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## Diesel concentration's influence on phenanthrene fate

Researchers from the United Kingdom investigated the process leading to biodegradation for multi-contaminant systems, in particular, polycyclic aromatic hydrocarbons (PAH) in the presence of a non-aqueous phase liquid (NAPL). "The persistence of pollutants in the environment is dependent on the intrinsic biodegradability of these pollutants and the ability of the indigenous microflora to adapt by developing metabolic capacities toward these pollutants... Given the occurrence of subsurface contamination through spillage of multi-component NAPLs, of which PAHs are a major component, there is a need for investigation to be carried out to elucidate the fate of hydrophobic organic compounds (HOCs) in multiple contaminant systems where compounds are of dissimilar classes." The researchers investigated the relationship of diesel concentration to the fate of [ $^{14}\text{C}$ ]phenanthrene and "assessed the temporal development of catabolic activity and the impact of these co-contaminant mixtures on the soil microflora" (Swindell and Reid, 2006).

### Materials and methods

Scientists employed chemicals and products including:

- phenanthrene
- [ $^{14}\text{C}$ ]phenanthrene
- cyclohexamide
- hydroxypropyl- $\beta$ -cyclodextrin (HPDC)
- toluene
- GF/A filter paper
- oxidizer scintillation cocktails
- micro agar
- phosphate-buffered saline (PBS)

Swindell and Reid (2006) collected sandy loam soil from a pasture. The soil was air-dried, sieved, weighed and measured for pH and particle size distribution. Scientists then spiked and rehydrated the soil to 65 percent water holding capacity (WHC) and placed it in a beaker. They added [ $^{12}\text{C}$ ]phenanthrene and [ $^{14}\text{C}$ ]phenanthrene, prepared in toluene, to the water. They also added diesel. Additional air-dried soil "was added to the resulting solution in increments of 50 to 100 g and thoroughly mixed using a spatula. Control treatments containing only single contaminants were also produced, as were blanks that had not been augmented with contaminants." Researchers stored treatments in glass jars and aged them in the dark at 15°C for 1, 50, 100 and 225 days. After aging, the soils were analyzed. "The soils were not sterilized to allow both degradation and sequestration to occur in parallel."

Scientists determined total [ $^{14}\text{C}$ ]phenanthrene activity by sample oxidation in which soil was packed into cellulose combustion cones and combusted using a Packard 307 sample oxidizer. Resulting solutions were counted on a liquid scintillation counter. They determined the bioavailability of [ $^{14}\text{C}$ ]phenanthrene to microorganisms using respirometer mineralization assays. The respirometers consisted of 250-ml reagent bottles, Teflon-lined screw cap, and  $\text{CO}_2$  trap made of 7-ml glass scintillation vial, sodium hydroxide, and filter paper.

Scientists added an inoculum of catabolically active *Pseudomonas sp.*, a phenanthrene-degrading microorganism isolated from PAH-contaminated soil, to the slurries at the start of the assay. The strain was grown in isolation on minimal basal salts (MBS)-phenanthrene agar plates and incubated for a week at 22°C. Following 4 days of incubation, scientists centrifuged the culture. "The supernatant was poured off and the cells were resuspended in fresh MBS (repeated

twice) to ensure thorough washing of the cells. The respirometers were agitated on a flat bed rotary shaker" and as "soil-associated [ $^{14}\text{C}$ ]phenanthrene was mineralized to produce  $^{14}\text{CO}_2$ , the gas was trapped upon reaction with the NaOH contained within the 7-ml vial. The  $\text{CO}_2$  traps were changed periodically over an assay time of 192 hours." They filled removal vials "with scintillation liquid and their  $^{14}\text{C}$ -labelled activity [was] assessed by liquid scintillation counting." Scientists considered the values for bioavailability to "refer to the percent mineralized relative to remaining [ $^{14}\text{C}$ ]phenanthrene activity in the treatments at the time of sampling" (Swindell and Reid, 2006).

Scientists then determined the total culturable bacterial cells using the colony forming units (CFU) after 225 days of soil-contaminant contact time. To extract the microorganisms, they added phosphate-buffered solution (PBS) to treated soil in flasks and shook the flasks overnight. "The extracted microorganisms were diluted in PBS by progressive 10-fold steps. Aliquots of each dilution were then inoculated onto sterile nutrient agar plates augmented with cyclohexamide to inhibit fungal growth. The plates were produced in triplicate and incubated at 22°C for 7 days, after which time colonies were enumerated. The phenanthrene catabolic activity of the soils' indigenous microbial communities in each different treatment was determined using respirometers," using the same treatment as the soil-spiking section. "However, phenanthrene was added to the soils at time of spiking as [ $^{12}\text{C}$ ]phenanthrene only. These soils were incubated in the dark at 15°C for 1, 50, 100 and 225 days. Following incubation, the catabolic activity in the soils was assessed by respirometry." The same procedure was used for these soils as those previously described; however, no microbial inoculums were added. Mineralization assays were run in triplicate (Swindell and Reid, 2006).

## Results and discussion

### Phenanthrene

Swindell and Reid (2006) found:

- biphasic loss, “whereby an initial rapid phase of loss was followed by a much slower phase of loss” in four treatments
- general trend of increasing loss with increasing diesel concentration
- no significant difference between treatments D1 and D2
- at 50 days, only D1 was not significantly different from the control (D0)
- at 100 and 225 days, all treatments were significantly different from the phenanthrene control
- treatments D3 and D4 were significantly different from D0 and the other treatments throughout the experiment

Based on these results, the researchers suggested that, “This enhancement in the temporal loss of phenanthrene with increasing diesel concentration could be due to both competitive sorption for soil sorption sites and to a lesser extent to displacement of phenanthrene from soil sorption sites by diesel. As a consequence of these processes, phenanthrene availability would be higher and these more available molecules more readily biodegraded.” Alternatively, “the enhancement in temporal loss of phenanthrene with increasing diesel concentration could be due to an increase in general microbial activity resulting in increased phenanthrene degradation” (Swindell and Reid, 2006).

### Bioavailability

Scientists observed equivalent mineralization for all treatments after the first day of incubation; “however, after 50 days of incubation the D0, D1, D2 and D3 treatments showed a significant decrease in the bioavailable fractions of soil-associated phenanthrene

compared to the 1-day values. These results are in keeping with the observed loss in these treatments. Similarly, as aging progressed, the rate of decline in mineralization decreased.” They suggested this loss with increasing diesel concentrations could occur at the expense of the bioavailable pool. Therefore, “above a threshold value, between 2,000 and 20,000 mg kg<sup>-1</sup> in this study, partitioning of phenanthrene from the NAPL to the aqueous phase was reduced, as would be expected at concentrations consistent with the critical separate phase concentration (CSPC)” (Swindell and Reid, 2006).

### Total culturable bacterial cell numbers

Researchers used cell counts “to examine the effects of increasing diesel concentrations on the total bacterial cell numbers.” While these numbers were relative, they could be used to compare between samples. “In the two treatments with no diesel (blank and D0), the total cell numbers were roughly equivalent and not statistically different. This value was about half the value of the D1, D control, D2 and D3 treatments. These results suggest that phenanthrene did not influence total culturable cell numbers in the D control and D2 treatments as comparable CFUs were observed. These values were significantly different from the blank treatment. Thus, these results suggested that diesel did increase CFUs.” In addition, for D4, “conditions may have led to a shift in the microbial community from autochthonous to zymogenous diesel utilizing microorganisms... It follows that the lower extent of phenanthrene loss in the D4 treatment may have been due to a lack of active phenanthrene-utilizing microorganisms. This possibility was investigated through respirometer assays” (Swindell and Reid, 2006).

### Phenanthrene catabolic induction

Swindell and Reid (2006) also found phenanthrene catabolic activities to be high after the first day of incubation for all the treatments. They noted, “for each aging time, there was no significant difference in the catabolic activities for treatments D0 through D3. Thus diesel, applied at a range of concentrations, did not enhance the catabolic activity with respect to phenanthrene in this study. Furthermore...diesel did not reduce the lag phase nor did it increase the rates and extent of phenanthrene mineralization. In the D4 treatment, the extent of phenanthrene mineralization was significantly lower than the other treatments.” They suggested “that the extensive loss observed in treatments D0 to D3 resulted from the high phenanthrene catabolism in these treatments, while the low phenanthrene loss in the D4 treatment could be attributed to low phenanthrene catabolic activity in addition to the physical/chemical factors already discussed.” They reported that D4 also “showed a general decrease in extent of phenanthrene mineralization with time” which could be due to “nutrient limitation of the phenanthrene degraders at high organic carbon concentration.” They surmised, “after this extended period of incubation under low catabolic activity,” that an endpoint was achieved in the D4 treatment that was comparable to those in the D0 to D3 treatments.

## Conclusion

Researchers concluded that their data suggested “diesel concentration did affect the fate of [<sup>12</sup>C]phenanthrene. Results suggested that low diesel concentration (up to 2000 mg kg<sup>-1</sup>) had a positive effect on phenanthrene loss, while high diesel concentration (20,000 mg kg<sup>-1</sup>) retarded phenanthrene loss. It is proposed that diesel affected both the sorption of phenanthrene, most notably above a CSPC between 2000 and 20,000 mg kg<sup>-1</sup> diesel, and the functional activity

of the microbial community. These results underline the fact that the mixed compound systems influence compound sorption/desorption and partitioning. As a consequence, contaminant persistence and risk is altered" (Swindell and Reid, 2006).

## Reference

Swindell, A.L. and B.J. Reid, "Influence of diesel concentration on the fate of phenanthrene in soil," *Environmental Pollution*, Vol. 140, 2006; [www.elsevier.com/locate/envpol](http://www.elsevier.com/locate/envpol)

UTTU thanks Dr. Brian Reid, [b.reid@uea.ac.uk](mailto:b.reid@uea.ac.uk), for providing this article.



## Shop-fabricated secondary containment steel storage tanks

By Wayne B. Geyer

### Reasons for using secondary containment

Secondary containment tanks were first introduced in the United States in the early 1980s. Since that time, technological advances have accelerated and acceptance has become nearly universal from the regulated community. Meanwhile, standards, codes and regulations, developed and revised numerous times over the past 20 years, address both underground and aboveground storage tanks. This article will provide background and an update on the following:

- Underground storage tank (UST) secondary containment technology
- Integrity verification of secondary containment
- Aboveground storage tank (AST) secondary containment technology
- Standards and codes

- Reasons for using secondary containment

### Underground storage tank (UST) secondary containment technology

The first secondary containment underground storage tanks, introduced in California, were constructed of two walls of steel physically separated with angles or channels to create an annular interstice several inches wide. Initial regulations encouraged secondary containment to hold 110 percent of the primary tank capacity. Designated "Type II" by Underwriters Laboratories in 1985 for their double-walled construction, these tanks were both costly and bulky - leading the industry to explore other methods. One early outcome was recognition that 100 percent containment was sufficient to hold the entire contents of the primary tank in the unlikely event of a catastrophic failure.

In Germany, secondary containment tank technology had already evolved to facilitate environmental safety needs and requirements. The Steel Tank Institute (STI) introduced the first American national construction standard for secondary containment tanks in 1984, based in part on this German technology. Coined "Type I" steel secondary containment tank by Underwriters Laboratories, the outer steel wall was intimately wrapped over the primary tank. The two walls could act as a single structural unit, reducing fabrication (and end user) costs.

Any product or groundwater that penetrated into the interstice would drain to a monitoring port for detection. STI's philosophy was to give tank users flexibility to determine the best type of technology to detect liquids in the interstice and to enable such technology to develop. Thus, the STI Dual Wall Tank Standard gave limited specification to leak detection, but rather focused on the need for the tank construction to incorporate monitoring accessibility.

Several years later, the jacketed steel tank containment system was introduced. Nomenclature was a major issue, but over time, the jacketed tank meant that the construction used plastic rather than steel for the outer containment. Having been used as a means of corrosion control for many years (via bonding of the fiberglass-reinforced plastic to a steel tank to form a coating and via non-metallic tank construction), fiberglass-reinforced plastic was one such system that was separated from the steel primary tank to create an interstitial space to monitor and contain releases. The fiberglass-reinforced plastic is considered a thermoset plastic. Alternative jacketed steel tank systems utilized various thermoplastics as the outer wall material. With the jacketed tank, the jacket material must also be capable of withstanding various chemical/soil environments.

With over half a billion gallons of steel secondary containment tank storage capacity installed in the United States, the environmental benefits have clearly been proven. In addition, according to the U.S. Environmental Protection Agency, all secondary contained steel tanks installed in the United States must also have some form of corrosion control technology applied to the secondary containment. (See EPA Technical Compendium 18 for how this impacts EPA monitoring requirements of cathodic protected tanks.) Construction standards developed by Steel Tank Institute and Underwriters Laboratories have given the tank builder and user multiple options to comply with this requirement.

Since U.S. EPA regulations were first promulgated in 1988, the installation of secondary contained tanks as a percentage of all steel USTs installed has increased three to four-fold. This rate of increase is mirrored in STI's verified database of secondary containment tanks constructed to STI standards. Similarly, double-wall fiberglass tanks likely comprise the majority share of

all-FRP USTs. Secondary containment has made even greater strides in other countries – for example, Mexico, much of Europe and portions of Canada require that all USTs have secondary containment.

Similar acceptance and technological advances have developed with pipe systems, sumps and dispenser boxes. Today, installation of secondary contained pipe has become the norm at most service stations.

### How is the integrity of secondary containment verified?

The secondary containment must be sturdy to assure that it will not lose its integrity after it has been built and tested at a fabrication facility. A tank may get shipped long distances. It may sit in storage at a job site, or alternatively, be moved around to facilitate construction. The tank gets lowered into an excavation and backfill is poured around and over the tank.

One common technology used today to verify containment integrity is a vacuum, factory-installed in the interstice of shop-fabricated steel USTs and shipped to the installation site for tightness/integrity verification during storage and installation. By verifying that the interstice maintains the factory vacuum before backfilling the tank, the installer need not conduct a separate air pressure test of the primary tank and the interstice. The vacuum already ensures that both the primary and secondary vessels are tight. After the tank has been installed and the integrity of the tank is assured, the system is backfilled. Many installers release the vacuum and place a release detection probe into the secondary containment monitor opening. In Europe and soon to be required in California, a vacuum or pressure must be maintained within the interstice during operations as well.

### Aboveground storage tank (UST) secondary containment technology

Since 1990, there has been a tremendous movement toward the installation of secondary contained aboveground storage tanks. As old tank systems were removed from the ground due to EPA regulation, tank owners looked to alternative storage options. One option was to place the tank aboveground, where visual leak detection became possible. Common applications included motor vehicle fueling for private fleets, airports, and fuel for either back-up power or heating.

As the 1990s proceeded, environmental regulations for aboveground storage tanks were reinforced nationally and became promulgated in various states and regions. Wanting to keep the containment impermeable until a spill or release could be removed, many operators considered an impermeable outer containment such as steel for the primary shop-built tank. Fire codes also gave recognition to shop-built secondary containment tanks as an alternative spill control method to diking or remote impounding.

Fire codes also became concerned with the potential hazards of motor vehicle fueling operations from aboveground tanks. As a result, some codes created new tank construction methods, such as protected tanks. A protected tank included insulation to protect the tank, along with an emergency vent, during a very hot petroleum pool fire. The codes required protected tanks to be secondary containment tanks.

As a result, aboveground tanks were shipped as Type I double-wall tank construction, as protected tank construction and as tanks inside a steel dike or bund. Some fabricators indicated that their aboveground tank orders included some form of secondary containment at least 50% of the time, whereas such construction was nearly non-existent in 1990.

### Code requirements and third party test laboratories for tank construction

#### *Underwriters Laboratories*

Concurrent with the industry development of secondary containment, Underwriters Laboratories (UL) in 1985 adopted secondary containment into its UL 58 standard. In 1989, UL issued UL 1746, a corrosion control standard for steel-jacketed tanks that also incorporates a qualification test protocol for jacketed tanks. In 1992, UL expanded its UL 142 standard for construction of tanks storing flammable and combustible liquids to include secondary containment options. The protected tank standard, UL 2085, was published in 1993. Since then, UL has also created standards for fire-resistant tanks and vault construction that enable an aboveground tank to be installed and subsequently inspected.

#### *Southwest Research Institute*

Southwest Research Institute has also created standards for protected tanks, SwRI 93-01, and fire-resistant tanks, SwRI 97-04.

#### *National Fire Protection Association*

The National Fire Protection Association's NFPA 30, the Flammable and Combustible Liquids Code, references UL 58, UL 1746, UL 142, and UL 2085 construction standards, as well as the use of air pressure or vacuum as a means to ensure that the shop-fabricated tank and its containment are tight before tank use to permanently store flammable liquids. NFPA 30 requires all tanks to be tested after installation and before being placed into service – as well as after repairs, relocation or when suspected of leaking.

#### *Environmental Protection Agency*

The U.S. Environmental Protection Agency (EPA) recognized secondary containment as one of the solutions to the problem of storage tank leaks. In July of

1986, the EPA issued in the Federal Register their final rule for hazardous waste storage, 40 CFR Part 265, Sub-Part J. This rule requires that double-wall tanks (1) be designed as an integral structure so that any release from the inner tank would be contained by the outer shell, (2) protect the primary tank from corrosion, and (3) be provided with a built-in continuous leak detection system capable of detecting a release within 24 hours.

In September of 1988, EPA published further rules on underground storage tanks as 40 CFR Part 280. Under this rule, all hazardous stored substances required secondary containment, mirroring the hazardous waste rule, except it further required the secondary containment system to be checked for evidence of release at least every 30 days. However, petroleum UST systems were exempted from the secondary containment requirement, even though petroleum storage systems accounted for approximately 90 percent of all USTs. The EPA focused its regulation on corrosion protection, overfill prevention, and release detection as its primary means to protect the environment. With regulated tanks incorporating these measures, EPA expected that single-wall systems would adequately protect human health and the environment.

#### *State and local jurisdictions*

In the early 1980s, several local and state jurisdictions were beginning to investigate tank leakage and promulgate rules for hazardous wastes and chemical storage. A number of states have imposed their own requirements for secondary containment systems of underground storage tanks, with California being one of the first to require secondary containment for storage of petroleum liquids. Florida and most of the New England states also require secondary containment for all USTs, while other states such as Michigan, Nebraska and New Jersey mandate secondary containment for USTs in sensitive areas such as near certain public water supplies and aquifers.

Particularly noteworthy are very recent California regulations stipulating that all UST systems (tanks and piping) installed on or after July 1, 2003 must be impervious to the liquid and vapor of the contained substance [H&S Code §25290.2(a)], a requirement readily met by steel with its innate impermeability to both liquid and vapor. California's H&S Code was also revised to require that the interstitial space of underground tanks and product piping installed on or after July 1, 2004 be maintained under constant vacuum or pressure, and that a breach in the primary or secondary containment be detected before the liquid or vapor of the stored substance escapes to the environment [H&S Code §25290.1(e)]. Tanks installed prior to 7/1/04 must still have a continuous monitoring system, although the code is a bit less specific, stating that the continuous monitoring system be "capable of detecting the entry of the hazardous substance stored in the primary containment into the secondary containment." [H&S Code §25290.2(d); CCR §2630(d)] California further requires tanks to be tested every three years to verify integrity of containment. Dispenser boxes and sumps must be integrity tested every three years. However, UST components monitored continuously using vacuum, pressure, or interstitial liquid level measurement methods are not subject to further testing or evaluation.

#### **Is secondary containment worth it?**

Regardless of any mandates, secondary containment is a logical choice for UST owners or operators. From a pure safety perspective, secondary containment provides that extra insurance against releases of contaminants into the soil or groundwater and prevents release of flammable liquids from draining into buildings or public ways and causing a fire or explosion.

The benefits extend beyond safety stewardship. From a straightforward financial analysis, there

are numerous costs – potentially devastating to a business – associated with product releases into soil or groundwater: fines, cleanup costs, report writing, lawsuits, and business interruption. And in the event that the tank was improperly installed or maintained, secondary containment provides an added level of protection. Simply put, secondary containment offers peace of mind to the tank owner.

Further, the cost of a secondary containment system does not necessarily double the cost of the installed tank system – far from it! Installation and labor costs account for a significant portion of a new installation. The labor to install either single-wall or secondary contained tanks and piping will be similar.

Given the significant advances in secondary containment options over the past 20 years, tank specifiers and owners have a wide range of choices to consider. But no matter which technology is chosen, secondary containment is a prudent decision.

#### **Reference**

Geyer, Wayne B., "Shop-fabricated secondary containment steel storage tanks," *Petroleum Equipment & Technology*, January 2004.

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## Optimizing unconfined aquifer remediation

Scientists presented a hybrid algorithm, “integrating a genetic algorithm (GA) and constrained differential dynamic programming (CDDP), to achieve remediation planning for an unconfined aquifer” (Hsiao and Chang, 2005). Unconfined aquifers are particularly susceptible to contamination by surface sources because they lack an upper confining layer and are near the ground surface. The scientists were interested in determining the optimal modes of remediation in terms of effectiveness and cost. They examined the cost of pump-and-treat systems because they are the most common remediation technique for contaminated aquifers.

The researchers reported that a GA system is appealing because “it does not require the objective function to be differentiable. It can thus easily incorporate the fixed costs associated with ground water remediation. However, applying only this method to solve time-varying policies would drastically increase the computational resources required.” They thus combined a GA with CDDP in which a ground water simulator was embedded (Hsiao and Chang, 2005).

### Model formulation

Scientists considered three types of decision variables:

- number of extraction wells
- location of well installations
- well pumping rate

Hsiao and Chang (2005) sought to reduce total remediation costs when using pump and treat remediation for an unconfined aquifer. The costs they considered for this type of remediation included:

- fixed costs, such as well installation

- operating costs, such as those associated with the time-varying pumping rates

Scientists formulated equations represented in GA and CDDP that considered the following variables:

- the set of indexes that define candidate locations of wells within the aquifer
- possible network alternatives
- hydraulic head of groundwater
- the set of observation wells, constant
- time varying pumping policy
- coefficients used to convert the well installation cost, the treatment cost, and the operating cost into monetary values, as constants
- well depth in a network design, constant
- the maximum allowable concentration of contaminants, constant
- the maximum allowable total pumping rate from all extraction wells, constant

One equation yielded the total cost, another the water quality standard at the end of each planning period, while another specified the capacity constraints on each well (Hsiao and Chang, 2005).

The total cost equation’s objective function was mixed integer and nonlinear. Scientists therefore defined their ground water remediation model by these equations, which represented a mixed-integer, time-varying optimization problem. The cost equation first considered “the cost of installing a well for pumping. The installations of wells are discrete operations that depend on binary variables in the optimization model.” The cost equation secondly considered the operating cost, “which includes the pumping and treatment costs. These costs are continuous functions of the control variables and are separable functions in each time stage. In contrast, the fixed cost indicated by the first component is nonseparable” (Hsiao and Chang, 2005).

They created a hybrid algorithm in order to solve for the aforementioned equations, which incorporated GA and CDDP (GCDDP). This integrated approach allowed GA to be used to determine the optimal network design, such as the number and location of wells, “while CDDP was used to calculate the optimal pumping policy associated with each network design” (Hsiao and Chang, 2005).

### Encoding and decoding chromosomes

Hsiao and Chang (2005) explained, “GA uses a binary string (also referred to as a chromosome) to encode a trial solution; the string comprises numerous binary bits. In this investigation, a binary representation is mapped to real-world locations of wells; each bit in a chromosome is associated with a candidate site, and the length of the chromosome equals the total number of candidate sites available for installing wells. If the value of a bit is 1, then a well will be installed at the associated candidate site; otherwise, the value of a bit is 0, and no well is installed.” They used 91 nodes, 24 candidate well sites, and 17 observation wells as a part of the finite-element mesh and assumed that the optimal network would be symmetrical. “This assumption reduces the number of combinations of network configurations in GA and the computational effort... The chromosome can be easily encoded and decoded since the well selection is binary.”

### Chromosome fitness

To evaluate chromosome fitness, researchers used an algorithm where CDDP was embedded in GA “to compute the optimal operating costs of a potential network alternative (represented by a chromosome). The CDDP used herein modifies the successive approximation linear quadratic regulator algorithm (SALQR). The SALQR algorithm incorporates the water quality and extraction constraints to solve the optimization problem as an unconstrained one. This

study employs a penalty function to consider the water quality constraints...and applies quadratic programming at each stage in the backward and forward sweep of CDDP to handle the control constraints." The researchers assumed all pumping wells to have rates of  $0.1 \text{ m}^3/\text{s}$  as an initial nominal policy for all chromosomes. Researchers considered chromosome fitness to be a function of its optimal total cost where a higher total cost corresponds to a lower fitness (Hsiao and Chang, 2005).

## Results

### *Fixed costs*

For fixed costs in unconfined aquifer remediation, researchers determined that the number of wells decreases as the unit fixed cost increases from \$0 to \$240/m while the operating costs increase with the unit fixed cost. They found that an optimal design includes seven wells when the fixed cost is zero and two wells when the unit fixed cost is \$240/m. In this design, required pumping rates are distributed evenly among wells, reducing total drawdown and operation costs. Researchers reported that the minimum total pumping volume of the wells was 39.74 L/s during the simulation period in the case of zero fixed cost and 583.17 L/s during the simulation period when the unit fixed cost was \$240/m. Therefore, "an optimal design tends to include wells that pump at low rates if the fixed cost is neglected" (Hsiao and Chang, 2005).

As a standard for comparison, scientists also evaluated the total cost of the design with zero fixed cost by adding the calculated operating costs to the fixed costs. Fixed costs were estimated by multiplying the well depth by the unit fixed cost. They determined that the total cost of the design without fixed cost was 47.24% higher than that of the design with fixed costs, which was \$240/m. "Accordingly, a significant total cost saving can be realized by applying the novel GCDDP algorithm and

considering the fixed cost in the design process" (Hsiao and Chang, 2005).

Scientists used the optimal network design and pollutant concentration distribution at the end of the planning period where fixed costs were \$60 and \$240/m to determine "that as the plume moves from west to east, the pumping wells in the western region are better able to remove the contaminant. The hydraulic head of the western region is higher than that of the eastern region. Therefore, the pumping cost of the former well is lower. Consequently, pumping wells with uniform unit fixed costs are more likely to be situated in the west" (Hsiao and Chang, 2005).

### *Confined versus unconfined*

Hsiao and Chang (2005) further examined the network design for an unconfined aquifer. "The nonlinearity of the unconfined transition equation complicates the simulation and the associated calculation on which the CDDP algorithm depends. Therefore, an approximate confined transition equation is commonly embedded into the management model to simulate the ground water flow and contaminant transport of an unconfined aquifer in order to simplify the computation. However, this approximation can generate a situation in which the optimal design, including the pumping rates obtained using an embedded confined transition equation, fails to meet concentration constraints according to an unconfined simulation model." Their comparison included the following:

- "An unconfined aquifer remediation problem is solved using the embedded unconfined transition equation.
- "An unconfined aquifer remediation problem is solved using the embedded confined transition equation, wherein the initial hydraulic head of the unconfined aquifer is applied as the thickness of the

confined simulator."

- "An unconfined aquifer simulation is performed using the optimal pumping policy generated from the unconfined aquifer remediation problem using the embedded confined transition equation" (Hsiao and Chang, 2005).

The scientists determined the optimal locations of each pumping well with the embedded, confined, and unconfined transition equations. These locations differed significantly. They reported that, "penalties are small for the two optimal designs but large for the comparative simulation. The large penalty implies that the optimal design obtained by the management model with the embedded confined transition equation fails to meet the required concentration constraints when the optimal design is reevaluated using an unconfined model." With a unit fixed cost of \$60/m, the concentration of contaminants at the end of the planning period, 1.0 ppm, exceeded the required concentration of 0.5 ppm. "The optimal design obtained using the management model with the embedded confined transition equation is not a feasible solution for an unconfined aquifer. Therefore, the management model of an unconfined aquifer requires an unconfined simulator, especially for small remediation sites, which exhibit largely varying hydraulic heads" (Hsiao and Chang, 2005.)

### *Aquifer heterogeneity*

The scientists reported that the proposed algorithm is able, based upon the examples given, "to solve a remediation design problem with aquifer heterogeneity and examine its effect on the optimal design." The researchers, however, considered hydraulic conductivity and unit fixed cost to be constant in the preceding examples, which is unlikely because aquifers are generally heterogeneous. In heterogeneous cases, they noted, "the unit fixed cost and the hydraulic conductivity are spatially varied to simulate geological

heterogeneity." They created a study area separated into two subareas with different unit fixed costs and hydraulic conductivities. "For uniform geological conditions and a constant fixed cost, the algorithm tended to select pumping wells from subarea I in which the initial concentration and hydraulic head are high." The number and locations of wells varied by price of installation as well as by the magnitude and distribution of fixed costs, which depend on geologic conditions. Because the phenomenon cannot easily be derived for a conventional network design procedure that neglects fixed cost, the researchers proposed the GCDDP algorithm, which "provides a design that is nearer to the true optimal solution than that provided by conventional algorithms" (Hsiao and Chang, 2005).

### Computational issues

Hsiao and Chang (2005) noted, "Efforts to implement particular programming techniques to increase computational efficiency are an expected response to the complexity of the proposed remediation problem. Four approaches, two of which have been implemented here, can accelerate the computation." These were:

- considering sparseness for CDDP
- bookkeeping
- parallel computation
- response function (or surrogate model)

### Conclusions

Researchers presented GCDDP, an integration of GA and CDDP, as an unconfined aquifer remediation model that would reduce the total cost of remediation using pump and treat systems. They considered both fixed and time-varying operation costs. They determined that "the total cost, including the fixed and operating costs, is the objective function of a ground water remediation problem. This total cost had not been

previously addressed because of the combinatory and dynamic characteristics of the problem. This investigation calculated the fixed cost term using GA and evaluated the time-varying operating costs using the CDDP algorithm." (Hsiao and Chang, 2005) Hsiao and Chang (2005) reported that, "When the optimization model neglects fixed costs, the GCDDP algorithm consistently designs a remediation plan with numerous wells pumping at low rates. However, incorporating the fixed costs can reduce the number of wells and affect their locations in the network design. Hence, the GCDDP design can provide significant savings by considering the fixed costs. Using the confined model instead of the unconfined model can avoid the need to solve the nonlinear flow equation and the derivative calculations of the unconfined aquifer. However, this approximation can cause the solution obtained by the confined model to fail to satisfy the required water quality standard, when the design is reviewed by an unconfined model. The test cases demonstrate that when the flow domain is heterogeneous, the number and locations of pumping wells may vary with the fixed cost, determined by hydrogeological conditions." They noted that this phenomenon, however, is not easily determined using a conventional network design procedure that neglects fixed cost. "This investigation improves the computational efficiency of the proposed GCDDP algorithm at the expense of an increase in the computational burden by considering the sparse structure of the derivative matrices of the transition equation and applying a bookkeeping programming procedure. The GCDDP algorithm is thus a feasible ground water remediation planning approach." The researchers suggested parallel computation as a method of further improving GCDDP computation capacity for solving large-scale problems.

### Reference

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**UTTU thanks Dr. Hsiao, [chhsiao@chang.cv.nctu.edu.tw](mailto:chhsiao@chang.cv.nctu.edu.tw), for his help on this article.**



### Building trouble-free underground tank systems

*By John P. Hartmann*

Newly installed and upgraded tank systems continue to cause problems resulting in deficient monitoring and leakage. According to the U.S. EPA, over 12,000 new releases were reported in 2003, including many from new or upgraded systems. The cost of repairs, environmental work and lost business is excessive and generally avoidable.

This is not to say that all tank system problems result from deficient design or installation, but inherent problems in a system are not cured by subsequent operation and maintenance, no matter how diligent they are performed. Good operating and maintenance procedures will identify problems sooner than if done poorly or not done at all. This may reduce the consequences of the problems but cannot cure them.

Following are some well-established good practices that reduce the incidence of failure. To begin with, owners, operators, regulators, inspectors and equipment providers and contractors should recognize three realities about underground and aboveground motor fuel tank systems:

1. Tank systems are sophisticated and complex.
2. Available equipment components are not equal.

3. No system will be reliable unless it is designed and installed correctly

...especially as designs change to meet more stringent regulations and enforcement of mandatory operating and maintenance requirements. For example, the proliferation of secondary containment, electronic gauges and sophisticated leak monitoring systems, vapor recovery and new innovations in dispensing, containment and piping technology increase the complexity of the systems and the demands on the installer.

The benefits of secondary containment have become widely recognized and are mandated by some state regulations. The principal benefit is often not fully appreciated; it simplifies leak monitoring. Monitoring the interstices of double-wall tanks, piping, and more recently, containment sumps to detect leaks is the simplest leak detection method available. It is much easier than trying to identify releases of small quantities by reconciling inventories or sampling groundwater or soil vapors. While monitoring can be done manually, electronic systems, usually tied into electronic tank gauging electronics, provide timely alerts with reasonable accuracy. Third-party monitoring laboratories offer a variety of services and can greatly reduce reliance on on-site personnel to monitor, interpret the warnings and alarms, and correctly respond to them.

As stated earlier, tank systems are complex. Secondary containment, interstitial monitoring, and electronic gauges were not typical components of tank systems before enactment of federal UST regulations in 1986. These regulations increased the knowledge necessary to correctly design and install tank systems. The number of regulations, industry codes and standards related to tank systems imposed additional responsibilities on the owner/operator to see that the systems were designed

and installed correctly. However, a significant part of the market continues to ignore the complexity of the systems and bases buying decisions on the lowest price that meets the minimum acceptable regulation in force.

This leads to the second premise that all available equipment components are not equal. Virtually every component of a tank system is required by fire code to be listed by a third-party testing laboratory. The most commonly used by manufacturers are Underwriters Laboratories and Southwest Research, although other laboratories are offering these services. The fire codes typically require that the tank, dispenser, piping system, valves, etc. meet criteria, established by the laboratory and the manufacturers, that will provide a reasonable degree of fire safety and environmental protection. In a way, fire code and environmental regulations share a common purpose—keeping the motor fuel contained and controlled. Doing so accomplishes the objective of both sets of rules.

Having a listing by an acceptable approval agency does not mean that the product was tested exhaustively for its functionality, only that the product meets the minimum requirements of the listing. The materials of construction, manufacturing tolerances, design, durability and expected service life may vary considerably between products all bearing the same listing. Unless you have the need and ability to test various alternative products, a good rule to follow is “you get what you pay for”. Higher-priced products may have longer or better warranties, or be supported by a more effective service organization. When making a selection from among options with varying prices, keep in mind the potential cost of a failure of the component.

The third reality is that no system will be reliable unless it is designed and installed correctly. The design of tank systems requires an accurate assessment of the owner’s needs, knowledge of the available equipment

alternatives and codes and regulations of the local jurisdiction. A designer with general engineering background but without this specific knowledge may not produce an optimum design.

Tank installation, a term that defies definition, has been blamed for a multitude of equipment failures and the resulting damages. Attempts to tighten the requirements for installation include education, testing and licensing, all worthwhile efforts. However, education requirements are frequently lax. In some cases, the licensing regulation only requires that the individual attend training by a manufacturer; while this serves the installer and manufacturer and meets the requirements, it is very limited. Manufacturers only instruct on the installation of their products, not similar products of other manufacturers or other system components.

Unless an owner is familiar with the installer, licensing may be counter-productive unless the rules and regulations are enforced. It may give an unwarranted appearance of competence. The purchaser of equipment should look beyond the mere fact that an installer is licensed and require that the candidate for a project produce references. Checking references is essential.

When an installer is selected, the responsibilities of the parties should be clearly set out in a legally binding agreement. Among the requirements to ensure that the installation is done correctly are

- a clearly stated scope of work
- installer's responsibility for equipment provided by the owner
- coordination of work performed by other contractors
- testing to be performed, witnessed and approved during and after construction
- requirements for instruction and documentation of the equipment provided and work performed

A letter proposal with a list of equipment to be provided and the phrase “to be installed according to manufacturers’ instructions” is totally inadequate and will likely result in disputes, particularly if a component fails and substantial legal and environmental costs are incurred. Manufacturers’ instructions should be considered the minimum standard to ensure that the warranty will be in effect. Industry standards, federal and state laws and local fire and environmental codes may be more demanding than those of the manufacturer. When conflicting standards are encountered, the consequences of a system failure dictate that the most stringent be followed.

One key to trouble-free installation is the active participation of the owner or the owner’s designee. Direct involvement can prevent misunderstanding and mistakes and promote responsibility and the completion of quality work by all parties. Oversight of key phases of the work, particularly the initial phases and testing, is essential. The petroleum equipment industry is capable of producing tank systems with a useful service life of 30-50 years, with only routine maintenance and component replacement. The continued incidence of system failures indicates a need for a change in the attitudes of the parties. This may be forced on the industry by more stringent enforcement of fire, environmental and licensing regulations.

## Reference

Hartmann, J.P., “Building trouble-free underground tank systems,” *Petroleum Equipment & Technology*, July 2004.

**UTTU thanks John Hartmann, publisher of *Petroleum Equipment & Technology Magazine Archive* ([www.pe-t.com](http://www.pe-t.com)), for allowing us to reprint this article. John Hartmann & Associates may be reached at [Jhartmann@pe-t.com](mailto:Jhartmann@pe-t.com).**



## In situ BTEX biotransformation

Researchers were interested in evaluating “whether BTEX biotransformation continues in the absence of electron acceptors other than CO<sub>2</sub>.” They investigated the in situ biotransformation of benzene, toluene, ethylbenzene, *o*-, *m*-, and *p*-xylenes (BTEX) under methanogenic conditions in three controlled-release push-pull experiments at the site of a gasoline spill on the Seal Beach Naval Weapons Station (Reinhard and others, 2005).

Reinhard and others (2005) explained, “BTEX compounds are relatively water soluble and mobile and therefore a potential threat to nearby receptors (drinking water wells, ecosystems). At most sites, significant pure-phase residuals remain, even after routine source removal, which may act as a continuous source for many years. Remediation of fuel hydrocarbon sites therefore requires that microbial degradation is sustained for many years.” Sulfate reduction and methanogenesis have been found to be the most important processes involved, contributing 70 percent and 16 percent, respectively, to biodegradation. “Sulfate inhibits methanogenesis by effectively competing for hydrogen; however, once sulfate is depleted to below a threshold value, methanogenic conditions develop.”

## Methods

The researchers performed all tests sequentially in the same well. “For the methanogenic tests, a ground water test zone ~1000 L in size was inundated with ground water that was pretreated for oxygen, nitrate, and sulfate removal to induce methanogenic conditions. The absence of Fe(II) was verified colorimetrically to rule out Fe(III) reduction. Known amounts of BTEX

compounds were added to the injection volume so that mass balances could be evaluated upon extraction.” (Reinhard and others, 2005)

The site of the study was about a kilometer from the Pacific Ocean near a marsh and wildlife refuge. Site characteristics included:

- water table located ~2 m below the surface
- aquifer make-up of sandy/silty alluvial and coastal deposits
- radially shaped plume

Reinhard and others (2005) performed tests at the East Observation (EO) test well. The methanogenic push-pull experiments were denoted as EO8, EO9, and EO10. Pretest ground water collected from the site contained the following:

- 750 µg/L benzene
- 74 µg/L toluene
- 89 µg/L ethylbenzene
- 16 µg/L *m*- and *p*-xylenes
- 150 µg/L *o*-xylene
- ~0.6 mg/L bromide (background concentration)

Each test consisted of the following sequence of steps:

- extracted “approximately twice the final injection volume from the observation well into a holding tank”
- pretreated the extracted water
- pumped the water “through two granular activated carbon (GAC) filters providing ~2-min contact time to remove BTEX and other organic compounds”
- filtered GAC effluent with a 1-µm cotton filter
- removed “the existing electron acceptors, nitrate and sulfate” by deionization “using multiple mixed-bed ion exchange resin canisters”

- monitored effluent of the ion exchange bed with a 200 K ohm conductivity detector light
- passed deionized water through a helium-purged gas-stripping tower in order to remove dissolved oxygen and residual BTEX
- monitored effluent of the gas-stripping column with a dissolved oxygen probe
- pretreated the deionized water
- amended the deionized water with "the chloride salts of calcium, magnesium, and sodium such that the resulting electrolyte solution was approximately equal in ionic strength to the original ground water" (Reinhard and others, 2005)

Scientists then reinjected about "half of the previously extracted and cleaned volume...to provide a geochemical buffer between the high-sulfate background water and the experimental test volume. The other half was augmented with benzene, toluene, ethylbenzene, and *o*-xylene in each case (EO8, EO9, EO10). In addition, *m*-xylene was added for EO8 and EO10, and *p*-xylene was added for EO9. *m*-Xylene and *p*-xylene were evaluated separately because they were not resolved chromatographically. Concentrations of the BTEX compounds ranged from 218 to 347  $\mu\text{g/L}$ . Finally, bicarbonate and bromide tracers were added. In each case, the augmented volumes were then injected into the well through the composite tube at an average flow rate of 1.5 L/min to minimize pressure mounding during the injection" (Reinhard and others, 2005).

The tested zone was between  $\sim 1.5$  m and  $\sim 0.3$  m below the water table. The scientists lowered a multitube sampler, consisting of screened stainless steel tubing, into a screened 5.08-cm-diameter well. They collected samples weekly or biweekly during the 2 to 4 months of experiments. "After purging the well of 50 L, 40-mL samples were taken from each

individual sampling port and from the composite tube using a sampling manifold. Bottles were filled slowly, leaving no headspace. Duplicate BTEX samples were preserved with one drop of concentrated HCL. BTEX compounds were analyzed using a purge-and-trap sampler connected to a gas chromatograph (GC) with a photoionization detector. The GC procedure used had a detection limit of 0.01  $\mu\text{g/L}$  but did not separate *m*-xylene and *p*-xylene. The anions  $\text{Br}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$  were analyzed by ion chromatography (IC) (Reinhard and others, 2005).

"The detection limit for IC was below 0.5 mg/L. In a few selected samples, the absence of soluble iron, Fe(II), was verified by colorimetry. Methane was measured by headspace analysis with GC in subsamples obtained for BTEX analysis. Methane was difficult to preserve due to its volatility, and measurements provided a lower estimate with a detection limit of 0.5  $\mu\text{g/L}$ . Methane data were interpreted qualitatively to indicate the presence or absence of methane." (Reinhard and others, 2005)

Reinhard and others (2005) determined initial concentrations "immediately after injection by collecting samples taken from inside the well casing." After these initial concentrations were taken, "samples were collected at regular intervals with sufficient flushing of the well borehole to produce water from outside of the well casing. Flushing required a minimum of 50 L but was increased in some cases to accelerate extraction of the residual bromide such that the next experiment could begin" (Reinhard and others, 2005).

## Results

### Normalization

Researchers considered levels 2, 3 and 4 of the well to be representative of the test conditions because "the first level was too close to the vadose zone and thus contained higher concentrations of BTEX due to

its proximity to the light non-aqueous phase liquid, as indicated by a sheen on the samples collected from this level." Conversely, levels 5 and 6 "tended to be more variable, possibly because of mixing of test-zone water with the underlying native ground water" (Reinhard and others, 2005).

Reinhard and others (2005) determined that "in all three experiments (EO8, EO9, and EO10), it is clear that toluene and *o*- and *m*-xylenes (where present) were rapidly transformed within the first 25 d. During this time, bromide tracer concentrations were essentially constant, indicating that no dilution took place... This requires the consideration of data points from beyond the region in which bromide concentrations remained constant, even though geochemical conditions remained constant throughout the experiments due to the presence of the buffer volume. In order to account for dilution effects, the data points were normalized with respect to initial respective BTEX concentration and the ratio of initial to current bromide concentration." They used a mathematical calculation to determine the normalized values.

The scientists noted, "Since the normalization thus introduces an additional error that increases with falling bromide concentrations, the results were only considered up to the point at which the bromide concentrations in each case were approximately half of their initial values, which happened at or around day 75 in each case" (Reinhard and others, 2005).

### BTEX removal and methane formation

Reinhard and others (2005) found the following for each experiment:

- EO8, toluene, *m*-xylene and *o*-xylene were removed in less than 30 days and benzene and ethylbenzene were reduced to 50 percent of their initial concentration by day 75

- EO9, toluene and o-xylene were removed in 25 days and p-xylene, at a slower rate, was reduced to 30 percent of its initial concentration
- EO10, toluene, m-xylene and o-xylene reduced rapidly and benzene and ethylbenzene "showed distinct downward trends"

Researchers statistically analyzed the data for all three experiments by using simple hypothesis testing.

#### *Sulfate, Iron(III) and nitrate*

Researchers reported that, following "seven push-pull experiments (EO1 to EO7) under aerobic, then nitrate-reducing, and finally sulfate-reducing conditions each lasting several months, it can be assumed that all bioavailable electron acceptors (nitrate, sulfate, Fe(III), etc.) had been consumed unless they diffused in from the background water or from impermeable zones" (Reinhard and others, 2005).

The researchers also found that in all three experiments, "the sulfate concentrations were relatively stable at low concentrations (~1 mg/L) as the pumping progressed and were always lower than the lowest reported methanogenesis inhibition threshold of 3 mg/L." They assumed that "sulfate did not act as the electron acceptor in any of these experiments" because if it had, "a pronounced rise in sulfate concentration would have been observed as the influx of sulfate with background water continued but degradation of the BTEX compounds slowed down." Instead, "in all three experiments, the sulfate concentration profiles changed significantly neither in the first 20 days, during which the fastest degradation was observed, nor during later segments of the experiment, in which much slower degradation took place" (Reinhard and others, 2005).

## Conclusions

Reinhard and others (2005) concluded, "The purpose of this study was to show that BTEX biotransformation

continues without the stoichiometric availability of electron acceptors such as sulfate, iron(III), and nitrate. Transformation of all BTEX compounds including benzene was observed under such conditions, as was the ubiquitous presence of methane, indicating a methanogenic transformation process."

They observed that "toluene and m- and o-xylenes transformed quickly (complete disappearance in < 30 d), while benzene and ethylbenzene were the slowest to transform (ca. 50% after 75 d). New observations were that p-xylene transformed more slowly than its m- and o-isomers (ca. 50% in 50 d) and that the disappearance of benzene and ethylbenzene was only observed when p-xylene was not present in the test volume" (Reinhard and others, 2005).

"The data have shown that all BTEX compounds are transformed under methanogenic conditions. This will have wide-reaching implications for predicting the efficacy of natural attenuation, since these results imply that natural attenuation can be an effective option for remediating gasoline spills given sufficient time (on the order of years because removals appear to be sequential). Particularly, these results are encouraging in that they imply that residuals of gasoline spills that escape other forms of treatment will eventually be completely attenuated even in the absence of soluble electron acceptors, such as oxygen, nitrate, or sulfate, which can be added in active remediation approaches" (Reinhard and others, 2005).

## Reference

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## Research notes

### Interactive ground water

Li, Shu-Guang and Qun Liu, "Interactive Ground Water," *Environmental Modeling & Software*, Vol. 21, 2006; [www.elsevier.com/locate/envsoft](http://www.elsevier.com/locate/envsoft)

Li, Shu-Guang and Qun Liu, "A real-time computational steering environment for integrated groundwater modeling," *Journal of Ground Water*, in press.

Li, Shu-Guang and Qun Liu, "Interactive Groundwater (IGW): An Innovative Digital Laboratory for Groundwater Education and Research," *Computer Applications in Engineering Education*, Vol. 11, No. 4, 2003; <http://www3.interscience.wiley.com>

Researchers from Michigan State University designed interactive ground water (IGW) software for 2-dimensional and 3-dimensional ground water modeling. Li and Liu (2006) developed the software for "real-time, unified deterministic and stochastic groundwater modeling. Based on efficient computational algorithms, IGW allows simulating complex 2D and 3D flow and transport in saturated aquifers subject to systematic and 'random' stresses and geological and chemical heterogeneity." IGW allows many problems to be visualized, analyzed and modeled in real-time.

The researchers reported that IGW's "model and data integration, visualization, and real-time processing communication capability allow the modeler to focus on critical conceptual issues and to quickly and iteratively examine approximations and hypotheses, to identify dominant processes, to assess data worth, and to experiment in real-time with sampling, management, and remedial options." The IGW software also allows:

- real-time conceptual modeling

- real-time flow and transport modeling
- real-time hierarchical modeling
- real-time stochastic modeling
- real-time geographical information system (GIS) mapping
- real-time model analysis

IGW employs parallel computing, which “does not mean modeling on parallel machines but, rather, a new way of structuring computation—one that allows efficient data routing and dynamic integration of flow and transport modeling, data processing, analyses, GIS mapping, and 3D visualization” (Li and Liu, 2006; in press).

Li and Liu (2003) reported that, in traditional modeling programs, a processing bottleneck occurs because the modeling paradigm “involves a scheme based on intermittent sequential data processing between periods of off-line visualization and analysis. The processes employed to move information between various models and to the visualization programs” are inefficient. Researchers explained, “A single object-oriented application forms the core of IGW. It employs multiple modeling tasks to rapidly integrate complex data in a sophisticated graphical format. IGW permits the modeler to pause program execution and rapidly explore and edit, on-line, in order to provide greater detail where it is required while numerically coupling the two scales of modeling” (Li and Liu, 2006).

IGW “takes advantage of recent dramatic developments in computer technologies, software engineering, image processing, visualization software, GIS technologies, as well as research in subsurface flow and contaminant transport processes and modeling. It provides an interactive, graphical environment for defining the aquifer framework, for inputting parameters, properties and stresses, for

changing grid resolution, solvers, numerical schemes and modeling methods, for controlling and managing program execution and for integrating, overlaying and visualizing data and results” (Li and Liu, 2003).

Li and Liu (2006) concluded, “With 4 GHz desktops available now, 10 GHz microprocessor technology in the labs and faster than 20 GHz technology clearly in sight, actively visualized subsurface flow dynamics and contaminant hydrology incorporating live-linked component technologies promise potentially significant scientific, economic and societal benefits. IGW eliminates the fragmentation in the problem-solving process and narrows the gap between what is technologically possible and what is practically implementable. Our actual ability to model, to investigate and to discover may finally increase in pace with the rapidly advancing computer technologies.”

The researchers noted that the IGW program may also be used for educational purposes as a hands-on learning experience for students. It has already been incorporated into ground water study at more than 50 universities worldwide.

**UTTU thanks Dr. Shu-Guang Li, [lishug@egr.msu.edu](mailto:lishug@egr.msu.edu), for his help on this article. More information about IGW can be found at <http://www.egr.msu.edu/igw>.**

### **What information can we get from pumping tests? Comparing pumping test configurations using sensitivity coefficients**

Leven, C. and P. Dietrich, *Journal of Hydrology*, Vol. 319, No. 1-4, 2006; <http://www.sciencedirect.com>

A comparison of two pumping test configurations, the two-well pumping test and the single-well pumping test, was made with sensitivity coefficients. Researchers used sensitivity coefficients, “which are a measure for the relationship between a change in drawdown and

a change in the parameter distribution,” because they “allow the analysis of the intrinsic characteristics of pumping tests in order to provide a better understanding of their response to aquifer heterogeneity. By considering the evolution of changes in the sensitivity distribution, a direct link between temporal and spatial information is given.” Therefore, the understanding “of the response of pumping tests to aquifer heterogeneity” may be improved (Leven and Dietrich, 2006).

Leven and Dietrich (2006) determined that “single-well tests allow a relatively simple spatial assignment of estimated parameters in contrast to two-well pumping tests for which different areas contribute with different sign and weight. Due to the particularities of the sensitivity distribution of the single-well configuration, an aquifer characterization with a high resolution is possible while two-well tests require sophisticated inverse modeling for a reliable description of aquifer heterogeneity.” Single-well tests, however, were determined to be limited in the reliability of their storativity and in the area of investigation, thus requiring more wells for an area than two-well tests. However for the latter, the interpretation was more complex and the spatial resolution was inferior due to the considerably larger area of investigation.

From the single-well tests, though, “a good estimation of transmissivity values will succeed, even if the interpretation is based on late-time drawdown data... Using the estimated parameters, a sensitivity distribution and relative changes of sensitivity can be calculated for each well position. This allows linking of temporal information, i.e. the hydraulic parameters estimated at different times, to a spatial distribution of transmissivity.”

**UTTU thanks Dr. Carsten Leven, [carsten.leven@ufz.de](mailto:carsten.leven@ufz.de), for his help on this article.**