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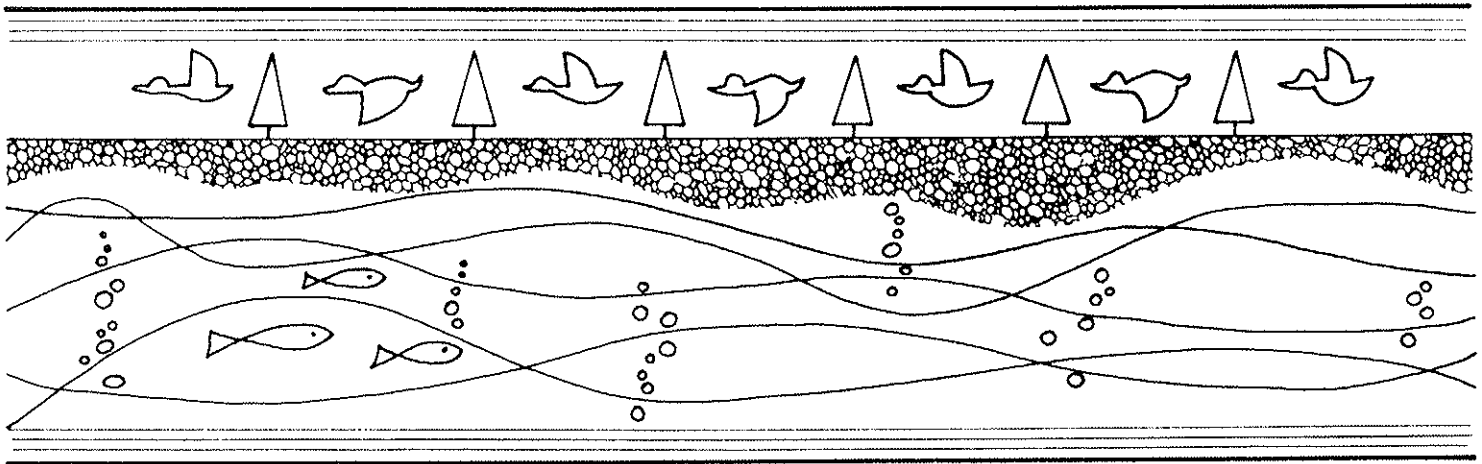


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The Spill Technology Newsletter was started with modest intentions in 1976 to provide a forum for the exchange of information on oil spill countermeasures and other related matters. We now have over 2000 subscribers in over 40 countries.

To broaden the scope of this newsletter, and to provide more information on industry and foreign activities in the field of oil spill control and prevention, readers are encouraged to submit articles on their work and views in this area.

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et demandez Bulletin de la lutte contre les déversements

INTRODUCTION

The first article of this issue by Richard Rush and others describes a PCB cleanup of the Pottersburg Creek area in London, Ontario. The cleanup was difficult and included cleaning trees and even children's swings. The second article of this issue is by Don Mackay and George Hoag who present an interesting perspective on cleaning up chemicals spilled in soil. They describe a cleanup of a gasoline spill using the unique method of removing and purifying the soil by air alone.

REMEDIATION OF PCB CONTAMINATION IN THE KIWANIS PARK SECTION OF POTTERSBERG CREEK, LONDON, ONTARIO

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ABSTRACT

PCB contamination of the Pottersburg Creek bed sediments and flood plain soil has been identified over a distance of 5 km through the City of London. Clean-up work is underway throughout the watershed under the direction of the Ontario Ministry of the Environment. This paper focuses on the remediation work in Kiwanis Park, which is a large public park area that was of particular concern to the local residents. The paper provides an overview of the entire remediation effort, including the delineation of areas requiring remediation; the development of the strategy for remediation; the required health and safety protocols, the implementation of the remediation plan and the associated construction costs. The emphasis of the paper is on the valuable experience gained during the design and implementation of the remediation plan for the park.

INTRODUCTION

In 1980, the Ontario Ministry of the Environment (MOE) found elevated concentrations of PCBs in minnows collected from the Thames River at the mouth of Pottersburg Creek. A subsequent investigation of PCBs in the water, sediment and minnows of the creek led the MOE to industries in the Huron Street area, which were a major source of the PCB contamination in the creek. This industrial area is shown with respect to Pottersburg Creek in Figure 1. Storm water had washed PCB contaminated oil and soil from these industrial areas into storm sewers. From the sewers, PCB contaminated soil and oil were washed into the Walker Drain and Pottersburg Creek.

The sources of PCB contamination on these industrial properties have been controlled and now the more complex task of remediating Pottersburg Creek must be performed. Prior to the clean-up of the industrial properties, PCB contamination had been identified from the Walker Drain to south of Trafalgar Street, which represents approximately 5 km of the creek's length. In February 1985, CANVIRO Consultants Ltd., under contract to the MOE, initiated a program to sample and analyze the creek bed sediments and flood plain soils of Pottersburg Creek for PCB levels, delineate area of PCB contamination and develop strategies for the remediation of these areas.

A Technical Review Committee (TRC) was convened by the MOE to provide direction regarding the selection of technically sound strategies to remediate the PCB contamination in Pottersburg Creek. The TRC has reviewed and evaluated all aspects of CANVIRO's remediation program for Pottersburg Creek to date through a series of meetings, and the committee has provided considerable technical input to the remediation

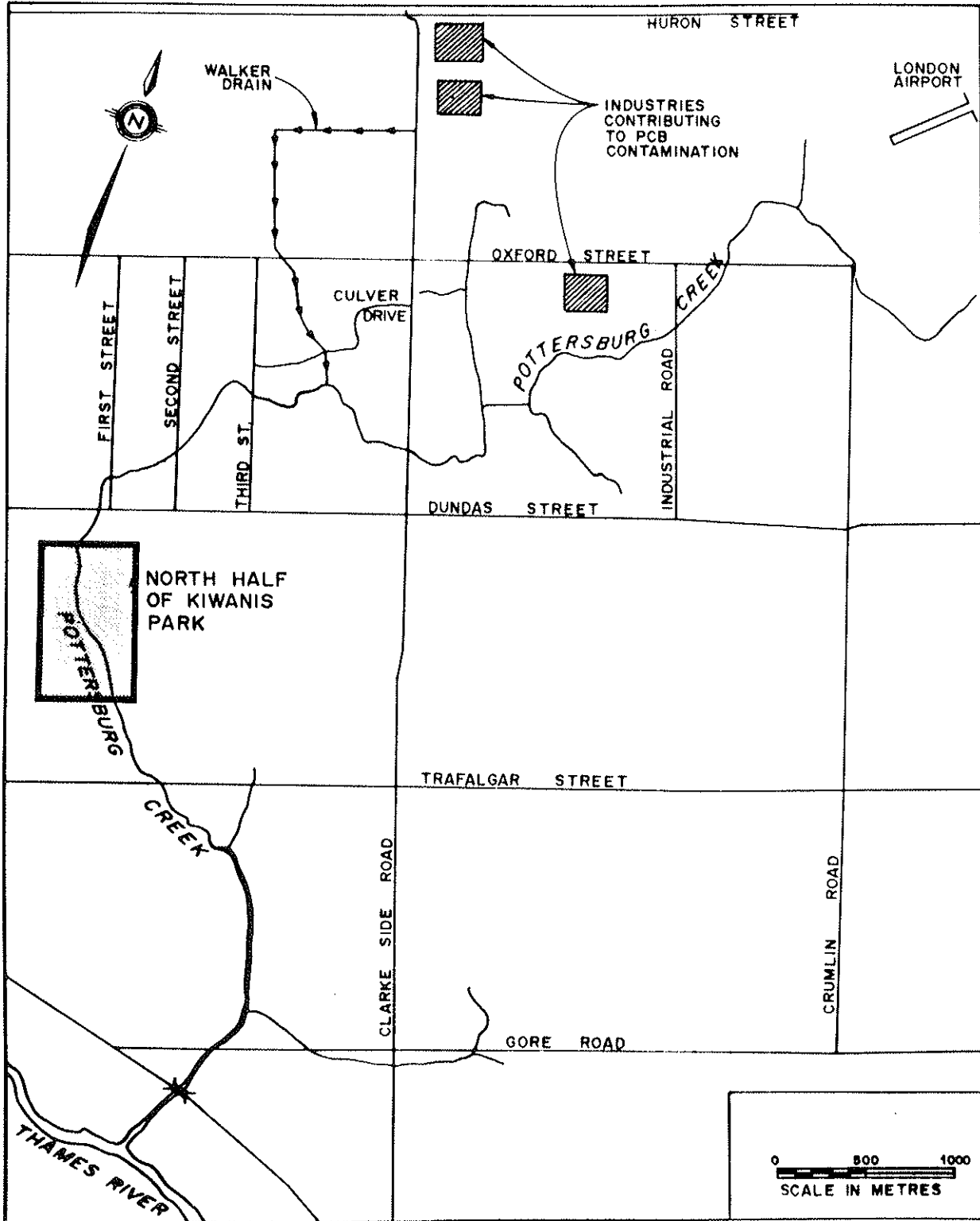


FIGURE 1 SITE PLAN OF POTTERSBURG CREEK

program. The TRC provided CANVIRO with a broad set of guidelines for remediating Pottersburg Creek based on the measured PCB contamination levels. These guidelines are shown in Table 1.

TABLE 1 REMEDIATION CRITERIA FOR POTTERSBURG CREEK

Area Type	Definition	Remediation Requirement
High PCB Contamination	Greater than 20 ppm	Remove from the site and store at secure vault
Low PCB Contamination	Generally between 1 ppm and 20 ppm	Isolate from potential contact with the public by covering with a minimum 15 cm of clean soil
Negligible PCB Contamination	Generally less than 1 ppm	No action required

Generally, a waste containing more than 50 ppm total PCBs would be designated as a high PCB waste under the hazardous waste definition. However, the TRC concluded that based on the combined effects of typical analytical errors, the quantification problems that arise from trying to "fingerprint" non-homogeneous Aroclors that have been exposed to environmental degradation and the typical sample characteristics (i.e. large range of particle size, organic content, oil content, etc.), it was possible (but not probable) for some samples to exhibit PCB concentrations which varied from 20 ppm to 50 ppm during replicate analysis. Consequently, to ensure that all potentially high PCB material was identified and handled properly and to maximize public safety, any soil or sediment with a total PCB concentration of 20 ppm or greater was designated as a "high" PCB material for the purpose of this study. The majority of the samples with greater than 20 ppm PCB concentration occurred immediately downstream from the Walker Drain.

The guidelines provided in Table 1 and the PCB data obtained as part of the remediation effort were used by CANVIRO to subdivide the Pottersburg watershed into smaller areas or creek segments, so that the varying remediation requirements along the creek could be more readily addressed. These remediation areas were prioritized for clean-up based on the PCB contamination levels, as defined in Table 1, and the public access or usage of each area. In June, 1985 Kiwanis Park was selected as one of the first areas to be remediated because it is an area of high public usage and as such, it was of particular concern to the local residents.

Work in 1985 was restricted to the North Half of Kiwanis Park, as outlined in Figure 1, due to the limited time available before the start of the winter season. This paper describes the remediation of the North Half of Kiwanis Park, which was performed as planned in September, October and November of 1985.

THE PARK SETTING

A site plan of the North Half of Kiwanis Park is presented in Figure 2. The park extends approximately 585 m north of Brydges Street, and the southern limit of work for the 1985 remediation effort was approximately 335 m south of Brydges Street. In this area the park width ranges between 100 m and 300 m. Pottersburg Creek flows from north to south through the park.

Prior to remediation, park maintenance was, for the most part, restricted to the care of the grassed areas and the clean-up of park debris. The creek had been allowed to meander, and large willows had grown along the creek banks. Due to the changing course of the creek, many of the willows encroached the creek, reducing the creek flow rates through the area and causing local pockets of significant erosion and sedimentation. Gabion baskets and rip rap had only been installed in areas where significant creek bank erosion had occurred.

The creek flood plain, which constitutes a large portion of the park, was characterized by large willow trees and young, recently planted maple trees. The park was poorly drained, with standing water often occurring in low-lying areas after rain storms. Spring runoff each year caused the creek to overflow its banks, and typically the area remained flooded for several weeks.

The park contains two areas of higher usage which were of particular concern with regard to the PCB contamination. The play area on the west side of the creek at the north end of the park contains a wading pool, several play structures (swings, see-saws, etc.) and benches, which are particularly used during the summer months. The second area of concern was at the footbridge near the southern limit of work for 1985. School children use this footbridge when travelling to and from Prince Charles School, which is shown in Figure 2. The southern limit of work was chosen specifically to include this area because of the footbridge and a zone of furan contamination immediately to the east of this footbridge, which is described in the subsequent section.

DETERMINATION OF THE SCOPE AND EXTENT OF THE REMEDIATION EFFORT

The PCB data for the North Half of Kiwanis Park are provided in Table 2. These data indicate that the North Half of Kiwanis Park was well within classification of a Low PCB Contamination Area, in that PCB contamination levels greater than 20 ppm were not detected. In fact, 43 percent of the soil and sediment samples were found to have less than 1 ppm PCB contamination, which according to the remediation criteria (Table 1) is negligible PCB contamination. Only 8 percent of the samples had PCB contamination levels greater than 10 ppm. Thus removal of the PCB contaminated soils and sediments from Kiwanis Park did not warrant consideration. The park was classified as a Low PCB Contamination Area, and as such a minimum of 15 cm of clean topsoil had to be placed over all areas of PCB contamination as a protective cap to isolate the public from this contamination.

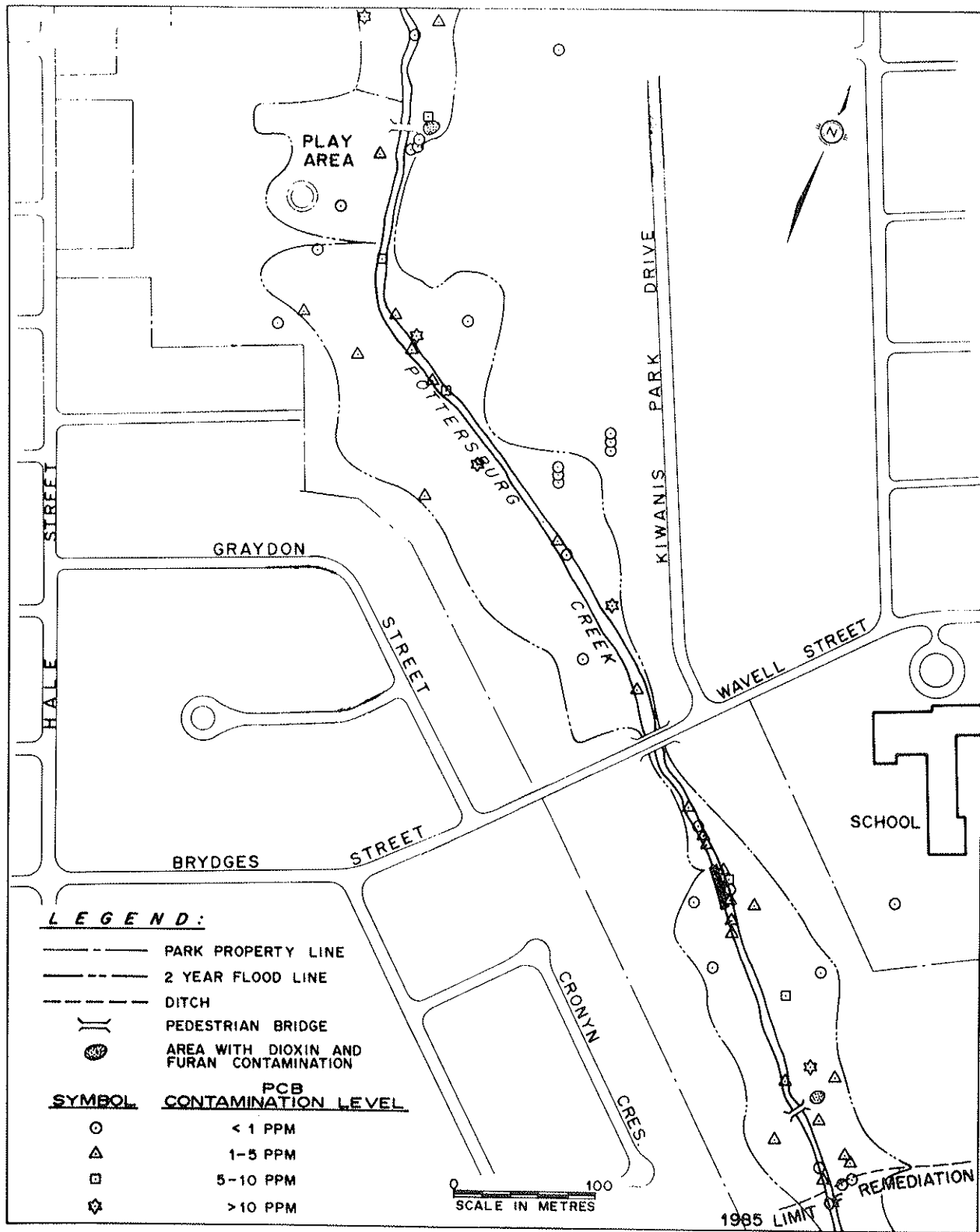


FIGURE 2 SITE PLAN OF THE NORTH HALF OF KIWANIS PARK

TABLE 2 PCB CONTAMINATION LEVELS IN THE NORTH HALF OF KIWANIS PARK

PCB Contamination Range (ppm)	Number of Measurements			
	Creek Bed	Flood Plain	Subsurface	Total
f20	-	-	-	-
15-20	-	1	-	1
10-15	-	4	-	4
5-10	3	2	-	5
1-5	14	10	1	25
F1	6	14	6	26
	23	31	7	61

Because dioxins and furans are often found in trace amounts in PCB spill areas, several of the soil and creek bed sediments were also tested for dioxins/furans. Three isolated areas were identified in which dioxin/furan concentrations exceeded 1 ppb, as shown in Figure 2. The action levels for removal to a secure vault on other remediation projects for dioxins and furans have been in the range of 1 to 2 ppb, and the local residents were particularly concerned about the dioxin and furan contamination in the park. Thus, it was decided to excavate and remove the soils/sediments in all three areas of concern.

The key issue with regard to the remediation design was the distance to which the topsoil cap had to extend from the creek banks in order to encompass the PCB contamination. While PCB contamination levels generally decreased with distance from the creek, the data did not indicate an obvious distance versus contamination level relationship in the immediate vicinity of the creek. This may be due to the fact that sedimentation during flood events had occurred preferentially in certain areas which were consequently characterized by higher PCB contamination levels. Additionally, the process of PCB contamination of the flood plain would have had a significant random component, as only a small portion of the sediments deposited on the flood plain would have been contaminated with PCBs.

Since it was impossible to sample all locations for PCB contamination, a physically-based action line was required to coarsely delineate areas of potential PCB contamination from those areas that were not anticipated to be contaminated with PCBs. Creek flooding had been identified as the mechanism by which the areas adjacent to the creek were contaminated with PCBs. Thus the one, two, five, and ten year flood lines were superimposed on a map showing the PCB data to determine the suitability of these lines for use as remedial action lines. The two year flood line, as shown in Figure 2, was selected because it was the narrowest flood line that encompassed all sample locations

with PCB contamination levels greater than 1 ppm. Thus all areas encompassed by the two year flood line were recommended for capping with a minimum of 15 cm of clean topsoil.

REMEDICATION PLAN AND IMPLEMENTATION

It was recognized that the park's appearance after remediation would be a significant factor in the public's acceptance of the remediation design. The local residents considered the park to be an integral component of their community, and they were uneasy about the effects that the remediation effort would have on the park's appearance. Justifiably, the local residents did not want to have their parklands adversely affected as a result of PCB contamination that they did not cause to occur. As a consequence, the preservation of trees and park structures (e.g. swing sets, benches, pathways) was integrated into the park remediation design to ensure that the use and enjoyment of these aspects of the park would not be impaired by the remediation effort. Additionally, several park improvements were identified that could be incorporated into the remediation design at minimal cost. These park improvements were included in the remediation design to restore the park to "better than original conditions".

Key aspects of the remediation plan as implemented in Kiwanis Park are outlined below. The discussions address the treatment of potentially contaminated areas that could not be effectively capped with clean topsoil, the steps taken to preserve the park trees and the remediation details to accommodate the existing park structures. The efforts made to improve the appearance and use of the park are then highlighted.

Key Aspects of the Remediation Effort

Dioxin and Furan Contaminated Areas - Since the three areas of dioxin and furan contamination were the only areas deemed to require removal from the park area and storage at a secure vault, this effort was the first to be completed. This work was included in a related Ministry of the Environment effort to remediate the more highly PCB contaminated areas along Pottersburg Creek. A secure vault was constructed for the cleanup of the more highly PCB contaminated areas, and the contractor performing the work was trained in the stringent health and safety protocols warranted for the remediation of High PCB Contaminated Areas. By removing these three areas of dioxin and furan contamination prior to the PCB remediation work, it was possible to perform the PCB remediation work under less costly health and safety protocols for Low PCB Contaminated Areas.

Creek Banks and Sediments - The creek banks and creek bed sediments posed a problem, in that they could not be effectively capped with clean topsoil. Based on the design approach of defining the two year flood line as the remediation action line, these sediments and soils had to be considered to be contaminated with PCBs. Thus, excavation was required for the potentially contaminated creek banks and sediments. However, removal from the site and storage in a secure vault was not required, as the PCB data indicated that the creek banks and sediments were no more contaminated than the flood

plain soils which were to be capped with topsoil. The excavated creek banks and sediments were therefore spread in a thin layer over the two year flood plain prior to the installation of the 15 cm topsoil cap. The volumes of sediments and soils excavated resulted in a layer of material that was less than 2 cm thick.

Due to the flow velocities in Pottersburg Creek, the creek bed sediments were sparse and generally on the order of only 5 to 10 cm thick. The affected areas were enclosed with temporary sandbag walls and dewatered, to prevent entrainment of the sediments during the excavation operation. The creek banks were excavated to depths of between 15 and 20 cm, to distances of approximately 3 m back from the edges of the creek banks. Where rip had been used to stabilize the banks, the rip rap were buried in shallow pits under the two year flood plain, rather than attempting to remove the potentially contaminated soils that were adhering to the stones. Because of the high flow velocities in the creek, the creek banks were capped with a 30 cm thick layer of new rip rap stone rather than 15 cm of topsoil. In a few selected erosion-prone areas such as creek bends, gabion baskets were installed along the creek banks instead of rip rap so that the topsoil cap could be better protected.

Trees Adjacent to the Creek Banks - Most of the trees growing adjacent to the creek had exposed roots as a result of creek bank erosion. The soils bound by these roots were hand excavated and spread over the two year flood plain with the excavated creek banks and sediments prior to the installation of the 15 cm topsoil cap. Rip rap was then placed on top of these roots to provide a protective barrier in the event that the roots are significantly contaminated with PCBs. Where trees had encroached on the creek, it was not possible to cover the tree roots with rip rap. In all such cases, these trees were hindering creek flows, and the resultant eddies in the creek were causing localized zones of accelerated creek bank erosion and sediment deposition. Tree and stump removal was determined to be the only effective approach to protecting the public from any PCB contamination on the roots of these trees, and in fact, removing the trees improved the alignment of the creek and reduced the rate of erosion in these areas. A total of 15 trees were removed. Due to the large number of trees remaining in the park, these removals resulted in a minimal change to the overall park appearance.

The removed trees were deemed to be uncontaminated and were disposed off-site, however, the root systems and the lowermost portions of the tree trunks were buried in shallow pits bellow the two year flood plain, as were the excavated rip rap stones. Burial of the tree roots and existing rip rap and other potentially contaminated items, such as debris removed from the creek bed, within the two year flood plain (which was later capped) provided a method of on-site disposal for potentially contaminated materials that otherwise would have required off-site disposal at a secure vault.

Trees on Flood Plain - Each tree on the flood plain was evaluated with regard to the tree's tolerance to the placement of the 15 cm topsoil cap over its roots and against the base of its trunk. Additionally, consideration was given to the maximum size of bulldozer that could be driven over the tree's root system without causing root damage. For the most part, the large trees (predominantly willows) on the flood plain (approximately 125 trees)

were deemed to be able to withstand the additional soil cover. The exceptions were the trees that were located in natural drainage swales, as a topsoil cap would have remained saturated in these areas for excessive periods of time and thus reduced root aeration. In these instances, a drainage system was required in addition to the topsoil cap. Therefore, drainage tile was first installed in swale areas with trees along the length of the swale, with the outlet at the creek bank. Gravel was placed over the drainage tile to aid the drainage process and reduce the potential for soil particles to block the drainage holes in the tile. The topsoil cap was then installed over the gravel bed.

Small trees with trunks less than 10 cm in diameter (predominantly maples, approximately 50 trees) were deemed to be unable to withstand the 15 cm of topsoil cap. In order to accommodate the 15 cm topsoil cap, these trees were raised 15 cm by removing them with a tree spade and transplanting them adjacent to their original locations, 15 cm above the existing grade. The exposed grass and topsoil on the tops of the root balls of the transplanted trees were removed to permit partial coverage with new topsoil. Thus by raising the small trees 15 cm and removing the surficial grass and topsoil, it was possible to install the 15 cm topsoil cap up to the transplanted trees and provide some coverage to the tree rootballs.

Park Structures - It was necessary to consider the park structures individually in developing the remediation plan. Structures that could be raised, such as swing sets and see-saws, were removed and installed 15 cm above existing grade. Concrete structures, such as the wading pool, could not be raised. In these instances, 15 cm of topsoil was first removed along the perimeters of these structures and spread over the two year flood plain with the potentially contaminated creek bed sediments and bank soils. This permitted the installation of 15 cm of new topsoil up to the structure, without changing the ground surface elevation adjacent to the structure. A third general category of park structures was the asphalt and gravel pathways. Within the limits of the two year flood plain, asphalt and gravel pathways were essentially reconstructed 15 cm higher than the existing grade to conform with the 15 cm topsoil cap.

Flood Plain Restoration - The activities outlined above comprise the preparatory steps that were required before installation of the 15 cm topsoil cap. Work began at the northern end of the park, and proceeded in a southerly, downstream direction to the 1985 Limit of Remediation (see Figure 2). The topsoil cap was installed as areas were prepared in order to minimize the size of the flood plain area with exposed potentially contaminated creek bed sediments and bank soils. Either hydroseed or new sod was installed on top of the topsoil cap, depending on the anticipated level of usage of the area of concern (high usage areas were sodded) and the time of year (hydroseed was not installed after October 15).

Park Improvements Included in the Remediation Effort

As discussed above, park improvements that could be easily and cost-effectively integrated into the remediation plan were performed to ensure that the park was remediated to "better than original conditions". Examples of the park improvements are as follows:

Low-Lying Areas - Several depressions and low-lying areas were located in Kiwanis Park that retained water for periods of weeks after heavy rainfall events. These low-lying areas were eliminated to provide positive drainage throughout the park by implementing one or more of the following corrective actions:

- recontour the low-lying area prior to installation of the topsoil cap
- construct a swale to drain the low-lying area to the creek prior to installation of the topsoil cap
- place greater thicknesses of potentially contaminated soils and sediments in the low-lying area prior to installation of the topsoil cap
- place more than 15 cm of clean topsoil in the low-lying areas

A catchbasin and drainage pipe system was installed in a particularly large low-lying area in the high-usage play area.

Creek Banks - As previously discussed, rip rap or gabion baskets were installed along the entire length of the creek to aid in erosion protection. Also, problem trees were removed to improve the flow characteristics of the creek.

Additional/Improved Pathways - In areas where the Public Utilities Commission of the City of London planned to install new pathways in the park, the gravel base for the pathway was installed as part of the remediation work to reduce the need for future excavations in the remediated areas.

Miscellaneous Improvements

- damaged storm drains were repaired
- dead tree limbs were removed
- discarded tires and other debris were removed from the creek bed.

HEALTH AND SAFETY PLAN

A health and safety plan was required for the remediation of Kiwanis Park to protect the construction workers from the potentially contaminated soils and to prevent the contamination of areas outside the two year flood plain. Careful consideration was given to ensure that the health and safety plan was in line with the levels of PCB contamination observed. An overly conservative health and safety plan would have increased the costs for the remediation effort, and it might have unduly alarmed local residents who had used the park in the past. Thus, it was essential for the health and safety plan developed for the remediation of Kiwanis Park to "fit" the levels of PCB contamination observed.

The health and safety plan was keyed to two defined areas. These were:

1. the work area, which included all lands used by the contractor during the remediation effort, and

2. the excavation area, which was the sub-area of the work area where excavated, potentially contaminated soils were being, or had been, spread across the flood plain and had not yet been covered with clean topsoil.

The work area was delineated by temporary snow fence, which was installed to restrict access by the public into the remediation area. Signs were posted around this snow fence perimeter to warn the public that the area was a PCB clean-up zone and to tell the public to keep out of the area. A security firm was retained to watch over the work area during non-working hours to ensure that the public was in fact obeying the warning signs.

The excavation area was delineated with yellow "caution" tape supported by fence posts. The contractor was encouraged to cover potentially contaminated soils/sediments with clean topsoil as soon as possible after the potentially contaminated soils/sediments had been spread over the flood plain, thus minimizing the size of the excavation area. The excavation area was relocated as remediation proceeded along the creek.

The construction workers were required to wear protective equipment in the excavation area only, as this was the only area where they could come in contact with potentially contaminated soils/sediments. Workers were required to wear rubber boots, disposable coveralls, gloves and hard hats. The contractor supplied a change truck that had an enclosed payload with standing room at the edge of the excavation area, for the workers to change into and out of their protective equipment. Used coveralls were disposed in a metal drum if they were significantly soiled. Alternatively the coveralls were hung on hooks if they were suitable for reuse. The drums of discarded coveralls were transported to the secure vault mentioned earlier at the end of the contract for storage.

The movement of equipment, such as hand tools and heavy machinery, out of the excavation area was also closely monitored. Before equipment was removed from the excavation area, the contractor was required to thoroughly wash the equipment with water on the edge of the excavation area. In this way the transport of potentially contaminated materials outside of the excavation area was prevented.

After changing out of the protective equipment at the edge of the excavation area, the construction workers were transported to the wash-up trailer. The workers were not allowed to eat, drink or smoke inside the work area, and the wash-up trailer was positioned near the exit from the work area, to ensure that the workers always washed up before leaving the work area at the end of the day or to eat, drink or smoke. The workers were required to thoroughly wash all parts of their bodies not covered by protective equipment, namely their faces and necks, as well as their hands.

The washwaters were retained in a holding tank and tested for PCB levels as significant volumes of water accumulated. In all cases the washwaters were found to have significantly less than the MOE Interim Maximum Allowable Limit for PCBs in drinking water of 3 ppb, and as such the waters were discharged to a nearby sanitary sewer.

The above information was provided each worker on his first day on the job site in the form of a health and safety training session. Follow-up instructions and reminders were provided to the workers as required. The health and safety plan was approved during the design phase of the remediation effort by the Ministry of Labour for use in Kiwanis Park.

REMEDICATION COSTS

The construction costs to remediate the PCB contamination in the North Half of Kiwanis Park as described above are summarized in Table 3. The data show that the costs to supply and install the topsoil and sod/hydroseed were the most significant remediation costs. The cost of these two items of \$262,000 represented 69% of the total remediation cost of \$380,000. Also, note the small relative costs of park improvements such as ensuring positive drainage (\$7,000, or 1.8 percent of the remediation cost).

TABLE 3 COST BREAKDOWN FOR THE REMEDIATION OF THE PCB CONTAMINATION IN THE NORTH HALF OF KIWANIS PARK

Remediation Item	Cost
Mobilize, including the supply of all health and safety equipment and installation of security fence	\$ 24,000
Excavate creek bed sediments and creek banks, and remediate trees along the creek	21,000
Supply and install rip rap and gabion baskets	31,000
Transplant 50 trees and raise walkways and park structures	18,000
Construct swales and install a drainage system in low-lying area to provide positive drainage	7,000
Supply and install 15 cm of new topsoil over 71,000 m ² of flood plain	174,000
Supply and install sod and hydroseed over 71,000 m ² of flood plain	88,000
Security guard for 1,300 hours	10,000
Demobilize, restore site and remove security fence	<u>7,000</u>
TOTAL	\$380,000

CONCLUSIONS

The remediation work for the North Half of Kiwanis Park demonstrates an effective method for remediating large areas with low PCB contamination levels, without off-site

disposal of large quantities of contaminated materials. In Kiwanis Park, essentially all of the contaminated materials were isolated from public contact beneath 15 cm of clean topsoil. The 71,000 square meters in the north half of the park were remediated to better-than-original conditions for a total construction cost of \$380,000. Health and safety protocols were implemented that both protected workers from the contaminated materials and prevented the contamination of areas outside the designated remediation area.

The most important evaluation criteria for the success of the remediation work in Kiwanis Park will be the PCB contamination levels in the park after remediation. Post-remediation monitoring will be conducted in the spring of 1986 throughout the North Half of Kiwanis Park. Samples of creek sediments and flood plain soils will be tested for PCB contamination levels, to determine the success of the remediation work in terms of the degree to which PCB contamination levels have been reduced in the park.

ACKNOWLEDGEMENTS

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A PERSPECTIVE ON THE BEHAVIOUR OF CHEMICALS SPILLED IN SOIL

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INTRODUCTION

The purpose of this paper is to present a new perspective on the issue of soil contamination by chemicals. It is an unashamedly academic perspective, which it is hoped will bring some new insights and ideas into this increasingly important subject.

Chemicals enter soil from spills, from landfill and dump leachates, from leaking tanks and pipes, and by deliberate addition for agricultural or pest control purposes. They may also be present as a result of atmospheric deposition processes, thus even soils in "pristine" areas may be contaminated. In many cases the level of contamination is clearly unacceptable because the chemical can migrate into air which will be inhaled, into water which will be drunk, or into food which will be eaten. It may have profound ecological effects. Action is then required to decontaminate the soil, or at least to reduce the chemical concentrations to a tolerable level. The problem is "how do we do this?"

In the last three decades there have been massive developments in technology to decontaminate water and air. There are numerous texts on biological oxidation, filtration, scrubbing, absorbing, stripping, precipitation etc., especially from controlled sources. But there is little information about soil decontamination. Perhaps "soil treatment" is the next growth industry.

Air and water are fluids, thus the overwhelming preference when treating them is to induce them to flow to a stationary piece of equipment through which they pass and are subject to chemical removal. Soils are not (usually) fluids thus inducing them to move to the equipment is not nearly as easy. It can be done by excavating, transporting and, for example, incinerating, but the costs are often prohibitive. The process is very disruptive and can result in severe occupational exposure to the workers. Few localities relish being the dumping ground for contaminated solids.

Perhaps these brute force techniques can be replaced by more subtle interventions. There is increasing evidence that such intervention is possible and economical. In this paper we explore these possibilities.

In-situ or ex-situ?

The first question is "should we treat the soil in-situ, leaving it stationary, but inducing the chemical to move - or should we move the soil to a treatment facility?" Perhaps a guiding principle may emerge that in-situ treatment is preferred and excavation should be viewed only as a last resort. To be more specific, perhaps a series or hierarchy of options is emerging in order of decreasing subtlety and desirability and increasing cost. These may be:

- (1) Leave the soil alone to decontaminate naturally
- (2) Intervene by in-situ enhancement of natural processes of decontamination
- (3) Intervene by in-situ treatment involving introduction of an artificial decontamination process
- (4) When all else fails, remove the soil, treat it and return it to the site.

If this approach is accepted, even in part, then it is essential to start with an appreciation of the condition of the chemical in the soil. Only if we understand its partitioning can we understand its natural fate. It is thus useful to digress to consider the chemical's condition as it exists in the soil.

CHEMICAL PARTITIONING AND TRANSPORT IN SOILS

We can regard soils as consisting of four phases, mineral matter (sand, clays etc.), organic matter (humic material etc.), water and air. The volume percentages could be respectively 65, 5, 10, 20, a typical bulk density being 1500 kg/m^3 . When a chemical is introduced into this matrix it partitions between these phases as shown in Figure 1. The concentrations in each phase differ and are multiples of partition coefficients of each other. For example, the air-water partition coefficient is a Henry's Law Constant.

As the amount of chemical increases, the concentrations increase until a point of saturation is reached at which all phases simultaneously refuse to accept more chemical. Any additional chemical will form a separate "pure chemical" phase which may displace the air or water.

It is critically important to know which regime applies because the chemical behaviour in these regimes is quite different.

There are several methods of calculating these partitioning properties, but basically the approach is mass balancing subject to the partition coefficient constraints. Table 1 gives an example of such a partitioning calculation for benzene in a soil, the three conditions representing subsaturation, saturation and supersaturation with pure benzene present displacing some air.

Having established the condition of the chemical it may be possible to estimate the rates of the various transport and transformation processes to which the chemical is subject. This problem has been tackled by Jury et al (1, 2, 3, 4) in an excellent series of papers in which an algebraic evaluative soil fate model has been developed. Recently we have simplified that model, with some loss of fidelity, to give a method of estimating loss by volatilization, leaching in water and reaction (5). It is also possible to include pure phase migration rate as an additional process, which is, of course, applicable only in the supersaturated regime. This is illustrated conceptually in Figure 2 for benzene.

Such assessments demonstrate three rather obvious principles.

1. If supersaturation conditions apply and the pure liquid phase is mobile and not appreciably water soluble, then the dominant method of transport is usually by pure phase flow or migration. Movement of the chemical in "solution" in air and water is usually relatively slower and can often be neglected. The free or pure phase liquid may tend to be drawn by capillary forces into the interstices or pores of the soil matrix, thus becoming immobilized. Continued flow of the free liquid thus leaves behind a residual volume of immobile liquid which may be very difficult to remove.
2. If subsaturation conditions apply the chemical can migrate only if an appreciable fraction (e.g. 0.1% or greater) of it is present in the mobile air or water phases and is thus subject to flow and diffusion.
3. Chemicals differ greatly in their partitioning characteristics in a manner dependent primarily on their vapour pressure and water solubility.
4. If the chemical is a mixture (as occurs with gasoline, fuel oils and many PCB fluids) the behaviour is more complex. The mixture's "solubility" and "vapour pressure" are presumably some weighted mean of the properties of the pure components, thus they depend on composition. As the liquid composition changes due to evaporation, dissolution and reaction, the composition and these properties change accordingly.

CHEMICAL TRANSFORMATION IN SOILS

It is possible to conduct experiments to determine the rate of chemical transformation in soils. Biodegradation is usually the dominant process, but rates of hydrolysis oxidation and even photolysis can be appreciable. The rate constants or half lives can also be incorporated into the fate model to give a perspective on the relative contributions of transport and transformation. The overall half life can be evaluated. This is illustrated in Figure 3 for benzene using an assumed degradation half life of 10 days.

Unfortunately, when pure phase is present the supersaturation conditions may often be too toxic for microorganisms to be effective. It is then necessary to wait for more dilute conditions to prevail before relying on biodegradation to be effective.

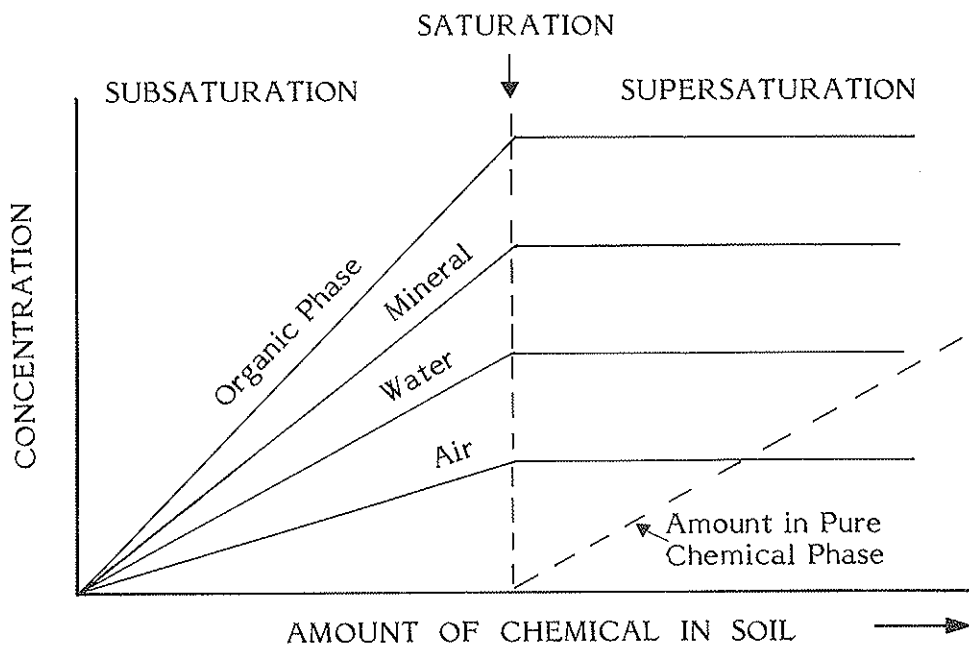


FIGURE 1 VARIATION OF PARTITIONING OF CHEMICAL IN SOIL

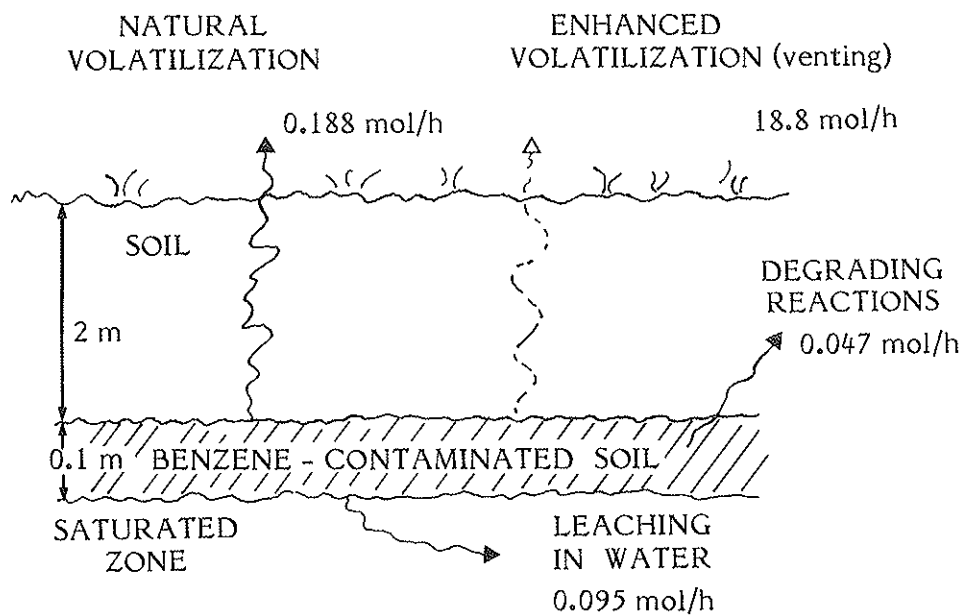


FIGURE 2 ILLUSTRATION OF RELATIVE CHEMICAL FATES
SEE TABLE 1C FOR MORE DETAIL

TABLE 1A SUBSATURATED CONDITIONS

CHEMICAL DISTRIBUTION AND FATE

benzene/gasoline

PROPERTIES

MOLECULAR WEIGHT g/mol	78	
SOLUBILITY g/m ³	1780	
VAPOR PRESSURE Pa	10000	
VAPOR DENSITY g/m ³	314.8244	
LOG KOW & KOW	2.13	134.8964
KOC	55.30751	
DENSITY kg/m ³	879	

HALF LIFE HOURS & DAYS	48000	2000
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AREA m ² 100	THICKNESS OF CHEMICAL LAYER m 0.2	DEPTH IN SOIL m 2
AMOUNT kg 150	GRAMS 150000	

CONDITION OF CHEMICAL IS SUBSATURATED

	AIR	WATER	ORGANIC	MINERAL	CHEMICAL
DENSITIES	0.119E+01	0.100E+04	0.100E+04	0.220E+04	0.879E+03
VOLUMES	0.400E+01	0.200E+01	0.100E+01	0.130E+02	0.000E+00
Z VALUES	0.404E-03	0.228E-02	0.223E-01	0.228E-01	0.113E+01
CONC mol/m ³	0.239E+01	0.135E+02	0.132E+03	0.135E+03	0.000E+00
CONC g/m ³	0.186E+03	0.105E+04	0.103E+05	0.105E+05	0.000E+00
CONC ug/g	0.157E+06	0.105E+04	0.103E+05	0.479E+04	0.000E+00
MOLES	0.955E+01	0.270E+02	0.132E+03	0.175E+04	0.000E+00
GRAMS	0.745E+03	0.211E+04	0.103E+05	0.137E+06	0.000E+00
PERCENT	0.497E+00	0.140E+01	0.687E+01	0.912E+02	0.000E+00
	0.5% in air	1.4% in water	7% in organic matter	most (91%) sorbed to mineral matter	

FUGACITY (Pa)=	5914.093	
VOLUME OF CONTAMINATED SOIL m ³		20
SOIL DENSITY kg/m ³	1580.237	

PROCESS	D VALUES	FLUXES	PERCENTS
REACTION	0.469E-05	0.278E-01	0.142E+02
LEACHING	0.951E-05	0.562E-01	0.288E+02
VOLATILIZATION	0.188E-04	0.111E+00	0.570E+02
TOTAL	0.330E-04	0.195E+00	

TABLE 1A SUBSATURATED CONDITIONS (Cont'd)

OVERALL HALF LIFE hours & days		6829.036	284.5432 9 months
AIR DIFFUSION D VALUE		1.87957E-05	
WATER DIFFUSION D VALUE		1.054331E-09	
AIR BOUNDARY LAYER D VALUE		0.152243	
EQUIVALENT AIR FLOW RATE m ³ /h		4.656456E-02	
ENHANCED FATE WITH THE FOLLOWING FACTORS			
VOLATILIZATION FACTOR	$\frac{100}{1}$		
DEGRADATION FACTOR	1		
LEACHING FACTOR	1		
PROCESS	D VALUES	FLUXES	PERCENTS
REACTION	0.469E-05	0.278E-01	0.248E+00
LEACHING	0.951E-05	0.562E-01	0.502E+00
VOLATILIZATION	0.188E-02	0.111E+02	0.992E+02
TOTAL	0.189E-02	0.112E+02	
OVERALL HALF LIFE hours & days		118.9989	4.958287 5 days

It is thus possible (in theory at least), to deduce the transport fate of the chemical in the soil and pose the questions, "is allowing decontamination to proceed at its natural rate acceptable, i.e. is "do nothing" a reasonable option?" The answer is likely to be "yes" when natural soil biodegradation rates are fast or when volatilization is rapid. If there is a possibility of groundwater or deep soil contamination the answer will probably be "no".

But at least the question should be asked.

INTERVENTION

Intervention to Enhance Natural Rates of Recovery

If natural decontamination processes are unacceptably slow and intervention is necessary, it seems likely that the best approach is to enhance the rates of those natural processes which result in mitigation. Nature is thus given a "helping hand" to accomplish in 1 month what may have taken 3 years naturally.

When a model of soil fate is available it is easy to explore the possibility of increasing the (mathematical) rates of the various transport and transformation parameters and determine how these enhancements accelerate recovery. For example, for benzene or gasoline spilled in the unsaturated zone in soil from a leaking underground storage tank, the obvious approach is to enhance volatilization by artificial soil venting.

TABLE 1B SUBSATURATED CONDITIONS

CHEMICAL DISTRIBUTION AND FATE

benzene/gasoline

PROPERTIES

MOLECULAR WEIGHT g/mol	78	
SOLUBILITY g/m ³	1780	
VAPOR PRESSURE Pa	10000	
VAPOR DENSITY g/m ³	314.8244	
LOG KOW & KOW	2.13	134.8964
KOC	55.30751	
DENSITY kg/m ³	879	

HALF LIFE HOURS & DAYS	48000	2000
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AREA m ² 100	THICKNESS OF CHEMICAL LAYER m 0.2	DEPTH IN SOIL m 2
AMOUNT kg 253.632	GRAMS 253632	

CONDITION OF CHEMICAL IS SATURATED

	AIR	WATER	ORGANIC	MINERAL	CHEMICAL
DENSITIES	0.119E+01	0.100E+04	0.100E+04	0.220E+04	0.879E+03
VOLUMES	0.400E+01	0.200E+01	0.100E+01	0.130E+02	0.607E-06
Z VALUES	0.404E-03	0.228E-02	0.223E-01	0.228E-01	0.113E+01
CONC mol/m ³	0.404E+01	0.228E+02	0.223E+03	0.228E+03	0.113E+05
CONC g/m ³	0.315E+03	0.178E+04	0.174E+05	0.178E+05	0.879E+06
CONC ug/g	0.265E+06	0.178E+04	0.174E+05	0.809E+04	0.100E+07
MOLES	0.161E+02	0.456E+02	0.223E+03	0.297E+04	0.684E-02
GRAMS	0.126E+04	0.356E+04	0.174E+05	0.231E+06	0.533E+00
PERCENT	0.497E+00	0.140E+01	0.687E+01	0.912E+02	0.210E-03
					Negligible Amount

FUGACITY (Pa)=	10000	
VOLUME OF CONTAMINATED SOIL m ³		20
SOIL DENSITY kg/m ³	1580.237	

PROCESS	D VALUES	FLUXES	PERCENTS
REACTION	0.469E-05	0.469E-01	0.142E+02
LEACHING	0.951E-05	0.951E-01	0.288E+02
VOLATILIZATION	0.188E-04	0.188E+00	0.570E+02
TOTAL	0.330E-04	0.330E+00	

TABLE 1B SUBSATURATED CONDITIONS (Cont'd)

OVERALL HALF LIFE hours & days	6829.051	284.5438 9 months
AIR DIFFUSION D VALUE	1.87957E-05	
WATER DIFFUSION D VALUE	1.054331E-09	
AIR BOUNDARY LAYER D VALUE	0.152243	
EQUIVALENT AIR FLOW RATE m ³ /h	4.656456E-02	
ENHANCED FATE WITH THE FOLLOWING FACTORS		
VOLATILIZATION FACTOR	100	
DEGRADATION FACTOR	1	
LEACHING FACTOR	1	
PROCESS	D VALUES	FLUXES
REACTION	0.469E-05	0.469E-01
LEACHING	0.951E-05	0.951E-01
VOLATILIZATION	0.188E-02	0.188E+02
TOTAL	0.189E-02	0.189E+02
OVERALL HALF LIFE hours & days	118.9992	4.958298 5 days

In other cases, nutrients and aeration have been used to enhance natural biodegradation rates. In some cases it may be possible to remove chemicals by pumping water from the soil with natural or artificial replenishment. Several techniques are available to treat the water. The study of natural and enhanced chemical biodegradation in the subsurface environment, and in particular in groundwater, is the subject of increasing attention, but the literature remains sparse. An excellent recent review is that of Lee and Ward (6) which is part of a published symposium held in 1983 (7).

The key quantitative information is the factor by which the natural rate can be increased - is it 1.1 or 10 or 1000?

We return to this issue of enhanced recovery shortly giving an example of a successful remediation effort involving enhanced volatilization.

Intervention by Artificial Recovery

If enhanced recovery is not feasible or too slow the next option is to intervene by introducing a new mobile medium into the soil (in addition to air and water) and induce the chemical to migrate in it. For organic chemicals such as PCBs the obvious approach is to extract with a hydrocarbon such as kerosene. Other possibilities exist such as supercritical CO₂, surfactant solutions and even subsurface combustion. The petroleum

TABLE IC APPROXIMATE SIMULATION OF CONNECTICUT SPILL

CHEMICAL DISTRIBUTION AND FATE

benzene/gasoline

PROPERTIES

MOLECULAR WEIGHT g/mol	78	
SOLUBILITY g/m ³	1780	
VAPOR PRESSURE Pa	10000	
VAPOR DENSITY g/m ³	314.8244	
LOG KOW & KOW	2.13	134.8964
KOC	55.30751	
DENSITY kg/m ³	879	

HALF LIFE HOURS & DAYS	48000	2000
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AREA m ² 100	THICKNESS OF CHEMICAL LAYER m 0.2	DEPTH IN SOIL m 2
AMOUNT kg 1500	GRAMS 1500000	

CONDITION OF CHEMICAL IS SUPERSATURATED

	AIR	WATER	ORGANIC	MINERAL	CHEMICAL
DENSITIES	0.119E+01	0.100E+04	0.100E+04	0.220E+04	0.879E+03
VOLUMES	0.258E+01	0.200E+01	0.100E+01	0.130E+02	0.142E+01
Z VALUES	0.404E-03	0.228E-02	0.223E-01	0.228E-01	0.113E+01
CONC mol/m ³	0.404E+01	0.228E+02	0.223E+03	0.228E+03	0.113E+05
CONC g/m ³	0.315E+03	0.178E+04	0.174E+05	0.178E+05	0.879E+06
CONC ug/g	0.265E+06	0.178E+04	0.174E+05	0.809E+04	0.100E+07
MOLES	0.104E+02	0.456E+02	0.223E+03	0.297E+04	0.160E+05
GRAMS	0.813E+03	0.356E+04	0.174E+05	0.231E+06	0.125E+07
PERCENT	0.542E-01	0.237E+00	0.116E+01	0.154E+02	0.831E+02 83%

FUGACITY (Pa)=	10000	
VOLUME OF CONTAMINATED SOIL m ³		20
SOIL DENSITY kg/m ³	1580.237	

PROCESS REACTION	D VALUES	FLUXES	PERCENTS
	0.469E-05	0.469E-01	0.142E+02 14%
LEACHING	0.951E-05	0.951E-01	0.288E+02 29% (Leads to Ground- Water Problems)

TABLE 1C SUBSATURATED CONDITIONS (Cont'd)

VOLATILIZATION	0.188E-04	0.188E+00	0.570E+02 57%
TOTAL	0.330E-04	0.330E+00	
OVERALL HALF LIFE hours & days		40387.56	<u>1682.815</u> 4.6 Years Half-Life if Left Alone
AIR DIFFUSION D VALUE		1.87957E-05	
WATER DIFFUSION D VALUE		1.054331E-09	
AIR BOUNDARY LAYER D VALUE		0.152243	
EQUIVALENT AIR FLOW RATE m ³ /h		4.656456E-02	
ENHANCED FATE WITH THE FOLLOWING FACTORS			
VOLATILIZATION FACTOR	$\frac{100}{1}$		
DEGRADATION FACTOR	1		
LEACHING FACTOR	1		
PROCESS REACTION	D VALUES 0.469E-05	FLUXES 0.469E-01	PERCENTS 0.248E+00 Now Negligible
LEACHING	0.951E-05	0.951E-01	0.502E+00 Now Negligible
VOLATILIZATION	0.188E-02	0.188E+02	0.992E+02
TOTAL	0.189E-02	0.189E+02	
OVERALL HALL LIFE hours & days		703.7705	<u>29.32377</u> reduced to 1 month by enhance- ment

industry is particularly expert at inducing reluctant organics to flow from the subsurface environment at depths of thousands of meters. It is puzzling that so little has been done on analogous technologies at a few metres depth.

The use of an innocuous liquid such as low aromatic content kerosene is particularly attractive for removal of chlorinated hydrocarbons with on site distillation and recycle. The residual in situ kerosene can be later biodegraded or evaporated.

Soil Removal and Decontamination

There is a growing literature on the excavation of soils, especially from landfill sites or dumps, and their treatment. The treatment methods include incineration using various configurations, extraction using various agents, treatment with various chemical agents such as acids, bases and oxidants. These processes have been reviewed recently by Rulkers and Assink (8).

The principal problems of removal are the disruption, exposure of workers and nearby residents to evaporated and of course the cost of the operation which can amount to hundreds of dollars per ton of soil. We suggest that in many cases it may be preferable to avoid the high intensity exposure events by more prolonged treatment by an in situ method.

AN EXAMPLE OF ENHANCED SOIL REMEDIATION

Approximately 500 U.S. gallons of unleaded gasoline were accidentally spilled into the unsaturated zone at a service station in Connecticut. The property was approximately 125 x 150 feet with a building and two pump islands. The site is shown in Figure 3 which also shows the general plume shape as determined by taking vapour samples from wells.

Excavation and soil removal would have been very disruptive and expensive. Fortunately, it proved possible to clean up the site with minimal disruption and cost by enhancing the rate of gasoline evaporation. This possibility was recognized because some laboratory soil column experiments had been done in which evaporation or venting had been simulated, thus establishing the feasibility of the approach.

The laboratory experiments conducted by Hoag et al (9) showed (Figure 4) that 99.0% of benzene could be removed from soil in 100 minutes. 3.3 L of air was required to remove 1 g of benzene. This benzene vapour concentration (300 g/m^3) corresponds at 20°C to 9400 Pa partial pressure which is close to the saturation vapour pressure. The rate of air withdrawal per unit area was $26 \text{ cm}^3/\text{cm}^2\cdot\text{min}$ or a superficial velocity of 26 cm/min. Tests with gasoline were done at 23 to 160 cm/min (10, 11) at which all the gasoline was removed. The air/gasoline ratio was 16 to 20 L air/g gasoline for soils of 25 and 125 g gasoline per kg soil. Clearly it is feasible not only to remove gasoline by venting or enhanced evaporation, but it is also feasible to quantify the process. An equilibrium model was devised in which the gasoline was treated as a 52 hydrocarbon mixture and it was concluded that equilibrium conditions were approached in the soil-air-gasoline subsurface system.

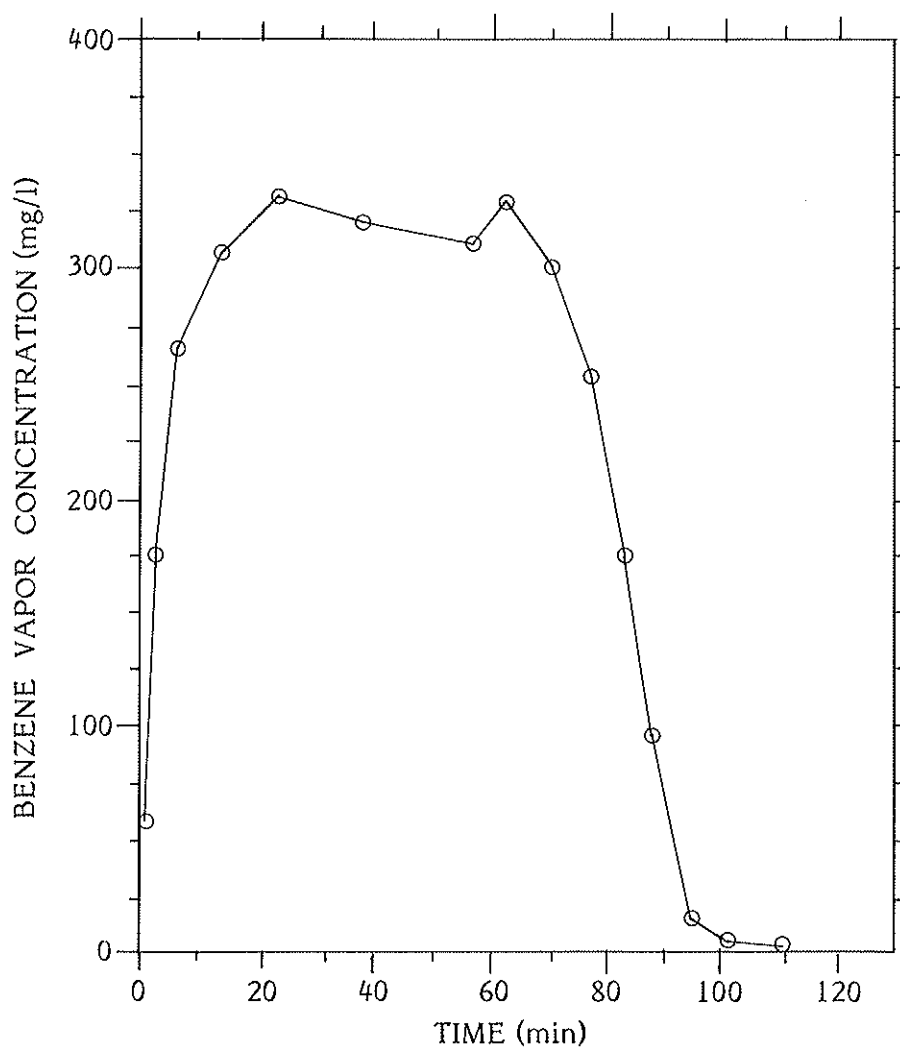
At the spill site three six inch diameter vacuum soil venting wells each connected to 20 cfm vacuum pumps were used to remove gasoline spill in the soil. A cross-section of the monitoring and soil venting installation can be seen in Figure 5. A plan view showing the various monitoring and recovery systems, with a total vapor hydrocarbon contour plume map is shown in Figure 3. It was assumed that the outer boundaries of the gasoline product plume were within the 10 mg/L and 50 mg/L vapour phase hydrocarbon concentrations.

LEGEND

System Temperature = 20 °C

Induced Air Flow Rate = 0.3 l/min

Initial Mass of Benzene Present = 9.0 g

Mass of Benzene Removed by Venting
Process = 9.0 gBenzene Vapor Phase Saturation
Concentration = 320 mg/l○ - Measured Values of Benzene Vapor
ConcentrationFIGURE 4 TRIAL VENTING RUN; BENZENE VAPOR CONCENTRATION
VERSUS TIME

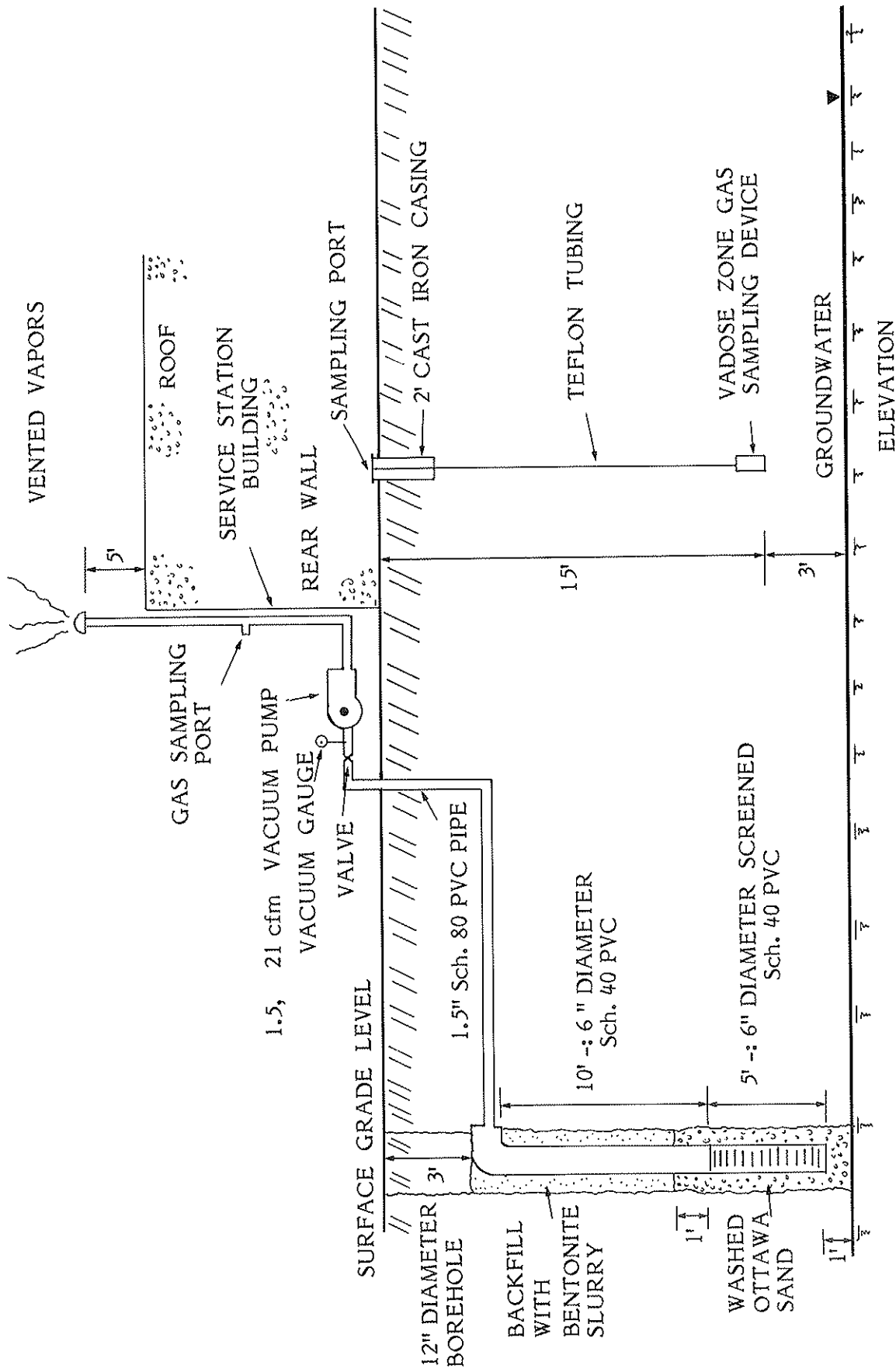


FIGURE 5 SCHEMATIC PLAN FOR SOIL VENTING SYSTEM WITH GAS SAMPLING PROBES

Cumulative volumes of gasoline recovered in the three venting wells using the in-site process are shown in Figure 6. More than 90 percent of the gasoline recovery by the venting system occurred during the first 60 days of operation. A total of 1376 L of gasoline was removed by the venting process. A total of 303 L of gasoline was removed by bailing from the recovery well over a 6 month period. Virtually no gasoline was recovered using an automated gasoline scavenger pump in the recovery well.

After the first 60 days of soil venting the vapour phase hydrocarbon concentrations in the soil probes fell dramatically as shown in Figure 7. After 88 days of venting all hydrocarbon vapour concentrations were below 0.5 mg/L. At this time there was no detectable gasoline in any of the groundwater monitoring wells, whereas prior to soil venting several wells contained more than 2 feet of gasoline.

In the field soil venting system an areal withdrawal rate of air was designed and operated to be $31 \text{ cm}^3/\text{cm}^2\text{-min}$. The air to gasoline ration was 62 L air/g gasoline; about 3 times greater than experienced in laboratory under ideal conditions. The difference is probably attributable to failure to equilibrate the entire air flow, some "by-passing" or subsaturation occurring.

The remediation was thus successful from both the scientific and practical viewpoints. In 3 months the site had been substantially decontaminated. An obvious question is the issue of air pollution. No attempt was made to remove the gasoline from the air. If deemed necessary an absorber system could have been installed. Fortunately these hydrocarbons have a relatively short half life in air. It should be noted that excavation would also result in substantial evaporation and even an explosion hazard. If atmospheric dispersion characteristics are not favourable the system could be turned off. The air pollution disadvantages are considered to be small compared to the problems which could have resulted if the plume had spread out, and contaminated groundwater had reached the local water supply well.

CONCLUSIONS

In this paper we have attempted to present a new perspective on soil treatment to remove chemicals. This technology is still in its infancy and there is enormous scope for innovation. There is a certain inherent elegance in approaching soil treatment from the viewpoint of enhancing natural processes such as evaporation or biodegradation when possible. Clearly it is important to document the successes in the hope that these good examples will be copied. A key component of this enhancement is the "design" of the system in which quantitative expressions are developed using appropriate models, validated by laboratory and field data.

Further, we suggest that there is considerable scope for development of in situ interventions with solvents, surfactants and other treating agents and mechanisms. Perhaps a sequence of treatments may be optimal. Excavation and remote treatment may emerge as a "last resort", "brute force" approach. Undoubtedly the greatest challenge is the remediation of hazardous waste dump sites containing persistent toxic organic

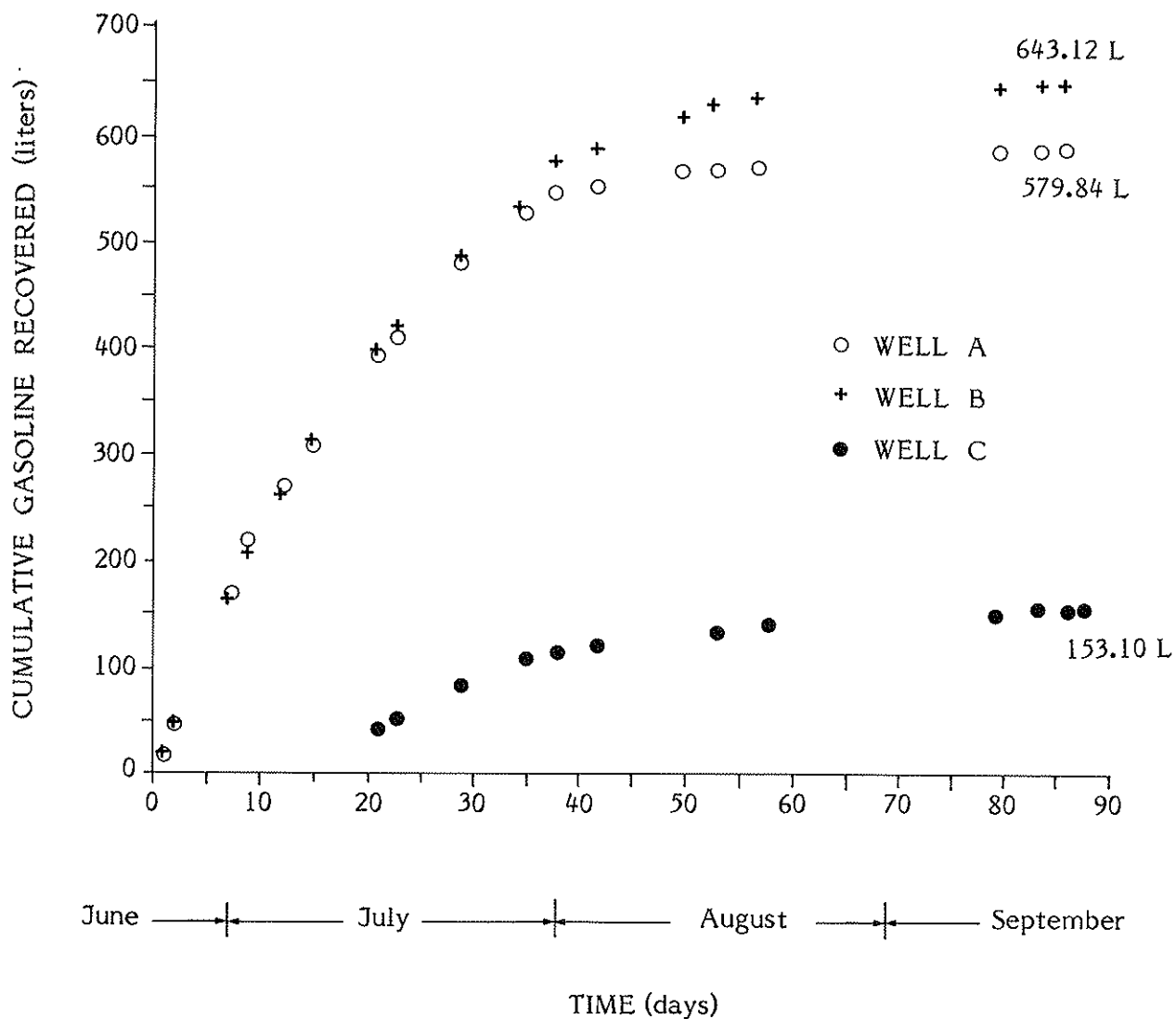


FIGURE 6 SOIL VENTING GASOLINE RECOVERY

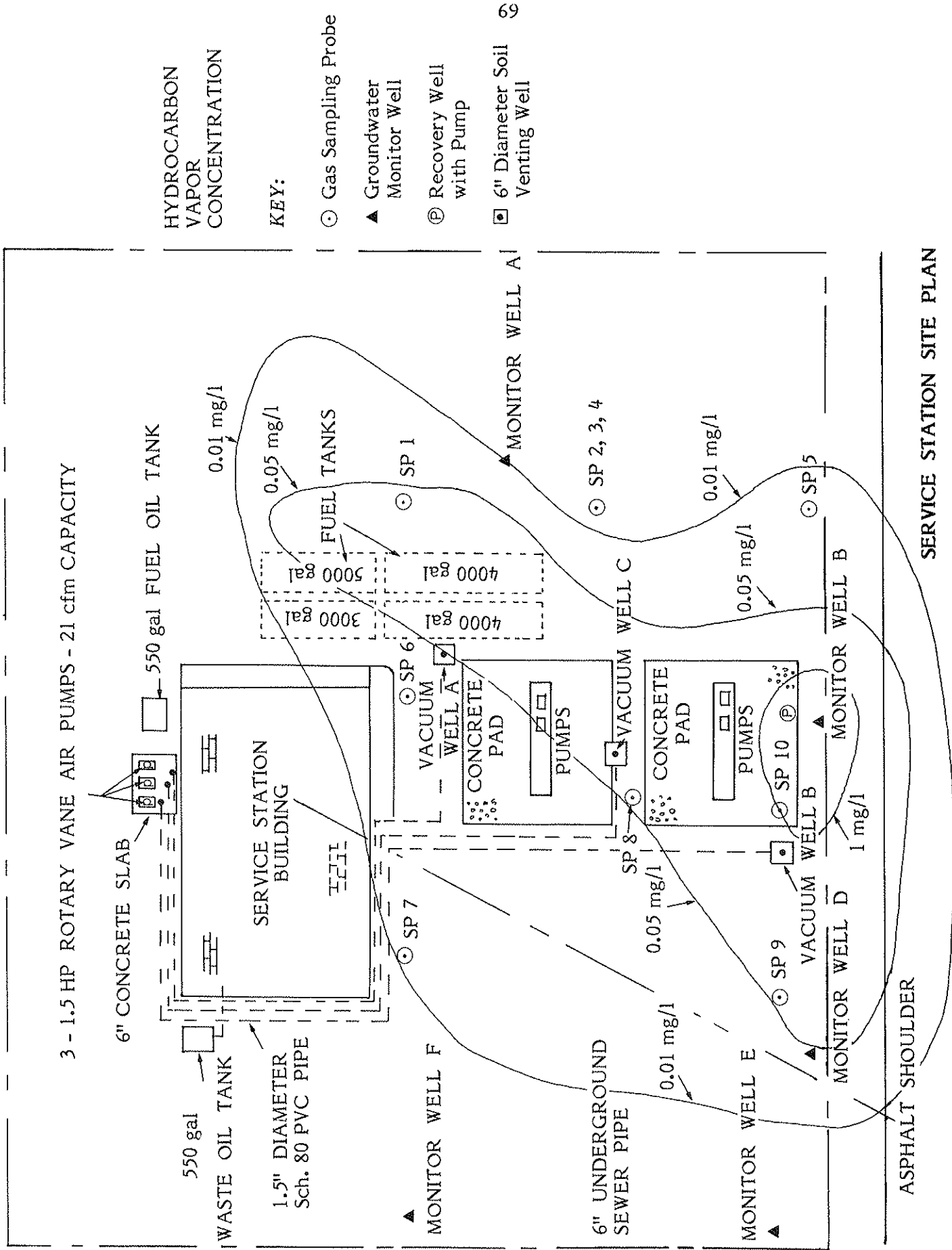


FIGURE 7 FINAL HYDROCARBON CONCENTRATIONS

chemicals. Of particular concern are those sites which are close to valuable aquifers or waterways - the Niagara River being a prime example. Nowhere is there greater need to seek remediation with subtlety.

Underlying this discussion is a growing appreciation that it is unacceptable to leave soils in a state of continued chemical contamination. The generation which caused the contamination (and therefore benefitted from it) has no right to pass on the cost, inconvenience and health risks to other generations. Encapsulation or barrier containment systems are inherently unsatisfactory. Surely we have an ethical obligation to pass on to others a biosphere, of which soils are a fundamental part, which is in a healthful uncontaminated condition?

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