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OPTIONS AND RECOMMENDATIONS FOR A POLYBROMOBIPHENYL CONTROL STRATEGY
AT THE GRATIOT COUNTY, MICHIGAN LANDFILL

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The Gratiot County (Michigan) Landfill received large amounts of waste polybrominated biphenyls (PBBs) in the period 1971 to 1973. With use of the Preliminary Pollutant Limit Value (PPLV) method, provisional limits were calculated for PBB concentration in soil and water in the area surrounding the landfill. Separate PPLV values were calculated for agricultural, residential and industrial land use scenarios. The method begins with an estimate of a maximum allowable daily dose for man. Then for each land use scenario, significant pathways from soil or water to man are identified. For each

20. Abstract (continued)

pathway taken by itself a maximal allowable PBB level (single-pathway PPLV) is calculated. Relevant single-pathway PPLVs are then used to calculate a PPLV value for each land use scenario.

Results indicate that the agricultural use scenario is associated with the most stringent soil PPLV (0.18 ppm), due largely to ingestion of soil by cattle. The corresponding value for residential use, 45 ppm, was governed by soil ingestion by children. Least stringent was the PPLV for industrial use, 700 ppm, based on dust inhalation. Potable water for humans was not considered in the above figures, but the (perhaps avoidable) contamination of such water was shown to require corresponding reductions in the soil PPLVs. PPLVs for water alone are 0.013 ppm for human consumption and 0.0029 ppm for watering cattle. Calculations concerning movement of PBBs by wind erosion and by the entry of leachate into groundwater indicated that near-term risks were slight, but it is recommended that a long-term program of monitoring of both soils and waters be followed. Proper security and maintenance for the landfill is also recommended.

In an Appendix, contributed by G.F. Fries, US Department of Agriculture, acceptable concentrations in soil have been derived using experimentally derived values for PBB concentrations in soils and in animal fat and for animal soil ingestion. Resulting estimates of the acceptable soil concentration of PBBs for single pathways through three animal species are in substantial agreement with the value proposed above for an agricultural use scenario.

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INTRODUCTION

The Gratiot County Landfill is a 40-acre disposal site that was formerly used for general and industrial wastes.[1] During the period 1971 to 1973, PBBs (polybrominated biphenyls) were deposited in the landfill.[2] The site has since been closed, and limited restoration has begun.[2]

The environmental as well as the human health effects resulting from PBB disposal at the site and the effects of its presence on surrounding areas are of major concern to the US Environmental Protection Agency (EPA). Aspects to be addressed are: (a) potential limitations on the use of the area for agriculture, housing, or industrial activities; (b) possible movement of contamination as a result of wind erosion; (c) the possible movement of contamination as a result of leaching from the landfill into groundwater, and in some cases migration thence to surface waters.

The present evaluation was undertaken as a technology transfer demonstration to the EPA of the philosophy and methodology currently in use by the US Army Medical Research and Development Command for assessing human health effects. This has been termed the PPLV (preliminary pollutant limit value) approach. It addresses contaminated areas on a site-specific basis[3,4] and incorporates reasonable (and generally safe-sided) assumptions for environmental decision-making. It should be helpful in arriving at decisions concerning security of the landfill, use of surrounding real estate, and groundwater monitoring of the area on a periodic basis. The utilization of accepted estimation methods to address problems where insufficient physicochemical information exists serves to fill gaps in data otherwise available through literature search or research.[3]

HISTORY OF CONTAMINATION

In March 1977, 269,000 pounds (122,000 kg) of PBBs were discovered to have been buried in the landfill.[1] The PBBs had been dumped there between 1971 and 1973[2] by the Michigan Chemical Plant, Velsicol Corporation (MCP), which was the major producer of PBBs in the United States.[5] The MCP, between 1970 and 1978, produced and disposed of many types of organic and inorganic chemicals, including PBBs, in the Gratiot County Landfill.[6] In view of previous PBB-related occurrences in the state, an immediate investigation of the impact of this disposal was begun by the Michigan Department of Natural Resources. Soil sampling subsequently revealed that some PBBs had also been deposited on adjacent land. This material could have blown off trucks carrying PBBs from the MCP plant for disposal at the landfill; however, "track out" of PBBs from the MCP could not be confirmed.[7] Of two surface soil samples from the uppermost 2.5 cm (1.0 in) in the landfill (evidently after partial capping of the landfill), the one with the higher PPB concentration showed 12 ppm of PBBs.[6] The one measured soil sample from a source somewhat distant from the landfill, in the area of the chemical plant, showed 61 ppb of PBBs; presumably, other samples contained less than the detectable amount (unspecified).[6] PBB concentrations reported for groundwater (location unspecified) varied from undetectable to 26 ppb.[1] Surface water samples at or near the margin contained no more than 0.2 ppb of PBBs, with a single exception (14 ppb).[1] Associated sediments were more heavily contaminated (up to 17,000 ppb).[1] The small area covered by these sediments would probably make them relatively insignificant as sources for continued dispersal of PBBs.

SITE BACKGROUND

The nearly square 40-acre Gratiot County Landfill is located 1/2 mile southeast of St. Louis, Michigan[1] (map, Fig. 1). Surface water at the site flows toward the northeast, north and northwest; ground water flows toward both the northeast and southeast.[1] The Pine River, 1.5 miles north of the landfill, is part of the Tittabawasee drainage basin.[1] An aquifer under the disposal site is protected by two natural clay barriers. The upper clay barrier was breached by the landfill in a few locations.[1] The area has a rolling slope, between 2 and 6%, with a surface composed of sand, loamy sand, sandy loam, and loam soils.[8] It is covered with grass, shrubs and occasional trees.[8] Approximately 11 percent of the area is susceptible to wind erosion.[9] The land is moist during 38 days of rainfall in May-September and is protected from erosion during 68 days of snow coverage in October-April.[8]

The population of St. Louis, MI, as of the 1980 census, is 4,197. The landfill is bordered by property parcels whose ownership and location are shown in Table 1.

TABLE 1. PROPERTY IN THE VICINITY OF GRATIOT COUNTY LANDFILL.[1]

| Owner | Location | Size (acres) | |
		Surrounding	Bordering[a]
I. Ball	West	40	40
J. Hodges	NW Corner	18	18
W. Hall	NW Corner	22	22
L. Sanchez	North	40	40
W. McFee	NE Corner	40	40
Gratiot County Dept. of Public Works	East	40	40
D. Reichard	SE Corner	80	40
M. Spangler	South	10	10
Camp Monroe[b]	South	70	30
P. Burnham	SW Corner	20	20
St. Louis Schools	SW Corner	20	20
	total	400	320

a. "Bordering" refers to acreage directly adjacent to landfill.
b. Retarded children's camp.

CHARACTERISTICS OF THE PRINCIPAL POLLUTANT - PBBs

GENERAL PHYSICOCHEMICAL BEHAVIOR

The pollutant of primary concern in the Gratiot County Landfill is the mixture of PBBs known as Firemaster BP6.[10] This was manufactured for use as a flame retardant for business machines, electrical housings, and textiles.[11] PBBs are aromatic halogenated organic compounds, with properties similar to
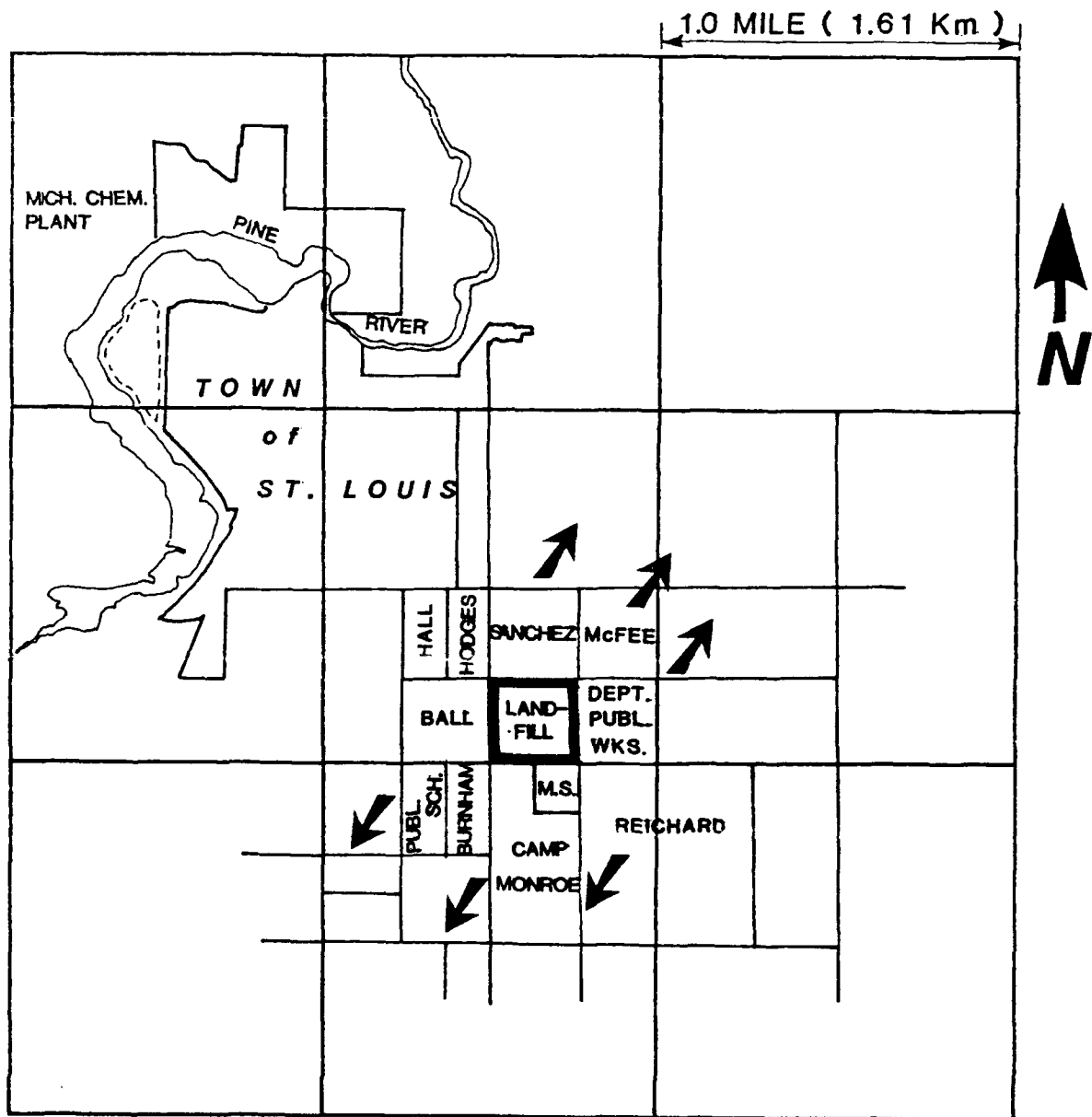
4

Figure 1. Vicinity map for Gratiot County Landfill, showing
location and ownership of adjacent properties.
Arrows indicate groundwater flow in upper aquifer.

those of polychlorinated biphenyls (PCBs).[11-13] The compounds are formed by substitution of bromine for hydrogen on the biphenyl structure. About 40 PBB compounds (including isomers) have been completely identified.[14]

The proportion of each PBB isomer varies with the batch; however, the predominant forms in Firemaster BP6, hexabromobiphenyls, have six bromine atoms per molecule. Position numbers are shown in Figure 2. The diversity of compounds in this mixture makes it difficult to speak with precision about its physicochemical properties. When we estimate such properties, the estimates are for hexabromobiphenyls. It should be borne in mind, however, that the properties of the mixture are not necessarily those of such fractions as may be separated out by environmental processes—for example, by leaching. Thus, leachate may contain comparatively high concentrations of biphenyls carrying fewer bromines than hexabromobiphenyls. The more soluble low-bromine compounds would be less likely to bioaccumulate and probably less toxic, as well. The data base for toxicity of these compounds is not sufficient to permit estimation of how much less toxic the more soluble components would be.
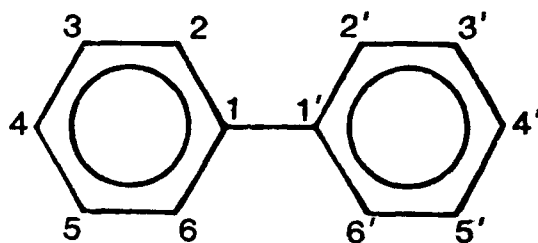
Figure 2. Numbering of ring system for substituted biphenyls.

The solubility of PBBs in water (0.057-16.9 ppb)[12] is significantly less than that of PCBs (7-5,900 ppb).[11] Since the higher values are for solubility in landfill leachates (see Table 2), the ranges probably reflect the presence of co-solvents in the water, in which case dissolved organics must have an unusually large effect on PBB solubility.[12] Lipid solubilities of both PBBs and PCBs are rather high.[11,12] PBBs are poorly metabolized and tend to accumulate in adipose tissue.[12] Environmental transport by vaporization of PBBs is very slow, owing to the low vapor pressures of these compounds.[12]

Sunlight and artificial ultraviolet light easily degrade PBBs;[14] in the process, less brominated biphenyls are formed. The photolytic loss rate of hexabromobiphenyl is reportedly greater than that of the hexachloro analog; less than 10 percent of the initial hexabromobiphenyl compound remained after 9 minutes of illumination under specified conditions.[12] However, degradation in the soil is not normally appreciable because sunlight cannot penetrate to any extent.[15,16] PBBs are extremely persistent in the ground, and there is no evidence to support the idea that microbial degradation can occur.[12,17] It can be assumed that the half-life of PBBs is greater than the 4-year half-life of hexachlorobenzene that was observed in one instance.[12] Furthermore, PBBs are rather strongly sorbed by the organic components of soil, so that their tendency to migrate is slight.[12,17]

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TABLE 2. THE RELATIONSHIP BETWEEN ORGANIC CARBON CONTENT
AND SOLUBILITY OF PBBs IN WATER[12]

| Type of Water | Total Organic Carbon (ppb) | Solubility[a] (ppb) | |
		PBBs[b]	Hexachlorobenzene[c]
Distilled water	335	0.057	1.75
Deionized water	336	0.317	1.78
Sugar Creek water	1,841	0.497	2.22
Blackwell Landfill leachate	63,030	8.889	4.14
Du Page Landfill leachate	83,690	16.892	4.47

a. Filtered through a solute-presaturated 0.22-μm Millipore cellulose
    acetate membrane.
b. Average for solubilities at 2, 4, and 7 days.
c. Hexachlorobenzene is used for comparison. Values are for solubilities
    at 30 days.

Estimated physicochemical properties for hexabromobiphenyl are shown in
Table 3. These are used in place of the less easily calculated values for the
Firemaster BP6 mixture.

SPECIAL CONSIDERATIONS OF WATER SOLUBILITY, ADSORPTION ON SOIL, AND MOBILITY
IN SOIL

Effect of Organic Carbon Content on PBB Solubility

As demonstrated by the data of Table 2, the solubility of PBBs in
distilled water is magnified to a remarkable degree by the presence in the
water of small percentages of organic substances. For example, 83,690 ppb of
organic carbon in one leachate, which amounts to only about 0.01 percent
organic matter, appears to increase the solubility of PBBs nearly 300-fold.
We do not know if this effect is general for compounds of very low solubility
in distilled water, nor whether the effect results from the presence of
colloidal, as opposed to truly dissolved, organic molecules.

Adsorption Equilibria and Their Significance

When the investigators of PBB adsorption were determining Freundlich
isotherms, they elected to use Blackwell Landfill leachate as the aqueous
medium, rather than distilled or deionized water, even though they used
deionized water for a parallel determination (in the same publication) of
isotherms for hexachlorobenzene.[12] We infer that the choice of leachate had
to do with the considerably higher--hence more convenient for analysis--

solubility of PBBs in leachate than in distilled water; the choice was evidently not due to any desire to duplicate field conditions. The result of this choice was to obtain a Freundlich parameter, K, that is probably much smaller than would have been observed with a water of significantly lower organic content.

The Freundlich equation is written as $\log (x/m) = \log K + (1/n) \log C_w$, where x/m and K are in ng PBBs/g soil, and $1/n \cong 1.8$ (a dimensionless number whose particular value, 1.8, is estimated for a soil containing about 2 percent organic carbon).[12] For 1 ppb of PBBs in the water phase (i.e., $C_w = 1$ ng/mL), $K \equiv x/m$, since, under this condition, $1/n \log C_w = 0$. Values of K for Blackwell Landfill leachate, in ng/g, are related to the organic content of the soil, specifically percent total organic carbon (designated % TOC), by the equation, $K = 64.92 + (17.57 \times [\% \; TOC])$.[12] For soil containing 2 percent TOC, the calculated value is $\log K = 2.00$, or $K = 100$. From this information, we can infer equilibria for other aqueous PBB concentrations in Blackwell Landfill leachate, defining an <u>apparent</u> equilibrium constant, $K' = (x/m)/C_w$. For example, at 0.1 ppb of PBBs in the aqueous phase, $\log (x/m) = 0.2$, so that $(x/m) = 1.58$ and $K' = 15.8$.

The consequence of the foregoing is that K' is variable: if $1/n$ had had a value of unity, K' would have been independent of C_w and always equal to K. The usual regressions linking K (via K_{oc}, the constant for equilibrium between organic carbon and water) to solubility or to the octanol/water partition coefficient, K_{ow}, do tacitly assume that $1/n$ is close to unity.[18] This comment is introduced because it is germane to what now follows:

Were one to determine a value of K' for PBBs in distilled water, rather than in Blackwell Landfill leachate, one would certainly expect this value of K' to exceed considerably that for the leachate. The question is, by how much? Perhaps, for $x/m = 100$, where leachate $C_w = 1$ ppb, the value of C_w would be reduced in proportion to the solubility ratio, namely, (solubility in leachate)/(solubility in distilled water) = 8.889/0.057 = 156. If so, $K' = 100 \times 156 = 1.56 \times 10^4$. The latter value is fortuitously close to the estimate for K, shown in Table 3, for hexabromobiphenyl. We have chosen to use the value from Table 3, but do so with reservations, in view of the uncertainty posed by the leachate-related evidence.

TABLE 3. PHYSICOCHEMICAL PROPERTIES ESTIMATED FOR HEXABROMOBIPHENYL (MW = 627.7)

Name	Property Symbol	How Estimated	Value	Method Reference
Log octanol-water partition coefficient	Log K_{ow}	Substitution of Br values for Cl values for hexachlorobiphenyl	7.62	Lyman et al.[18] Chap. 1
Organic carbon-water adsorption coefficient for soil	K_{oc}	Log K_{oc} = -0.557 log S + 4.277 (S = 7.96 x 10^{-4} µm, from value of 0.5 ppb in creek water)	1.01×10^6	Lyman et al.[18] Chap. 4
Soil-water adsorption coefficient[a]	K or K_{sw}^{-1}	K = (Wt fraction soil org. matter x K_{oc}) = 0.02 K_{oc}	2.01×10^4	Lyman et al.[18] Chap. 4
Soil-water partition coefficient	K_{sw}	K_{sw} = 1/K = 5 x 10^{-5}	5.0×10^{-5}	
Water-plant partition coefficient	K_{wp}	Assumed[b]	5	
Soil-plant partition coefficient	K_{sp}	K_{sp} = K_{sw} x K_{wp}	2.5×10^{-4}	
Bioconcentration factor (feed to beef fat)	BF_1[c]	log BF_1 = -3.457 + 0.500 (log K_{ow})	2.254	Kenaga[19]

a. Based on an assumed 2% organic carbon content in the soil.
b. The water-plant partition coefficient adopted here derives from an initial assumption that water internal to the growing plant has the same PBB concentration as the soil water with which the roots are in contact. The plant is roughly 5/6 water (M.J. Small, unpublished average of plant water contents). Thus, when water is removed during drying, and the PBBs are left deposited on the remaining dry plant matter, the result is a fivefold increase in concentration as compared to that originally in the aqueous phase. This assumed value, 5, is highly uncertain.
c. See text.

Ultimately, K is used to derive a partition coefficient, K_{sp}, between soil and plants. To the uncertainty in K (or its inverse, K_{sw}), there is added the uncertainty in the water-to-plant partition coefficient, K_{wp}, for which there is no direct experimental evidence. Thus, we are not very comfortable with the product, $K_{sp} = K_{sw} \times K_{wp}$. It is to be hoped that further research will be carried out to refine these values. The most that can be said now is that all evidence points to a very low likelihood of PBB accumulation in plants.[17]

Mobility in Soil

Thin-layer chromatography (TLC) was employed in the attempt to measure PBB mobility in soil.[12] In no case, where natural water or leachate was used, was it possible to detect movement. In an extreme case, leachate of the highest organic content (from Du Page Landfill) was used as the eluent for Ottawa sand, a mineral material of negligible organic content and low mineral surface area. Indeed, the previously quoted regression equation, relating the Freundlich parameter to percent TOC, indicates a relatively strong tendency for PBBs to be adsorbed on a purely mineral--but especially clay--surface. All this supports the conclusion that PBBs would not travel through the ground as leachate once they were adsorbed on soil. Nevertheless, caution might be advisable. TLC experiments involve very limited quantities of solvents, here a leachate, which may not adequately represent environmental behavior.

TOXICOLOGY

Such toxicological data concerning PBBs as exist have largely been assembled in several papers, particularly in Volume 23 of Environmental Health Perspectives.[5,17,20-25] These papers include information on uptake, distribution and elimination. The effects of PBBs described in these publications have been used as general guidance for our toxicological evaluation without specific reference. Unfortunately, all these investigations were of the effects of short-term exposures.

D_T, the acceptable daily dose, is an essential ingredient for most PPLV calculations.[3,4] It may be arrived at by several approaches. The preferred approach is to start with a regulatory value, if one is available. At present, one can begin with the permissible PBB concentration in the fat of beef, according to the following equations (symbols shown in Appendix):

$$D_T \times BWA = MC \times \frac{\text{Total PBB in animal}}{\text{Total meat in animal}} \tag{1a}$$

But
$$\frac{\text{Total PBB}}{\text{in animal}} = \frac{\text{Total fat}}{\text{in animal}} \times \frac{\text{Allowable PBB}}{\text{concentration in fat}} \tag{1b}$$

$$D_T = \frac{MC \times \dfrac{\text{Total fat}}{\text{in animal}} \times \dfrac{\text{Allowable PBB}}{\text{concentration in fat}}}{\dfrac{\text{Total meat}}{\text{in animal}} \times BWA} \tag{1c}$$

$$= \frac{MC \times \frac{\text{Fraction of fat}}{\text{in meat}} \times \frac{\text{Allowable PBB}}{\text{concentration in fat}}}{BWA} \qquad (1d)$$

From previously published material,[3]

   MC = 0.29 kg/day
   Fraction of fat in meat (beef) = 0.3

   In November 1974, the Food and Drug Administration (FDA) established human consumption guidelines of 0.3 mg/kg for PBBs contained in the fat of meat, poultry and milk.[26] Although this guideline was further reduced by the Michigan State Legislature in July 1977 to a level of 0.02 mg/kg for PBBs in cattle,[20] the FDA guideline level will be used for all calculations in this evaluation.

   Hence D_T = (0.29 x 0.3 x 0.3/70) mg/kg/day $\qquad (1e)$
   = 3.73 x 10^{-4} mg/kg/day

Alternatively, and as happens, more conservatively, one may look for a no-effects level in a suitable species and apply an appropriate safety factor. It would appear that no effects were seen, other than enzyme induction, in a 5-day rat feeding study at 1 ppm in the diet, whereas teratogenic effects appeared at 50 ppm.[20] One might assume the no-effects level to be at the geometric mean between these two, namely 7 ppm. Since a 250-g rat ingests about 15 g of feed per day, this is a dose of 0.42 mg/kg. For a 5-day feeding experiment, in our view, starting with a safety factor for a single dose[4] of 10^5, an appropriate safety factor would be $10^5 \div 5$ = 20,000. Thus D_T = 0.42/(2 x 10^4) mg/kg/day, or 2.1 x 10^{-5} mg/kg/day. The latter value is included here for illustrative purposes and will not figure in further calculations.

   Note: Following completion of the first draft of this study, the authors became aware of two draft reports by B.N. Gupta, et al.,[27,28] on chronic exposure investigations relating to the carcinogenic and toxic potentials of PBBs. Statistically significant evidence of malignant liver tumor induction occurred in rodents that were exposed to 3 mg/kg of PBB or more (but not to 1 mg/kg or less) for 6 months, then observed for the rest of their lives (up to 30 months of age) and necropsied. The toxic effects were dose-related. As yet, no criteria have been developed from the experimental results. For this reason, the present study did not address the possible shift in D_T that may eventuate as a result of these important new carcinogenicity data.

SCENARIOS FOR EFFECTIVE LAND USE

   The scenarios for land use rest on the proposition that the landfill itself will be restricted in access and undisturbed. Thus our concern is only with use of border areas for agriculture, residential housing, and industrial operations. The human exposure pathways within scenarios for such uses involve vegetable and meat consumption, soil ingestion and inhalation of contaminated dust. Vapor inhalation is not an important exposure route since the vapor pressure of PBBs is extremely low.

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AGRICULTURAL USE SCENARIO

The agricultural use scenario centers on farming in the fields bordering the landfill, 320 acres (Table 1). Crops and meat raised on contaminated soil and sent to market become commingled with farm products from many other sources. Thus the present treatment focuses on the more serious threat of PBB in such products to those few people, mainly members of farmers' families, who might derive a major part of their nourishment from the potentially contaminated farmland of interest. We call these "subsistence farmers". They might consume contaminated vegetables, meat, or both. On the other hand, some of their food, such as fruits, bread, and sugar, would surely come from external sources. We have assumed in most of the calculations that, whereas the humans would drink well water, animals raised for food would be watered only from intercepted rainfall or surface runoff. Thus, as an example, one could envision human exposure to water from a contaminated aquifer and consumption of the meat of animals that had ingested contaminated soil. Other routes of exposure, including that through vegetables grown in the soil, will be shown to be probably less serious than the two in the example. However, a distinct possibility exists that these animals would be watered from a groundwater source; and the implications of this are also calculated and discussed.

The contamination of the aquifer and of the surface soil are not dependent on one another; hence there is a tradeoff between the PPLV for water destined for human and possibly animal consumption and the PPLV related to animal soil ingestion that results in human consumption of contaminated meat. This tradeoff will be addressed later.

When beef cattle graze, it is not possible to prevent them from ingesting soil. Inasmuch as swine are usually provided with feed, they can be kept on concrete pads and prevented from eating dirt; this should always be done when soil contamination may be a problem.

RESIDENTIAL USE SCENARIO

The 320 acres of border area discussed above could be the site of a medium light residential community housing perhaps 6,200 adults and children. We envision the householders as growing some of their own vegetables and drinking well water. The chief media of exposure to PBBs would be the water supply, directly ingested soil (chiefly by children), and home-grown vegetables.

INDUSTRIAL ACTIVITY SCENARIO

Industrial activity might expose certain out-of-doors laborers—for example, forklift operators—to the inhalation of PBB-bearing dust. If the level of dust inhalation were limited to the TLV (Threshold Limit Value) for nuisance dust, the acceptable PBB level in soil for exposure from this source alone would be quite high. Actually, PBBs in contaminated well water used for drinking at industrial locations should also be taken into account (see below). Other exposures to dust, such as farming, hunting, construction work, well-drilling or lumbering, would entail shorter exposure periods than those considered in the forklift operator model, to be treated quantitatively below.

PATHWAY ASSUMPTIONS

Vegetable Consumption - Human

Vegetables are treated here as if they were consumed throughout the year as major dietary components. This assumption is on the safe side, since most locally grown vegetables in Michigan would be quite seasonal.

Forage Consumption-Animal

Consideration is restricted to cattle raised on the land for meat and, less directly, dairy products. Chickens are not included, since most chickens are not permitted to scratch feed. Pork is excluded because swine in the area of immediate interest should be raised only on unpolluted concrete pads; they need not graze or run free. Dairy products contain far less fat than meat (about 4% versus 30%), and butterfat contains only 40 percent of the PBB concentration found in the fat of the animal from which it comes;[26,29] thus, restrictions affecting PBB content of the animal fat automatically protect the dairy products.[29]

Soil Ingestion - Animal

Soil ingestion by cattle is an important pathway, since grazing animals inadvertently consume significant amounts of soil.

Water Consumption - Animal

The ingestion of contaminated groundwater by cattle would be of consequence. Although we have supposed that animals in Michigan obtain all their water needs from surface supplies, which would have relatively low PBB concentrations, both surface water and groundwater have been considered.

Soil Ingestion - Children Only

These pathways include casual (incidental) ingestion and habitual ingestion (pica). The pica syndrome is usually associated with children suffering from psychological problems or nutritional deficiencies[30]; it is the habitual ingestion of abnormally high amounts of non-food substances. Attention has been focused on pica because of inner city children's habits of eating peeling paint flakes from old buildings. The percentage of children with pica is not well-known; estimates ranging from 6 to 50 percent in young children have been advanced.[31] Pica in small children could be applicable in the scenarios considered; for this reason a pica soil-ingestion value of 0.5 g/day has been adopted somewhat arbitrarily.[31]

Water Ingestion - Human

The use of drinking water containing PBBs is considered in this pathway. The normal adult consumption rate is taken as 2 kg/day (i.e., 2 L/day).[4]

Dust Inhalation - Human

Exposure can occur as a result of inhalation of dust stirred up by human activity or wind. We assume that the dust concentration would be subject to

occupational safety restrictions for nuisance dust (the TLV), normally 10 mg/m^3.[32] Additional assumptions are a breathing rate[4] of 12.1 m^3 per 8-hour workday, a 225-day work year (our estimate), and exposure for 0.5 day per workday (since half the time the laborer would be upwind of the dust he stirred up, according to our judgment).

CALCULATIONS FOR SPPPLVs (SINGLE-PATHWAY PRELIMINARY LIMIT VALUES; see Summary, Table 4)

Vegetable Consumption - Human

Vegetable consumption involves the use of indigenously grown crops as the major source of vegetables in the diet. The transport of PBBs from the soil through vegetables to man is considered as a possible pathway of exposure and is modeled by the following SPPPLV equation (vegetable consumption taken as 0.459 kg/day^3 with dry weight fraction = 0.16).[26]

$$\text{Acceptable Concentration in Soil)} = \frac{\text{Body Wt., Adult Human} \times \text{Acceptable Daily Dose}}{\text{Dry Wt. of Vegetables Consumed} \times \text{Soil-to-Plant Partition Coefficient}} \qquad (2a)$$

$$C_s = \frac{BWA \times D_T}{VC \times K_{sp}} = \frac{BWA \times D_T}{VC \times K_{sw} \times K_{wp}} \qquad (2b)$$

$$C_s = \frac{70 \text{ kg} \times (3.73 \times 10^{-4} \text{ mg/kg/day})}{(0.073 \text{ kg/day}) \times (5 \times 10^{-5}) \times 5} = 1,430 \text{ mg/kg} = 1,430 \text{ ppm} \qquad (2c)$$

The value of C_s may be in error by a factor of 10 or 0.1. The acceptable concentration of PBBs in the soil is relatively high because PBBs are expected to be strongly held by the organic components of the soil.

Forage Consumption - Animal

In view of the existence of an FDA human consumption guideline, 0.3 mg/kg in beef fat, the SPPPLV is calculated to meet that criterion, rather than being carried all the way to the human exposure. (Since D_T was derived from this guideline, the two approaches are equivalent.) The daily intake of forage by cattle is assumed to be 16.5 kg/day on a dry weight basis.[3]

Three models may be considered in estimating the accumulative tendencies of PBBs in animal tissue. In the first of these, one postulates establishment of an equilibrium between an animal's fat and feed, with a constant level of fat-soluble contaminant, here PBBs; the equilibrium ratio of concentration in the fat to concentration in the feed is the bioconcentration factor, BF_1, as calculated from the octanol-water partition coefficient (see Table 3). A soil concentration is calculated such that the PBB concentration in the animal fat should equal the FDA-mandated maximum level of 0.3 mg/kg. (Note: $BF = C_f/C_p$).

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In the second model, a bioconcentration factor, BF_2, is derived from the half-life of PBBs in the fat, $t_{1/2}$ = 120 days ($\pm$ 60 days).[29] One equates the first-order rate of loss of PBBs from the fat, rate = C_f x 0.693 $\div$ $t_{1/2}$, to the rate of increase of PBBs in the fat, assuming total transfer from feed to fat, where rate = $M_p C_p$ $\div$ M_f (M_p = 16.5 kg/day of feed and M_f = 75 kg of fat, per animal calculated as 30 percent of an average beef yield of 227 kg/head).[33] Hence, because $BF = C_f/C_p$:

$$BF_2 = \frac{M_p \times t_{1/2}}{M_f \times 0.693} = 38.1 \tag{3}$$

In this model, PBB absorption from the gut has been assumed 100 percent efficient; this is a very safe-sided assumption.

In the third (continuous accumulation) model, it is assumed that the animal accumulates all ingested PBBs that it has ever eaten through forage. If the animal grazes for a total of 594 days before slaughter (allowing for nongrazing during the winter) at 2 years of age, the effective bioconcentration factor is

$$BF_3 = \frac{594 \ M_p}{M_f} = 146 \tag{4}$$

The general equation for the soil SPPPLV is:

$$\text{Acceptable Concentration in Soil} = \frac{\text{Allowable Concentration in Fat}}{\text{Soil-to fat Partition Coefficient}} \tag{5a}$$

$$C_s = \frac{C_f}{K_{sf}} = \frac{C_f}{K_{sw} \times K_{wp} \times BF} \tag{5b}$$

$$C_s = \frac{0.3}{(5 \times 10^{-5}) \times 5 \times BF} = (1{,}200 \div BF) \text{ mg/kg} \tag{5c}$$

Values for C_s, i.e., soil SPPPLVs, according to the various assumptions, are given in Table 4. We prefer the value associated with BF_2, which leads to intermediate C_s values.

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TABLE 4. SPPPLVs FOR POLYBROMOBIPHENYLS

Pathway	SPPPLVs (in ppm)	Comments
Vegetable consumption - human	1,430	
Forage consumption - animal	532	Assuming BF_1
	31.5	Assuming BF_2 (preferred)
	8.2	Assuming BF_3
Soil ingestion - animal	3.1	Assuming BF_1
	0.18	Assuming BF_2 (preferred)
	0.047	Assuming BF_3
Water ingestion - animal	0.048	Assuming BF_1
	0.0029	Assuming BF_2 (preferred)
	0.00061	Assuming BF_4
Soil ingestion - children	45	Normal (preferred)
	9	With pica considered
Water ingestion - human	0.013	
Dust inhalation - human	700 conditions	Industrial exposure

Soil Ingestion - Animal

As in the case of forage consumption, one uses the FDA guidelines as a target. The quantity of soil adopted for calculations concerning soil ingestion by grazing beef cattle is 0.72 kg/day,[34] although this is subject to variations with individual animals, as well as with grazing conditions. If we look upon the PBBs from this source as undergoing a preliminary transfer from the soil to the forage, it is possible to adapt equations (5) to this source, i.e.: (Note that for soil ingestion, K_{sf} = BF)

$$\text{Acceptable Concentration In Soil} = \frac{\text{Allowable Concentration in fat} \times \text{Daily Intake of Forage (Feed)}}{\text{Bioconcentration Factor} \times \text{Daily Intake or Soil}} \tag{6a}$$

$$C_s = \frac{C_f \times M_p}{BF \times D_{soil}} \tag{6b}$$

$$C_s = \frac{0.3 \times 16.5}{BF \times 0.72} = 6.88 \div BF \tag{6c}$$

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Values for C_s (i.e., SPPPLVs) according to the various assumptions are given in Table 4. We prefer the value associated with BF_2.

Water Ingestion - Animal

Again, as in the case of forage consumption, one uses the FDA guideline as a target. The value adopted as the daily water ingestion rate for cattle is 45.4 kg/day (100 lbs/day).[35] If we look upon the PBBs from this source as undergoing a preliminary transfer from the water to the forage, it is possible to adapt equations (5) to this source, recognizing that the source of PBBs is the water itself:

$$\text{Acceptable Concentration in Water} = \frac{\text{Allowable Concentration in Fat} \times \text{Daily Intake of Forage (Feed)}}{\text{Bioconcentration Factor} \times \text{Daily Water Intake}} \tag{7a}$$

$$C_w = \frac{C_f \times M_p}{BF \times D_{water}} \tag{7b}$$

$$C_w = \frac{0.3 \times 16.5}{BF \times 45.4} = 0.109 \div BF \tag{7c}$$

The value of BF in the continuous accumulation model is not the same as for grazed forage or ingested soil, since the two-year (i.e., lifetime to slaughter) exposure equation would not be modified by subtraction of nongrazing days:

$$BF_4 = \frac{730 \, M_p}{M_f} = 180 \tag{8}$$

Values for C_w (i.e., drinking water SPPPLVs) according to the various assumptions (BF_1, BF_2, or BF_4) are given in Table 4. That associated with BF_2 is preferred by the authors.

Soil Ingestion - Children Only

With respect to soil ingestion, both normal and unusual (or habitual) ingestion of soil by children are addressed (weight of child taken as 12 kg).[3]

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Normal soil consumption (10^{-4} kg/day):[3]

$$\text{Acceptable Concentration in Soil} = \frac{\text{Body Wt., Child} \times \text{Acceptable Daily Dose}}{\text{Normal Child Soil Consumption}} \tag{9a}$$

$$C_s = \frac{\text{BWC} \times D_T}{\text{NCSC}} \tag{9b}$$

$$C_s = \frac{12 \text{ kg} \times (3.73 \times 10^{-4} \text{ mg/kg/day})}{10^{-4} \text{ kg/day}} = 45 \text{ mg/kg} = 45 \text{ ppm} \tag{9c}$$

Habitual soil consumption (5×10^{-4} kg/day):[31]

$$\text{Acceptable Concentration in Soil} = \frac{\text{Body Wt. Child} \times \text{Acceptable Daily Dose}}{\text{Pica Child Soil Consumption}} \tag{10a}$$

$$C_s = \frac{12 \text{ kg} \times (3.73 \times 10^{-4} \text{ mg/kg/day})}{5 \times 10^{-4} \text{ kg/day}} = 9 \text{ mg/kg} = 9 \text{ ppm} \tag{10b}$$

Water Ingestion - Human

$$\text{Acceptable Concentration in Water} = \frac{\text{Body Wt. Adult Human} \times \text{Acceptable Daily Dose}}{\text{Wt. of Water Ingested}} \tag{11a}$$

$$C_w = \frac{\text{BWA} \times D_T}{W_w} \tag{11b}$$

$$C_w = \frac{70 \text{ kg} \times (3.73 \times 10^{-4} \text{ mg/kg/day})}{2 \text{ kg/day}} = 0.013 \text{ mg/kg} = 0.013 \text{ ppm} \tag{11c}$$

Note: For this discussion, we have not considered that a 40-hour per week industrial scenario might permit an increased value of C_w. This might be considered if the actual PBB concentration were slightly higher than 0.013 ppm.

Dust Inhalation - Human

Industrial workers may inhale PBB-bearing dust during out-of-doors activities:

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$$\text{Acceptable Concentration in Soil} = \frac{\frac{\text{Total Days per Year}}{\text{Days Exposed per Year}} \times \frac{\text{Body Wt. Human Adult}}{\text{Fraction of Workday Exposed}} \times \frac{\text{Acceptable Daily Dose}}{\frac{\text{Vol. of Air Breathed in Workday}}{} \times \frac{\text{TLV for Nuisance Dust}}{}}}{} \tag{12a}$$

$$C_s = \frac{DPY \times BWA \times D_T}{DEx \times FWEx \times V \times TLV} \tag{12b}$$

$$C_s = \frac{365 \text{ days} \times 70 \text{ kg} \times 3.73 \times 10^{-4} \text{ mg/kg}}{225 \text{ days} \times 0.5 \times (12.1 \text{ m}^3/\text{day}) \times (10^{-5} \text{ kg/m}^3)} = 700 \text{ mg/kg} = 700 \text{ ppm} \tag{12c}$$

MULTIPLE PATHWAYS OF EXPOSURE

When SPPPLVs for two or more exposure pathways from a single source are of like magnitude, the PPLV will be lower than either.[3] For example, suppose the principal sources of PBBs were believed to be consumption of vegetables and inhalation of dust during industrial activity. In this case,[3,4]

$$PPLV = \frac{1}{(1/1430 + 1/700)} = 470 \text{ mg/kg} = 470 \text{ ppm} \tag{13}$$

When the SPPPLVs are of different orders of magnitude, only the lowest need be considered.

For the three scenarios in question, with preferred SPPPLVs (in the absence of water supply contamination), the soil PPLVs would be as follows:

- Agricultural (governed by animal soil ingestion):

$$C_s = 0.18 \text{ ppm (or 180 ppb)} \tag{14}$$

- Residential (governed by childrens' normal soil ingestion)

$$C_s = 45 \text{ ppm} \tag{15}$$

- Industrial (governed by dust inhalation):

$$C_s = 700 \text{ ppm} \tag{16}$$

It is to be noted that any of the above PPLVs would be impacted by PBBs from an independent source, i.e., other than soil. Most typically, this would be water drawn from an aquifer contaminated with Gratiot County Landfill leachate. The PPLVs would depend on each other as shown in Figures 3 through 5. For example, if the drinking-water supply were to contain 0.0065 ppm of PBBs, then persons using this would obtain 50 percent of the allowable daily dose (D_T) from this source (Table 4). Then the PPLV for soil in agricultural use should be reduced by 50 percent to 0.09. Of course, other decision alternatives exist, such as removing PBBs from the water by means of activated carbon.
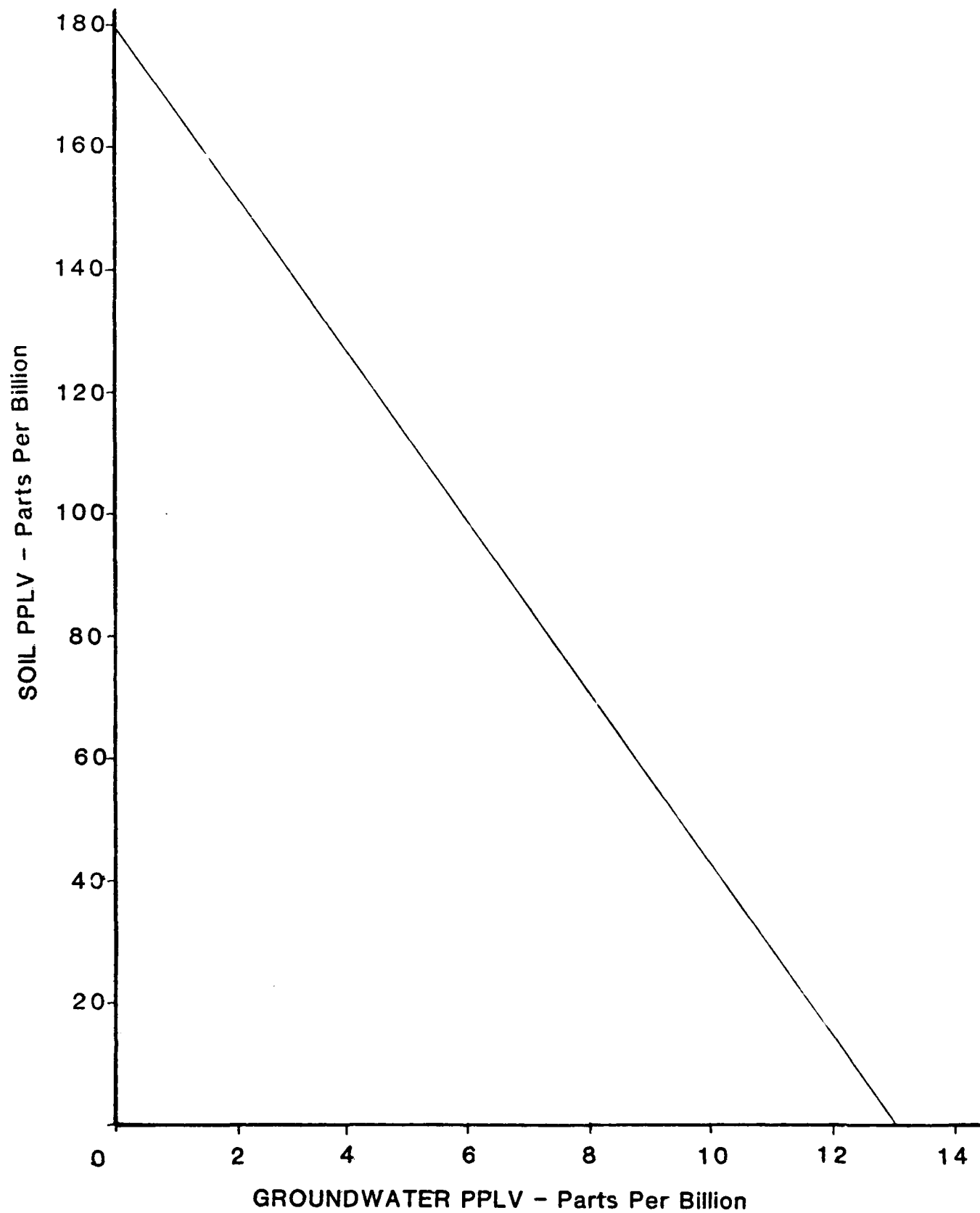
19

Figure 3. Tradeoff relationship between groundwater and soil PPLVs for an agricultural scenario.
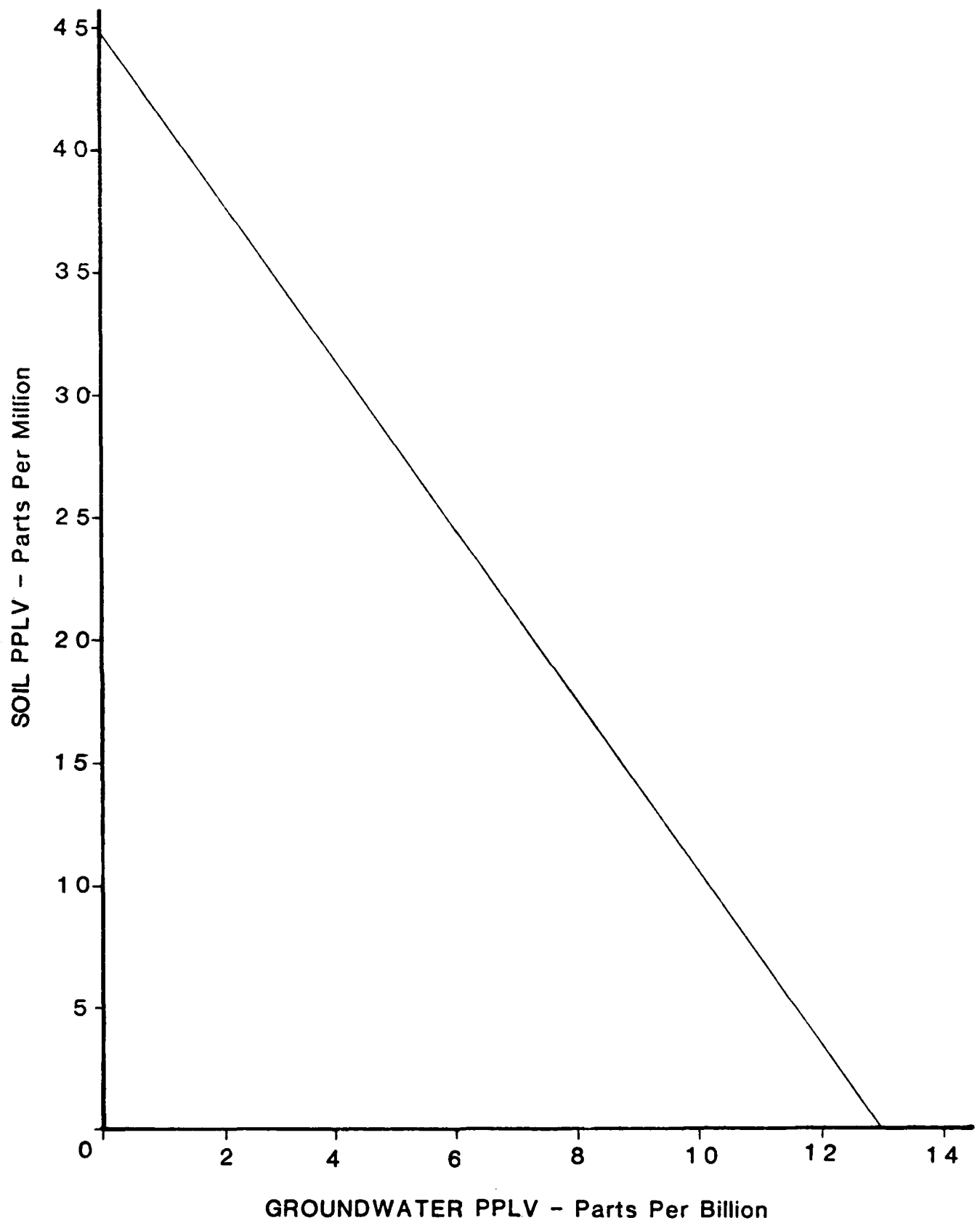
Figure 4. Tradeoff relationship between groundwater and
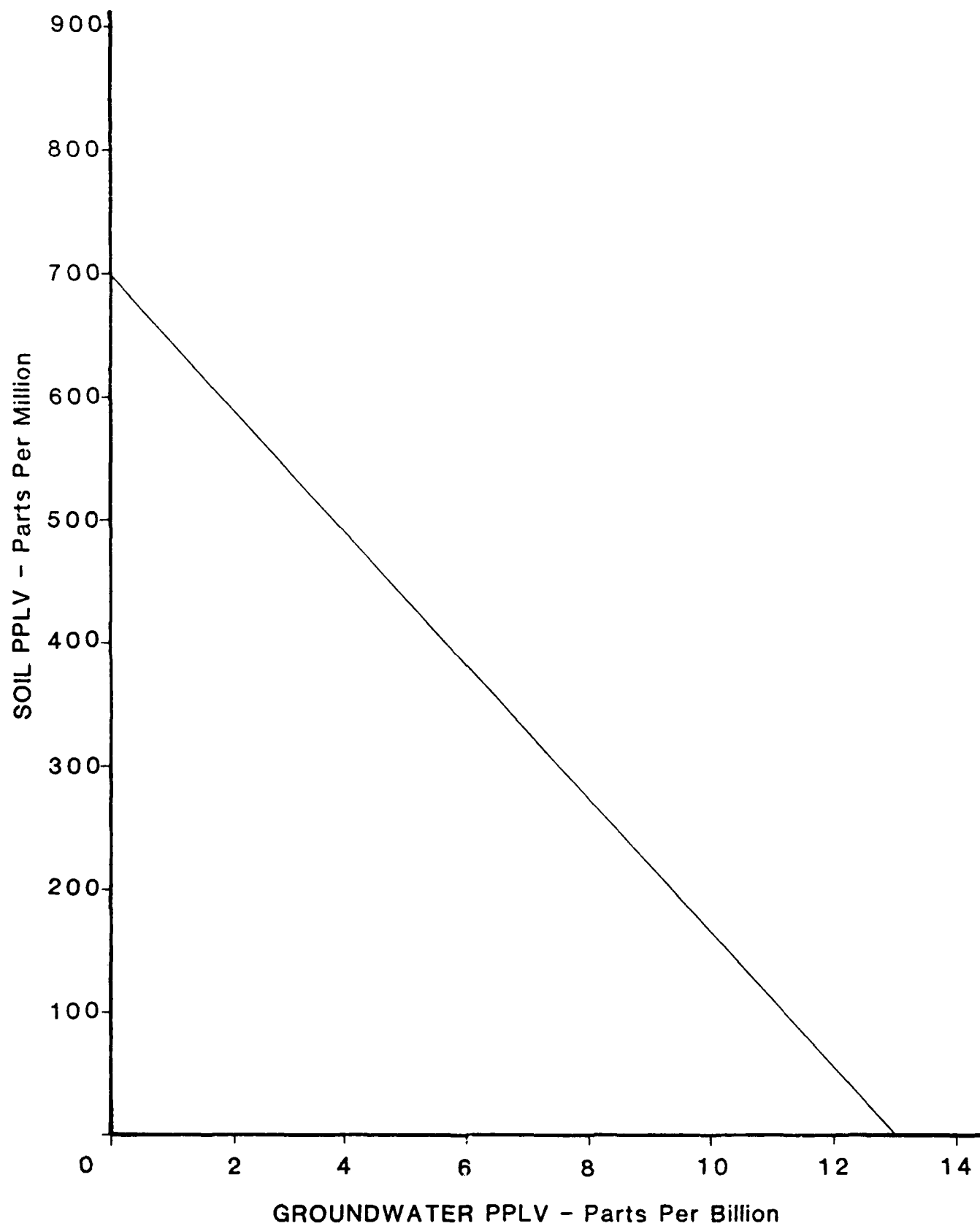soil PPLVs for a residential housing scenario.

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Figure 5.   Tradeoff relationship between groundwater and
soil PPLVs for an industrial scenario.

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The soil PPLV would be more sensitive to aquifer contamination if cattle are watered from this source. This situation would alter calculations for the agricultural scenario only. Because the water would then be consumed by both animals and man, two SPPPLVs, here allowable concentrations in water, must be considered. These are (Table 4): 0.0029 ppm for animal water consumption and 0.013 ppm for human consumption. Because these values differ by less than an order of magnitude the multiple pathway PPLV for water, assuming no soil contamination is:

$$PPLV = \frac{1}{1/0.0029 + 1/0.013} = 0.0024 \text{ mg/kg} = 0.0024 \text{ ppm} \qquad (17)$$

On this assumption, the tradeoff curve for the agricultural use scenario (Fig. 3) would be altered in that the X-intercept would be 2.4 ppb rather than the 13 ppb shown.

It is not practical to deal with all possible combinations of exposure routes in this discussion. The combination of appropriate soil SPPPLVs and PPLVs can be made according to References 3 and 4, as shown above for the residential situation.

MOVEMENT OF PBB SOIL CONTAMINATION BY WIND EROSION

Spreading of contamination by wind erosion from the vicinity of the land-fill depends on numerous factors. The present discussion of the erosion effect addresses a worst-case scenario, safe-sided to ensure reasonable monitoring frequency in the area.

It is expected that erosion of the soil in the landfill area will be eliminated by a cap constructed over the entire area. Thus, major concern is with wind erosion of the land surrounding the landfill. Sixteen percent of this area is susceptible to wind erosion, with slopes of the soil ranging from 0 through 12 percent.[8] Soil loss for areas adjacent to the landfill is estimated to be in the range of 1-5 ton/acre/year, based on several conditions.[9] Farms bordering the landfill comprise 320 acres, which might lose as much as 1,600 tons of soil annually, if the surface were bare. Five tons per acre annually represents an average loss of 1/34 inch (0.75 mm) or less in soil thickness as an average. This is based on a soil specific gravity[36] of 1.5. Soil moisture content strongly influences the effect of wind. Approximately 29 percent of the year the soil moisture (38 days rain) or snow cover (68 days) would be sufficiently high to prevent any extensive wind erosion. We believe the soil of major concern to be in the first inch of the surface, and, under the assumed circumstances, 30 years or longer would elapse before the first inch of surface would be removed (on average). This process would be further delayed by the protection afforded by grass covering the surface or by barriers surrounding the land. If all contaminated soil in a particular field were moved in one direction and redeposited in a field of the same size, less than 1/30 of the surface contamination in the first field would be transported to the second in the course of a year. Thus, one may estimate that the contamination of an adjacent field should not increase in any year by more than 1/30 of that in the contaminated land surrounding the landfill. The assumption of 100 percent redeposition is extremely safe-sided.

Some reduction in PBB levels can be expected as a result of ultraviolet light degradation. Degradation of PBBs should occur on the surface of airborne particles and on soil surfaces exposed to the light,[15] but one cannot assign a numerical value for such degradation.

The highest surface level of PBB at the landfill (within the first inch of soil) was approximately 16 ppm.[6] If soil with such a concentration were allowed to remain exposed, less than 0.5 ppm of PBBs would be transferred annually from the landfill surface to an adjacent area.

PBB MOVEMENT BY LEACHING

In one study, the solubility of PBB in leachates was as high as 16.9 ppb,[12] which is rather low as compared to most organic environmental contaminants. The measured solubility of PBBs in creek water, however, was approximately 0.5 ppb.[12]

Groundwater measurements in the middle of the sand aquifer below the landfill were used to develop the piezometric map.[2] The maximum head difference across the site is about 20 feet. A groundwater divide runs northwest to southeast through the site, with movement of water roughly east, south, and southwest from the divide. A groundwater mound in the center of the site and a groundwater channel along the southwest corner also influence flows. This results in an irregular ground flow pattern for the landfill site.[2] Within the immediate vicinity of the landfill site, water is drawn for drinking purposes from the upper shallow aquifer and the aquifer below the lower clay barrier. The lower aquifer provides the greater supply of water for area residents. Nonetheless, 8 to 10 residents draw water from the upper aquifer within a mile of the landfill.[1] Because the upper aquifer had been breached by the landfill, measurable PBB levels were found in water drawn from there.[1] As a result of the groundwater movement described above, PBBs could be expected, eventually, to infiltrate potable drinking water sources.

Groundwater levels of PBB ranged from zero through 26.0 ppb during a 15-month period.[1]

WATER CONTAMINATION BY PBBs

Surface water generally flows northward from the landfill site and adjacent areas. Levels of PBBs found in surface water in the vicinity of the site have been reported in the range 0.1 to 14.0 ppb. Concentrations of PBBs in sediments around the site ranged from 100 to 17,000 ppb.[1]

PPBs in the surface water and sediments can be assumed to have come from surface spillage of PBB waste and some surface escape of PBBs from the landfill. When this landfill is capped, an important source of PBB surface contamination spread is expected to be substantially reduced. Specific sources of PBB contamination in adjacent areas can be individually addressed by traditional technology.

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Movement of PBBs by surface runoff should diminish if a clay cap is used over the entire landfill. The cap will also largely prevent water from infiltrating the landfill and thence the aquifer.

DISCUSSION

The temptation is great to spend huge sums of public money to eliminate an embarrassing environmental problem that has received lots of publicity and has been associated with very real horror stories. Such is the case with PBBs in Michigan, and specifically in the Gratiot County landfill. There is reason for caution, however. A large part of the funds required, for example to remove and incinerate the contaminants, would have to be diverted from other renovation projects, where the public benefit might be much greater. What is more, excavation of the PBBs could mobilize them and increase the pollution level in surrounding areas markedly; whereas proper sealing (for example, capping with clay), maintenance, and continued monitoring of both the site and related groundwater might be both prudent and less costly. We are not aware of a current cost-effective technology to destroy PBBs in lieu of the foregoing solution.

The PPLV approach has been applied here for the first time to a nonmilitary site. We realize that the numbers derived are no better than the original assumptions, some of which involve considerable uncertainty. For that reason, the entire derivation process should be subjected to scrutiny and reasoned public debate. The SPPPLVs (single-pathway preliminary pollutant limit values) shown in Table 4 provide the basis for the combined-exposure scenario treatments that were developed in this paper for three potential uses of somewhat contaminated land surrounding the Gratiot County landfill. It must be realized, however, that the actual intended use of a tract of land might deviate from these examples. It is to be hoped, if such is the case, that the property owners would employ variants of the approach developed here to make land-use decisions likely to hold human exposures to safe levels.

Our calculations suggest that groundwater ought not to be used for human consumption if it contains more than 13 ppb of PBBs, or for watering cattle if the level is higher than 2.9 ppb (Table 4). As explained above, the values would be still lower if there were other sources of PBBs to contribute to total exposures.

The slow and massive movement of sub-surface water makes it unlikely that significantly contaminated groundwater would be quickly replaced by clean water. We recommend prudent steps to cap the landfill and possibly to draw down the water table beneath the lowest PBB deposits by pumping. However, we do not think these measures will be rapidly effective in reducing aquifer contamination. Direct use of such a water supply would be inadvisable for years to come. If necessary, treatment of such water with an activated carbon adsorbent should inexpensively remove PBBs, but care would be required to ensure timely replacement of exhausted adsorbent. Since the solubility of PBBs is quite low, infiltration of nearby surface streams with relatively high flow rates, particularly the Pine River, by PBB-containing groundwater is not likely to add dangerously high PBB concentrations to those waters.

In the event that criteria based on carcinogenicity studies by Gupta et al.[27,28] drastically lower acceptable PBB concentration values, it may be necessary to reexamine the assumption that no danger exists for significant contamination of the Pine River.

Presently contaminated surface areas and aquifers should be monitored at appropriate time intervals, with the hope that decreasing levels of PBBs would permit uses, in the future, that are now considered unsafe. Although our chief concern is with PBBs, the monitoring should also be used to warn of other environmental contaminants originating in the Gratiot County landfill. Furthermore, tracts adjacent to those bordering the landfill, and of comparable size, should be monitored to ensure that PBB accumulations from PBB-laden dust do not eventually exceed applicable PPLVs. Schedules for such monitoring would be based on the assumed introduction of PBBs at the annual rate of 1/30 of the concentration (in the top 2.5 cm of soil) of the worst contaminated neighboring field each year. For example, suppose a presently clean tract were used as a pasture; the PPLV for this land, based on soil ingestion by cattle, would be 160 ppb. If the PBB level at the surface of an adjoining tract were currently 1.5 ppm, the clean plot would have to be monitored about every 4 years. Also, the aquifer should be monitored in the direction of expected leachate migration.

The major use of the conclusions reached in this paper is to permit various public and private parties to make more informed decisions than were heretofore possible. They should not be a tool of compulsion to force strict conformance to a set of "standards" that, at best, involve considerable uncertainty. It is to be hoped that the present knowledge gaps will be filled by appropriate toxicological and physicochemical research so that the PPLVs derived here can be refined.

CONCLUSIONS

If properly capped and maintained (and especially if the groundwater level beneath is kept below all PBB deposits by drawing down), the Gratiot County Landfill should cease to add significantly to the PBB burden of surrounding land or the underlying aquifer.

There would be considerable environmental risks in disturbing the landfill by PBB removal operations. A cost-effective technology for ultimate disposal of its PBB-rich contents has yet to be proposed. Thus, the best course for protecting public health is to provide the landfill with all proper security (including limited access) and maintenance, and to monitor nearby soils, sediments, and aquifers. Monitoring should also address any other pollutants originating in the landfill.

Land adjacent to the landfill may be sufficiently contaminated with PBBs to preclude certain uses or modes of use. Criteria have been suggested (PPLVs) against which to judge the seriousness of this contamination. Uncertainties in the assumptions are such that there may be some legitimate disagreement concerning the criteria derived by the use of these assumptions.

A simplistic worst-case model has been proposed for movement of PBB-contaminated soil (dust) by wind erosion from one tract to another in the

affected Michigan area. The sole purpose of this model is to assist in establishing more or less reasonable schedules for monitoring fields contiguous to contaminated tracts near the Gratiot County Landfill.

If Gratiot County groundwater is already significantly contaminated by PBBs, as defined by the criteria in this paper, human or animal consumption of the raw water would best be avoided altogether. Removal of the contaminant by treatment with activated carbon would be advisable if the groundwater must be used as a drinking water supply.

It is not considered likely that, by itself, PBB-contaminated groundwater could add dangerous quantities of PBBs to nearby waterways, but new carcinogenicity-based criteria could alter this perception. Such criteria should be derived from recently obtained research results.*

A research program should be undertaken to bolster the scientific underpinnings of decisions regarding the threat of various levels of PBB exposure to the public health.

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*Note in Proof: Telephonic contacts were recently made with (1) Dr. E.E. McConnell of the National Institute of Environmental Health Sciences, Research Triangle Park, NC, and (2) Dr. I.J. Selikoff, Mt. Sinai Hospital, New York, NY. These investigators view the immunosuppressive and enzyme induction effects of PBBs as being especially serious. Such effects may outweigh carcinogenicity in determining an acceptable daily dose. Particular PBB isomers (those in which the two benzene rings can easily achieve coplanarity), as well as certain impurities (such as 2,3,6,7-tetrabromonaphthalene), are considered especially toxic; these may, however, be more short-lived than the less toxic constituents.

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EXPERIMENTAL EVIDENCE CONCERNING PBB ACCUMULATION THROUGH
SOIL INGESTION BY NONLACTATING CATTLE, SHEEP, AND SWINE

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The purpose of this summary is to focus on specific experimental results relating to PBB (polybrominated biphenyl) accumulation in meat fat when the only important route of animal exposure was by consumption of contaminated soil of unpaved lots and pastures. Lot values were derived from Michigan livestock farms that had residual PBB contamination.[1] These values are the only values available in which it is possible to compare directly PBB concentrations in soil and in fat of animals exposed to those soils. Values were obtained under normal agriculture and livestock management conditions. There were no observations for pasture under farm conditions, but limited information on sheep under experimental conditions was available.[2]

Experimentally derived values are listed in Table A-1 in the form of observed ratios (R) of concentration in fat to concentration in soil. Values for cattle included growing dairy heifers as well as growing and mature beef cattle. There was no substantial difference among these classes, but lactating dairy cattle had lower Rs and are not included here because they will not be the limiting factor in land use.

An acceptable concentration in soil (C_s) is derived from R by

$$C_s = C_f/R \qquad (1)$$

where C_f = 0.3 mg/kg, as explained in the main report. The values for C_s are in Table A-1. There is consistency between the ruminant species on lots and between sheep on lots and on pasture. The R for swine was considerably higher than the Rs for ruminants.

Values for acceptable soil concentration can also be derived from soil ingestion levels and bioconcentration factors obtained experimentally. In this summary the model used was

$$C_s = \frac{C_f}{D_{dm} \times D_s \times BF_a \times T} \qquad (2)$$

where D_{dm} is daily dry matter consumption as a fraction of body weight, D_s is soil ingestion as a fraction of D_{dm}, BF_a is an experimentally obtained bioconcentration factor, T is time of exposure in days, and the other terms are as above.

TABLE A-1. OBSERVED RATIOS AND ACCEPTABLE
SOIL CONCENTRATIONS DERIVED FROM
DIRECT OBSERVATIONS[a]

Species	Lot		Pasture	
	R	C_s (mg/kg)	R	C_s (mg/kg)
Cattle	0.34	0.88	–	–
Sheep	0.29	1.03	0.25	1.20
Swine	1.71	0.0	–	–

a. See Equation (1).

TABLE A-2. SOIL INGESTION FACTORS AND ACCEPTABLE
SOIL CONCENTRATIONS ASSOCIATED WITH USE
OF EQUATION (2)

Species	Confinement	D_s	C_s (mg/kg)
Cattle	Lot	0.020[a]	0.63
	Pasture-supplement	0.019[a]	0.66
	Pasture	0.045[b]	0.28
Sheep	Lot	–	–
	Pasture-supplement	–	–
	Pasture	0.045[c]	0.28
Swine	Lot	0.031[d]	0.40
	Pasture-supplement	0.067[d]	0.19

a. Reference 5.
b. Reference 6.
c. Reference 7.
d. Reference 4.

Values for acceptable soil concentrations with this model are in Table A-2. The value for D_{dm} was assumed to be 0.02, which is typical of nonlactating animals. Experimental values for D_s of various animal classes were from the references cited in Table A-2. The feeding studies of Willett and Durst[3] provided data for BF_a, and this value was 4.0. The same value was adopted for all species, because most evidence suggests little variation among farm animals with regard to bioconcentration of PBBs.[4] Time of exposure was set at 300 days, which is a reasonable maximum for the time that nonlactating animals will be in a given environment under farm conditions.

The values obtained for acceptable PBB soil concentrations in pastures by the two methods (i.e., that developed in this Appendix and that developed in the main report for cattle) do not vary by a factor greater than two, which is remarkably close agreement for estimates of this sort. Both methods demonstrate the greater sensitivity of swine to PBB in soil because of greater soil ingestion by swine than by cattle. The values for cattle derived from direct observations in this summary are somewhat greater than the preferred (BF_2) value of 0.18 in the main report. However, the discrepancy is not great, and the methodology used in the main report should be useful for other compounds, where direct observations are not usually available, especially inasmuch as the deviation was in the more conservative (i.e., lower) direction.

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GLOSSARY

Abbreviations

FDA	Food and Drug Administration (US)
MCP	Michigan Chemical Plant, Velsicol Corporation
ng	Nanograms
PBB	Polybrominated Biphenyls
PCB	Polychlorinated Biphenyls
ppb	Parts per Billion
PPLV	Preliminary Pollutant Limit Value
ppm	Parts per Million
SPPPLV	Single Pathway Preliminary Pollutant Limit Value
TLC	Thin-Layer Chromatography
TLV	Threshold Limit Value
TOC	Total Organic Carbon

Symbols

BF	Bioconcentration factor (feed to fat)
BWC	Body weight, child
BWA	Body weight, adult
C_f	Allowable concentration in animal fat, mg/kg
C_p	Allowable concentration in food crop or forage, mg/kg
C_s	Allowable concentration in soil, mg/kg
C_w	Allowable concentration in water, mg/L
DEx	Days exposed to hazard, per year
DPY	Total days per year (365)
D_{soil}	Daily intake of soil, kg
D_t	Acceptable daily dose, mg $kg^{-1}day^{-1}$
D_{water}	Daily water intake, kg
FWEx	Fraction of workday exposed to hazard
K	Soil-water adsorption coefficient
K′	Apparent soil-water adsorption coefficient
K_{oc}	Organic carbon-water adsorption coefficient for soil
K_{ow}	Octanol-water partition coefficient
K_{sf}	Soil to fat partition coefficient
K_{sp}	Soil to plant partition coefficient
K_{sw}	Soil to water partition coefficient
K_{wp}	Water to plant partition coefficient
m	In Freundlich isotherm equation, weight of adsorbent, g
x	In Freundlich isotherm equation, ng material adsorbed
MC	Meat consumed
M_f	Mass of fat/animal, kg
M_p	Mass of animal feed consumed, kg/day
NCSC	Normal child soil consumption
$t_{1/2}$	Half-life
V	Volume of air breathed, m^3/day
VC	Vegetable consumed, dry wt.
W_w	Weight of water ingested

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