CHAPTER 1

APPLICATIONS OF ENVIRONMENTAL FORENSICS

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1.1 INTRODUCTION

There are two separate motivations for environmental forensic studies. First, such studies may be performed for the sake of obtaining knowledge of historical emissions to the environment or historical environmental processes and for no other reason, what might be termed purely research or academic studies. Second, such studies are carried out to determine liability in a variety of contexts. This latter purpose is the focus of this chapter.

Table 1.1

Liability context and related forensic issues.

Context	Forensic Issues
Cost allocation at Superfund sites	Responsibility for waste streams or areas of contamination Contribution of waste streams to remedial cost or to the need for a remedy
Site investigation for property transfer	Existence and extent of contamination Cost of remediation Existence of other responsible parties
Insurance litigation	Policies triggered by a release Characteristics of a release or of contamination relative to contract language Equity of liability allocation
Toxic tort	Probability that chemical exposure caused manifest or latent injury
Natural resource damage	Distinguishing anthropogenic from natural effects
Assessment	Monetizing anthropogenic damages
Marine oil pollution	Determining spill source

Our discussion of liability-driven forensic studies is based on liability under U.S. laws. However, we do not focus on the law itself, although some of the references given discuss various legal issues. Rather we focus on how the legal requirements concerning liability translate into technical issues and questions, which can be answered using forensic methods.

We discuss liability in six different contexts, as shown in Table 1.1. This table also lists key forensic issues for each context. In the remainder of this chapter we describe how measurements of chemical concentrations or other properties combined with the forensic techniques described later in this book can be used to illuminate these issues.

These six contexts probably represent a good proportion of the situations in which the tools of environmental forensics are employed to allocate liability. However, they do not represent all such situations. For example, environmental forensics techniques also are used to identify air pollution sources, including in international or transboundary air pollution situations. Techniques relevant to air pollution sources are discussed elsewhere in this text, particularly Chapters 8 and 12. We have selected these six contexts because they are the most structured and universally applicable in the United States.

1.2 LIABILITY ALLOCATION AT SUPERFUND SITES

The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), commonly referred to as Superfund, prescribes specific procedures for dealing with chemical release or disposal sites that are considered to be the most hazardous in the United States. States also have hazardous waste site remediation programs patterned to varying degrees after the federal program. Thus state lead occurs at many sites deemed less hazardous than those in the federal Superfund program, for example at dry cleaning facilities across the country. Also, because the federal Superfund legislation excludes petroleum release sites, state lead occurs at facilities such as gasoline stations and former manufactured gas plant sites.

State laws often are modeled after CERCLA, although as discussed later, CERCLA does not provide much guidance on liability allocation. In any case, the discussion in this chapter of methods of liability allocation at federal Superfund sites is still relevant but the details may vary from state to state.

Potentially responsible parties (PRPs) at Superfund sites include present owners and operators, past owners and operators, waste generators, and transporters or arrangers for transport of waste. Costs borne by PRPs at CERCLA sites may be for site remediation or in payment for past, present, and future damage to natural resources. Payment for future damages arises when the site cannot be totally remediated so that the habitat is restored.

Superfund liability includes for actions that predate the CERCLA legislation. Furthermore, liability is perpetual; it cannot be circumvented by being assigned to someone else. Liability does not depend on fault but simply on being a member of one of the classes of PRP just described. Finally, Superfund liability can be *joint and several*; that is, in principle all liability may be borne by a single PRP irrespective of the relative degree of fault.

Two sections of CERCLA touch on allocation of liability among the PRPs. Section 107 provides for recovery of remediation costs. Plaintiffs in a recovery action may be the U.S. Environmental Protection Agency (EPA) or states. Courts are divided on whether a PRP may be a plaintiff but the recent trend has been to deny Section 107 to PRP plaintiffs (Aronovsky, 2000). Although Section 107 specifies joint and several liability, this is discretionary with the court. In particular, where a PRP can demonstrate distinct harm or divisibility of harm, that party may be responsible just for their contribution to harm. A distinct harm arises, for example, when there are separate groundwater plumes or areas of surface soil contamination. A divisible harm might be where there are successive site owners conducting the same operation. The basis for divisibility in that case might be the relative number of years of operation.

Section 113 of CERCLA allows a party who has incurred response costs to seek contribution from other PRPs.[1] This section also provides contribution protection for parties that have settled with the United States. Under Section 113 the liability of nonsettling PRPs is limited to their proportionate share. The nonsettling PRP's liability may be determined in either of two ways. It may be determined by subtracting out the amount of prior settlements or by

[1] In 2004 the United States Supreme Court in *Cooper Industries, Inc. v. Aviall Services, Inc.* that the right of Superfund contribution is only available to PRPs who have been subject to a federal "civil action" under CERCLA Sections 106 or 107. Settlement with the government does not qualify as a civil action and does not permit a PRP to seek contribution from other PRPs. The Court left open the issue of whether contribution from other PRPs could still be sought in that case under Section 107. However, only a few lower courts have recognized a right of PRP cost recovery under this section. The net effect has been to provide on incentive for PRPs to wait until they are sued before incurring response costs.

subtracting out the proportionate share of the harm for the settling PRPs. As Ferrey (1994) points out, the results of these two approaches may be quite different. No guidance in determining proportionate shares, beyond citing equitable factors, is found in CERCLA.

The equitable factors most often cited are the Gore factors proposed by then-Representative Albert Gore in 1980 but not enacted. They are: (1) the ability to distinguish the party's contribution to the nature and extent of the problem, (2) the degree of the party's involvement in the activities that caused the problem, (3) the degree of care exercised by the party, (4) the degree of cooperation of the party with governmental agencies, (5) the quantity of the hazardous waste involved, and (6) the toxicity of the waste. These factors have been found to be far from sufficient and in some cases may not be applicable at all. Furthermore, they are simply a list; they provide no conceptual framework for allocation.

Other factors that have been suggested include: (7) existing contracts between the parties, (8) the owner's acquiescence in the operator's activities, and (9) the benefit to the owner from the increase in land value due to remediation.

Thus CERCLA and its legislative history are not particularly helpful in specifying how liability is to be allocated. Courts generally have determined that there is a presumption of joint and several liability unless harm is distinct or there is a reasonable basis for its division.

1.2.1 EQUIVALENCE OF HARM AND RISK

What is harm at a Superfund site? It seems logical that it be closely identified with the concept of risk. A baseline risk assessment is conducted at all Superfund sites. Removal actions may precede completion of the risk assessment for urgent matters but the continued remediation of a site is based on a finding that the computed baseline risks, either human or ecological, are unacceptable. Therefore, it is logical to identify the risks at a site, including those requiring removal action with harm. As discussed by Rockwood and Harrison (1993) several federal circuit court rulings also support this notion.

Thus, an argument can be made that risk assessment is the appropriate tool to use in apportioning liability. However, in fact risk is often not a consideration in apportioning liability. If the PRPs at a Superfund site agree on an allocation scheme, then that scheme is by definition satisfactory, assuming that there is no second guessing by other parties such as insurers. PRPs often decide to allocate liability based on the contribution of each to the cost of the remedy. Of course, surrogate measures for estimating contribution to costs may be used, such as counting barrels or estimating plume areas.

There are several common situations where the harm due to multiple PRPs is not distinct but requires division; for example, (1) commingled groundwater plumes, (2) hazardous waste disposal sites with multiple users, and (3) successive site ownership. If these situations result in contamination by similar chemicals, a straightforward allocation based on contribution to the cost of a remedy may make sense. However, when one or more PRPs' wastes differ significantly from the others in the risk they pose, those PRPs may wish to consider a risk-based approach.

1.2.2 ALLOCATION PRINCIPLES

Economic principles of cost allocation, including the stand-alone cost method, have been discussed by Butler *et al.* (1993) and by Wise *et al.* (1997). The cost allocation matrix approach of Hall *et al.* (1994) also is based on determining contribution to the cost of a remedy. Marryott *et al.* (2000) present a stand-alone cost type model in which a weighted sum of contaminant mass in the plume and plume volume serves a surrogate for remediation costs. The basic equation for calculating stand-alone costs is:

$$f_i = \frac{SAC_i}{\sum_i SAC_i} \tag{1.1}$$

where SAC_i is the stand-alone cost for the waste stream due to the ith PRP generator/transporter.

This equation does not address how liability is to be allocated between the generator, transporter, and site owner, nor does it address orphan shares, such as from unidentified or defunct parties. It is solely an allocation by waste stream. Equation 1.1 states that each PRP pays in proportion to the cost that would have been incurred if there were no other PRPs at the site. Because of redundancy of cost items and economies of scale the total cost of a remedy will generally be less than the denominator of Equation 1.1 and hence each PRP actually will pay less than their computed stand-alone cost.

Risk-based allocation methods have been discussed by Murphy (1996, 2000) and by Mink *et al.* (1997). The risk contribution analogue to Equation 1.1 is:

$$g_i = \frac{SAR_i}{\sum_i SAR_i} \tag{1.2}$$

where g_i is the cost fraction for the ith generator/transporter based on stand-alone contribution to risk SAR_i. The analogy with stand-alone costs is incomplete; however, the total risk is equal to the sum of the individual PRP-caused risks rather than generally being less.

Of course cost allocation may be a mixture of cost-based and risk-based methods:

$$h_i = \alpha f_i + (1-\alpha) g_i \tag{1.3}$$

where α is a constant. As α decreases from 1, a "contribution to the need for a remedy" component is mixed in with the "contribution to the cost of a remedy."

The kind of information needed to calculate f_i or g_i differs. For example, in computing stand-alone costs, well installation costs may vary as plume area and groundwater treatment costs may vary as contaminant mass in the plume. How long a pump and treat remedy needs to be maintained will depend on the ratio of individual chemical concentrations to acceptable levels in groundwater and on chemical properties that determine partitioning to soil. In computing stand-alone risks, concentrations and toxicities of specific chemicals will be required. Of course, as indicated earlier, it may be to the advantage of all PRPs to lower transaction costs by using surrogate quantities rather than attempting to collect the additional information necessary for refined or precise calculations.

For a cost-based allocation, typical forensic issues are:

- Attributing different groundwater plumes to individual parties or where plumes are inextricably commingled to two or more parties.
- For successive site owners, determining when major releases occurred, or for contamination by chronic operating discharges determining relative production amounts or years of operation.
- At hazardous waste sites accepting waste from multiple parties, determining waste stream volumes attributable to individual generators or transporters.

The additional information needed for a risk-based allocation is concentrations of specific chemicals in groundwater plumes, waste streams, or historical releases.

Time is a missing factor in many allocations whether by risk or by cost. For example, a PRP's wastes in groundwater might not arrive at an extraction point for many years because of a slow groundwater velocity or retardation effects. If the remedy will not be relevant to that PRP's wastes until some possibly distant future time, it can be argued that that PRP's contribution should be discounted to a smaller present value.

1.3 ENVIRONMENTAL SITE ASSESSMENT

As the term is used in this chapter, an environmental site assessment is conducted as a preliminary to a real estate transfer. (Similar tasks may be conducted as part of an internal management assessment, a process generally known as an *environmental audit*. An audit may be concerned solely with compliance with applicable laws and regulations or it may include a more management-oriented review of responsibilities, organization, communications, and measurement of progress.) The main purposes of an environmental assessment are to determine:

- Whether contaminants are present on site
- If present, the extent of contamination so that likely remediation requirements and costs can be estimated

The American Society for Testing and Materials (ASTM) has published two Standard Practices for conducting Phase I Assessments. Phase I is intended to assess the likelihood of site contamination. As the term is used in these standard practices, a Phase I Assessment does not include any environmental sampling. These Standard Practices originally were developed to satisfy one of the requirements for the innocent landowner defense under CERCLA.

ASTM Standard Practice E 1527 describes the four components of a Phase I site assessment as on-site reconnaissance, interview of site owners and occupants as well as local government officials, records review, and report preparation. This Standard Practice is intended to be conducted by an environmental professional. ASTM Standard Practice E 1528 on the other hand may be conducted by any of the parties to a real estate transaction as well as an environmental professional. This Standard Practice is based on a transaction screen process, consisting of the same three components prior to report preparation: a site visit, questions for the owner/occupants, and a records review. The difference is that the questions or issues to be addressed during the conduct of these components are all prescripted.

In the ASTM description, sampling of soils, groundwater, or other media would be a Phase II Assessment. ASTM has published a framework for the Phase II Assessment as Standard Guide 1903–97, and has published a number of standards dealing with sampling methods. These have been collected in the document ASTM Standards Related to the Phase II Environmental Site Assessment Process. A Phase II Assessment is generally necessary in order to determine the extent of contamination and hence the likely remedial requirements and associated costs. The Phase II Assessment would be guided by the results of Phase I.

The ASTM descriptions provide a framework but not one that should be followed slavishly. For example, at some sites the necessity of sampling certain locations and media may be evident and it may make the most sense to conduct sampling simultaneously with the components of a Phase I Assessment. Similarly, if one or more potential fatal flaws are obvious, the Phase I or Phase II Assessments may focus solely on those areas.

As noted earlier, if contamination is found, an understanding of the extent and options for remediation to regulatory acceptable limits becomes important. If the cost of remediation and the uncertainties are determined, this may become the basis for structuring a deal by allocating risks between the parties. Ideally, one would like a description of the complete spectrum of cost possibilities and their associated probabilities. An estimate of the expected time to regulatory closure and the associated uncertainties may also be factored in.

Environmental forensics enters into the site assessment process in several ways. First, in Phase I the site use history, as revealed by interviews and records, and visual clues during reconnaissance are combined with the analyst's knowledge of specific industrial operations to develop expectations of the presence and type of contamination. Second, in Phase II this information is augmented by sampling data to determine the extent of contamination. Finally, determining who is responsible for the contamination may involve other parties and hence introduce other remediation cost-sharing options. For example, groundwater contamination under a site in fact may originate from off-site sources.

1.4 INSURANCE LITIGATION

Insurance claims are based on the contract language between insurer and insured. Contracts until the mid-1980s were based on comprehensive general liability (CGL) policies. Subsequently, environmental impairment liability (EIL) policies were introduced to deal specifically with contamination and other environmental issues. Interpretation of the language is governed by state law and can vary greatly. However, the same phrases in the contract and the same issues produce the need for forensic information in any state in order to determine matters of fact.

Insurance coverage for damages associated with chemical contamination in the environment may depend, among other things, on the imminence of off-site migration, whether coverage was triggered during a policy period, and whether the release was expected and intended, or sudden and accidental. When multiple parties have contaminated a site, equitable cost sharing may also be a coverage issue (Murphy, 1993).

Parties may agree on the facts but still produce different descriptions for the same facts in order to construe the policy language most effectively. Several examples of this are noted in the Trigger of Coverage and Sudden and Accidental sections. Although there may be no correct point of view, it may be useful to consider whether a particular point of view only arises in a litigation context and hence is not a customary point of view.

1.4.1 IMMINENCE OF OFF-SITE MIGRATION

Policies often apply only to third-party property. However, if there is an imminent threat to off-site locations, coverage may exist for on-site cleanup. In some states, groundwater under a site is off-site. To predict whether significant migration off-site is likely, soil leaching and soil erosion runoff models may be used. If the chemicals of concern are only slightly soluble in water and sorb appreciably to soils, then chemical transport through the vadose zone will be slow and concentrations reaching the water table may be below regulatory limits.

Groundwater transport models may be used to determine if a threat is imminent when groundwater contamination has not yet reached the property line and groundwater is considered off-site. Because of biodegradation in the plume as well as weathering and sequestration of mobile waste constituents in the source region, some plumes may reach a steady state before going off-site, or even recede over time. This is a common observation for BTEX (benzene, toluene, ethylbenzene, and xylene) plumes from gasoline spills (National Research Council, 2000).

1.4.2 TRIGGER OF COVERAGE

Some policies provide coverage only if in force when a claim is made. Coverage in other policies is triggered in environmental remediation cases by property damage. However, states differ in their determination of when damage actually occurs and if it can occur only once or can occur in a continuing fashion.

The possibility of triggering multiple policies in different time periods with multiple triggering events can lead to different interpretations of the same events. For example, a groundwater plume from a spill on one occasion may be stabilized and even shrinking, but since new water molecules are always entering the plume, some might argue that new damage is continually being done. Others, of course, would argue that the plume itself demarcates the extent of the damage.

Determining when policies are triggered often involves back-calculating a time of release or time to reach the water table as described in Chapter 8. In some cases, structures such as cesspools, french drains, and leaching pits, which were specifically designed and installed to facilitate disposal of wastes to groundwater, negate the need for model calculations. A one-time liquid release, which is large enough to penetrate to groundwater, will generally do so over a period of hours or days. A cumulative or drip release will reach groundwater over a period determined by the drip rate. If the total quantity released is insufficient to reach the water table, the rate of contaminant travel will be controlled by the rate at which precipitation infiltrates the soil column and carries soluble waste components downward.

Reverse groundwater modeling, discussed in Chapter 11, can be used to determine the time when a property line was crossed or groundwater was first contaminated. However, there are always substantial uncertainties introduced by limited measurements in the subterranean environment. In addition, care must be used in defining the plume front; while the peak plume concentration may move with the retarded velocity, contamination in front of the peak moves more rapidly, up to and in theory even exceeding the groundwater velocity.

It may be possible to establish the time of release by linking the observed contamination to known process changes, such as a change in degreasing fluids from trichloroethylene to 1,1,1-trichloroethane (TCA). TCA releases can also be dated by the amount of the hydrolysis product, 1,1-dichloroethylene, present (Morrison and Murphy, 2006).

1.4.3 EXPECTED AND INTENDED

It generally will be important to determine if the damage was expected and intended. There can be issues that vary from state to state as to precisely what was expected and intended; that is, the release to the environment or the damage. Depending on the state, a "reasonable man" standard may apply or it may be necessary to produce evidence of actual knowledge by specific individuals. Of course what is reasonable for an individual to know depends on his or her background and role in an organization. Expectations are different for an accountant and an engineer, whose job might require him or her to read professional literature in that field.

Thus in some cases it will be useful to compare facility practices with historical waste disposal practices as evidenced by the engineering literature for the appropriate time period. The following illustrate the type of information that can be found.

- "The old fallacy of the speedy self-purification of streams was once pretty firmly fastened upon the engineering profession itself, and it is only in relatively recent times that it has been wholly abandoned." Editor of Engineering News, Stream Pollution Fallacies, *Engineering News*, Vol. 42, No. 9, 1899.

- "The discharge of manufactural waste into streams without purification and treatment has frequently resulted in serious pollution. Manufacturers are coming to realize the seriousness of the conditions and consequently much study is being devoted to methods of rendering the wastes innocuous before their discharge into bodies of water." Disposal Methods for Manufactural Wastes, *Engineering Record*, August 27, 1910.
- "In the arid and semi-arid regions of the West, many large communities are virtually dependent upon groundwater supplies . . . Surveys show that refinery wastes in particular penetrate to considerable distances from sumps and stream beds." Burt Harmon, Contamination of Ground-Water Resources, *Civil Engineering*, June 1941.

As evidenced by these examples, the early pollution incident literature tends not to be chemical specific. It also is concerned with levels of contamination much higher than the levels that can be recorded with present measurement technology.

Pollution control legislation, practices at other companies in the same field, or trade association publications also may be introduced to illustrate the state of knowledge or practice at a given time. Generally, the engineering literature will provide a picture of a more advanced state of knowledge at an earlier time than these other references. Chapter 2 describes some sources of historical information.

If documentary information as to practices at a particular facility is lacking, it may still be possible to discern historical waste disposal practices from the spatial location or footprint of contamination at the site. For example, a groundwater plume emanating from a dry well could be linked to disposal of chemicals down a laboratory sink drain.

It may be important to distinguish contamination that arose from routine operational spills, which could be argued to be expected and intended, from such things as tank failures. Estimating the mass of contamination in soils and groundwater and characterizing the location relative to process areas can help in making such a distinction by determining the origin of contamination.

1.4.4 SUDDEN AND ACCIDENTAL

In the 1970s a clause was introduced to CGL policies that stated coverage for various kinds of releases would apply only if these were sudden and accidental. Some states consider sudden to have a temporal meaning and others consider it to be more akin to unexpected. In the former case, it may be important to determine if a release was gradual or sudden in a temporal sense. However, even if the parties agree on the facts different interpretations can arise. For example, a leaking underground storage tank might be viewed as the result of years of electrochemical corrosion or it might be viewed in terms of a single instant when the tank is finally breached. Similarly, routine periodic degreaser cleaning and discharge to the environment might be characterized as a series of sudden releases or as a chronic operating condition.

1.4.5 EQUITABLE COST SHARING

Equitable cost sharing becomes an issue if there are multiple PRPs at a site. An unfavorable cost allocation scheme may be a basis to dispute full policy coverage. For example, as discussed in Section 1.2, when there are wastes that differ greatly in toxicity or mobility, a scheme based solely on the quantity of waste will be unfair to the disposer of large volumes of innocuous waste and its insurers.

Equitable cost sharing requires that waste streams be identified with specific PRPs. Methods are available for unmixing commingled waste streams. These include isotope techniques, discussed in Chapter 10, as well as principal components analysis (PCA) and polytopic vector analysis (PVA), discussed in Chapter 7. When indemnification costs are presented or settlements proposed, the question may arise, Should these techniques have been used?

1.5 TOXIC TORTS

In a toxic tort the issue is most often whether an injury was more likely than not caused by exposure to chemicals or other substances (e.g., radiological or biological). The causation requirement may also be phrased as “but for” the exposure the injury would not have occurred or that the exposure was a substantial contributing cause. Environmental forensics enters because historical chemical concentrations in air, water, soil, or foodstuffs are needed to estimate exposure and dose.

Dose is exposure times some uptake rate (e.g., cubic meters of air inhaled or an average number of grams of fish eaten per day). Exposure is determined by the concentration in environmental media (air or fish in the preceding examples), and by the time period over which uptake occurs. Since chemical concentrations may vary with time, exposure may be characterized over various time periods, acute or peak exposure, subchronic, or chronic (long-term) exposure. The averaging time of interest depends on the specific health effect being investigated.

Proof of causation for the injury may proceed in at least three ways: (1) if a sufficient number of people have been exposed epidemiological evidence may be offered, (2) a differential diagnosis may be performed for specific individuals, (3) although this is less frequent than the other two procedures, a risk assessment may be performed.

1.5.1 EPIDEMIOLOGY

Epidemiological information often is presented as an odds ratio for a specific type of injury. The odds ratio is the ratio of the number of observed cases in the putatively exposed community to the expected number of cases for a community of that size and demographic composition. Usually adjustments are made for age, smoking, ethnicity, and so on in determining the expected number of cases. It is often claimed that a probability of causation can be calculated directly from the odds ratio. If the odds ratio is OR, the probability of causation, P_c, is said to be

$$P_c = \frac{\mathrm{OR} - 1}{\mathrm{OR}} \tag{1.4}$$

P_c is thus just the fraction of total number of cases represented by the excess cases above background. When the OR > 2, then $P_c > 0.5$ and a cause other than background is sometimes said to be "more likely than not."

However, this equation is based on the assumption that background and source-specific causes act independently. In reality, disease manifestation may be a result of multiple causal factors, some of which are related to background and some of which are related to the specific source. The causal chain may be different for different individuals and the role played by background and the specific source may differ even for the same causal chain. In addition, as just presented there are three other things wrong with this argument and they show the role that historical exposure information, and hence forensic analysis, can play in assessing epidemiological evidence of causation: (1) association is being confused with causation; (2) no accounting is given of the number of different disease endpoints that were examined in order to find an OR > 2; and (3) in the preceding discussion the uncertainty associated with OR itself does not enter into determining P_c.

1.5.1.1 Association and Causation

Epidemiological evidence by itself describes association, not causation. To move from association to causation the Hill criteria formulated by Sir Austin Bradford Hill often are invoked (Hill, 1965).

These criteria are:

(1) *Strength of the statistical association*. As noted earlier, this is often measured by an odds ratio, comparing exposed and unexposed populations.
(2) *Consistency of the association*. Is the disease observed with similar exposures in other places and times? Do studies using a variety of techniques arrive at similar conclusions?
(3) *Specificity of the association*. Does the disease have many causes? Can the chemical in question cause many diseases?
(4) *Temporality*. Does exposure precede disease? Is the disease onset consistent with what is known concerning latency?
(5) *Biological gradient of the disease with exposure*. Are data for the population under study consistent with a dose–response relationship? Do the data show increasing rates of disease with increasing dose?
(6) *Plausibility*. Is a causal relationship between disease and exposure biologically plausible?
(7) *Coherence*. Is a causal interpretation consistent with other scientific understanding?
(8) *Experiment*. For example, if the suspected cause is removed, does the disease rate change?
(9) *Analogy*. Does experience with similar situations give any guidance?

The Hill criteria are intended as different viewpoints for examining causality rather than constituting a pass/fail exam. An additional criterion, which is sometimes added, is:

(10) *Elimination of confounders*.

Several of the Hill criteria are exposure related. The biological gradient criterion asks whether the number of cases increases with increasing exposure. The temporality criterion asks whether exposure preceded effect and if so whether it was by enough time to be consistent with what is known about disease latency. Consistency of the association is also exposure related. The injury may have been observed to occur elsewhere only when exposure was above some level. Both concentration in the exposure medium and averaging time enter into level of exposure.

1.5.1.2 Texas Sharpshooter Effect

The second thing that is wrong with the simple odds ratio/probability of causation argument is that how many end points were looked at is an important consideration in interpreting the results. If enough disease end points are examined, an odds ratio greater than 2 may be found for some condition on a purely statistical basis. Restricting results to a 95% confidence level will not prevent this. At a 95% confidence level one test out of 20 will appear to be statistically significant, even if exposure conditions are actually identical in the two communities being compared. If a large number of disease end points are examined and only the high odds ratio and high confidence level cases are then presented, this constitutes what is sometimes called the Texas sharpshooter effect—where the bull's eye is drawn after the gun is fired!

1.5.1.3 Statistical Significance

The third thing that is wrong with an odds ratio greater than 2 simply equating to a causation probability greater than 50% has to do with the statistical uncertainty inherent in the odds ratio determination.

The basic concept is that even if we could do a series of identical studies with identical test populations and exposures, there would be a distribution of odds ratios because of statistical fluctuations. Let x be the odds ratio and $f(x)$ the distribution of odds ratios. Then the probability of causation is:

$$P_c = 1 - \int_0^{\infty} \frac{f(x)dx}{x} \tag{1.5}$$

Charrow and Bernstein (1994) show that Equation 1.5 implies:

$$P_c < 1 - \frac{1}{\int_0^{\infty} xf(x)dx} \tag{1.6}$$

for any distribution $f(x)$ subject to the normalization condition:

$$\int_0^{\infty} f(x)dx = 1 \tag{1.7}$$

If the odds ratio is identified with the expectation value of x:

$$\text{OR} = \int_0^{\infty} xf(x)dx \tag{1.8}$$

then it follows that:

$$P_c < 1 - \frac{1}{\text{OR}} \tag{1.9}$$

Thus just the fact that a distribution of odds ratios would occur if the epidemiological study could be repeated with different, but equivalent, populations causes the probability of causation to be overestimated by the simple expression $P_c = 1 - 1/\mathrm{OR}$.

1.5.2 DIFFERENTIAL DIAGNOSIS

The second way of determining causation is through a differential diagnosis. In a clinical setting this term means determining the underlying disease from among various possibilities through an analysis of symptoms. In a toxic tort context the term has taken on the meaning of determining the cause of a disease from among various possibilities. For example, if the claim is that a heart attack was chemically induced, among the factors that should be looked at as part of a differential diagnosis are the individual's weight, smoking habits, blood pressure, and age. This is in addition to whether the specific chemical is associated with heart disease and what the level of exposure was.

Causation is often considered in two parts. General causation addresses the question of whether the chemical in question is believed capable of causing the injury in question at any level of exposure. Specific causation addresses the question of whether the chemical caused the injury in the specific individual. The Hill criteria are used to support the general causation argument. Of course, for substances where the effect is well known, appeal to medical textbooks or government documents may be sufficient. Specific causation relies on the subset of the Hill criteria that may be applied to an individual rather than a population. These are the consistency of the association for the level of exposure, specificity of the individual's injury for the chemical, temporality (e.g., exposure preceding disease), experiment, or whether symptoms are alleviated when the supposed chemical cause is removed. In addition, as indicated earlier, confounding factors or other potential causes are eliminated as part of a differential diagnosis.

Historical exposure is thus an essential part of a correct differential diagnosis and can enter into a causation analysis in a quantitative way, most obviously, if we know the human exposure level at which disease is likely to occur. However, this condition is a rarity. More often we know the exposure level at which disease is not likely to occur. Thus one may compare the estimated historical exposure for an individual with chemical specific standards and criteria, both public health and occupational. Chemical exposure is unlikely to be a significant cause of disease if this exposure is less than these criteria. Of course, some caveats are necessary. Occupational criteria are generally less stringent than public health criteria and there may be issues in comparing a healthy worker to the general population. Also criteria may not be based on carcinogenic effects, particularly for chemicals with limited evidence of carcinogenicity.

Similarly, one may investigate the significance of specific exposure levels by comparing the exposures or the concentrations involved with the exposures and concentrations of those same chemicals that people normally are exposed to through the natural or anthropogenic background, such as consumer products or urban air.

1.5.3 RISK ASSESSMENT

The basic risk assessment algorithm, risk = toxicity × dose, demonstrates the key role that dose and hence exposure plays. A risk assessment may be conducted at a hazardous waste site using EPA methods to calculate the lifetime risk of excess cancer; that is, of a cancer that would not have occurred otherwise. EPA's criterion for cleanup at a Superfund site is a computed risk, ΔR, larger than 10^{-4} to 10^{-6}. Computed risks rarely approach the more likely than not criterion of 0.50. This might be taken to imply that risk assessment is not a useful tool for demonstrating a causal toxic exposure. However, when there is a background rate for cancer of a certain type of R_0 and a computed chemical risk ΔR, the probability of causation for an individual who has cancer of that type can be written as:

$$P_c = \Delta R/(\Delta R + R_0) \tag{1.10}$$

Thus, even computed risks in the 10^{-4} to 10^{-6} range can be used to support a causation argument for an individual who already has cancer. Of course, as discussed in Section 1.5.1, this assumes a single cause for disease, and that background and other factors operate independently.

EPA risk assessment methods also can be used to calculate what is known as a *hazard index* for noncarcinogens. The hazard index is simply the computed dose over some averaging time, usually 24 hours, divided by a reference dose. The reference dose is a dose at which no adverse effects are believed to occur. Thus computing a hazard index <1 means that no adverse effect would have been expected from the exposure. Computing a hazard index >1 leaves the question of a chemically caused adverse effect open. In that case an informed judgment requires reviewing the primary medical literature including the occupational or animal studies upon which the reference dose is based.

1.6 NATURAL RESOURCE DAMAGE ASSESSMENT

In the United States, Natural Resource Damage claims can be brought by federal and state government agencies and Indian tribes (the "Trustees") under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Oil Pollution Act (OPA), the Clean Water Act (CWA), as well as numerous state statutes. The Department of Interior and the National Oceanic and Atmospheric Administration have issued regulations indicating how assessments are to be done (http://www.epa.gov/superfund/programs/nrd/nrda2.htm).

Natural resource damage claims seek compensation to the public for damages resulting from a release of a hazardous substance or oil. The affected area can include virtually any aquatic or terrestrial environment and is not limited to living organisms or ecosystems. For example, many claims recently have been brought in the United States seeking damages to groundwater. Damages may be monetary or service-based, or a combination of the two, and are based on the value of "primary" restoration, compensatory restoration for lost natural resource services from the time of the release until such time as baseline services are restored, and reimbursement of assessment and response costs of the Trustees. For example, the compensatory damage component for the *Exxon Valdez* oil spill has cost Exxon close to $1 billion in addition to a cleanup bill ("primary" restoration cost) of nearly $2 billion.

Because of the varied nature of natural resource damages, the value of any Natural Resource Damage claim must be expressed in terms of some common currency. In some cases resources services can be monetized because there are markets for the services provided. Two such cases are: (1) diminished recreational fishing due to placement of fishing advisories, and (2) restriction of a groundwater source for drinking due exceedances of drinking water standards. The impact on fishing, for example, can be quantified by the travel cost to alternate fishing locations and/or lost fishing days. Similarly, the groundwater impacts can be quantified by the cost of providing an alternative water supply and/or the cost of treatment. More controversial methods include contingent valuation, a technique used to provide monetary values for goods, services, and public programs for which market data do not exist. The technique determines the value of goods and services based on the results of opinion surveys. In other cases, such as degradation of habitat and reduction of populations of biota, tools such as habitat equivalency analysis (Dunford *et al.*, 2004) can be used to determine the amount of restoration needed to offset lost services over time, thereby avoiding the need for a direct monetary metric.

Forensic issues, which frequently arise in Natural Resource Damage Assessments, whether conducted according to the preceding framework or just as a scientific matter, include: (1) establishing the baseline conditions that would exist absent the release, recognizing that the baseline itself may change over time; (2) determining the area of injury; (3) determining how much of the variation from the theoretical baseline may be attributable to natural variation; (4) determining causal relationships between injured resources and hazardous substances or petroleum compounds; and (5) sampling, laboratory, and statistical strategies to determine (1–4). An ecological issue that may arise is the significance of injury to individual organisms versus communities since a community of organisms may compensate for loss or injury to individual organisms so that the overall viability of the community is unaffected.

1.7 MARINE OIL POLLUTION

Marine petroleum pollution can result from tanker accidents; bilge water and ballast water discharges, or disposal of tank wash slops containing oil; runoff from land-based sources; and natural seeps. The petroleum can be in the form of crude oil or refined products. Generally the forensic task is to match the fingerprint of the suspected petroleum source to the petroleum found in the environment. Both the place of origin of the crude oil and the refining process contribute to a refined product fingerprint. The National Research Council estimated in 2002 that 1,300,000 tons of petroleum are spilled into the sea worldwide.

Prevention of operating and accidental discharges from vessels are controlled under the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto commonly referred to as MARPOL 73/78 (http://www.imo.org/Conventions/contents.asp?doc_id=678&topic_id=258). In the United States the Oil Pollution Act of 1990 (OPA 90), administered by USEPA, provides resources to deal with oil spills including an Oil Spill Liability Trust Fund to address accidental spills. The Act also establishes requirements for contingency planning for both government and industry. Even when a source seems obvious because of a tanker accident or specific spill event, there is still a fingerprinting issue since in determining the extent of the impact, the background due to natural and other anthropogenic sources must be accounted for.

Petroleum biomarkers feature prominently in marine petroleum fingerprinting because of their strong dependence on the characteristics of petroleum formation or crude oil source(s) and because of their resistance to weathering. A review of this topic is provided by Wang *et al.* (2005a, 2005b).

ACKNOWLEDGMENTS

Some of this material appeared in different forms in *Environmental Claims Journal*, Vol. 5, No. 4, Summer 1993 and Vol. 8, No. 3, Spring 1996 © Aspen Law & Business, Inc. as well as in *Environmental Forensics*, Vol. 1, No. 3, September 2000 © Academic Press.

REFERENCES

Aronovsky, R.G. (2000) Liability theories in contaminated ground water litigation. University of Wisconsin, Environmental Litigation: Advanced Forensics and Legal Strategies, April 13–14.

Butler, J.C. III, Schneider, M.W., Hall, G.R., and Burton, M.E. (1993) Allocating superfund costs: Cleaning up the controversy. *Environmental Law Reporter* 23, 10133–10144.

Charrow, R. and Bernstein, D. (1994) *Scientific Evidence in the Courtroom: Admissibility and Statistical Significance after Daubert.* Washington Legal Foundation, Washington, DC.

Dunford, R.W., Ginn, T.C., and Desvousges, W.H. (2004) The use of habitat equivalency analysis in natural resource damage assessments. *Ecological Economics* 48(1), 49–70.

Ferrey, S. (1994) The new wave: Superfund allocation strategies and outcomes. BNA *Environmental Reporter* 25, 790–803.

Hall, R.M., Harris, R.H., and Reinsdorf, J.A. (1994) Superfund response cost allocations: The law, the science and the practice. *The Business Lawyer* 49, 1489–1540.

Hill, A.B. (1965) The environment and disease: Association or causation. *Proceedings of the Royal Society of Medicine* 58, 295–300.

Marryott, R.A., Sabadell, G.P., Ahlfeld, D.P., Harris, R.H., and Pinder, G.F. (2000) Allocating remedial costs at Superfund sites with commingled groundwater contaminant plumes. *Environmental Forensics* 1(1), 47–54.

Mink, F.L., Nash, D.E., and Coleman, J.C. II (1997) Superfund site contamination: Apportionment of liability. *Natural Resources and Environment* 12, 68–79.

Murphy, B. (1993) Technical issues in Superfund insurance litigation. *Environmental Claims Journal* 5, 573–592.

Murphy, B. (1996) Risk assessment as a liability allocation tool. *Environmental Claims Journal* 8, 129–144.

Murphy, B. (2000) Allocation by contribution to cost and risk at Superfund sites. *Journal of Environmental Forensics* 1(3), 117–120.

National Research Council. (2000) *Natural Attenuation Groundwater Remediation*, National Academy Press, Washington, DC.

National Research Council. (2002) *Oil in the sea III: Inputs, fates, and effects*, National Academy Press, Washington, DC.

Rockwood, L.L. and Harrison, J.L. (1993) The Alcan decisions: Causation through the back door. *Environmental Law Reporter* 25 ELR 10542.

Stewart, R.B., Clegg, R., and Goldsmith, B.J. (eds.). (1995) Natural resource damages: A legal, economic, and policy analysis. Nat. Legal Center for the Public Interest. Washington, DC, 208.

Wang, Z., Fingas, M., Yang, C., and Christensen, J.H. (2005a) Crude oil and refined product fingerprinting: Principles, Chapter 16 in *Environmental Forensics: A Contaminant Specific Guide*, Robert D. Morrison and Brian L. Murphy, eds. Academic Press, Burlington, MA.

Wang, Z. and Christensen, J.H. (2005b) Crude oil and refined product fingerprinting: Applications, Chapter 17 in *Environmental Forensics: A Contaminant Specific Guide*, Robert D. Morrison and Brian L. Murphy, eds. Academic Press, Burlington, MA.

Wise, K.T., Maniatis, M.A., and Koch, G.S. (1997) Allocating CERCLA liabilities: The applications and limitations of economics. *BNA Toxics Law Reporter* 11, 830–833.