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Industrial surface impoundments: environmental settings, release and exposure potential and risk characterization

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Abstract

This paper presents the results of a national scale evaluation of the environmental impact of surface impoundments that contain non-hazardous wastewaters. In the 1990s, it was found that approximately 18 000 surface impoundments existed in the US for treating, storing or disposing of non-hazardous wastewater. In this study, the focus was on the subset of 11 900 impoundments that contain at least one of 256 chemicals of interest or high or low pH wastewater. Questionnaires were sent to facilities chosen in a two-phase nationally representative random sample. The nature, extent and use of surface impoundments across manufacturing industries were characterized using the information collected in the survey. Also, the chemical composition of impounded wastewaters; the potential for chemical releases to the environment from the impoundments; and the risk from these releases were assessed. It is estimated that only approximately 5–6% of facilities with impoundments have the potential to pose risks to human health, although approximately 19–46% of facilities with impoundments release chemicals of concern to the environment. The information in this study should help environmental managers evaluate and avoid those risk factors that have the potential to result in environmental harm, particularly when present in combination.

Keywords: Surface impoundment; Wastewater; Waste management; Contaminant release; Exposure; Risk

1. Introduction

Many industries use large volumes of water for various purposes. Once used, the water is sometimes placed in lagoons, ponds, or impoundments (Arands et al., 1991; Barkley and Bryant, 1990; Barth et al., 1990; Krueger et al., 1991; National Research Council, 2002; Rebhun and Galil, 1994; Reeves and Falivene, 1992). These waste management units are often built and integrated into a wastewater management system to remove contaminants, control temperature, facilitate groundwater infiltration, or hold and condition water for reuse (Tchobanoglous and Burton, 1991). While surface impoundments have been instrumental in eliminating pollutants from wastewater prior to its discharge into surface water, there have also been

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long standing concerns that management of contaminated wastewater in surface impoundments may lead to the release of harmful substances into the environment and human or ecological exposures (Freeman, 1997; LaGrega et al., 1994). During the last 25 years, the US Environmental Protection Agency, other federal agencies and the states have taken action to characterize and control releases from surface impoundments.

In 1979 and again in 1985, EPA characterized the number and nature of industrial surface impoundments that were used throughout the US. The 1979 study indicated there were 30 000 surface impoundments in use in various industrial sectors (USEPA, 1983). Subsequent to this initial study, EPA developed a comprehensive set of national performance standards for the control of hazardous wastes. Hazardous wastes managed in surface impoundments were subject to these standards. In response to these and other environmental standards, wastewater operators redesigned their hazardous wastewater systems. Many closed their impoundments and began to rely predominantly on tank-based treatment systems to minimize the potential for releases, particularly to groundwater. In 1985, after implementation of the hazardous waste regulations, EPA conducted another national survey of surface impoundments. In this study, EPA focused largely on non-hazardous[1] wastes managed by the manufacturing and utility sectors and found there were approximately 15 000 surface impoundments in operation (USEPA, 1988b).

In the mid-1990s, in response to legislative (Land Disposal Program Flexibility Act, 1996, Public Law 104-119) and judicial directives (*Environmental Defense Fund vs. Whitman*, D.C. Circuit, 89-0598), EPA initiated the study reported in this paper. This study focuses on characterizing the environmental impacts and potential risks from the management of non-hazardous wastewaters in surface impoundments. In approaching the study, it was found that there was little current information to help design the study other than summaries of findings from previous studies. While state programs for managing non-hazardous waste have improved, there has been no evaluation of these programs' successes in encouraging conversion to tank-based management or elimination of contaminants in wastewaters. Given the tremendous change that has taken place throughout the country in how hazardous wastewaters were managed, there was the possibility that fewer surface impoundments were in operation than had been observed in the 1980s or that waste minimization programs may have eliminated significant contamination from wastewaters.

The first objective of this study was to update the previous national characterization of industrial non-hazardous surface impoundments with a focus on describing operations during the 1990s. The intent was then to go beyond what had been explored previously and learn about the design features, management practices and contents of these surface impoundments. In addition, the environmental settings, the potential for contaminant release, the proximity to populations and potential exposure pathways were of particular interest considering the obligation to characterize the risks associated with such impoundments (USEPA, 2001, 2002).

2. Data collection methodology

The overall strategy for this study was to collect a nationally representative sample of site specific survey information from impoundment owners on facility history, surface impoundment attributes, environmental settings, wastewater chemical concentrations and the attributes of nearby receptors and sensitive habitats. This information was collected following a statistical design that would facilitate inferences about the entire population of non-hazardous waste industrial surface impoundments across the US. The survey information was used to conduct screening level risk assessments. In addition, a focused field effort was included in the study to obtain wastewater and sludge samples and analyze the chemicals that were present. This

[1] The term non-hazardous as used in this paper derives from Subtitle D of the federal Resource Conservation and Recovery Act. Wastes classified as non-hazardous are wastes that have not met the regulatory definition of hazardous waste. Wastes not meeting such a definition are referred to as non-hazardous but, as demonstrated in this study, may nevertheless contain toxic or harmful chemicals that are not addressed by the hazardous waste definition.

field sampling information was used to evaluate the survey information that was obtained from facility respondents.

2.1. Scope

The bounds of the study were established by defining the economic sectors and chemicals that would be included as well as the temporal and spatial breadth of the study. Surface impoundments throughout the US that had received waste between June 1990 and June 2000 were eligible for inclusion in the study. Manufacturing and service industries were the focus of this study and included food processing; textiles; paper and allied products; stone, clay and glass; chemicals and allied products; petroleum and allied products; primary metals; bulk chemical and petroleum storage; sewerage and refuse systems; scrap and waste materials; airport terminals; truck transportation terminals and national security. The mining, petroleum extraction and utility sectors are widely known to use surface impoundments but were not included because they have been evaluated in detail in previous studies (USEPA, 1985, 1988a, 1999). Similarly impoundments associated with run-off control, agriculture and municipal sewerage treatment have also received a great deal of attention in prior studies (USEPA, 1988b). This study addressed 256 chemicals that historically had been of greatest concern in wastes. In addition, wastes with high or low pH, which would not be otherwise hazardous were also examined.

2.2. Survey design

A two-phase stratified random sample design was developed to identify a representative sample of facilities with impoundments meeting the study criteria. Because there was no existing list frame[2] of non-hazardous waste surface impoundments an initial list frame of wastewater handlers was used instead. The frame that provided the facilities for sampling in the first stage consisted of 43 050 facilities that discharge their wastewater directly to surface water, known as direct dischargers, and 5807 facilities with no discharge, known as zero dischargers. The list frame of direct discharge facilities was developed from EPA's Permit Compliance System and the frame for the zero dischargers was developed using a variety of federal and state databases. Data collection during the initial phase of sampling was limited to a short and focused questionnaire to obtain information from a random sample of 2017 facilities. The focus of the initial questionnaire was (1) to determine whether the facility had a surface impoundment and (2) to generate information that could be used to create strata for the second phase of sampling. The second phase sample was a subsample of the facilities that were identified during the first phase as having an impoundment that also fell within the scope of the study.

Stratification and unequal sample allocation was used during both phases of sampling. During the first phase of sampling, the direct dischargers were generally stratified by Standard Industrial Classification (SIC) categories; a subset of industries were identified as being more likely to have surface impoundments and were, therefore, sampled at a higher rate. The zero discharge list was generally sampled with an equal probability of selection.

The second phase sample included 221 facilities. The second stage sample was stratified by SIC code and whether facilities were direct or zero dischargers. The sample allocation was unequal with sampling weights developed to increase the probability of selecting impoundments of most interest in terms of their potential for risk. Each facility in the second phase of sampling was asked to complete a long, more in-depth questionnaire.

2.3. Data collection

Information for the study was acquired through site-specific questionnaires completed by impoundment operators, publicly available data bases, and field sampling. The first-phase questionnaire described the purpose and scope of the study to the respondents and then asked for responses to a few questions. There were questions designed to identify and locate facilities, characterize wastes, and determine whether each facility

[2] The term list frame means the study population defined as a list of facilities.

had an impoundment and if so classify each impoundment.

The second-phase questionnaire consisted of a three-part form plus instructions and relevant appendices. It was designed to collect the detailed information necessary to perform risk assessments and develop general characteristics of the study population. This information included each facility's environmental setting, receptor locations, details on the design, operation and history of each eligible surface impoundment, and the chemical composition of wastewater and sludge managed within the impoundments.

Survey data together with data from publicly available sources were used to describe hydrogeologic settings (Aller et al., 1987), soils, surficial water bodies and land use (Hunt, 1974; van der Leeden et al., 1990). These data were used to build the environmental settings needed to conduct the risk assessment. In addition, US Geological Survey 1:24 000 topographic maps were used for digitizing site features including topography, physiographic locations, and nearby populations if maps were not otherwise provided by the survey respondents. These map data were supplemented with 1990 US Census data to determine population characteristics around each surface impoundment.

A limited field sampling program was also conducted to directly measure the levels of hazardous chemicals present in selected impoundments. Twelve facilities were selected for sampling from a range of industries. An overall quality assurance plan was developed and 12 sampling and analysis protocols were developed to take into account the specific nature of each facility.

At each facility, samples were generally collected at one or more surface impoundments to represent wastewater at various points in the surface impoundment system such as in the influent and effluent, sludge layer, leachate and groundwater monitoring well water. Site specific circumstances dictated the nature and extent of sampling at each facility.

2.4. Statistical estimation of facility and impoundment attributes

The main objective of the statistical estimation protocol was to make valid national inferences regarding the overall surface impoundment universe as well as make inferences regarding the attributes of subgroups or analysis domains within the overall universe. Hence, to ensure that robust inferences were made, stratified random sampling was used to select sample facilities, and statistical analysis weights were used when analyzing the data (Kalton, 1983). The initial sampling weights were the reciprocals of the probabilities of selection in each of the two phases of sampling. This was done to ensure design-unbiased analyses. The number of linkages to the frame for each sample facility was determined to ensure that each eligible facility had only one record on the sampling frame. The initial sampling weights were divided by these multiplicities to compensate for the higher likelihood of inclusion in the sample for facilities with multiple linkages to the frame (Lessler and Kalsbeek, 1992). The weights of ineligible facilities were then set to zero to account for the fact that the sampling frame contained many facilities that had no eligible impoundments. Class weight adjustments were then used to correct for nonresponse of sample facilities as well as lack of data for individual impoundments at otherwise responding facilities (Brick and Kalton, 1996).

2.5. Risk analysis methodology

Chronic risks were estimated for each chemical contaminant in the air, groundwater, and groundwater to surface water pathways. A screening assessment was used to consider the potential for indirect pathway risks and ecological hazards. The objective of the screening was to determine the worst case potential for wastes of concern to cause harm. Indirect pathway risks can occur when humans ingest foods that have been contaminated indirectly by surface impoundment releases. For example, chemicals can evaporate, move by dispersion through air, and then deposit on nearby crops and contaminate food sources. Ecological damage can be mediated by similar indirect or direct pathways. Fig. 1 depicts the releases, pathways and exposure routes that were considered in the risk evaluation.

The risk analysis and risk screening were conducted in stages in order to screen the thousands

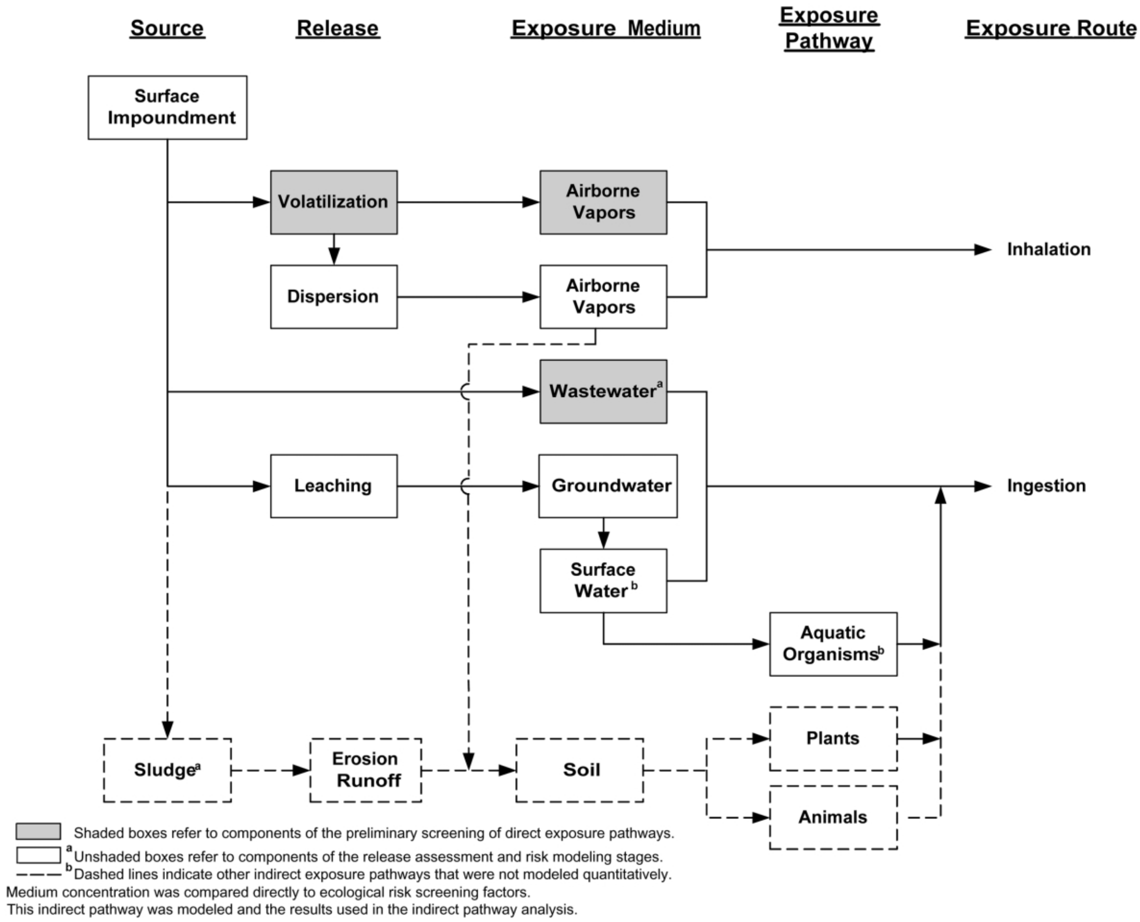


Fig. 1. Summary of release mechanisms and exposure pathways considered in the evaluation of risk to human and ecological receptors.

of possible risk estimates, focus the analysis where most warranted, and, ultimately, characterize the potential risks associated with industrial surface impoundments. The first stage applied precautionary exposure assumptions to identify those impoundments that merited additional analysis. In subsequent stages, data on environmental setting and unit characteristics were used to determine whether releases are likely now or in the future and then, in the final stage of analysis, information on surrounding populations was used to estimate potential risks. Qualitative risk screening of the other indirect pathways and ecological hazards was similar to the initial stages of the risk analysis. Thus, the characterization of indirect pathway hazards and ecological hazards developed in this study is less certain than the characterization of risks via air, groundwater, and groundwater to surface water exposures.

In the risk analysis, several chronic risk and hazard measures were used to evaluate potential threats to human and ecological receptors from chemicals managed in surface impoundments. Cancer risk to humans was estimated as the probability of excess individual lifetime cancer from exposure to carcinogenic chemicals. Non-cancer health effects for humans were evaluated using hazard quotients (HQs), which are the ratio of the

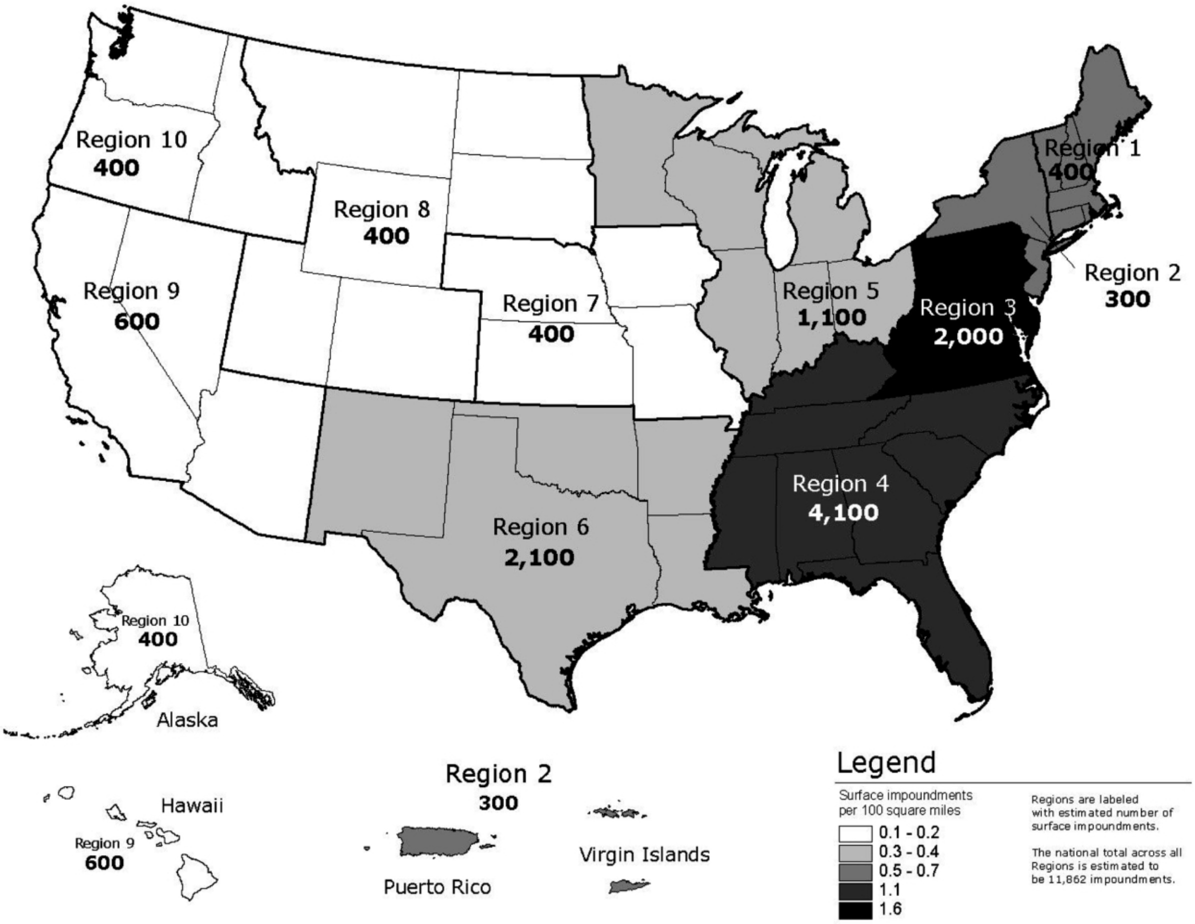


Fig. 2. Regional distribution of surface impoundments.

dose of contaminant expected at an exposure point to an appropriate safe reference dose. The dose of contaminant at an exposure point varies with time, according to a 'breakthrough curve' a plot of concentration vs. time. The screening and characterization analysis used the maximum concentration on the breakthrough curve for the HQ calculation. Other risk measures were also developed for the risk screening to examine the threats associated with consumption of contaminated fish and with ecological hazards. In determining, what risks were of concern at each stage of the analysis, a cancer risk of one or more in 100 000 and a HQ of one or more were the criteria for deciding whether to retain an impoundment for the next stage of evaluation.

The analysis examined those facilities and impoundments with the potential for contaminants to be released and subsequently be present at concentrations that exceed levels of concern if humans were to be exposed for long periods of time. The analysis also examined the impoundments and facilities that had, in addition to a release, the potential for human exposure and, therefore, a human health risk. At the group of facilities with a human health risk, contaminant concentrations exceeded levels of concern in combination with information indicating the presence of contemporary human activity such as groundwater use that would lead to an exposure. Only this latter group of facilities is described as posing a risk.

The release and risk analyses include two sets of results. The first set was calculated using values, which were reported by the survey respondents, for specified chemical concentrations greater than a limit of detection. The second set was calculated using imputed values. The imputation protocol, outlined in detail in USEPA (2001), was used when survey respondents reported that chemicals were present but did not provide quantities, or when chemicals were reported at less than a limit of detection. Consequently, the second set of risk results is considerably less certain.

3. Results and discussion

3.1. Impoundment population size and distribution

There were estimated to be approximately 18 400 (1760)[3] industrial surface impoundments that manage materials outside of the federal hazardous waste program. These impoundments were located at 7500 (390) facilities that received waste between June 1990 and June 2000 and met the other criteria for inclusion in this study. Of these non-hazardous industrial impoundments, approximately 11 900 (1900) managed wastewaters that contain one or more of the 256 chemicals of concern or have either high or low pH. These impoundments are located at an estimated 4500 (520) facilities and account for roughly 650 (330) million metric tons of wastewater quantity managed.

Of the 11 900 impoundments with chemicals or pH levels of concern, approximately 11 000 (1700) sent their discharge directly to a surface water body and 900 (140) had no discharge because of either reuse, infiltration or evaporation.

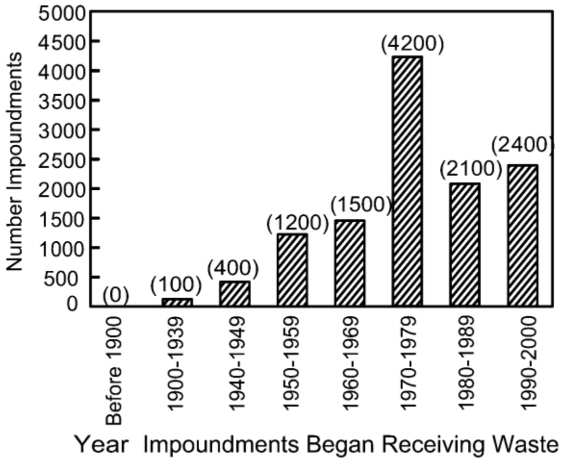


Fig. 3. Distribution of the estimated number of impoundments beginning operation over time.

Statistical estimates of the number of impoundments with discharges to centralized wastewater treatment facilities were not possible, but the numbers are believed to be low as most indirect dischargers rely entirely on tank-based systems.

Approximately two-thirds of all facilities with impoundments had more than one impoundment onsite; roughly 5% had more than 10 impoundments onsite.

Surface impoundments are located across the country, but the greatest numbers and density are located in the eastern quarter of the US (Fig. 2). In the west, the density and number of impoundments is far less.

Temporal trends presented in Fig. 3 show that the majority of impoundments were constructed within the past 30 years. Furthermore, 40% of impoundments were put into service in the 1970s, possibly in response to environmental programs requiring greater treatment of industrial wastewaters. Approximately one-quarter of the surface impoundment population was in operation before 1970.

Approximately two-thirds of the total wastewater quantity managed in the 11 900 impoundments was managed at facilities in the paper and allied products sector. This industrial sector represented only 6% of the population of facilities and just over 10% of the 11 900 impoundments.

[3] Several of the more important estimates in this paper are accompanied by their standard errors; which when reported are in parenthesis following the estimate. The methodology for calculating these is explained in USEPA (2001). A 95% confidence interval about the estimate can be determined by creating an interval extending from approximately two standard errors above to two standard errors below the estimate.

Table 1
National distribution of impoundment surface areas

Impoundment surface area size range in hectares	Estimated number of impoundments (percent of 11 900 total)
0–0.25	6000 (51)
0.25–1	3000 (25)
1–5	2000 (17)
5–10	500 (4)
10–500	500 (4)

More than 75% of the surface impoundments had a surface area of less than 1 ha while 8% had surface areas in excess of 5 ha (Table 1). In sharp contrast, the few large impoundments handle the vast majority of the wastewater. For example, those relatively few impoundments that are greater than 5 ha handled more than 75% of the wastewater volume.

3.2. Impoundment contaminants, release potential and proximity to human receptors

In looking further at the nation's industrial surface impoundments and their characteristics, the classic risk assessment framework developed by the National Research Council (1983) was used to help organize, discuss and understand the environmental settings and risk potential of surface impoundments. The initial examination of the source reveals the characteristics of the contaminants present in the impoundments. Impoundments' locations and construction practices were evaluated to assess their tendency to contribute to releases to and movement through the surrounding environment. Finally, the impoundments' proximities to humans was assessed to gauge the potential for human exposure.

3.2.1. Impoundment contaminants

In evaluating the release potential from surface impoundments one key factor is the potential hazard of the chemicals generally found in impoundments. More than half of the impoundments contained wastewater with six or more of the target chemicals while the sludges within the impoundments were reported to contained far fewer contaminants (Fig. 4).

The most common class of chemicals in impoundments was metals, followed by volatile and semivolatile organic compounds. Mercury was estimated to be present in 30% of impoundment waters and in the sludge of 66% of impoundment waters across the nation (Table 2). While the number and classes of chemicals present in the impoundments were clearly significant, the range of concentrations of the most prevalent compounds relative to standard health based benchmarks did not reveal a large proportion of impoundments with extremely harmful levels. Table 3 indicates that the 90th percentile impoundment influent wastewater concentrations of arsenic, benzene, cadmium, methyl ethyl ketone and selenium were found to be in excess of highly protective risk based screening levels that were used in the initial phases of the groundwater pathway risk analysis.

The field sampling results also provide some insight regarding the nature of the contaminants found in impoundments. The field sampling effort was designed as an independent verification of the self-reported survey data on chemical levels and presence. When a chemical was both reported in the survey and analyzed as part of the field sampling effort, the concentrations reported in the survey agreed, in most instances, within an order of magnitude of the corresponding field sampling quantity (Fig. 5). There was seldom an instance in which the reported survey values were more than two orders of magnitude different than the corresponding field sampling values. In addition,

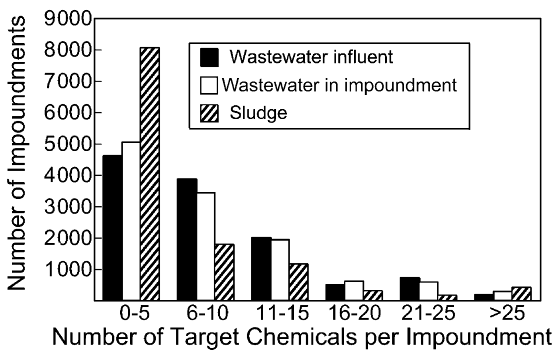


Fig. 4. Number of chemicals in wastewater and sludge managed in impoundments.

Table 2
Number of impoundments and percent of volume having selected chemical categories present at selected locations in the impoundment system

Chemical categories	Wastewater						Sludge					
	Influent		In impoundment		Effluent		Influent		In impoundment		Effluent	
	#	Vol.%	#	Vol.%	#	Vol.%	#	Vol.%	#	Vol.%	#	Vol.%
VOCs	5900	76	5400	76	4800	72	1700	4	2000	21	1300	14
SVOCs	3800	75	3800	75	3500	69	900	7	1300	24	600	3
Metals	10 000	84	10 000	83	7800	85	3900	42	5600	98	3100	88
Dioxin-like compounds	300	24	200	21	300	22	200	10	900	35	400	41
Mercury	2500	27	2500	30	2200	31	1000	0.9	1700	66	800	6
Any chemical or high/low pH	10 700	96	10 800	97	8200	92	4100	45	5800	100	3200	89

#, number of impoundments; Vol.%, percent of total waste volume containing at least one chemical in the category; SVOCs, semivolatile organic compounds; VOCs, Volatile organic compounds.

Table 3
Comparison of 50th and 90th percentile influent wastewater concentrations with toxicity characteristic (TC) limits and health-based screening factors for selected chemicals

Chemical (CAS registry)	Risk-based screening factor[a] (mg/l)		TC limit[b] (mg/l)	Influent waste water concentrations (mg/l)	
	Carcinogenic	Non-carcinogenic		50th percentile	90th percentile
Arsenic (7440-38-2)	6.6E−04	6.9E−03	5.0	9.0E−03	2.1E−02
Barium (7440-39-3)	NA	1.6E+00	100.0	1.3E−01	3.5E−01
Benzene (71-43-2)	1.8E−02	NA	0.5	2.1E−02	8.0E−01
Cadmium (7440-43-9)	NA	1.2E−02	1.0	3.1E−03	1.5E−01
Chloroform (67-66-3)	1.6E−01	2.3E−01	6.0	4.0E−03	3.0E−02
Chromium (7440-47-3)	NA	6.9E−02	5.0	6.4E−03	2.7E−02
Cresol (1319-77-3)	NA	1.2E+00	200.0	3.1E−02	1.1E−01
Lead (7439-92-1)	NA	NA	5.0	1.0E−02	2.0E−02
Mercury (7439-97-6)	NA	6.9E−03	0.2	3.0E−04	3.8E−03
Methyl ethyl ketone (78-93-3)	NA	1.4E+01	200.0	6.1E−01	5.9E+00
Selenium (7782-49-2)	NA	1.2E−01	1.0	5.3E−03	1.4E−01

NA, not available.

[a] Human health screening factors used in the first phase of the risk analysis for carcinogens and non-carcinogens in drinking water.

[b] *Source:* 40 code of federal regulations §261.24, Table 1—maximum concentration of contaminants for the toxicity characteristic.

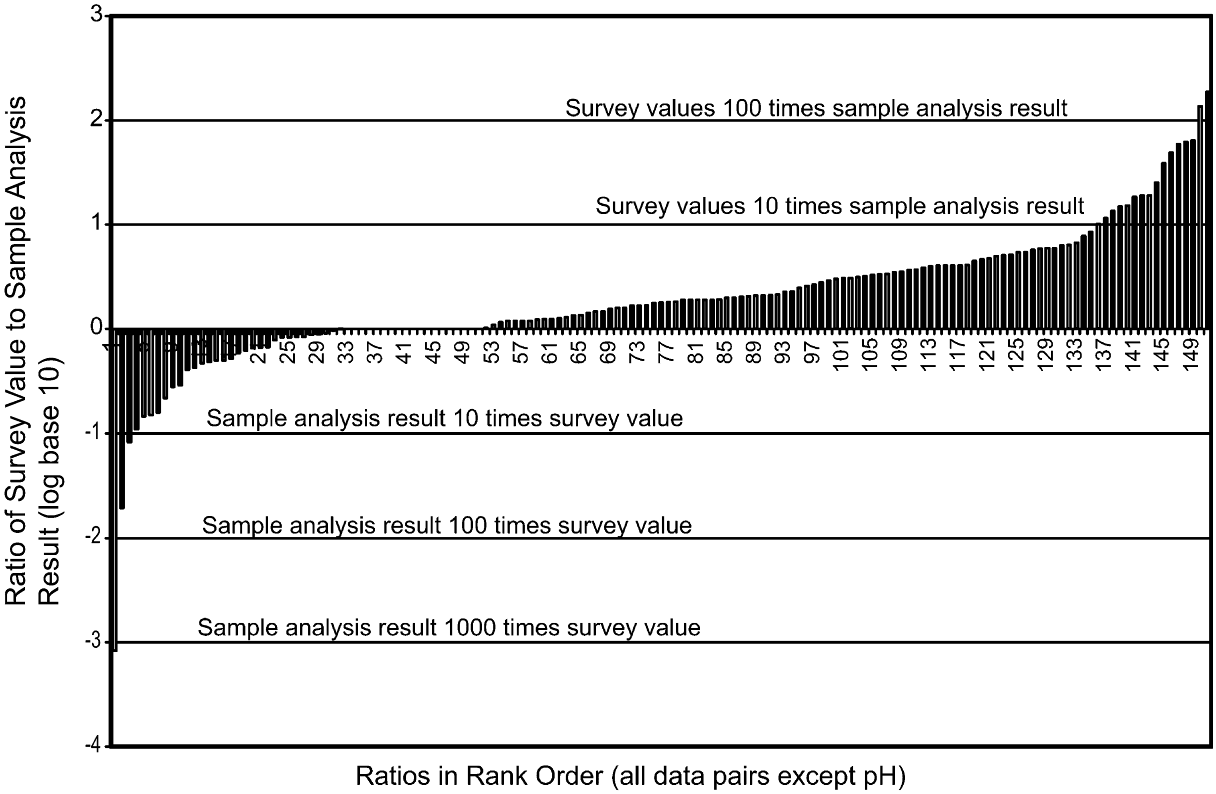


Fig. 5. Relationship between survey values and corresponding measurements from the field samples.

the study results indicate that the self-reported survey data were greater than the comparable field sampling data more often than not. This finding suggests that the field sampling did not find evidence that chemical concentrations were under reported by survey respondents.

As an indication of whether chemicals may tend to be present that were not reported in the survey, at each of the 12 facilities that were field sampled the number of chemicals reported in the survey was compared with the number of chemicals found in the field sampling. Table 4 presents the results of this comparison and suggests that there may have been under reporting of the number of chemicals. At each of the 12 facilities visited for sampling, additional chemicals were found that were not self-reported but were present above a limit of detection. The number of unreported chemicals found at a facility ranged from 3 to 30. It is important to note that this does not suggest that respondents failed in their reporting as they were only asked to report information that they had available.

Based on the agreement between the concentrations reported in the survey and those measured during the field study, it appears that there is no reason to collectively question the self-reported concentration measurements provided by the facility operators. However, based on the discrepancies observed as to the presence of some chemicals in the impoundments sampled, there is evidence to suggest that facility operators often may not have comprehensive knowledge of all the individual chemicals contained in their impoundments.

3.2.2. Releases to the air

Impoundments have the potential to release contaminants to the air, subsurface and surface

Table 4
Constituents confirmed with field sampling and unreported constituents

Facility SIC code	Facility operations	Number of constituents reported in survey[a]	Number of same constituents detected in a corresponding field sample	Number of additional constituents detected in field sampling and not reported by facility
2037	Fruit processing	0	0	11
2621	Paper milling	15	8	18
2611	Pulp milling	11	10	30
2821	Nylon manufacturing	8	6	18
2819	Inorganic chemical manufacturing	6	4	13
2911	Petroleum refining #1	55	17	7
2911	Petroleum refining #2	11	11	13
3087	Rubber mixing	10	5	3
3273	Ready mix concrete processing	0	0	10
3313	Electrometallurgical product manufacturing	17	15	13
3353	Aluminum manufacturing	7	7	11
3674	Semiconductor manufacturing	4	4	9

SIC, standard industrial classification.
[a] Includes concentration values reported as '<', and constituents reported as 'present but quantity unknown.'

water. First releases to the air pathway were examined. Volatile organic compounds (VOCs) offer the greatest potential for release to the air. The uncontrolled release of VOCs from wastewaters is, therefore, an area of concern (Hedden et al., 1990). There are many factors that affect the volatilization of a chemical from the water surface of an impoundment and its subsequent transport in the atmosphere. These factors include the properties of the chemical such as its tendency to partition between water and air, the concentration and mass of the chemical, the temperature of the air above the impoundment and of the wastewater in the impoundment, the local meteorological conditions including wind speed and atmospheric stability class, and the characteristics of the impoundment such as its surface area and aeration level.

Approximately 5950 impoundments managed wastewaters that contained VOCs (Table 5); these impoundments contained approximately 75% of wastewaters nationally. The most common VOCs by volume reported to be in wastewater were methanol, acetone, methyl ethyl ketone and acetaldehyde. Impoundment size is one important factor influencing the potential for atmospheric contaminant releases. Approximately 70% of the large impoundments in the 5–500 ha category contained VOCs, while 50% of the small impoundments under 1 ha contained VOCs. Aeration was a common management practice for these impoundments and is performed to improve the efficiency of wastewater treatment. Approximately 25% of all facilities used aerated impoundments and an estimated 45% of the total wastewater volume was aerated. Approximately 950 or more than half of the estimated 1740 impoundments where aeration was conducted contained VOCs. Approximately 50% of those impoundments conducting aeration were over 1 ha in size and almost 40% of impoundments in the 5–500 ha size range employed aeration practices.

3.2.3. Releases to the subsurface

The potential for release of chemicals to the subsurface was also examined and it is clear that many factors influence the release and migration of chemicals to the vadose zone and groundwater. The presence of an impoundment liner and depth to groundwater are two critical features that determine the potential for release to and movement through the subsurface. Subsurface monitoring is

Table 5
The relationship among residential proximity to impoundments, waste water quantities, the presence of VOCs and aeration status

VOC/aeration status of impoundments	Concentric area defined by this radial distance (m)			Total
	0–150	151–1000	1001–2000	
No VOCs in wastewater				
Number of impoundments with at least one residence within this area	3400	2200	240	6000
Percent of total wastewater quantity	14	8	3	25
Wastewater quantity (metric tons)				1.98×10^6
VOCs present in wastewater/no aeration				
Number of impoundments with at least one residence within this area	460	4100	340	5000
Percent of total wastewater quantity	8	24	1	33
Wastewater quantity (metric tons)				2.54×10^6
VOCs present in wastewater/aeration				
Number of impoundments with at least one residence within this area	410	430	100	950
Percent of total wastewater quantity	8	29	3	41
Wastewater quantity (metric tons)				3.07×10^6
Total				
Number of impoundments with at least one residence within this area	4300	6700	670	11 900
Percent of total wastewater quantity	30	60	8	100
Wastewater quantity (metric tons)				7.59×10^6

an important tool for generating the information needed to help manage the environmental impact of surface impoundment releases.

Impoundment owners were asked to report the elevation of their impoundments; the distribution of the depths to groundwater from the impoundment's bottom is shown in Fig. 6. Approximately 75% of impoundments were located in areas where the depth to the uppermost groundwater system was within 4 m of the bottom of the impoundment,

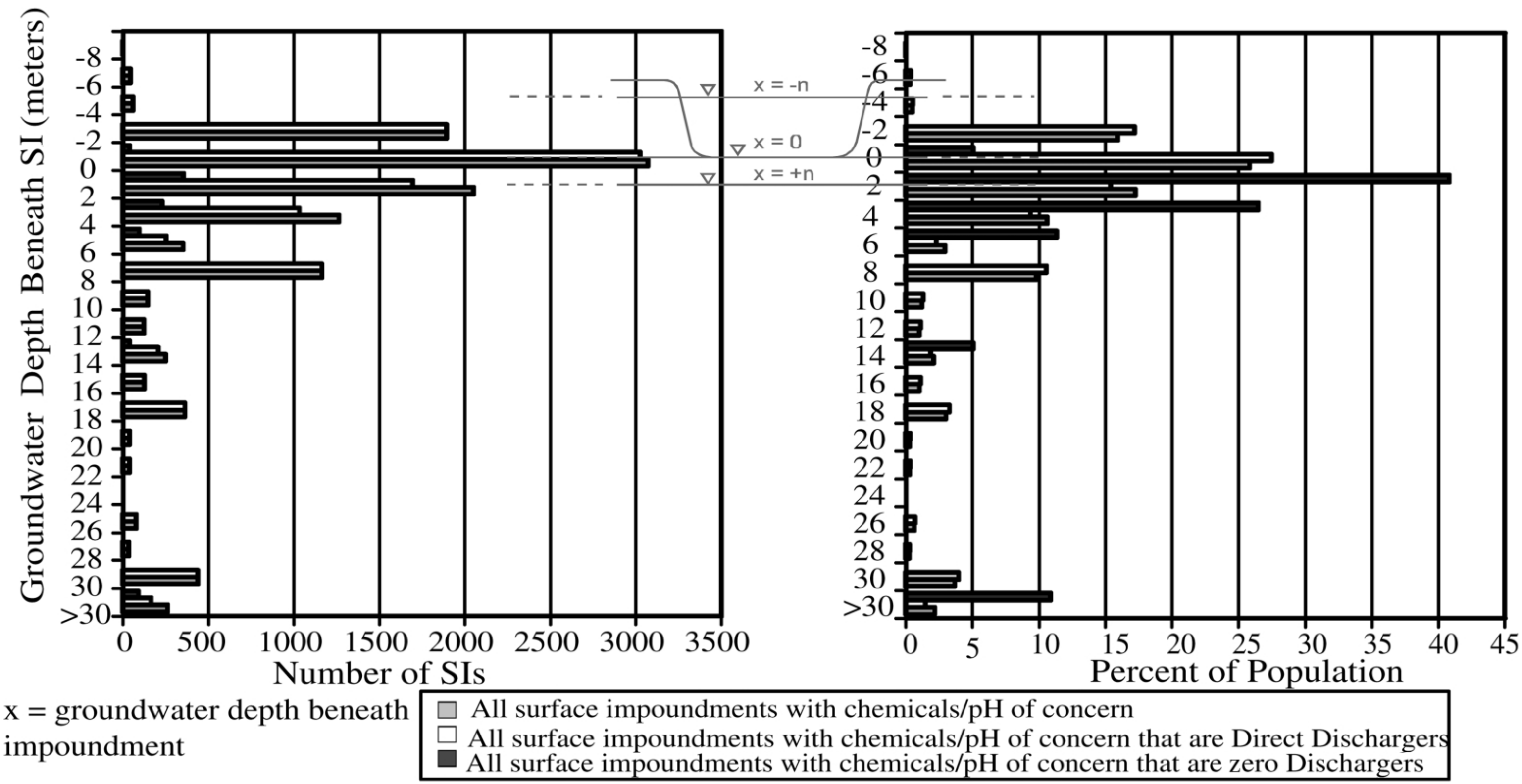
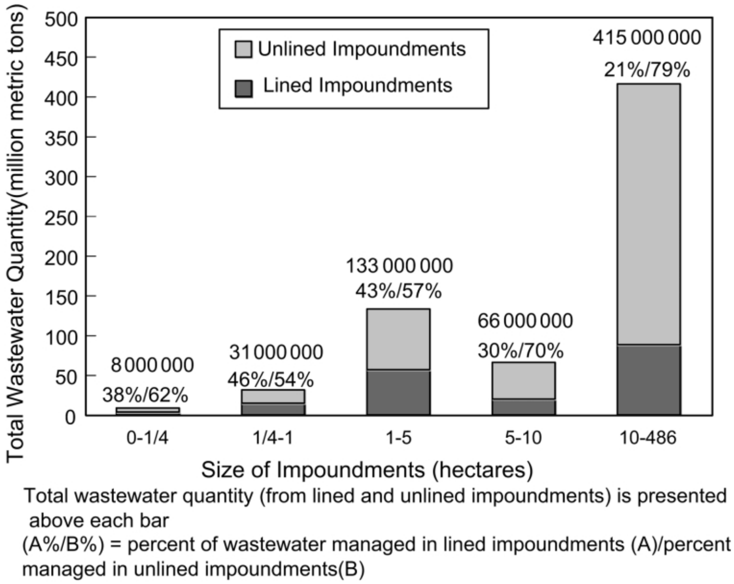


Fig. 6. National distribution of depth to groundwater beneath impoundments by impoundment discharge status.



Size of Impoundment (hectares)	0-1/4	1/4-1	1-5	5-10	10-486	All Impoundments
Number of Impoundments	6000	3000	2000	460	450	11900
Number of Lined Impoundments	2000	1900	800	100	140	5000
Number of Unlined Impoundments	4000	1100	1200	360	310	6900

Fig. 7. Number of impoundments and wastewater volumes by liner status and landfill size.

and almost 90% of impoundment bottoms were within 8 m of groundwater. It is not surprising to find that impoundments were often located over relatively shallow groundwater given that over 90% of impoundments in the population had direct discharges to surface water and were, therefore, located near surface water bodies. Given the proximity of impoundments to surface water, many of these groundwater levels may fluctuate seasonally or with significant precipitation events. Almost 20% of impoundments had impoundment bottoms that were below the groundwater surface. Although the presence of generally shallow groundwater conditions is significant in terms of the potential for contamination of groundwater by contaminants from impoundments, not all shallow groundwater is potable. Approximately one-third of the impoundments were located above groundwater that was not potable.

Liners are an important and commonly used method of preventing the release of impoundment contents to the subsurface environment. Liners can be constructed of a variety of materials and when properly installed and maintained will restrict the movement of waste from the impoundment (USEPA, 1993). Fig. 7 displays information on liner usage by impoundment size and wastewater volume. Approximately 5000 impoundments, or approximately 40% of the population, were lined. However, just under 25% of wastewater volumes were managed in lined units. Larger units were less likely to be lined. Just over 40% of impoundments under 1 ha were lined, but only 25% of those over 5 ha were lined.

The effectiveness of a liner system depends in part on the composition and structure of the liner system installed. As shown in Table 6, almost 32% of impoundments had clay, flexible membrane, or

Table 6
Number and percentage of impoundments by liner status

Liner status	Number of impoundments	Percentage of impoundments
Compacted clay	1700	14
Flexible membrane (FML)	1600	13
Composite (FML and clay)	500	5
Concrete	600	5
Asphalt	60	<1
Other	400	3
Unlined[a]	7000	59
Total	11 900	100

[a] This estimate differs from the estimate of unlined impoundments shown in Fig. 7. This is due to missing data associated with this variable.

composite (flexible membrane and clay) liners. Eighteen percent of the impoundments had flexible membrane or composite liners, which were generally more effective than alternative liner types. Asphalt was the least common liner material, employed at less than 1% of lined impoundments.

Nearly 60% of the impoundments had no liner. Moreover, not all liners were constructed to contain and isolate wastewaters; several respondents suggested that their impoundments were used for infiltration sources to groundwater and mentioned the presence of 'weep holes' or other engineered features to properly manage the hydraulic balance between the impoundment waters and natural waters outside the impoundment.

As engineered structures, liners may have flaws that derive from inadequate design and service. Routine wear and tear can eventually reduce their ability to restrict flow (USEPA, 1984, 1991). However, liner failure can occur in just one layer of a multi-liner system or occur in a place in the liner that is above the water surface. Release of contaminants through these flaws into groundwater can be delayed and insignificant. An estimated 12% of the impoundments with liners experienced liner failure, as reported in the survey data. Roughly 10% of all wastewater volumes were managed in impoundments that have had a liner failure.

Monitoring wells are installed to detect releases of chemicals from impoundments to groundwater. Approximately 31% of the population of impoundments or approximately 3900 impoundments reported the presence of a monitoring well system intended to detect releases. Of these impoundments, only approximately 190 surface impoundments had detected a release of chemicals to groundwater (Table 7).

Some non-hazardous surface impoundments are located at hazardous waste treatment, storage and disposal (TSD) facilities. This group of surface impoundments appeared to have a greater use of monitoring wells than the overall population of facilities. While only a third of all non-hazardous surface impoundments were located at hazardous waste TSD facilities nearly 50% of the impoundments with monitoring wells were located at hazardous waste TSD facilities. This increased attention to monitoring is not surprising given the federal and state oversight at these facilities.

3.2.4. Releases to the surface water

Uncontrolled transport of chemicals from surface impoundments to water bodies can occur either through contaminant discharge to the subsurface that ultimately recharges surface water or through direct overland flow due to failures or

Table 7
Number of impoundments with and without monitoring wells and the number of impoundments that have detected releases

Discharger type	Monitoring well present				No monitoring well to detect release	
	Detected release	Did not detect release	Total			
			Number	%	Number	%
Direct dischargers	190	3300	3400	31	7500	69
Zero dischargers	0	400	400	47	470	53
All impoundments	190	3700	3900	33	8000	67

Table 8
Number of individuals, residences, drinking water wells, and schools in a series of concentric areas as a function of distance from all non-hazardous surface impoundments

Concentric area defined by this radial distance (m)	Number of individuals	Number of residences	Number of drinking water wells	Number of schools
0–150	51 600	21 200	900	0
151–500	663 400	285 400	13 700	500
501–1000	3 284 400	1 341 800	56 200	2 400
1001–2000	14 414 200	5 898 800	205 000	9000

overtopping events. In cases, where there is a direct hydrogeological connection between groundwater and surface water, there is greater potential for adverse impact. Survey responses indicated that roughly 80% of impoundments were above groundwater systems that discharge to nearby surface water. This trend was even more significant for larger impoundments; approximately 95% of impoundments with a surface area over 5 ha were above groundwater that discharges to surface water. The larger impoundments may pose particular concern regarding their potential impact on nearby surface waters given that less than 30% of all impoundments in these size categories were lined (Fig. 7).

Overtopping or failure of impoundments can result in contamination of adjacent surface water bodies through overland transport of wastewaters. Based on the survey data, it appears that one-quarter of all facilities had an overtopping event. The survey respondents indicated that overtopping can occur during storm events when there is excessive precipitation, when dike or berm systems fail, or when handling devices including pump and pipe systems fail or malfunction.

The vulnerability of surface waters via either overtopping or subsurface releases is potentially high given that over 90% of impoundments in the population had discharges to surface water and, therefore, must be located near a surface water body. Moreover, approximately 20% of impoundments had a fishable water body within 150 m of the impoundment. The potential for adverse impact would certainly depend in part on the magnitude of the release. The data on overtopping releases indicate that these events ranged in magnitude from only a few hundred liters to multiple volumes of the surface impoundment.

3.2.5. Proximity to human receptors

Continuing with the National Research Council risk assessment framework, after evaluating the degree to which contaminants are released and move through the environment, the next element of the risk evaluation sequence is assessment of the potential for human or ecological exposure. The survey included a number of questions regarding the location and habits of surrounding inhabitants. The survey data were used to determine the general proximity of humans and human activities to surface impoundments and the potential for exposure to air, groundwater and surface water borne contamination.

The industrial facilities that employ surface impoundments to manage non-hazardous wastewater are located throughout the US in a wide array of settings. Some facilities are located in rural areas adjacent to agricultural land use, while other facilities are in heavily populated residential areas or in highly industrialized areas. Within this diversity of settings, there is potential for human exposure to chemicals managed in these impoundments. Table 8 presents information on the number of people living near impoundments. An estimated 14.4 million people living at 5.8 million residences were located within 2 km of an impoundment. Of this population, roughly 50 000 people lived within 150 m of an impoundment. Additionally, it is estimated that 500 schools were located within 500 m of an impoundment.

The subset of the impoundments that have a potential for producing releases to the air and also have people living nearby was estimated. Specifically, the study assessed how many impoundments have humans within various distances of surface impoundments that manage VOCs. As shown in Table 5, approximately 870 impoundments manage VOCs and had at least one residence within a 150-m radius. Roughly half of these impoundments managed VOCs in aerated systems which may increase VOC emissions.

Human activity also can influence the nature of the exposure that could occur near a surface impoundment. Farming occurred within 2 km of an impoundment at approximately 40% of all facilities. Roughly half of all facilities had fishing within 2 km of an impoundment, and two-thirds of all facilities indicated that people swam in surface water within 2 km of an impoundment. Hunting occurred within 2 km of an impoundment at approximately one in five facilities. It is important to understand that while the presence of an activity is a necessary condition of ultimately presenting a risk to fishers, hunters, farmers or swimmers, there are a number of complex environmental fate mechanisms and particular contaminants that would have to be present in order for there to be an actual risk (e.g. exposure through ingestion of produce grown at farms contaminated as a result of significant air deposition of chemicals from an adjacent impoundment).

Examining the proximity of drinking water wells to impoundments, especially impoundments without liners, provides a way to evaluate the potential for human exposure through groundwater. An estimated 8% of impoundments nationally, approximately 660, had drinking water wells within 150 m of an impoundment and 86%, approximately 570, of those impoundments were unlined. Within a 2 km radius from each impoundment, the estimated proportion of impoundments with wells jumped to 50% (5990 out of 11 900 impoundments), with an estimated 205 000 drinking water wells nearby (Table 8). Approximately 3290 or 55% of these were unlined units.

The study also considered the potential for surface water contamination through groundwater at a 150 meter distance. Just over 80% of all impoundments were located above groundwater systems that could discharge to a fishable water body. Furthermore, approximately 20% of all impoundments had a fishable water body within a 150-m radius.

3.3. Contaminant release and human health risk analysis

The previous summary of survey data explored a number of factors having to do with source characteristics, environmental setting and the proximity of nearby human populations. A number of these factors when looked at independently suggest that many impoundments have great potential for environmental or human impact. However, the actual risk posed by impoundments requires looking at all of these factors jointly via the risk assessment process.

On a national scale across all pathways in the risk analysis, only 5–6% of the estimated 4500 in-scope facilities had at least one impoundment that may pose a risk to human health. However, an additional 19–46% of facilities nationally had at least one impoundment with the potential for an environmental release to occur (Table 9). While these releases do not appear to pose risk to human health, they indicate that certain contaminants in excess of health-based levels have the potential to move beyond the surface impoundment confines and into the environment.

Risk estimates were developed for the three primary pathways of potential concern through which chemicals could move from an impoundment, through the environment, and be available to be inhaled or ingested by people nearby. Direct inhalation risks can occur if a chemical of concern evaporates from the impoundment's water surface, is carried by air dispersion to nearby residences and is then inhaled by residents. National risk estimates were developed for the closest residences, based on locations reported in the surveys or identified through current US census information. As indicated in Table 9, an estimated 4–5% of facilities pose a risk of concern from the inhalation of airborne contaminants. In addition to the 4–5% of facilities with an air inhalation risk of concern, an estimated additional 4–8% of facilities, while not posing an air inhalation risk to

Table 9
Overview of the risk assessment results

Pathway	Route	Facilities that have or will have environmental releases[a,b]		Facilities that may exceed risk criterion[b,c]		Number of chemicals and impoundments that may exceed risk criterion	
		RV	S/DL	RV	S/DL	Chemicals	Impoundments
Groundwater	Ingestion	640 (19%)	850 (19%)	30 (0.6%)	20 (0.5%)	15: 1 inorganic 2 metals 3 SVOCs 9 VOCs	130
Air	Inhalation	170 (4%)	170 (4%)	170 (4%)	60 (1%)	11: 1 dioxin-like 5 SVOCs 5 VOCs	240
Groundwater to surface water	Ingestion	790 (18%)	1080 (24%)	40 (1%)	30 (0.7%)	35: 1 dioxin-like 3 metals 20 SVOCs 7 VOCs	140
Total[d]		870 (19%)	1190 (27%)	220 (5%)	70 (1%)		

RV, reported values; S/DL, surrogate values/detection limits.

[a] An impoundment was determined to have an environmental release when there was evidence that contaminants had the potential to migrate from the impoundment into the media of concern at concentrations above health-based levels. The specific definitions vary by media; see USEPA (2001) for details.

[b] Number of facilities (percentages are of the total number of facilities, ≈ 4500).

[c] A facility was determined to exceed a risk criterion if individual constituents had concentrations in excess of 10^{-5} for cancer, an HQ greater than 1 for non-cancer effects, or concentrations in excess of the ambient water quality criteria in the case of surface water. Risks across constituents were summed where appropriate to identify any cases where, even though a particular constituent might not exceed a risk criterion, all of the constituents together might exceed a risk level.

[d] Total indicates the number and percentage of facilities with one or more pathways in excess of the risk criterion or with a release.

people nearby, did generate releases to the air that exceed health-based levels at a distance of 25 m.

Health risk due to ingestion of contaminated groundwater can occur if impoundments release a chemical of concern through the bottom or sides of the impoundment and the chemical enters groundwater and moves through the subsurface to a drinking water well. The analysis estimated risks that could occur due to consumption of water from the closest drinking water wells reported in the surveys or identified through census information, and then generated national estimates of the risk to human health. Groundwater contaminant migration depends on many factors, but migration can be slow. The modeling did not examine the speed of contaminant movement, so some of the reported risks may occur in the future.

Risks due to groundwater ingestion also appear low. Only approximately 1% of facilities had one or more impoundments that were predicted to have risks because of groundwater contamination at drinking water wells. In addition, between 14 and 33% of facilities had an impoundment with the potential to generate contaminated groundwater plumes that may extend 150 m or more beyond the unit boundary.

The contamination of surface waters by groundwater can occur if chemicals in an impoundment migrate through groundwater and discharge into nearby surface water. As a result, the quality of the surface water for drinking or consuming fish may be reduced. From the survey data situations were identified where human health ambient water quality criteria (HH-AWQC) might be exceeded in surface water bodies. Less than 2% of facilities had one or more impoundments that are estimated to have releases that exceed the HH-AWQC in nearby surface waters. Between 18 and 42% of facilities with impoundments, while not exceeding the HH-AWQC in surface water because of the dilution that occurs, generated releases that are estimated to exceed the HH-AWQC at the point of groundwater discharge into the surface water but prior to dilution in the surface water.

Finally, the analysis also screened for potential risks to human health through indirect pathways. The methodology categorically ranked estimates of potential indirect pathway hazards. Approximately 6% of the facilities fell into the highest category, indicating that this group of facilities had the greatest potential to result in an indirect risk of concern. However, this analysis does not confirm that facilities in this group actually have indirect risks of concern.

3.4. Ecological assessment

USEPA (2001) also examined the potential for surface impoundments to cause adverse effects on non-human organisms and natural systems. Many impoundments are located near water bodies and are freely accessible to wildlife. This study assessed the potential for impoundments to pose risks to populations and communities of ecological receptors that live in and near surface impoundments both during their operation and when the impoundments were closed with exposed wastes remaining in place. The results of the initial screening for ecological impact indicated that up to 76% of impoundments could not be ruled out as having the potential for adverse ecological impact. The results of the preliminary evaluation of ecological pathways merely indicate that a more detailed evaluation of potential impacts is needed.

4. Discussion and conclusions

This statistical study of the operational characteristics and patterns of releases of substances from impoundments has shown clearly that impoundments remain a significant contributor to the industrial landscape, with an estimated 18 000 impoundments in operation during the 1990s. An estimated 11 900 impoundments contain at least one chemical of concern or have pH levels of concern. The intense regulatory pressure that has been placed on hazardous waste facilities via federal regulatory programs has caused many owners to close their hazardous waste impoundments (e.g. Paulson and Schnettgoecke, 1991; Snell and Buchalter, 1994). However, the same reduction in the number of industrial impoundments that comprise the non-hazardous waste universe is not seen.

The study found that many non-hazardous impoundments have characteristics that may warrant closer attention on a site-specific basis. For example, a number of impoundments contain chemicals of concern, are constructed in ways that may lead to contaminant releases and are located near vulnerable habitats or close enough to human populations to create the potential for human exposure. However, in order for any individual impoundment to pose an actual chronic human health risk, contaminants must be present in the impoundment at significant levels and must be released from the impoundment, move through the environment, and ultimately reach human receptors at levels of health concern over a substantial period of time. These are the fundamental sequential building blocks of the modern assessment framework for environmental contaminant risk assessment (National Research Council, 1983). The analysis suggests that while the individual components may occur at significant frequency, they seldom occur all at the same time and do not often result in the potential for an actual present or future risk.

The study in fact found that only approximately 5 or 6% of facilities were likely to actually pose a human health risk. The predominant pathway with respect to human health risk was the air pathway, with an estimated 4–5% of facilities posing an air pathway risk concern. The predominant drivers of risk appeared to be when volatile organics were present and residences were nearby. The percentage of facilities posing risk concern via the groundwater pathway was only approximately 1%. One factor that seemed to explain the relatively low proportion of facilities with a groundwater risk was the frequent presence of surface water immediately next to the property boundary thereby limiting residential groundwater use. Overall, approximately 8% of impoundments had a well within 150 m. Another important reason why a greater percentage of impoundments do not have a groundwater risk of concern is simply because they do not appear to contain the chemicals of concern at unsafe levels.

Environmental program managers are often monitoring for and are responsive to contaminant releases to the environment regardless of whether there is human exposure. In addition, USEPA (2002) strongly recommended that these analyses should focus on the environmental release information. While the frequency of actual groundwater risks were low the frequency of releases to the groundwater is greater. Releases were evident both in groundwater where 14–33% of facilities experienced a release and in nearby surface waters that receive groundwater, where 18–42% of facilities may have a release of concern.

In addition to the concerns described above, it is important to recognize that impoundment releases also have the potential to create other long term chronic human health impacts via indirect pathways and could also potentially cause ecological damage. The surface impoundment study (USEPA, 2001) looked at the potential for human exposure via indirect pathways; pathways that are biologically mediated and removed from direct contaminant migration from the impoundment. For example, contaminants can migrate via volatilization and deposition to a nearby farming operation, where they can enter the farm food chain and cause human exposure via the consumption of farm produce. The study also examined the potential for ecological impact. Although the screening results were not sufficient to support national estimates of impacts, the analysis did suggest that indirect pathway risk and ecological risk should be examined further to determine if potential exposures may be of concern.

This study also examined the potential for catastrophic events such as a flood, equipment malfunction or structural failure of an impoundment structure. This very issue recently drew the attention of the National Academy of Sciences as they examined instances of such failures at large coal impoundments (National Research Council, 2002). There is a potential for catastrophic events; however, the most damaging events normally happen with a low probability. More in-depth evaluation of the acute or longer term impacts from such events could not be adequately characterized in this study. EPA's Science Advisory Board (USEPA, 2002) also has expressed particular concern regarding the potential impact of such transient events. Impoundment operators are well advised to be concerned and take the steps necessary to avoid the catastrophic release of materials from impoundments.

The risk results from this study demonstrate convincingly that the risks associated with non-hazardous surface impoundments as a group are low. A small fraction of the impoundments do pose risks and a more significant fraction have the potential to release harmful chemicals to the environment. Non-hazardous surface impoundments as a class do not seem to warrant one-size-fits-all programs to ensure their safe management. It is clear that the presence of multiple harmful chemicals, impoundment design features that can result in releases, and the proximity of human and ecological receptors to an impoundment can be evaluated and managed at specific sites to help ameliorate the potential for risk. By considering these risk factors on a site specific basis impoundment owners and operators can focus on the subgroups and characteristics of facilities with the greatest potential for creating environmental harm.

The information provided in this study should help impoundment managers better understand the critical features of their impoundments that can lead to contaminant release, migration, exposure and possibly risk. As a case in point the field sampling program associated with this study suggests that impoundment operators may want to begin by paying greater attention to the materials they are managing in their impoundments. At present there seems to be an incomplete knowledge of the chemicals that are present in these sorts of impoundments. EPA's recently released guidance on industrial waste management (USEPA, 2003) will provide a number of useful recommendations that should help address the environmental risks associated with the management of non-hazardous waste surface impoundments.

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