce vertical gradients to vigorously circulate and treat *all of the water in the aquifer* multiple times. While the interaction between the air and water in a traditional air sparging system is not well understood, or subject to modeling or calculation, the exact opposite is true for recirculating wells. The stripping and aeration processes are thorough and rapid, affecting all of the water in the treatment cell.

CHEAPER

- Lower initial capital costs, lower maintenance costs, and faster cleanups result in lower life-cycle costs.
- BAS wells are typically three-inch PVC construction, not much more expensive than traditional air sparging wells. But, the equipment in the well costs only a small fraction of the cost of a blower system in an enclosure.
- Fewer wells. Well spacing typically 2 to 5 times depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.
- Lower energy costs. Because BAS involves pumping an incompressible fluid (water instead of air), and because the air is compressed isothermally, energy costs are much lower than for traditional air sparging.

MORE FLEXIBLE

- Large well spacings at many sites allow great flexibility in placing wells. Placing wells at a gas station site, for example, can be quite flexible.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers as traditional air sparging systems can be, re-circulation patterns are enhanced by these typical real-world features.

- Pumping rates (skimmer pump and submersible pump) can be adjusted after installation to match actual aquifer response. Pumping rates can also be modified to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or parts of a plume can be targeted.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels beyond the immediate vicinity of the wells. No re-injection problems. Eliminates the need for water treatment at the surface, with the attendant routine monitoring and reporting.

BLOWERLESS IN-WELL STRIPPING

In-Well Stripping With No Aboveground Blower System

Blowerless In-Well Stripping (BIWS) is a simple patent-pending technology that strips the groundwater with air (or other sparging fluid) in the well, as in traditional in-well stripping. BIWS uses recirculating wells to accomplish the compression of the air and the stripping of the water. Recirculating wells enable BIWS to treat large capture widths.

There are two differences between blowerless in-well stripping and traditional in-well stripping:

- No blower system or other aboveground equipment. BIWS uses no blower, compressor, or air pump of any kind; unless the off-gas requires treatment, it uses no aboveground equipment other than a control panel.
- Power consumption is a small fraction of the power consumption of traditional in-well stripping. In-well stripping wells typically operate with positive displacement (PD) blowers. In a typical PD blower system operating at 15 psig, more than 75% of the energy used is wasted, largely in generation of useless heat. In BIWS, compression of the air is isothermal, eliminating the generation of waste heat.

  Typically an in-well stripping system uses 5 to 20 hp per well. Blowerless in-well stripping uses approximately one fifth the power that a traditional in-well stripping system uses.

The groundwater is circulated several times through the BIWS well and a large treatment zone established around the well, and treated for removal of contaminants (and saturation of the water with oxygen) during each of several passes through the well.

Dissolved volatile (and some semi-volatile) contaminants (e.g., BTEX, MTBE) are removed from the groundwater by the stripping action of the air, which occurs entirely inside the well.

The entire process is completed belowground, with the only aboveground expression of the system being a small manhole cover and a power pole with a power meter and a small control panel. BIWS systems can be located virtually anywhere a drill rig can drill a well, even in an active driveway or the middle of a busy street.

While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used. Figure 1 shows the basic configuration.

- The BIWS well penetrates to the maximum depth of the dissolved contamination, or to a depth chosen to achieve a desired capture width. An inlet screen is set at or near the top of the groundwater.

- The BIWS well incorporates a second screen, an outlet screen, usually at or near the bottom of the well.
- The inlet portion of the well is separated from the outlet portion by a packer.
- The water is pumped by a submersible pump (or other means) to a point above the static groundwater level, where its direction reverses and it begins to travel back down the well toward the outlet screen.
- As the water flows downward, a partial vacuum is formed in the down pipe.
- At a point along the downward path, a metered amount of air is admitted to the down pipe, where it mixes vigorously and thoroughly with the water.
- The water and air (bubble) mixture travel downward to the outlet portion of the well. As the water and air (bubble) mixture descend in the down pipe, the pressure increases to above atmospheric pressure, which increases the saturation concentration of oxygen in water, resulting in the water being oversaturated with oxygen (and other air components) when it reaches the outlet screen.
- The water and air (bubble) mixture separates below the packer. The air, laden with stripped contaminants, returns to the surface through a third pipe in the well. At the surface, the air is either released to the atmosphere or treated for removal of the contaminants. If the air is treated, it is returned to the well to serve again as the stripping fluid.
- At the exit screen, higher than normal pressures are formed, resulting in higher head values near the well.
- The treated water, containing the dissolved oxygen (and other components of air), flows outward from the well and upward under the influence of the vertical gradients created by the extraction process at the top of the well. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be even more outward than upward.
- A recirculation zone is created that typically returns the majority of the treated water to the inlet screen. The treated depth, the hydraulic gradient, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate largely determine the shape and size of the treatment zone.
- The water cycles through the treatment zone and the well several times, on average, before escaping down gradient. On each pass through the well, the water is stripped of contaminants.
- Unless the off-gas requires treatment, there are no aboveground systems or equipment. Typically, the only aboveground expression of a BIWS system is a manhole with an adjacent power pole that has a utility meter and a small control panel.

  If the off-gas requires treatment, a small vapor-phase carbon treatment system is used.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing Blowerless In-Well Stripping (BIWS) systems. Well diameter, optimal pumping rate, number of wells and well placement, length of the inlet and outlet screens, special development procedures, controls and instrumentation, in-well plumbing configuration, other pumping methods, constructability, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations and multiple rows of wells.

The major advantages of Blowerless In-Well Stripping technology are discussed below.

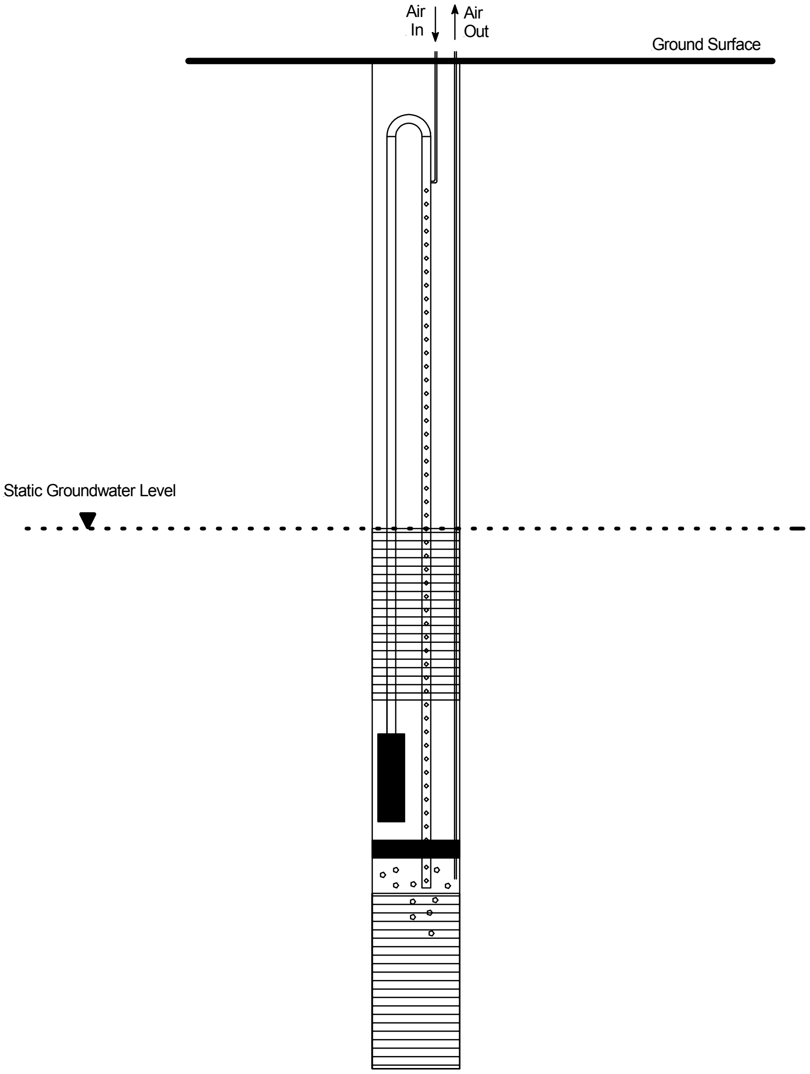


Figure 1 - Blowerless In-Well Stripping

PATENT PENDING

MAJOR ADVANTAGES OF BLOWERLESS IN-WELL STRIPPING WITH RECIRCULATING WELLS

NO SURFACE EQUIPMENT

- Constructed entirely belowground, BIWS systems take up no aboveground space. Unless the off-gas requires treatment, the only above ground equipment is a small control panel that operates the submersible pump.
- Silent operation.

FASTER

- Faster than air sparging. Pumping the water in an established treatment cell around the well and treating it on several passes through the well is much more thorough than the largely unknowable treatment process of an air sparging approach.
- More vigorous than traditional air sparging or pump-and-treat approaches. Air sparging flows air through paths of least resistance, often treating only a portion of the water that flows through the treatment zone. However, re-circulating wells induce vertical gradients to vigorously circulate and treat *all of the water in the aquifer* multiple times. While the interaction between the air and water in a traditional air sparging system is not well understood, or subject to modeling or calculation, the exact opposite is true for recirculating wells. The stripping and aeration processes are thorough and rapid, affecting all of the water in the treatment cell.

CHEAPER

- Lower initial capital costs, lower maintenance costs, and faster cleanups result in lower life-cycle costs.
- BIWS wells are typically three-inch PVC construction, not much more expensive than traditional air sparging wells. But, the equipment in the well costs only a small fraction of the cost of a blower system in an enclosure required by an air sparging approach.
- Fewer wells. Well spacing typically 2 to 5 times depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.
- Lower energy costs. Because BIWS involves pumping an incompressible fluid (water instead of air), and because the air is compressed isothermally, energy costs are much lower than for traditional in-well stripping.

MORE FLEXIBLE

- Large well spacings at many sites allow great flexibility in placing wells. Placing wells at a gas station site, for example, can be quite flexible.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers as traditional in-well stripping systems can be, re-circulation patterns are enhanced by these typical real-world features.

- The pumping rate can be adjusted after installation to match actual aquifer response. Pumping rate can be modified to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or parts of a plume can be targeted.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels beyond the immediate vicinity of the wells. No re-injection problems. Eliminates the need for water treatment at the surface, with the attendant routine monitoring and reporting.

DISSOLVED OXYGEN ENHANCEMENT

Full Oxygen Saturation of Aquifers With No Chemical Cost

Dissolved oxygen enhancement (DOE) is a simple patent-pending technology that saturates the groundwater with oxygen using a recirculating well and air as the oxygen source. It uses recirculating wells to treat a large capture width.

Unlike Oxygen Release Compound® and other chemical-based oxygenation approaches, DOE uses air as the oxygen source, making the oxygen essentially free.

Also unlike chemical-based approaches, which rely on the passive mechanisms of diffusion and dispersion to distribute the oxygen in the aquifer (typically unsuccessfully), DOE thoroughly mixes the oxygen into all of the water within a large and wide treatment cell by pumping all of the water through recirculating wells several times, oxygenating the water during each pass through the wells.

Important features of dissolved oxygen enhancement:

- No blower system or other aboveground equipment. DOE uses no blower, compressor, or air pump of any kind. Unless the very low-flow of off-gas (typically on the order of 0.1 cfm) requires treatment, DOE involves no aboveground equipment other than a control panel.
- Very low power consumption. Air sparging wells, which are often as useful for the aeration of the aquifer as for stripping contaminants, typically operate with positive displacement (PD) blowers. In a typical PD blower system operating at 15 psig, more than 75% of the energy used is wasted, largely in generation of useless heat. In DOE, compression of the air is isothermal, eliminating the generation of waste heat.

  Typically DOE systems run on a fraction of a horsepower per well.
- Free oxygen. Oxygen from ORC® or similar compounds can cost several dollars per pound. Using ORC® can cost tens of thousands to hundreds of thousands of dollars, essentially to purchase oxygen, which instead can be obtained free from the air.

  Using DOE, the cost of the oxygen delivered to the aquifer and dispersed thoroughly throughout the aquifer is simply the cost of running a small submersible pump.

  An example of the cost advantages over ORC® is shown in the table.

The groundwater is circulated several times through a DOE well and a large treatment zone established around the well, and is aerated to full oxygen saturation, and even greater than full saturation, during each of several passes through the well.

The entire process is completed below ground, with the only aboveground expression of the system being a small manhole cover and a power pole with a power meter and a small control panel. DOE systems can be located virtually anywhere a drill rig can drill a well, even in an active driveway or the middle of a busy street.

While there are numerous possible configurations, each optimized for a different set of geologic conditions, the most basic approach is also the most commonly used.   Figure 1 shows the basic configuration.

- The DOE well penetrates to the maximum depth of the dissolved contamination, or to a depth chosen to achieve a desired capture width. An inlet screen is set at or near the top of the groundwater.
- The DOE well incorporates a second screen, an outlet screen, usually at or near the bottom of the well.
- The inlet portion of the well is separated from the outlet portion by a packer.
- The water is pumped by a submersible pump (or other means) to a point above the static groundwater level, where its direction reverses and it begins to travel back down the well toward the outlet screen.
- As the water flows downward, a partial vacuum is formed in the down pipe.
- At a point along the downward path, a metered amount of air is admitted to the down pipe, where it mixes vigorously and thoroughly with the water.
- [Other gases than air can be used. Pure oxygen, for example can be used, though only rare situations might benefit from the added cost. Hydrogen can be added to the water very efficiently and effectively, to aid in anaerobic biodegradation of some contaminants. Other gases can be added as well, either alone or in combinations.]
- The water and air (bubble) mixture travel downward to the outlet portion of the well. As the water and air (bubble) mixture descend in the down pipe, the pressure increases to above atmospheric pressure, which increases the saturation concentration of oxygen in water, resulting in the water being oversaturated with oxygen (and other air components) when it reaches the outlet screen.
- The water and air (bubble) mixture separates below the packer. Any excess air returns to the surface through a third pipe in the well. Excess air returns to the surface bearing contaminants stripped from the water. At the surface, the air is either released to the atmosphere or treated for removal of the contaminants.
- At the exit screen, higher than normal pressures are formed from the release of the water back into the aquifer, resulting in higher head values near the well.
- The treated water, containing the dissolved oxygen (and other components of air), flows outward from the well and upward under the influence of the vertical gradients created by the extraction process at the top of the well. Because aquifer materials are typically anisotropic, allowing horizontal flows more readily than vertical flows, the flows tend to be even more outward than upward.

- A recirculation zone is created that typically returns the majority of the treated water to the inlet screen. The treated depth, the hydraulic gradient, the hydraulic conductivity, the anisotropy of the aquifer, and the pumping rate largely determine the shape and size of the treatment zone.
- The water cycles through the treatment zone and the well several times, on average, before escaping down gradient. On each pass through the well, the water is saturated or super-saturated with oxygen. (Less than saturation levels can also be used, where that would be beneficial.)
- Unless the off-gas requires treatment, there are no aboveground systems or equipment. Typically, the only aboveground expression of a DOE system is a manhole with an adjacent power pole that has a utility meter and a small control panel.

  If the off-gas requires treatment, a small vapor-phase carbon treatment system is used.

While the basic configuration and process are straightforward, even for this simplest case there are many considerations in designing and installing dissolved oxygen enhancement (DOE) systems. Well diameter, optimal pumping rate, number of wells and well placement, length of the inlet and outlet screens, special development procedures, controls and instrumentation, in-well plumbing configuration, other pumping methods, constructability, and many other factors must be addressed in developing a complete design. For more complex or challenging geology, there are additional considerations such as confined aquifer configurations and multiple rows of wells.

The major advantages of dissolved oxygen enhancement technology are discussed below.

COMPARISON OF PLUME CLEANUP COSTS
OXYGEN RELEASE COMPOUNDS vs. DISSOLVED OXYGEN ENHANCEMENT

THE PLUME

Plume Width (ft.)	200	
Plume Thickness (ft.)	65	
Plume Length (ft.)	500	
Porosity	0.3	
Plume Volume (Cu. Ft.)	1,950,000	
Plume Volume (Liters)	55,426,800	
Plume Volume (Gallons)	14,586,000	
Average Hydrocarbon Concentration (mg/L)	5	
Kilograms of Hydrocarbon Present	277	

OXYGEN RELEASE COMPOUND®

Kilograms of Oxygen Required	831	
Five Times Excess Oxygen (kg)	4157	
Kilograms of ORC® Required (10x)	41570	
Cost of ORC® per Kilogram	$ 17.60	
Cost of ORC®	$731,632	Cost of Oxygen

DISSOLVED OXYGEN ENHANCEMENT

Gallons of Air Required to Saturate Water Once	583,440	
Gallons of Air Required to Provide Five Times Excess Oxygen	4,272,364	
Saturation Level at Depth (mg/L)	30.6	
Gallons of Water to Pump	35,717,325	
Pumping Ratio (Pumping Volume/Plume Volume)	2.45	
Pumping Rate of Each DOE Well (gpm)	30	
Number of DOE Wells	6	
Days to Pump Plume Volume	138	
Horsepower Per Well	$ 0.25	
Electricity Cost (per kW-hr)	$ 0.10	
Operating Cost (Electricity)	$ 372	Cost of Oxygen

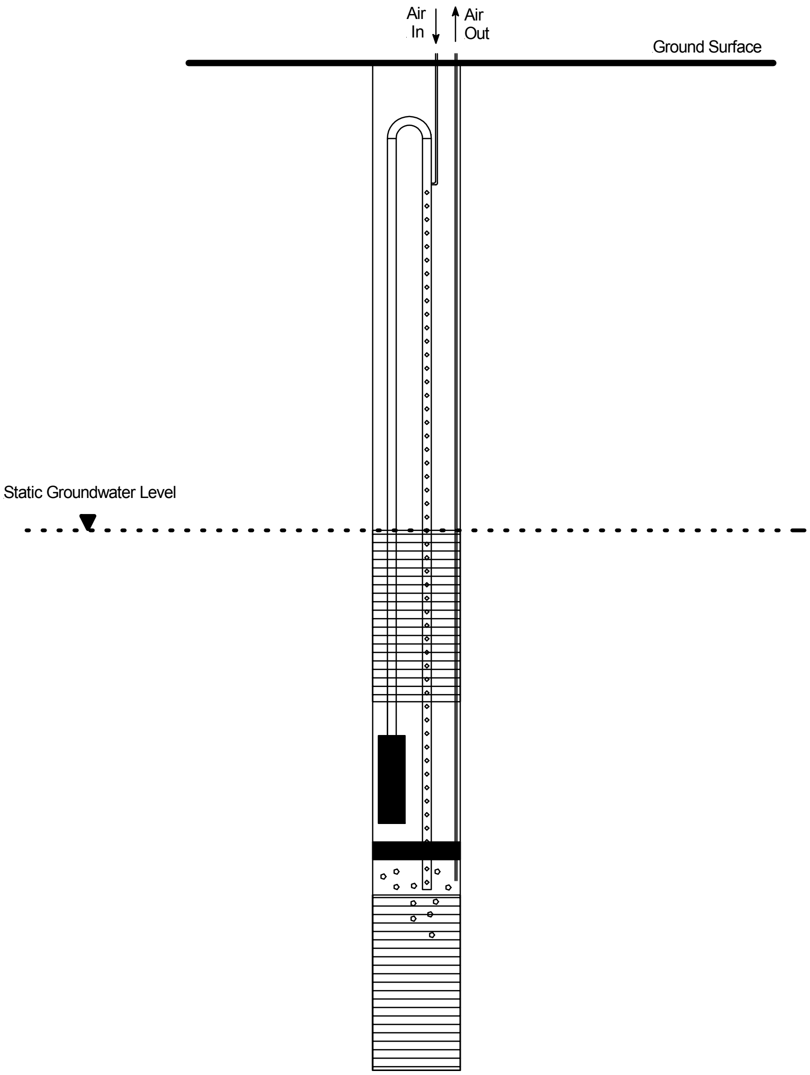


Figure 1 Dissolved Oxygen Enhancement PATENT PENDING

MAJOR ADVANTAGES OF DISSOLVED OXYGEN ENHANCEMENT WITH RECIRCULATING WELLS

NO SURFACE EQUIPMENT

- Constructed entirely belowground, DOE systems take up no aboveground space. The only aboveground equipment is a small control panel that operates the submersible pump.
- Silent operation.

FASTER

- Faster than air sparging or ORC®. Pumping the water in an established treatment cell around the well and oxygenating it on several passes through the well is much more thorough than the largely unknowable treatment process of an air sparging approach or the slow and uncertain dispersion and diffusion of ORC®.
- More vigorous than traditional air sparging or pump-and-treat approaches. Air sparging flows air through paths of least resistance, often treating only a portion of the water that flows through the treatment zone. However, re-circulating wells induce vertical gradients to vigorously circulate and treat all of the water in the aquifer multiple times. While the interaction between the air and water in a traditional air sparging system is not well understood, or subject to modeling or calculation, the exact opposite is true for recirculating wells. The pumping and aeration processes are thorough and rapid, affecting all of the water in the treatment cell.
- Active rather than passive treatment. ORC® is a passive approach that relies on natural aquifer flow to bring water to a well for treatment and relies on the passive mechanisms of dispersion and diffusion to distribute the evolved oxygen in the water. DOE actively pumps the water and thoroughly mixes the oxygen into the water.

CHEAPER

- Lower initial capital costs, low operation and maintenance costs, and faster cleanups result in lower life-cycle costs.
- DOE wells are typically three-inch PVC construction, not much more expensive than traditional air sparging wells or wells that might be used to introduce ORC®. But, the equipment in the well costs only a small fraction of the cost of a blower system in an enclosure required by an air sparging approach.
- Fewer wells than air sparging. Well spacing typically 2 to 5 times depth of contamination. At a site with 50 feet of saturated zone, well spacing can be 200+ feet.

- Lower energy costs. Because DOE involves pumping an incompressible fluid (water instead of air), and because the air that is compressed is compressed isothermally, energy costs are much lower than for traditional in-well sparging.
- The large savings of DOE over ORC® or other chemical-based approaches to oxygenating the groundwater are in the avoided costs of purchasing the chemicals that supply the oxygen. Rather than tens to hundreds of thousands of dollars to purchase what is instead available for free, oxygen, DOE uses a small amount of electricity and uses the free oxygen available from the air.

MORE FLEXIBLE

- Large well spacings at many sites allow great flexibility in placing wells. Placing wells at a gas station site, for example, can be quite flexible.
- Tolerant of variable geology. Rather than being impeded by thin silt lenses and discontinuous clay layers as traditional in-well stripping systems can be, re-circulation patterns are enhanced by these typical real-world features.
- The pumping rate can be adjusted after installation to match actual aquifer response. Pumping rates also can be changed to meet changing conditions during cleanup.
- Does not affect adjacent plumes. Because groundwater is not extracted, adjacent plumes are not drawn toward a re-circulating well. Specific plumes or parts of a plume can be targeted.
- Compatible with soil vapor extraction systems.

REGULATORY ADVANTAGES

- No extraction of groundwater. Does not lower groundwater levels beyond the immediate vicinity of the wells. No re-injection problems. Eliminates the need for water treatment at the surface, with the attendant routine monitoring and reporting.
- Does not add anything to the groundwater that is not already a natural component of the aquifer.

RECIRCULATING WELL TECHNOLOGY

DESIGN DATA FORM

Client____ Date____________________________

Contact Person_________________________________ Phone___________________________

Project Name / Location__________________________ Fax______________________________

If possible, please include:

Site map showing source(s), monitoring wells ☐ Yes ☐ No

Lithologic cross sections at right angles ☐ Yes ☐ No

Map showing horizontal and vertical distribution of contaminants in vadose zone ☐ Yes ☐ No

Map showing horizontal and vertical distribution of contaminants in saturated zone ☐ Yes ☐ No

Well logs, test borings ☐ Yes ☐ No

Treatment objective(s) ____

____

Contaminants of concern and their respective concentrations____________________________

____

Action levels for above contaminants____

____

Describe plume dimensions & depths____

____

Free product present?___________________________ Thickness______________________(ft)

LNAPLs / DNAPLs present? ____

Confined aquifer? ☐ Yes ☐ No If yes, please describe. ____________________

____

____

Saturated zone hydraulic conductivity _______________

Anisotropic ratio___________________

Depth to groundwater_______________ (ft bgs)

Seasonal variations in groundwater elevation ________________(ft)

Aquifer thickness (saturated depth)__________________ (ft) Porosity___________________

Plume thickness if less than saturated thickness_______________(ft)

Hydraulic gradient__________________ (ft / ft) Pump test results ________________(gpm) pH ______________________ Groundwater temperature______________________(^{0}C)

Dissolved iron______________ (ppm) Total iron _________________(ppm)

Other inorganics of concern ____(ppm)

Calcite precipitation potential for DDC (alkalinity, calcium, total dissolved solids, temperature, pH)

____

____

____

Off gas treatment requirements____

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Other relevant information____

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