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Environmental Contamination with Multiple Potential Sources and the Common Law-Current Approaches and Emerging Opportunities

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ENVIRONMENTAL CONTAMINATION WITH MULTIPLE POTENTIAL SOURCES AND THE COMMON LAW: CURRENT APPROACHES AND EMERGING OPPORTUNITIES

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I. INTRODUCTION

The recognition of the risks associated with environmental contamination started increasing dramatically in the 1960s, and have continued to increase since then.[1] Partly as a result of this shift, litigation associated with environmental contamination has become common.[2] Because "[t]echnological development entails the manufacture and dispersal into the environment of increasing numbers of new chemicals and other products in ever increasing amounts,"[3] this trend is likely to continue.

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1. *See, e.g.*, RACHEL CARSON, SILENT SPRING (1962); FRANK GRAHAM, SINCE SILENT SPRING (1970).

2. The U.S. Environmental Protection Agency ("EPA") has itself been party to over 5,000 civil cases since 1970, *available at* http://www.rtk.net/docketsearch.html (last visited June 11, 2002).

3. Gordon J. Apple et al., *Scientific Data and Environmental Regulation*, *in* STATISTICS AND THE LAW 417 (Morris H. DeGroot, et al. eds., 1986).

Although the source of the contaminant is known in some instances, there are, in other cases, several possible and plausible sources for the observed harm. Such cases are the focus of this paper. Typical examples of contamination with multiple potential sources are groundwater contamination in industrial areas[4] and atmospheric contamination over large spatial extents.[5] As the number and amount of chemicals being released into the environment continues to increase while at the same time the minimum detectable concentrations of these components continues to decrease,[6] contaminants can be tracked over larger areas. Therefore, the number of cases for which there is some question as to the source of contamination will continue to rise.

Environmental contamination issues have mainly been put under the jurisdiction of governmental departments and agencies.[7] These organizations have developed a statutory law basis for dealing with contamination from multiple potential sources. In some cases, statutory law defines *a priori* who is responsible for contamination.[8] In

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4. *See infra* notes 60-127 and accompanying text.

5. *See infra* notes 108-109 and accompanying text.

6. *See* STANDARD METHODS FOR THE EXAMINATION OF WATER AND WASTEWATER (Andrew D. Eaton, et al. eds., 19th ed. 1995). The detection limits for contaminants are now typically at the parts per billion (ppb or μg/l) level. For example, the detection limits for trichloroethene (TCE) and perchloroethene (PCE) are 1.9 and 4.1 ppb, respectively.

7. David Schoenbrod, *Reviving the Common Law*, *in* THE COMMON LAW AND THE ENVIRONMENT 3, at 3-17 (Robert E. Meiners & Andrew P. Moriss eds., 2000); Roger E. Meiner et al., *Burning Rivers, Common Law, and Institutional Choice for Water Quality*, *in* THE COMMON LAW AND THE ENVIRONMENT 54 (Robert E. Meiners & Andrew P. Morriss eds., 2000); RICHARD N.L. ANDREWS, MANAGING THE ENVIRONMENT MANAGING OURSELVES: A HISTORY OF AMERICAN ENVIRONMENTAL POLICY 227-54 (1999).

8. PHILIP B. BEDIENT ET AL., GROUND WATER CONTAMINATION TRANSPORT AND REMEDIATION 517 (1995) [hereinafter Bedient]. For example, in the application of the Comprehensive Environmental Response, Compensation and Liability Act ("CERCLA"), "if a defendant generated the waste, transported the waste, currently owns and/or operates the facility and formerly owned and/or operated the facility, liability exists."

others, all potential sources are dealt with in a uniform manner, without regard to the individual sources' impact on a given area.[9] In still other cases, a liability scheme is put in place, and the source must be identified before liability can be attributed.[10] The degree to which causality must be demonstrated is therefore highly variable.

Before the inception of current environmental regulations, the common law was the primary forum for resolving disputes resulting from environmental contamination.[11] Despite the trend toward statutory law, the common law approach is still broadly applicable to the resolution of environmental conflicts.[12] In a common law setting, when the source of the contaminant is known, the litigation centers on determining whether the contamination infringes on the property rights of others. When the source is unknown, on the other hand, an additional preliminary step must be taken to determine the actual source or individual source contributions of the contaminant.[13] As such, the common law requires proof of causation before it imposes liability for observed contamination.[14] This requirement – as well as the general approach taken – is uniform for all contamination cases, while allowing for cases to be treated on an individual basis.

When causality must be demonstrated, as in the common law approach, scientific methods can be applied in an attempt to determine the most probable source of observed contamination, or the individual contributions of several potential sources. This article examines

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9. For example, the Clean Air Act of 1970 "required every new 'point source' of air pollution to obtain a federal permit, and these permits were based not on risk but on technology" (*See* ANDREWS, *supra* note 7, at 233).

10. For example, the North Carolina Oil Pollution and Hazardous Substances Control Act of 1978 (OPHSCA), in "contrast to most environmental statutes, which extend the cleanup obligation to parties based solely on their status as owners or operators, . . . extends [liability] to persons who have control over such substances immediately prior to a discharge" A Lawyer's Guide to North Carolina – Environmental Law, *available at* http://www.hg.org/guide-northcarolina.html#environmental (last visited June 12, 2002).

11. ELIZABETH BRUBAKER, PROPERTY RIGHTS IN THE DEFENSE OF NATURE 29-34 (1995) [hereinafter BRUBAKER].

12. *See infra* notes 23-40 and accompanying text.

13. *See infra* Section II.

14. Meiners et. al, *supra* note 7.

the implications of liability as defined in the common law approach on the types of scientific methods that are applicable for source identification in a common law setting.

Current scientific methods of contaminant source identification have only found limited application in the common law setting and even more limited success. This article considers the extent to which this shortcoming is due to a mismatch between the common law approach and current scientific methods of contaminant source identification.

The article is organized as follows. It first examines common law approaches to environmental contamination cases.[15] These approaches aim to identify the most probable sources of contamination and thereby specify the responsibilities and liabilities associated with property rights, which are themselves never perfectly delineated.[16] The scientific methods that have been applied to identify sources of contamination in support of permitting and liability approaches are outlined, as are case studies illustrating their application in court settings.[17] These sections lead into a discussion of a statistical perspective on the problem.[18] A review of statistical methods that are currently being developed for the purpose of contaminant source estimation is then presented,[19] shedding light on ways in which a statistical perspective can be incorporated into conflict resolution in cases of environmental contamination from unknown sources. Sample applications illustrating the potential of the new methods are outlined.[20] Finally, the legal applicability of these methods is briefly examined in terms of the admissibility of the evidence and the standard of proof that must be met.[21] Potential applications of the proposed methods to other settings, such as statutory law and alternate forums for environmental conflict resolution, are also mentioned.[22]

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15. *See infra* notes 23-40 and accompanying text.
16. *See infra* notes 42-50 and accompanying text.
17. *See infra* notes 59-132 and accompanying text.
18. *See infra* notes 133-140 and accompanying text.
19. *See infra* notes 141-165 and accompanying text.
20. *See infra* notes 167-177 and accompanying text.
21. *See infra* notes 178-194 and accompanying text.
22. *See infra* notes 196-204 and accompanying text.

II. ENVIRONMENTAL CONTAMINATION UNDER THE COMMON LAW

> Rather than being written in statutes (by being passed as laws by legislatures), common law property rights have evolved in the courts through the ages. The doctrines of precedent and *stare decisis* (from a Latin phrase meaning "to stand by decisions and not to disturb settled matters") have governed the evolution of the common law, requiring judges to follow previous relevant court decisions and establishing a hierarchy of precedents. These doctrines have helped ensure that property rights' traditional importance continues to inform the common law to this day.[23]

Property rights, as related to environmental amenities, are defined here as the rules that specify who has access to resources and the authority to derive value from them. These rules may be formal, such as state enforced laws, or informal, such as customary rights.[24] In cases of environmental contamination, the issue is to enforce the rights and liabilities associated with a given environmental amenity, such as the water in a stream[25] or the air in a given area.

A. *Applicable Common Law Theories*

Many provisions of the common law allow for the definition and protection of property rights, including those related to environmental amenities. Property owners affected by contaminant migration from an adjoining property can defend their rights based on the legal theories of nuisance,[26] trespass,[27] and, in some cases, strict liability.[28]

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23. BRUBAKER, *supra* note 11, at 31.

24. *See* Andrew P. Morriss, *Miners, Vigilantes and Cattlemen: Overcoming Free Rider Problems in the Private Provision of Law*, 33 LAND & WATER L. REV. 581 (1998).

25. *See, e.g.*, Roger Bate, *Saving Our Streams: The Role of the English Anglers' Conservation Association in Protecting English and Welsh Rivers*, 14 FORDHAM ENVTL. L.J. (forthcoming Spring 2003).

26. *See, e.g.*, Walter v. Selfe 29 L.J.R. (20 N.S.) 433 (Ch.1851) (in which the owner and tenant of a house and garden neighboring brought suit against a neighbor who had recently started manufactur-

A nuisance is an interference with the private use and enjoyment of the property and does not require interference with the possession.[29] At the heart of the theory of nuisance is the maxim "use your own property so as not to harm another's" (*sic utere tuo ut alienum non laedas*).[30] This maxim reflects a balance under the common law between the right of an owner to use and enjoy his or her property and the right of the neighbor not to have his or her rights compro-

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ing bricks on his property). "They sought injunction against the burning process, objecting that the resulting smoke, vapour, and 'floating substances' caused inconvenience and discomfort. Knight Bruce, the Vice-Chancellor who heard the case, determined that the brick burning constituted a nuisance and issued an injunction prohibiting any burning that damaged or annoyed the plaintiffs or injured their garden." BRUBAKER, *supra* note 11, at 233-234.

27. *See, e.g.,* Sammons v. Gloversville, 70 N.Y.S. 284 (N.Y. App. Div. 1901) (in which the owner of a farm located on Cayadutta Creek sued upstream communities for waste being discharged into the creek). The "city of Gloversville emptied its sewers and drains into the creek, fouling its water and depositing filth on its beds and along its banks. So, too, did the city of Johnstown, along with several tanneries. . . . The court found that city's sewage disposal practices amounted to a continuing trespass that substantially injured Mr. Sammons' property rights. It issued an injunction . . . prohibiting Gloversville from fouling Mr. Sammons' premises by discharging its sewage into the creek." BRUBAKER, *supra* note 11, at 224.

28. *See* Rylands v. Fletcher, 3 L.R.-E. & I. App. 330 (1868) (presenting the theory of strict liability for the first time. The plaintiff owned a colliery with mine shafts that reached under the land of the defendant. The defendant built on his land a water reservoir. The soil between the mine shafts and the base of the reservoir collapsed causing the water to flood the mine. The plaintiff sought damages from the defendants, and won. During the appeal it was held that, if a person brings or keeps anything on his land that should later escape and is a cause of damage to neighboring properties, the owner is responsible for its effects no matter how careful he has been to retain that item).

29. Lopardo v. Fleming Cos., 97 F.3d 921, 929 (7th Cir. 1996).

30. "Common law maxim meaning that one should use his own property in such a manner as not to injure that of another" BLACK'S LAW DICTIONARY 1380 (6th ed. 1990).

mised.[31] Unlike trespass law, nuisance law requires proof of substantive harm.[32]

"A trespass is an invasion of the interest in the exclusive possession of property as by entry upon it."[33] Abbott states, "[e]vidence of any unlawful interference with plaintiff's personal property, or exercise of dominion over it, by which plaintiff is damnified – such as a wrongful levy – though without sale or removal, is enough. . . . There must be a positive act, such as if done without authority would be a trespass." [34] Furthermore, "[e]vidence of wrongful intrusion, however slight, is evidence of a trespass."[35] Any invasion of another's land – whether by people, flood-waters, structures, or pollutants – constitutes a trespass.[36]

Under the theory of strict liability, the responsible party is held accountable without regard to fault. The genesis of this theory stems from the "non-natural use" of land principle set forth in the landmark English case, *Rylands v. Fletcher.*[37] Strict liability allows for the imposition of liability for damages proximately caused by the defendant's dangerous, non-natural use of land regardless of the standard of care that the defendant utilized in conducting that activity. Generally, modern courts have applied this strict or absolute liability to activities "variously characterized as 'perilous,' 'ultra or extra-hazardous,' or 'abnormally dangerous'."[38] Strict liability is therefore

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31. BRUBAKER, *supra* note 11, at 40-41; *see generally* D. Schoenbrod, *Protecting the Environment in the Spirit of the Common Law, in* THE COMMON LAW AND THE ENVIRONMENT 3 (Robert E. Meiners & Andrew P. Morriss eds., 2000).

32. BRUBAKER, *supra* note 11, at 42; A.M. WILSHERE, PRINCIPLES OF THE COMMON LAW 308.

33. *Lopardo*, 97 F.3d at 928 (citing Restatement 2d of Torts).

34. AUSTIN ABBOTT, TRIAL EVIDENCE: THE RULES OF EVIDENCE APPLICABLE ON THE TRIAL OF CIVIL ACTIONS 1683 (1918) [hereinafter *Abbott*].

35. *Id.* at 1709.

36. BRUBAKER, *supra* note 11, at 31; WILSHERE, *supra* note 31, at 281.

37. Rylands v Fletcher, 3 L.R.-E & 1 App. 330, 339 (1868).

38. Woodrow Sterling v. Velsicol Chemical Corp., 647 F. Supp. 303, 312-313 (W.D.Tenn. 1986) (citing C. MORRIS & C.R. MORRIS, MORRIS ON TORTS 231 (2d ed. 1980).

only invoked in exceptional circumstances, whereas the theories of trespass and nuisance are more broadly applicable.

These common law theories are made even more powerful because courts have rejected two defenses that defendants have put forward to indemnify themselves against liability for environmental contamination. The first is that they are responsible for only a small fraction of the total contamination, and the second is that a long history of operation justifies continued pollution.[39] As Abbott states, the "fact that part of the injury results from the acts of one not a defendant, is available to defendant on the question of damages, but not otherwise."[40]

In order for the legal theories of the common law to be enforceable in cases of environmental contamination, the source(s) and the effect of the contaminant must be determined with a sufficient level of precision and accuracy to make legal theories capable of being applied in practice. In the allocation of responsibility, the fraction of contamination emanating from each source must be estimated.

Therefore, more so than in the case of statutory law, contaminant source identification is central to common law for resolving environmental disputes. If a suit is brought under the common law and contaminant migration has allegedly occurred, the source of this contamination must be identified if liability is to be imposed. When there is a dispute over the source of contamination, it is likely that the actual source of contamination will never be known with absolute certainty. This is not an unusual situation from the perspective of the common law, however, as the common law is typically applied as a direct result of the fact that property rights and liabilities are not fully delineated.[41]

Two principles are central to the application of the common law approach: the imperfect nature of the definition of property rights and the statistical nature of decisions made in legal settings such as court cases. These aspects are examined in the following sections.

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39. *Velsicol Chem. Corp.*, 647 F.Supp. at 310.

40. ABBOTT, *supra* note 34, at 1732.

41. BRUCE YANDLE, COMMON SENSE AND COMMON LAW FOR THE ENVIRONMENT 87-90 (1997).

B. *Imperfect Definition Of Property Rights*

In his book *Economic Analysis of Property Rights*, Yoram Barzel argues that property rights are never perfectly defined.[42] The degree of precision of property rights' definition is a function (i) of the transaction costs associated with more precise and accurate definition[43] and (ii) of the anticipated benefits of improved definition.[44]

The essence of his argument is that the concept of property rights is closely related to the transaction costs of defining and enforcing these rights. These transaction costs are defined as the costs associated with the transfer, capture, and protection of rights.[45] In order that the rights to an asset be completely or perfectly delineated, both its owner and other individuals potentially interested in the asset must possess full knowledge of all its valued attributes, which requires that product information be costless to obtain and the (relevant) costs of transacting be zero.[46] When transaction costs are positive, rights to assets will not be perfectly delineated because doing so would be prohibitively costly.[47] The degree of delineation would increase with an increase in the value of these rights or with a reduction in the costs of metering or policing.[48]

In short, by their own actions, individuals are able to control and to affect the delineation of their rights to property.[49] Whenever individuals find the existing level of delineation unsatisfactory, they will alter it until they are satisfied. Economic conditions are constantly changing, and with them the equilibrium property-rights delineation

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42. YORAM BARZEL, ECONOMIC ANALYSIS OF PROPERTY RIGHTS 3-15, 85-104 (1997); *see also* Bruce Yandle, *Legal Foundations for Evolving Property Rights, in* THE TECHNOLOGY OF PROPERTY RIGHTS 1 (Terry L. Anderson & Peter J. Hill eds., 2001).

43. *See infra* notes 45 to 47 and accompanying text.

44. *See infra* notes 48 to 50 and accompanying text.

45. BARZEL, *supra* note 42, at 4-5.

46. BARZEL, *supra* note 42 at 4, 7-9.

47. BARZEL, *supra* note 42 at 7-9, 92-96.

48. BARZEL, *supra* note 42 at 91-94; *see also* Terry L. Anderson & P. J. Hill, *The Evolution of Property Rights: A Study of the American West*, 18 J.L. & ECON. 163 (1975).

49. BARZEL, *supra* note 42, at 103.

is changing as well.[50] Because marginal benefits inevitably decline and the marginal costs inevitably rise as definition becomes more precise,[51] property rights will never be perfectly defined. As such, the delineation of property lies along a continuum ranging from leaving the rights in the public domain to defining them as precisely as other limiting factors, such as technology, will allow.

A simple example of this principle is the location of the boundary between the properties of two individuals. Suppose that two individuals own expanses of land that they use for nothing more than their own personal enjoyment. The value of each individual acre will be low. These individuals will most likely not define the boundary between their two properties precisely, because the incremental value of each acre of land is small relative to the cost of additional delineation of their property rights. They may be content with knowing that their property boundary lies somewhere along a given valley or within 500 feet of a given line. They will, however, still have an estimate of the location of the property line and an idea of the uncertainty associated with this estimate. If both property owners decide to start ranching and want to place a fence to separate their cattle, the incremental value of those undefined acres will now be higher because each owner can graze more cattle if their respective share of the land is larger. The value of each individual acre having increased, they will now be willing to incur additional costs to define their property rights more precisely. They may, for example, pay for a surveyor to establish the property line. To undertake the survey, the additional cost of defining this boundary must be less than the additional benefit for the property owner whose property area had been underestimated in the previous arrangement. The property owners will now have a new estimate, and a new level of uncertainty associated with their property rights. Some uncertainty

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50. *Id.* at 103-4. *See also* BHASKAR VIRA, RIGHTS, PROPERTY RIGHTS AND THEIR PROTECTION - IMPLICATIONS FOR THE ANALYSIS OF ENVIRONMENTAL POLICY 17 (Oxford Centre for the Environment research paper: no. 2, Ethics & Society, 1995). Vira reaches a similar conclusion, stating that "[t]here are circumstances where the definition of exclusive private rights, even if it is desirable, may be physically impossible or extremely costly. . . . However, this does *not* imply that no form of property rights can be defined with respect to these resources."

51. JOHN B. TAYLOR, ECONOMICS 106-7, 346 (2001).

as to the exact location of the property line will always remain, however.

In the case of environmental contamination, the benefit of definition for the party seeking higher environmental quality is the possibility of stopping a nuisance or trespass. For the party responsible for a given source, the benefit is the possibility of avoiding liability for the effects of contamination, if the contaminant can be shown to result from the activities of another party. As in the previous example, the property rights will never be perfectly determined and delineated, in this case because the source of contamination will not be perfectly defined, due to the declining marginal benefits and rising marginal costs. Depending on the legal context and on the cost associated with liability, the degree of property rights definition or the confidence associated with contaminant source identification will change. For example, as the cost of remediation or compensation to victims increases, property rights and liabilities will be better defined. If the contaminant in question can be shown to be responsible for the illness or disability of several individuals, the parties responsible for potential sources will be willing to incur higher costs to define the source more precisely than in the case where the contaminant merely causes an inconvenience to the receptor. However, absolute certainty as to the source will never be expected or achieved.

C. *Statistical Nature Of Legal Setting*

Because property rights are never perfectly delineated, when disputes occur, the legal setting within which the disputes are to be resolved needs to take into account the uncertainty associated with the delineation of property rights in making a decision. As such, the decisions made in a legal setting are statistical in nature.

The statistical nature of the legal system is embedded in the various terms used to describe the standard of proof or burden of persuasion needed to establish guilt or attribute liability in a court setting. Terms such as "preponderance of evidence," "clear and convincing evidence," "clear, unequivocal and convincing evidence," and "beyond a reasonable doubt" are used in various legal settings. These terms imply a certain statistical standard of proof to be met, although their exact meaning is often elusive. Broadly stated, the standard of proof reflects the risk of winning or losing the given adversary proceeding or, stated differently, the certainty with which the party bearing the burden of proof must convince the fact-finder. For a class of cases, therefore, the burden of proof lies along a continuum from low probability to high probability.[52]

Several authors and courts have made attempts to quantify, in a probabilistic sense, the various standards of evidence. For example, the preponderance of evidence standard requires that a given explanation is "more likely than not,"[53] that the judge or jury must be "more than 50% confident in its conclusion,"[54] that the "proposition in question is more likely true than not,"[55] or that the probability that "the defendant is in fact liable exceeds ½."[56] Although the other standards tend to be less well defined, there have also been a few attempts to assign numerical values to them.[57] Although general

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52. H. Solomon, *Measurement and Burden of Evidence, in* SOME RECENT ADVANCES IN STATISTICS 1, 20, 21-22 (J. Tiago de Oliveira & Benjamin Epstein eds., 1982).

53. Steve Gold, *Causation in Toxic Torts: Burdens of Proof, Standards of Persuasion, and Statistical Evidence,* 96 YALE L.J. 376, 378 (1996).

54. *Id.* at 383.

55. PAUL R. RICE, EVIDENCE: COMMON LAW AND FEDERAL RULES OF EVIDENCE 20 (1996).

56. David Kaye, *The Limits of the Preponderance of the Evidence Standard: Justifiably Naked Statistical Evidence and Multiple Causation,* 1982 AM. B. FOUND. RES. J. 487, 487 (no. 2, Spring 1982).

57. In United States v. Fatico, 458 F.Supp 388 (E.D.N.Y. 1978), "a court tries to relate various degrees of burden of proof to an exact probability figure.... The case derives from proceedings in which the key question was 'What burden of proof must the Government meet in establishing a critical fact not proved at a criminal trial that may substantially enhance the sentence to be imposed upon a defendant?'" Solomon, *supra* note 52 at 20. In *Fatico,* the standard of proof was identified as 50+ percent for the "preponderance of the evidence" standard, approximately 70 percent for the "clear and convincing evidence standard," approximately 80 percent for "clear, unequivocal and convincing evidence," and 95+ percent for "beyond a reasonable doubt." *See id.* at 21.

Table 1 shows the assessment of probabilities corresponding to various burdens of persuasion as viewed by Federal District Judges in the Eastern District of New York:

guidelines for the standard of proof that needs to be met in various legal settings can be defined, these standards are also a function of other variables. For example, if one considers the chance of handing down a wrongful verdict as a risk, the concept of allowable risk becomes applicable.[58]

Overall the various standards of evidence are essentially statistical risk measures. Property rights never being perfectly delineated, there will always be more than one possible resolution to a given conflict. The court's responsibility is to examine the evidence presented by each of the parties, and determine the probability that each of the possible scenarios is representative of what actually occurred. This probability is then compared with the applicable standard of proof. Although court decisions are rarely thought of in this strict probabilistic sense, they nevertheless ultimately come down to a statistical decision.

D. *Implications For Scientific Methods To Be Applied*

The common law recognizes that contamination can never be tracked with certainty. It views the probability of a given source being responsible for observed harm or the fraction of the harm that

Table 1. Probabilities Associated with Standards of Proof (Judges, Eastern District of New York, Solomon, *supra* note 52 at 22.

Judge	Preponderance (%)	Clear and convincing (%)	Clear, unequivocal and convincing (%)	Beyond a reasonable doubt (%)
1	50 +	60-70	65-75	80
2	50 +	67	70	76
3	50 +	60	70	85
4	51	65	67	90
5	50 +	Standard is elusive & unhelpful		90
6	50 +	70 +	70 +	85
7	50 +	70 +	80 +	95
8	50.1	75	75	85
9	50 +	60	90	85
10	51	Cannot estimate numerically		

58. *See infra* note 193 and accompanying text.

is attributable to a given source as not fully known. The degree of uncertainty can be decreased, however, if more information is gathered, but this has a cost. In this sense, common law is statistical or stochastic in nature, because it deals directly with the uncertainty associated with estimates.

Consequently, the scientific requirement for dealing with contamination from unknown or multiple sources in a common law setting will be the ability to reliably identify the most probable sources or causes of observed harm and their relative contributions to overall contamination. The scientific methods must be able to account for the imperfect nature of the delineation of property rights and the statistical nature of the legal setting in which they are applied. As such, they must either identify the source of contamination with sufficient accuracy and precision so as to eliminate any doubt as to the actual source (which is only feasible if one is willing to incur unreasonably high transaction costs) or offer a basis for determining the probability of various possible contamination scenarios.

III. CURRENT APPROACHES FOR CONTAMINANT SOURCE IDENTIFICATION

Having examined how the common law deals with environmental contamination in cases where the source is unknown, we now turn to determining how parties to such conflicts have attempted to demonstrate causality. This section examines sample court cases and analyzes the limitations of current approaches to source identification, especially with regard to determining the level of uncertainty associated with alternative contamination scenarios.

A. *Case Studies Of Conflicts Involving Contamination With Multiple Potential Sources*

This section presents cases involving conflict over the source of observed contamination along with a description of the methods applied in attempting to identify the source(s). The cases are subdivided into three categories that roughly correspond to increasing sophistication of the scientific methods used to identify sources. Although most of the cases pertain to a regulatory setting, general inferences applicable to a common law approach can nevertheless be derived.

1. Identification Of Contaminant At Source And Receptor

A first subset of cases involving a conflict about the source of observed contamination relies simply on the presence of contamination at the receptor site and on establishing that a release of such a contaminant occurred at a nearby potential source.

A large fraction of these types of cases involve claims for contribution by parties responsible for contamination at sites covered by The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Claims brought under CERCLA are somewhat unique in that, for on-site contamination, any party associated with a site is held liable for the full effect of contamination.[59] Therefore, there is less of a need to identify the individual contributions of various parties. One example of such a case is *Kalamazoo River Study Group v. Menasha Corporation et al.*,[60] where defendants were seeking summary judgment, claiming that there was no proof of their contribution to contamination at a site. The court ruled that fact issues existed as to parties' contribution of contamination to the site at issue, basing its opinion on proof of potential releases at the defendants' sites. Conversely, in *Andritz Sprout-Bauer, Inc. v. Beazer East, Inc., et al.*,[61] a landowner brought action against the previous owner under CERCLA, but failed to establish liability as there was no record of the previous owner having contributed contamination to the site. Similarly, in *American National Bank and Trust Company of Chicago v. Harcros Chemicals,*[62] current owners of a contaminated site failed to recover environmental response costs[63] from a past owner because, although there was proof of con-

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59. BEDIENT, *supra* note 8, at 562-64, 571-72.

60. Kalamazoo River Study Group v. Menasha Corp., 228 F.3d 648 (6th Cir. 2000).

61. Andritz Sprout-Bauer, Inc. v. Beazer East, Inc., 12 F.Supp.2d 391 (M.D. Pa. 1998).

62. American Nat'l Bank and Trust Co. of Chicago v. Harcros Chemicals, 997 F. Supp 994 (N.D. Ill. 1998)

63. BEDIENT, *supra* note 8, at 571 (noting that under CERCLA, environmental response costs include: "(A) all costs of removal or remedial action incurred by the United States Government or a state or an Indian tribe not inconsistent with the national contingency plan, (B) any other necessary costs of response incurred by any other person consistent with the national contingency plan, (C) damages

tamination by previous owners, there was no proof that chemicals covered by CERCLA had been released. Furthermore, other users of the site had also stored the hazardous chemicals contaminating the site.[64] As can be seen from these cases, such simple arguments rarely convince courts, even for CERCLA sites where the contaminated area is the same as the site from which contaminants were released.

Another set of cases covered by CERCLA involves the question of whether the contaminant contributions of several parties are divisible when costs covered by the National Contingency Plan (NCP)[65] are allocated. For example, in *Pneumo Abex Corp., et al. v. Bessemer and Lake Erie Railroad Company, Inc., et al.*[66] the current owner of property formerly used as a railroad parts foundry brought suit against sellers of scrap journal bearings to the foundry and others. Although the liability of these parties was recognized, the presence of contamination in areas of the property used by the defendants was not deemed sufficient evidence to adequately allocate response costs, and these were therefore distributed evenly among responsible parties.[67] Conversely, in *Bancamerica Commercial Corp et al. v. Trinity Industries, Inc. et al.*,[68]costs were successfully allocated based on volume contributions of waste as obtained from use records, adjusted

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for injury to, destruction of, or loss of natural resources, including the reasonable costs of assessing such injury, destruction, or loss resulting from such release; and (D) the costs of any health assessment or health effects study carried out under section 104(i)").

64. *See American National Bank and Trust Co.*, 997 F. Supp 994.

65. BEDIENT, *supra* note 8, at 564 ("The overall process for identifying and cleaning up Superfund sites is contained in a set of regulations titled the "National Contingency Plan." . . . Essentially, there are criteria for placing sites on the Superfund list. Then, there are criteria for studying and evaluating the site. And then there are criteria for cleaning up the site. No action may qualify for the use of Superfund monies unless the procedures outlined in the National Contingency Plan are followed.").

66. Pneumo Abex Corp. v. Bessemer & Lake Erie R.R. Co., Inc., 936 F.Supp. 1250 (E.D. Va. 1996).

67. *Id.* at 1255-59.

68. Bancamerica Commercial Corp. v. Trinity Indus., Inc., 900 F.Supp. 1427 (D. Kan. 1995).

for relative toxicity.[69] Similarly, in *Bell Petroleum Services, Inc. et al. v. Sequa Corp. et al.*,[70] the former owner of a chrome-plating facility met its burden of proving that there was reasonable basis for apportioning liability between it and other former owners on a volumetric basis, precluding imposition of joint and several liability.[71] These simple methods are therefore applicable in a statutory setting, where contributions are easily identifiable and where the contaminant has not migrated significantly away from the source. Typical bases for allocation include the relative volumes of waste disposed of by the parties and the relative toxicity of the wastes.[72]

In general, however, proof of contamination coupled with proof of contaminant release at a given site does not constitute strong enough evidence under any standard of proof, if there are other potential sources present. For example, in *Pistocco et al. v. Texas Natural Resource Conservation Commission et al.*[73] the plaintiffs sought to reverse a commission's decision to grant a landfill expansion based on the presence of contaminated groundwater in the area. Because other possible sources for the contamination existed, the court did not overturn the commission's decision.[74] Similarly, in *Ellington et al. v. Hester et al.*,[75] landowners brought action against neighboring landowners under North Carolina's Oil Pollution and Hazardous Substances Control Act (OPHSCA),[76] as well as common law theories, for groundwater contamination of their property.[77] However, because there was only evidence that there had been a release of gasoline from one of the neighbor's underground storage tanks, the plaintiffs' experts could only assert that contaminants from the

69. *Id.* at 1458-88.

70. Bell Petroleum Serv., Inc. v. Sequa Corp., 3 F.3d 889 (5th Cir. 1993).

71. *Id.* at 902-905.

72. Jeffrey M. Gaba, *Recovering Hazardous Waste Cleanup Costs: The Private Cause of Action Under CERCLA,* 13 ECOLOGY L.Q. 181 (1986).

73. Pistocco v. Texas Natural Res. Conservation Comm'n, No. 03-99-00275-CV, 2000 WL 190659 (Tex. App. Austin).

74. *Id.* at *6-*10.

75. Ellington v. Hester, 487 S.E.2d 843 (N.C. Ct. App. 1997).

76. *See* "A Lawyer's Guide to North Carolina – Environmental Law" *supra* note 10 for a description of OPHSCA.

77. *See Ellington*, 487 S.E.2d at 845.

neighbor's property could travel to plaintiff's property, and that statement was held not to be sufficient to establish causation.[78] In *Gerst et al. v. Marshall et al.,*[79] purchasers brought action against vendors after discovering contamination on their property. The court held that expert testimony that gasoline from a fuel delivery system had contaminated soil and groundwater was insufficient to generate jury question as to causation because the testimony did not establish when or where the release occurred.[80] In *Kinnick et al. v. Schierl, Inc. et al.*,[81] plaintiffs were unable to recover contribution for cleanup from owners of a neighboring property. Proof consisted of evidence of contamination of neighboring property by the same kinds of contaminants, but only a possible link between the two was presented.[82]

Conversely, in *Trinity American Corp. v. The United States Environmental Protection Agency,*[83] the owner of a polyurethane plant failed to convince the court to reverse an emergency order by the EPA under the Safe Drinking Water Act. EPA's finding that the plant had contributed to groundwater contamination was based on owner's history of improper waste handling and dumping of hazardous materials, presence of same chemicals on owner's property and offsite, and direction of water flow.[84] The court held that since the plant contributed to the contamination, the fact that other potential sources may have contributed to groundwater contamination was irrelevant.[85] In the case of an emergency order, however, the EPA must only demonstrate that its actions are not arbitrary and capricious.[86]

Therefore, arguments based exclusively on determining that contaminant was released at a potential source are only effective in a limited number of statutory settings. In cases where causation must be demonstrated, as is the case with common law approaches, such

78. *Id.* at 846.

79. Gerst v. Marshall, 549 N.W.2d 810 (Iowa 1996).

80. *Id.* at 13-26.

81. Kinnick v. Schierl, Inc., 541 N.W.2d 803 (Wis. Ct. App. 1995).

82. *Id.* at 804-06.

83. Trinity American Corp. v. EPA, 150 F.3d 389 (4th Cir. 1998).

84. *Id.* at 396-97.

85. *Id.* at 395-96.

86. *Id.* at 395.

arguments have systematically been held to be insufficient to establish causation.

2. Identification Of Contaminant At Source And Receptor, With No Other Plausible Sources Present

A second subset of cases involving contaminant source identification includes cases for which (i) contamination had occurred, (ii) contaminant had been released at the potential source and (iii) allegedly no other plausible sources were present in the area.

For example, in *Dexter v. Cosan Chemical Corp.*,[87] plaintiffs sought to recover damages for soil and groundwater contamination at a site covered by CERCLA. The court held that proof of Cosan's use and manufacture of products containing mercury, benzene and toluene, combined with a study indicating that there were no other sources of mercury or pure benzene pollution was sufficient to establish liability.[88] In *James et al. v. Clark et al.*[89] homeowners filed action against an owner of underground storage tanks alleging violations of the Oil Pollution and Hazardous Substance Control Act (OPHSCA), and asserting negligence, nuisance, and trespass arising from petroleum contamination of homeowners' well water.[90] Soil surrounding underground storage tanks controlled by the defendant was contaminated, and no other potential sources of contamination could be identified.[91] As a result, defendant's call for summary judgment was denied despite the lack of direct evidence of contaminant migration.[92] Therefore, being able to argue that no other plausible sources are present has been sufficient, even in cases where causality must be demonstrated. The number of such cases, however, is small.

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87. Dexter v. Cosan Chemical Corp., No. 91-5436, 1997 WL 557637 (D.N.J., Jan. 10, 1997).

88. *Id.* at *7-*8, *24.

89. James v. Clark, 454 S.E.2d 826 (N.C. Ct. App. 1995).

90. *Id.* at 827.

91. *Id.* at 832.

92. *Id.* at 833.

3. Application Of Scientific Methods Of Contaminant Source Identification

A third subset of cases involves the application of scientific methods specifically designed for contaminant source identification. A large number of methods, described below, are currently available for this purpose. Available methods differ in their ranges of applicability in terms of contaminants and media, the level of confidence associated with their conclusions and a variety of other factors. Despite such wide variability, contaminant source identification methods can be subdivided into three categories: compositional analysis, the use of either naturally occurring or introduced tracers, and methods based on conclusions derived from the contamination distribution itself.[93] These methods are relatively well-known to the scientific community, but the degree to which they have been applied in legal settings is limited.

4. Compositional Analysis

Compositional analysis methods identify specific components of a given contaminant. The source of the contamination can then be determined if the presence or abundance of these components correlates predictably with contaminant sources. These methods can generally be subdivided into methods that analyze the molecular composition of compounds and those that determine their isotopic composition. A typical example is the identification of sources of crude oil based on its molecular or isotopic composition, made possible by the fact that the fraction of each component varies naturally with the source.[94]

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93. A more detailed review of these methods is available in Anna M. Michalak, *Feasibility of Contaminant Source Identification for Property Rights Enforcement, in* THE TECHNOLOGY OF PROPERTY RIGHTS 123 (Terry L. Anderson & Peter J. Hill eds., 2001).

94. *See* Alan P. Bentz, *Who Spilled the Oil: Matching an Oil Spill with Its Source Requires Methods that Take into Account the Weathering of Oil in the Spill* 50 ANALYTICAL CHEMISTRY 655A (No. 7, 1978); L. Mansuy et al., *Source Identification of Oil Spills Based on the Isotopic Composition of Individual Components in Weathered Oil Samples*, 31 ENVTL. SCI. & TECHNOLOGY 3417 (1997).

Compositional analysis has been applied in a small number of court cases. In *Church, et al. v. General Electric Company*[95] plaintiffs used compositional analysis to show that PCBs contaminating their property were unweathered and therefore must have originated from a nearby upstream source along the river adjacent to their properties.[96] Because General Electric owned all contaminated property within a mile upstream of the contaminated site, its motion for summary judgment was denied.[97] The court found that the plaintiffs had supplied reasonable proof of the origin of the contamination.[98]

Compositional analysis was also an important part of the evidence presented in *Ethyl Corporation et al. v. Environmental Protection Agency,*[99] which involved various manufacturers of lead additives and refiners of gasoline appealing the promulgation of low-lead regulations by the Environmental Protection Agency (EPA). The court found in favor of the EPA based partly on clinical studies involving the analysis of the isotopic composition of lead as a means of demonstrating the relative importance of lead absorption by inhalation versus ingestion.[100]

Therefore, compositional analysis has been successfully applied in a few cases where causation needed to be demonstrated, both when a single source was being examined, and when the individual contributions of several sources were to be estimated.

5. Tracer Methods

The composition of a given contaminant can be used to determine its source only when the potential sources exhibit chemically distinct versions of the contaminant. Even in cases for which such analysis is not possible, however, tracer compounds discharged with the contaminant can be used to identify sources of contamination. The tracer compound can be a chemical that is naturally present in the discharge or a compound added to the source for the specific purpose of tracing a contaminant. In either case, care must be taken to

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95. Church v. General Electric Company, 138 F.Supp.2d 169 (D. Mass. 2001).
96. *Id.* at 171, 177-78.
97. *Id.*
98. *Id.* at 171.
99. Ethyl Corp. v. EPA, 541 F.2d 1 (D.C. Cir. 1976).
100. *Id.* at 41-43.

select a tracer with transport characteristics similar to those of the contaminant being traced in order to avoid misidentifying sources. A representative example of these methods is the use of uric acid as a naturally occurring tracer used to track untreated sewage. This is possible because uric acid is present at significant levels in untreated sewage and not normally detected in unpolluted waters.[101]

Tracer methods have been applied both in statutory and common law settings. In *Union Texas Petroleum Corp. et al. v. Jackson et al.*[102] the court found oil companies liable for saltwater contamination of a town's subsurface waters. Chloride was used as a naturally occurring tracer of the oil company's effects, and chloride content within the town's water supply was shown to increase dramatically during the company's operations.[103] In *Reserve Mining Co. v. United States Environmental Protection Agency,*[104] *Reserve Mining Co. v. United States of America,*[105] and *United States of America et al. v. Reserve Mining Company et al.*[106] a complaint was filed alleging that the defendant's discharge of tailings into Lake Superior violated the Rivers and Harbors Act of 1899, the pre-1972 Federal Water Pollution Control Act, and the federal common law of public nuisance. Reserve maintained that the tailings settled to the bottom of the lake in an area within close range of the plant, but plaintiffs used a tracer to demonstrate that over 2,000 square miles of the lake had been exposed to tailings.[107] Tracers were also used to determine the cause of visibility impairments at Grand Canyon National park in *Central Arizona Water Conservation District v. United States Environmental Protection Agency.*[108] The case involved petitioners contesting regulations promulgated by the EPA to partially remedy visibility impairments at the Grand Canyon National park. The standard

101. L. Brown, et al., *The Use of Uric acid as a Method of Tracing Domestic Sewage Discharges in Riverine, Estuarine and Coastal Water Environments,* 16 WATER RES. 1409 (1982).

102. Union Texas Petroleum Corp. v. Jackson, 909 P.2d 131 (Okl. Ct. App. 1995).

103. *Id.* at 136.

104. Reserve Mining Co. v. EPA, 514 F.2d 492 (8th Cir. 1975).

105. Reserve Mining Co. v. U. S., 498 F.2d 1073 (8th Cir. 1974).

106. U.S. v. Reserve Mining Co, 380 F.Supp. 11 (D. Minn. 1974).

107. *Id.* at 38-39; *Reserve Mining Co.*, 498 F.2d. at 1075-76.

108. Central Arizona Water Conservation District v. EPA, 990 F.2d 1531 (9th Cir. 1993).

of proof that needed to be met was that the impairments had to be "reasonably attributable" to the source, leaving the EPA with broad discretion in determining how and whether impairment may be attributed to an individual source.[109] Therefore, in cases where a appropriate tracer could be identified, courts have accepted tracer-based evidence. Tracers do not appear to have yet been applied, however, in cases where liability needed to be divided among several sources.

6. Analysis Of The Contaminant Distribution

When parameters affecting contaminant transport can be effectively quantified, the distribution of the contaminant itself can be used as a basis for determining its source, regardless of the composition of the source effluent. The effectiveness of methods based on this premise depends on the accuracy with which the current distribution of the contaminant, its transport behavior, as well as the medium within which it is traveling, can be characterized. A simple example is the problem of identifying the source of a contaminant along a river based on the extent of mixing that has occurred.[110]

Most of the cases involving the application of these principles have been in the use of hydrogeological modeling in cases of groundwater contamination. A relatively simple example of such an application can be found in *FAG Bearings Corp. v. Gulf States Paper Co. et al.*[111] FAG Bearings sued two defendants for contribution under CERCLA for damage caused by groundwater contamination of nearby villages and for contaminating its own property.[112] FAG was unable to show that any of the contaminants present at the defendants' sites migrated off the property, however, in large part due to the lack of contamination between their sites and FAG's site.[113]

109. *Id.* at 1534-35.

110. P. G. Whitehead et al., *On the Identification of Pollutant or Tracer Sources Using Dispersion Theory*, J. HYDROLOGY, March-April 1986, at 273.

111. 1998 WL 919115 (W.D. Mo. 1998).

112. *Id.* at 1-2.

113. *Id.* at 26, 28, 30.

Another example is *Forest City Enterprises Inc. et al. v. Leemon Oil Company et al.*[114] in which a commercial landowner brought action against a tenant operating a gas station on the property, seeking damages for an environmental cleanup of the landlord's property under CERCLA and a variety of other legal theories. Although the landlord claimed that the groundwater contamination was a result of a single spill caused by the tenant,[115] the defendant's expert showed that the plume was more consistent with a continuous release, indicating that the underground storage tanks had been leaking consistently, which was the responsibility of the landlord.[116]

In *The Nutrasweet Company et al. v. X-L Engineering Corporation et al.*[117] the plaintiffs brought suit against the corporate owner of a neighboring property and its president and majority shareholder, alleging violations of CERCLA and asserting claims under common law theories. The plaintiffs successfully used proof of dumping on the neighboring property, in combination with hydrogeological studies demonstrating the direction of groundwater flow, to demonstrate neighbor's liability for contamination.[118]

In *The Boeing Company v. Cascade Corp.*,[119] plaintiffs used hydrogeological modeling to establish a sufficient basis for allocating responsibility under CERCLA to avoid joint and several liability for a contaminated site. Modeling was relatively straightforward, because the two parties were responsible for contamination of different areas of the site, with only a small area of overlap.[120] Liability was allocated based on estimates of the mass of contaminant contributed by each party.[121]

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114. Forest City Enterprises Inc. v. Leemon Oil Co., 577 N.W.2d 150 (Mich. Ct. App. 1998).

115. *Id.* at 154.

116. *Id.* at 156-159.

117. The Nutrasweet Company v. X-L Engineering Corp., 933 F.Supp. 1409 (N.D. Ill. 1996).

118. *Id.* at 1415-16, 1425.

119. The Boeing Co. v. Cascade Corp., 920 F.Supp.1121 (D.Or. 1996).

120. *Id.* at 1125-26.

121. *Id.* at 1136-40.

In *Ammons et al. v. Wysong & Miles Company,*[122] defendants were awarded summary judgment after showing that they were not a probable cause of groundwater contamination at the plaintiffs' sites. The defendants used hydrogeologic information indicating flow from plaintiffs' property towards defendant's property, and not vice versa, and contaminant concentration gradient maps inconsistent with a conclusion that the source originated on the defendant's site.[123]

The cases of *Anne Anderson et al. v. Cryovac, Inc. et al.*[124] and *Anne Anderson et al. v. Grace Co. et al.*[125] involved a leukemia cluster that was allegedly the result of industrial contamination of municipal water supply wells. The plaintiffs' case was based upon the common law theories of negligence, nuisance, and strict liability. EPA had zeroed in on several potential sources of contamination. Hydrogeological modeling, however, was insufficient to conclusively determine the source of the contamination, mostly due to gross discrepancies between results presented by the plaintiffs' and defendants' expert witnesses.

In *Dedham Water Co. v. Cumberland Farms, Inc.*[126] a water company alleged that the defendant released hazardous wastes from its truck maintenance facility and that these wastes entered the groundwater, eventually causing contamination of the well field used by the water company to supply domestic water to two nearby towns. Cumberland used groundwater modeling and sampling data to convince the court that it was more probable than not that its releases were not the cause of plaintiff's response costs.[127]

Although the introduction of hydrogeological modeling does represent a more thorough analysis of contamination at a site, the methods applied have not taken into account the scientific uncertainties associated with source identification. Instead, when inconsistent evidence has been presented, the courts were faced with having to

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122. Ammons v. Wysong & Miles Co., 431 S.E.2d 524 (N.C. 1993).

123. *Id.* at 526-27.

124. Anne Anderson v. Cryovac, Inc., 862 F.2d 910 (1st Cir. 1988).

125. Anne Anderson v. W. R. Grace & Co., 628 F. Supp. 1219 (D. Mass. 1986).

126. Dedham Water Co. v. Cumberland Farms, Inc., 689 F.Supp. 1223 (D. Mass. 1988).

127. *Id.* at 1228-33, 1235.

choose between two or more sets of testimony, and taking that testimony as fact.[128]

7. Analysis Of Case Studies

Although many of the presented case studies did not involve the application of scientific methods of contaminant source identification, such methods are needed when causality must be demonstrated. In the first two sets of case studies, proof of contaminant release at a potential source was presented, source significance was estimated based on the use history of a given contaminant, or simple arguments identifying a given source as the only plausible source were used. These arguments were accepted in some instances, but only when applied in statutory settings where causality as defined in the common law did not need to be demonstrated or where it was demonstrated that no other plausible sources were present. In all other presented cases, such simple arguments had failed because the scientific evidence was viewed to be insufficient to prove causation. Therefore, except in very simple cases, a scientific approach to contaminant source identification is needed in the common law approach.

Although scientific methods of contaminant source identification have been applied in a limited number of court cases, the application of these methods has been restricted by several factors. In cases where compositional analysis and tracer studies are applicable, they often offer convincing evidence. They demonstrate a direct link between a source and a receptor, which is both powerful and simple to convey to a lay audience. Establishing the relative contribution of the source can be more problematic,[129] which is limiting in the common law setting. Furthermore, the range of cases for which these methods are applicable is restricted by the requirements of the

128. *See, e.g., supra* notes 111-116, 119-121 and accompanying text.

129. No cases where tracer methods were applied for this purpose were found. In Ethyl Corp. v. EPA, 426 U.S. 941, (Mem., 1976) the EPA used compositional analysis to apportion human lead intake between ingestion and inhalation, but more than two sources could not have been distinguished. *See* Michael B. Rabinowitz, *Stable Isotopes of Lead for Source Identification*, 33 CLINICAL TOXICOLOGY 649 (1995).

methods themselves.[130] Therefore, the use of methods based on analyzing the contaminant distribution is often critical to source identification. Current methods based on conclusions derived from the contaminant distribution itself also have scientific limitations, however. A main problem in applying these methods is the difficulty involved in quantifying the transport behavior of both the contaminant and the environment within which it is transported. Once these are estimated, the results are questionable because the effect of uncertainty is seldom quantified.[131] Although these factors are often overlooked in a statutory setting, common law forces opposing parties in an environmental dispute to consider them. These difficulties partly account for the lack of application of these methods in legal

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130. *See* Michalak, *supra* note 93 for a more detailed discussion. The applicability of compositional analysis and tracer-based methods have several scientific limitations. Both sets of methods have limited ranges of applicability. Compositional analysis can be used only when the contaminant itself consists of a source-specific combination of components (either at the molecular or atomic level). Tracers can only be used when a tracer that reproduces the transport behavior of a given contaminant can be identified. The number of sources that can be distinguished is also limited for these methods. The sources that can be discerned using tracers is limited, at any one time, to the number of distinct acceptable tracers found in the individual potential sources. With compositional analysis, the number of sources that can be distinguished depends on the number of identifiable contaminant components and their correlations among various sources. Furthermore, tracers cannot always be reused in an area due to the possibility for accumulation in the environment through processes such as sorption and deposition. The time scales involved in using introduced tracers can be limiting, especially when very large areas are affected or transport is slow. Finally, dilution effects can result in a tracer being below or very close to detection limits, making source identification impossible.

131. *See* Apple, *supra* note 3, at 424, where the authors point out, "Some troublesome aspects of typical sets of environmental data include measurement error, serial correlation and seasonal fluctuations, and complex cause-and-effect relationships. Factors such as these need to be considered when decisions are made concerning the collection and analysis of data to answer the questions at issue."

settings, despite the needs for scientific evidence for identifying contaminant sources.

Due to the lack of recognition of the uncertainty associated with results, opposing parties typically present contradictory results, and the court is forced to either take the evidence as fact or discard it, instead of determining the extent to which it may represent the actual situation. Therefore, more often than not, when conflicting scientific evidence is presented by opposing parties, the court makes a judgment as to which testimony is supported more strongly by other facts in the case and takes this testimony as fact. In a case where the current contaminant distribution is used to identify the source, expert witnesses will typically show that their assumed release scenario results in a contaminant distribution that is consistent with the actual current distribution, but without identifying the uncertainty associated with their source estimate. Although uncertainty is also present when compositional analysis or tracer methods are applied, these types of methods establish a direct link between source and receptor, making it easier to demonstrate that at least some of the contaminant originated from the purported source. In general, however, the courts tend to avoid dealing with the uncertainty in scientific evidence. As Scarrow[132] points out:

> By accepting one of the other sets of modeling results as fact without discussing the associated uncertainties, a court also creates a game of "chicken" between the parties. That is, the incentive to each party is not to generate the most accurate modeling results possible, but rather to present results that are only slightly more believable than the results put forth by the opposing party. While it could be argued that this tension tends to discourage parties from making unreasonable claims regarding contamination levels, the tension does not encourage the parties to discuss how accurate "reasonable" groundwater modeling results are.

In short, although scientific methods of contaminant source identification have sometimes been applied, they were not always successful, especially when causality as defined in a common law setting had to be established.

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132. James W. Scarrow, *The Use of Modeling in Groundwater Contamination Cases*, 9 VA. ENVTL. L.J. 185, 203 (1989) [hereinafter Scarrow.]

8. Stochastic Nature Of Contaminant Source Identification

The contaminant source identification methods based on analyzing the contaminant distribution itself that were applied in the presented case studies do not take into account the uncertainty associated with source identification. The cause of this uncertainty and the degree to which it can affect source identification are discussed in this section. The uncertainty goes beyond the errors associated with estimating the parameters describing the environment within which the contaminant is being transported and is compounded by the nature of the transport process itself.

A simple example illustrates the problems associated with analyzing the contaminant distribution as a means of estimating the source. Consider the contaminant plume profile represented by the small circles presented in Figure 1a. This might, for example, be the contaminant plume profile in a groundwater aquifer[133] adjacent to an industrial plant. We are assuming that the transport behavior of the contaminant and the medium is perfectly known and steady in time, leaving measurement error and the limited number of measurement points as the only sources of uncertainty.[134] If one is asked to deduce the contaminant release history at an upstream point that yielded these observations, the two release histories or scenarios presented in Figure 1b result in plumes that match the data equally well, in the sense that the distributions lie within the error bars of the observations. This fact is demonstrated by the solid and dotted lines in Figure 1a. The party responsible for the facility at this upstream point from time 50 to time 60, however, is clearly more likely to want to support the second potential release history relative to the first.

In a typical court setting, opposing parties might present two such conflicting explanations of the current contaminant distribution. In such cases, hearing the testimony of opposing experts, both of whom may, in fact, be presenting equally plausible scenarios, will be more confusing than useful to a jury or a judge, even if both experts are

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133. An aquifer is a "saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients." R. ALLAN FREEZE & JOHN A. CHERRY, 47 GROUNDWATER (1979). An aquifer can be composed of material as coarse as gravel or as fine as clay.

134. *See id.* at 531-33 for details about this example.

presenting valid models. Therefore, given the current modeling methods, conclusions may appear confusing and contradictory to a lay audience. This, in turn, decreases the weight of the evidence presented and decreases the chance of conclusive source identification and enforcement of the responsibilities resulting from contamination.

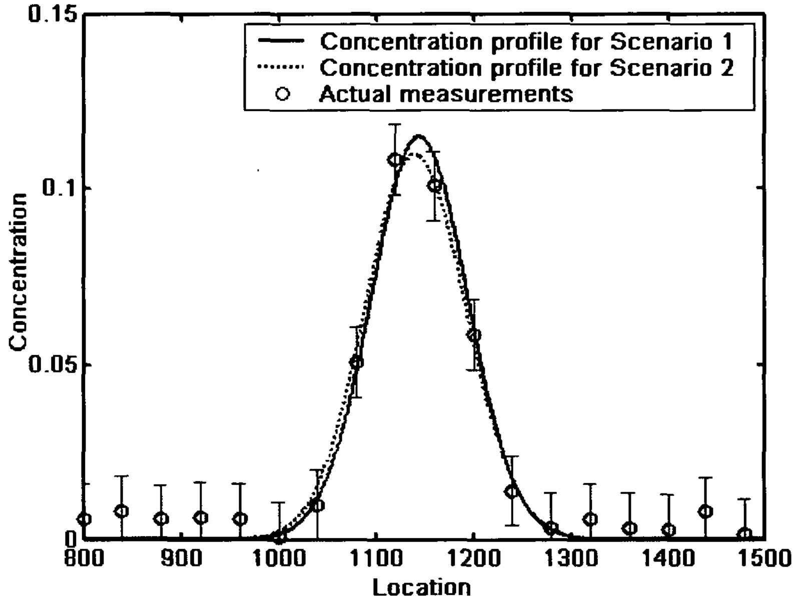

Figure 1a: Observed concentration profile and profiles that would have resulted from two possible scenarios.

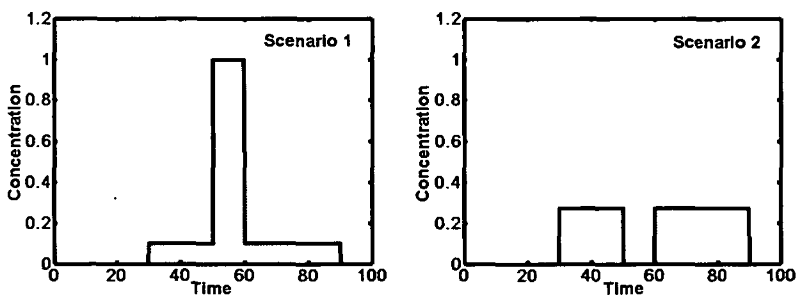

Figure 1b: Two possible release scenarios matching the observed measurements.

The basic problem is that both release histories are plausible, given the available data. In practice, the court decides which testimony is superior based on its interpretation of the available information, and this testimony is then treated as fact.[135] In reality, however, both testimonies may be neither correct nor incorrect, but simply fail to take into account the uncertainty inherent in the problem.[136]

In short, source identification methods based on analyzing the contaminant distribution itself are seldom capable of quantifying the uncertainty associated with results, especially when several sources of error are present. Uncertainty can result not only because the source location is unknown, but the sampling procedure generally introduces some error, and the release history and transport characteristics of the contaminant and medium within which it is transported may also not be fully known. In the presented example, the mixing that the contaminant undergoes as it is transported in the environment, combined with measurement error, causes the plumes resulting from two different release scenarios to appear very similar. Therefore, given only the measurements, the source cannot be defined very precisely. If this uncertainty is not recognized, however, a court has no basis for deciding whether the presented scenarios are reasonable. This constitutes a serious limitation to the legal applicability of currently available methods.

This uncertainty is caused by random errors introduced as a result of data collection and modeling, as well as by the nature of the contaminant transport process. In the case of source identification, random error consists of measurement error when data are collected, error in the estimates of parameters used to describe how a contaminant moves through the environment, as well as from any limitations of the model being applied. Furthermore, the mixing of contaminants in the environment results in smearing of concentration gradients, which magnifies the effect of random error when one is trying to recover the history of contamination. Given these limitations, it is impossible to determine release histories, volumes, and even source locations with certainty.

As a contaminant is transported in air, groundwater or surface water, it is not only advected[137] (e.g. smoke from a smokestack being

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135. *See* Scarrow, *supra* note 132.

136. *See* Scarrow, *supra* note 132, at 188-89 ("[M]odeling can be a valuable tool when studying . . . contamination problems; however, . . . modeling results should be thought of as a range of results instead of as a unique correct result because of the many uncertainties involved.")

transported downwind), but it is also dispersed, mixed and diluted (e.g. a sewage outfall plume entering a lake, with the entire lake eventually being contaminated, but at a lower concentration). All these mechanisms can be modeled, if the initial conditions (e.g. location and magnitude of the source) are specified. Because of the nature of the mixing process, the effects of small errors in the initial conditions will diminish over time, and, for example, the predicted concentration distribution of a contaminant in a lake will be only marginally affected if a slightly incorrect source location distribution is used. This is analogous to saying that, no matter where into a cup of coffee cream is poured, one can predict that sufficient stirring will evenly distribute the cream in the coffee. The nature of the mixing process results in information, in this case information about the source, being lost over time.

In the opposite case, however, when the current distribution is used to identify source conditions, the effect of any inaccuracies is amplified. If the information on the current distribution of contamination has small errors, and if we recognize that errors in the model exist, then a variety of initial conditions reproduce the data equally well. It is important to recognize that some error is always present, even if, at the limit, it is simply due to the number of significant digits reported by an instrument. This lack of source identification power is analogous to saying that, if someone is given a creamy cup of coffee, he or she could claim that the cream had initially been poured anywhere within the cup, and the data (in this case, the uniformly creamy coffee) could not contradict the claim.

In actual situations, contaminants are almost never perfectly mixed in the environment, and it is therefore possible to estimate the source. Many source distributions may reproduce the data (as was demonstrated in Figure 1), but there will be bounds on the possible source scenarios. For example, if the concentration of a contaminant is greater in one area of a lake, a hypothetical source located in a low-concentration area of the lake would most likely not reproduce the data.

This argument demonstrates the intrinsically statistical or probabilistic nature of the contaminant source identification problem. Because contaminants mix as they are transported, there is no unique

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137. Advection is the "process by which solutes are transported by the bulk motion" of the medium within which they are traveling. *See* FREEZE & CHERRY, *supra* note 133, at 75.

solution to the source identification problem. There are, however, statistical bounds that can be set on the range of possible sources. These bounds will depend on the precision with which transport behavior is quantified, the accuracy and precision of the data, and the quantity of data (i.e. the number of available samples).[138]

B. *Implications For Applications To Common Law*

Current modeling methods used in an attempt to identify sources do not recognize the statistical (or stochastic[139]) nature of source identification. Typically, following an estimate of the model parameters, an expert will generate a source distribution that would have lead to a contaminant distribution consistent with the available data and use this data reproduction as an argument for justifying the selected source distribution. Although such an estimate does represent one possible scenario, it has little value unless the uncertainty associated with this estimate is quantified, which it is not given current scientific methods for source identification.[140] It is not only the uncertainty associated with the model parameters that results in a non-unique solution, but the nature of the transport process itself combined with measurement error (no matter how small) that will always be present.

Therefore, a deterministic approach such as generating a possible contamination scenario and seeing whether it is consistent with the current distribution of the contaminant will seldom be sufficient to conclusively identify the source of contamination when the contaminant distribution is the primary tool for source identification. Current methods can be used to identify possible scenarios and even to eliminate some highly improbable scenarios. Such approaches can-

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138. *See infra* note 169 and accompanying text.

139. A stochastic process is one that has a random component that can be described using a probability distribution.

140. *See* Herbert Solomon, *Confidence Intervals in Legal Settings*, *in* STATISTICS AND THE LAW 455, 456 (Morris H. DeGroot et al. eds., 1986) ("[t]he point estimate . . . does not incorporate any aspect of the variability attached to estimation procedures." This relates back to a question posed by Painter when thinking about environmental dispute resolution: "Is there more than one 'real world' at the negotiation table?" *See* Ann Painter, *The Future of Environmental Dispute Resolution*, 28 NAT. RESOURCES J. 145, 146 (1988).

not be used, however, to identify the actual scenario unless perfect knowledge of the current distribution and of the parameters describing the surrounding environment is obtained, which would result in infinite transaction costs.

In short, contaminant source identification requires a stochastic approach, due to unavoidable scientific uncertainties. It is clear that there is a mismatch between the statistical nature of the common law, the statistical nature of contaminant source identification, and the deterministic nature of the source identification technologies that are currently being applied. Current technologies do not offer a basis for quantifying the uncertainty associated with source estimates. On the other hand, a more statistical or stochastic approach to source identification would have great potential, because it would be more consistent with the realities of dealing with contamination within the framework of the common law.

IV. OPPORTUNITIES FOR A STOCHASTIC APPROACH TO CONTAMINANT SOURCE IDENTIFICATION

Statistical analysis has been employed in legal settings for over a century,[141] and the last three decades have witnessed expanding use of statistical techniques in the law.[142] Perhaps the most important

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141. *See* Howland Will Case, 4 Am.L.Rev. 625 (1869) (early example of the use of mathematical probability to determine the chance of coincidence of signatures on a will in a forgery case). *See also* People v. Risley, 108 N.E. 200 (N.Y. 1915) (mathematical probability was employed in connection with whether a typewriter document was forged). *See also* Solomon, *supra* note 52 (which describes the Dreyfus Affair, in which the defendant was accused of espionage. The prosecution used a frequency count of the letters of the alphabet in a collection of the defendant's documents. These frequencies were compared to those in the prose writings of a number of French authors, in an attempt to establish the existence of unusual patterns in the defendant's writings.)

142. *See, e.g.,* DAVID W. BARNES, STATISTICS AS PROOF (1983); DAVID H. KAYE & DAVID A. FREEDMAN, REFERENCE GUIDE ON STATISTICS; *and* D.H. KAYE & MIKEL AICKIN, STATISTICAL METHODS IN DISCRIMINATION LITIGATION (1986); RAMONA L. PAETZOLD & STEVEN L. WILLBORN, THE STATISTICS OF

factor paving the way for judicial reliance on statistical techniques has been the realization of the tremendous utility of these techniques in legal applications.[143] Over the years, courts have become more sophisticated in their use of statistics. They were initially content to analyze raw numbers and percentages; they engaged in straight comparisons of numbers and relied on purely intuitive assessments of the disparities. More recently, however, courts have tended to insist upon more sophisticated statistical analyses. As the Fourth Circuit has remarked, in discussing the use of statistics in discrimination cases,

> Courts ... from time to time, have used straight percentage comparisons without the necessary standard deviation analysis in proving and rebutting discrimination cases. Statisticians do not simply look at two statistics, such as the actual and expected percentage of blacks on a grand jury, and make a subjective conclusion that the statistics are significantly different. Rather, statisticians compare figures through an objective process known as hypothesis testing.[144]

Therefore, because statistical evidence is increasingly being applied in the law, and because source identification would benefit from statistical approaches, such approaches would be beneficial in conflicts

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DISCRIMINATION (1999); P. Meier et al., *What Happened to the Hazelwood Statistics, Employment Discrimination and the 80% rule, in* STATISTICS AND THE LAW (Morris H DeGroot et al., eds., 1986); E.W. Shoben, *The Use of Statistics to Prove Intentional Employment Discrimination,* 46 LAW & CONTEMP. PROBS. 219 (Fall 1983) (discussing statistical methods applied in discrimination cases). *See, e.g.,* Paul C. Giannelli & Edward J. Imwinkelried, SCIENTIFIC EVIDENCE, VOL. 2, at 1-71 (1999); J.J. Koehler, *DNA Matches and Statistics, Important Questions, Surprising Answers,* 76 Judicature 222 (1993); (discussing statistical methods used for DNA cases); *and* Gold, *supra* note 54, at 377 (Even in toxic court cases, where the issue at hand is to determine whether a given contaminant is harmful to humans, courts "have allowed litigants to place increasing reliance on ... statistical proof in answering cause-in-fact questions").

143. *See* GIANNELLI & IMWINKELRIED, SCIENTIFIC EVIDENCE, VOL. 1, 655-58.

144. *Id.* at 657-58.

involving environmental contamination with multiple potential sources.

In a certain sense, many of the methods currently being applied for identifying sources of a contaminant are statistical in nature. For example, compositional analysis typically involves comparing the ratios of the mass fractions of either the molecular or isotopic components of a contaminant with those found in various potential sources. Furthermore, all available methods aim to identify the most probable or most likely source. From the statistical perspective, this can be viewed as looking for a best estimate of the source.

As demonstrated earlier in this paper, however, source identification should be examined from a more rigorous statistical perspective. The uncertainty associated with an estimate should be identified. This is especially important when the contaminant distribution itself is being used in an attempt to identify sources because uncertainty is introduced in a variety of way and because, as was demonstrated earlier, the mixing process results in a loss of information over time.

A. *New Statistical Methods For Contaminant Source Identification*

Although methods that intrinsically recognize and quantify the uncertainty associated with contaminant source identification have not been applied in legal settings, such methods are currently being developed in the scientific community. Given the need for such methods when causality must be demonstrated, the applicability of these methods needs to be examined.

There are currently three emerging stochastic methods that allow for the estimation of an unknown source based on the current distribution of a contaminant. These methods allow for the computation of both a best estimate for the source distribution and confidence intervals[145] about that estimate. They are minimum relative entropy inversion,[146] adjoint-derived source distribution probabilities,[147] and

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145. A confidence interval is the "interval estimate . . . measured by a confidence coefficient expressed as a percentage." Solomon, *supra* note 53, at 456.

146. *See* Allan E. Woodbury & Tadeusz J. Ulrych, *Minimum Relative Entropy Inversion: Theory and Application to Recovering the Release History of a Groundwater Contaminant*, 32 WATER RESOURCES RES. 2671 (1996) [hereinafter *Release History*]; Allan E. Woodbury & Tadeusz J. Ulrych, *Minimum Relative Entropy and*

the application of Bayesian inference methods to inverse modeling.[148]

These methods share the common thread of acknowledging and taking into account the intrinsically statistical nature of the source identification problem.[149] Furthermore, they all use the same basic mathematical formulation for describing the flow of contaminants

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Probabilistic Inversion in Groundwater Hydrology, 12 STOCHASTIC HYDROLOGY AND HYDRAULICS 317 (1998) [hereinafter *Probabilistic Inversion*]; Allan E. Woodbury & Tadeusz J. Ulrych, *Reply,* 34 WATER RESOURCES RES. 2081 (1998) [hereinafter *Probabilistic Inversion Reply*]; Allan E. Woodbury et al., *Three-dimensional Plume Source Reconstruction Using Minimum Relative Entropy Inversion,* 32 J. CONTAMINANT HYDROLOGY 131 (1998); Roseanna M. Neupauer et al., *Comparison of Inverse Methods for Reconstructing the Release History of a Groundwater Contamination Source,* 36 WATER RESOURCES RES. 2469 (2000).

147. *See* Roseanna M. Neupauer & John L. Wilson, *Adjoint Method for Obtaining Backward-in-time Location and Travel Time Probabilities of a Conservative Groundwater Contaminant,* 35 WATER RESOURCES RES. 3389 (1999) [hereinafter *Adjoint Method*]; Roseanna M. Neupauer & John L. Wilson, *Adjoint-derived Location and Travel Time Probabilities for a Multi-Dimensional Groundwater System,* 37 WATER RESOURCES RES. 1657 (2001) [hereinafter *Multi-dimensional*].

148. *See* Mark F. Snodgrass & Peter K. Kitanidis, *A Geostatistical Approach to Contaminant Source Identification,* 33 WATER RESOURCES RES. 537 (1997); Anna M. Michalak & Peter K. Kitanidis, *Application of Geostatistical Inverse Modeling to Contaminant Source Identification at Dover AFB, Delaware,* JOURNAL OF HYDRAULIC RESEARCH (2003) [hereinafter *Dover AFB*]; Anna M. Michalak & Peter K. Kitanidis, *Application of Bayesian Inference Methods to Inverse Modeling for Contaminant Source Identification at Gloucester Landfill, Canada,* COMPUTATIONAL METHODS IN WATER RESOURCES XIV 1259 (S. Majid Hassanizadeh, et al. eds., 2002) [hereinafter *Gloucester Landfill*].

149. These methods all fall into the category of stochastic contaminant source identification methods, meaning that, instead of yielding a single estimate of the source, they provide a probability distribution describing the possible contaminant source locations or release scenarios.

through the environment.[150] This is the same formulation as that used when modeling as described in the case studies is used to explain contaminant transport.[151] Contrary to methods that are currently applied, however, these new methods go beyond simply attempting to reproduce measurements. They instead identify the range of plausible source scenarios (i.e. source locations or release histories), given general assumptions about the source. These assumptions may include the fact that concentrations cannot be negative, that contaminants have limited solubilities in water or gases, or certain other source characteristics (such as whether the release is expected to have varied smoothly in time, or whether it consisted of a few short-term releases).

These statistical methods have already been applied to a variety of problems in the scientific literature. The release history of a contaminant in a hypothetical one-dimensional uniform domain has been estimated using minimum relative entropy[152] and the Bayesian inference approach.[153] These methods were then extended to allow for the recovery of the release history in a three-dimensional uniform domain.[154] The adjoint-derived source distribution has been applied to identifying the source location of a contaminant in both one-dimensional[155] and multi-dimensional[156] domains.

The minimum relative entropy and the Bayesian inference methods also have already been applied to field data. Minimum relative en-

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150. This basic formulation is the advection-dispersion equation, which describes transport as a combination of advection (for example, when a contaminant is transported along with the ambient current in a river) and diffusionaldispersion (such as, for example, when a contaminant is diluted over time).

151. See BEDIENT, *supra* note 8, at 368-9 and 371-5 (describing typical models used for modeling contaminant transport including MODPATH, PATH3D, MT3D, SEAM3D, RT3D and MT3DMS, among others).

152. *See* Woodbury & Ulrych, *Release History, supra* note 145; *see also* Neupauer et al., *supra* note 146.

153. *See* Snodgrass & Kitanidis, *supra* note 148.

154. *See* Woodbury & Ulrych, *Probabilitic Inversion, supra* note 146. *See also* Woodbury, et. al, *supra* note 145; Michalak & Kitanidis, *Glouchester Landfill, supra* note 148.

155. *See* Neupauer & Wilson, *Adjoint Method, supra* note 147.

156. Neupauer & Wilson, *Multi-dimensional, supra* note 147.

tropy[157] and Bayesian inference[158] were applied to estimate the contaminant release history from the Gloucester landfill site in Ontario, Canada. The Gloucester Landfill served as a disposal site for hazardous wastes from 1969 to 1980. These wastes, which were primarily organic solvents, were disposed of in a Special Waste Compound located along the western edge of the landfill.[159] The confined aquifer at the site has been significantly impacted by these wastes.[160] The contaminant exhibiting the greatest mobility at the site is 1,4-dioxane, and the release history was estimated for this compound based on downgradient groundwater samples.[161] A Bayesian inference approach was also used to estimate the history of contamination in an aquifer located at the Dover Air Force Base, Delaware.[162] Tetrachloroethene (PCE) and trichloroethene (TCE) are two principal chemical contaminants of the contaminant plume, and concentration profiles for both these chemicals were obtained in the underlying aquitard[163] at several locations.[164] These concentration profiles were analyzed to infer the contamination history in the overlying aquifer.[165] These applications demonstrate that these methods are capable of yielding useful results even given the types of data quality and quantity limitations that occur in field settings.

Because all three of these methods allow for the calculation of confidence intervals about source estimates, they allow the data to speak

157. *See* Woodbury, et al., *supra* note 146.

158. *See* Michalak & Kitanidis, *Gloucester Landfill*, *supra* note 148.

159. *See* Woodbury, et al., *supra* note 146.

160. *See* Woodbury, et al., *supra* note 145.

161. *See* Woodbury, et al., *supra* note 145; *see also* Michalak & Kitanidis, *Gloucester Landfill, supra* note 148.

162. *See* Michalak & Kitanidis, *Dover AFB*, *supra* note 148.

163. The term aquitard describes "the less-permeable beds in a stratigraphic sequence. These beds may be permeable enough to transmit water in quantities that are significant in the study of regional groundwater flow, but their permeability is not sufficient to allow the completion of production wells within them." FREEZE & CHERRY, *supra* note 133, at 47. In other words, an aquitard is a formation that, relative to an adjoining aquifer, can be assumed to transmit no water.

164. *See* Michalak & Kitanidis, *Dover AFB*, *supra* note 148.

165. *Id.*

for themselves as data quantity and quality affect the width of confidence intervals. It is important to understand that wider confidence intervals are not caused by shortcomings associated with the methods themselves, but rather are indicative of the actual amount of uncertainty in the system, given data restrictions. In other words, these methods are also able to point out whether conclusive results can be obtained given data availability. Additional data can then be collected if the cost of this additional work is small relative to the anticipated costs and legal consequences associated with the assignment of responsibility for observed contamination.

The application of these emerging methods to legal settings is promising. Statistical methods that account for the stochastic nature of the contaminant source identification problem are possible and allow for conclusive source identification where they have been applied. Due to their stochastic approach, they have the potential of overcoming the limitations of other source identification methods and are more consistent with the common law approach to dealing with contamination. Although much work remains to be done to make these methods applicable to a wider variety of problems, these methods are now at a stage where they can begin to be useful in the common law setting.

B. *Sample Applications Of New Methods*

In order to illustrate the possibilities of these emerging methods, two applications of the Bayesian inference based inverse modeling methods for contaminant source identification are presented. The methods used in these examples are based on the geostatistical methodology,[166] which uses information about how a source may have varied in space or time. In other words, some characteristics of the source, such as whether it is expected to have varied smoothly or erratically, are specified along with supplying any available physical data to the model.

The two examples are taken from studies reported in scientific literature. The first represents the recovery of the release of a dissolved compound into a hypothetical one-dimensional aquifer. Because this example is made up, the correct history is known, and the

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166. *See, e.g.*, PETER K. KITANIDIS, INTRODUCTION TO GEOSTATISTICS, APPLICATIONS TO HYDROGEOLOGY (1997).

effect of measurement error can be examined.[167] The second example involves the application of a similar method to field data in an attempt to recover the contamination history at Dover Air Force Base, Delaware, showing the applicability of the method to real cases of contamination.[168]

1. Contaminant Release Into A Hypothetical 1-Dimensional Aquifer

Suppose a dissolved compound that does not react with its surroundings is injected at the left boundary of an aquifer and, at some later time, the concentration is measured at various points in the aquifer. From these data, Snodgrass and Kitanidis[169] estimated the amount of solute injected as a function of time. Although, in this case, the authors used a hypothetical example to test their method, the example was based on realistic parameters and is representative of problems that may be encountered in field settings.

Figure 2b shows the plume as it was sampled, and the locations of the measurements. The solid line represents the actual concentration profile of the fictional plume, and the circles represent measurement values at observation locations, with measurement error. Figure 2a shows the recovered release history into the aquifer. The methodology yields both a best estimate of the release, which is an average of all plausible contaminant release scenarios given the available data, and confidence intervals about that estimate. In this case, 95 percent confidence intervals are presented. Both the best estimate and the confidence intervals take into account the fact that the data contain measurement error.

The actual release history (which would be unknown in a real setting) is shown as a solid line in Figure 2a, and falls within the 95 percent confidence intervals. These confidence intervals, however, are relatively wide. This uncertainty is due both to the measurement error, as evidence by the difference between the measured values (circles) and actual values (solid line) in Figure 2b, and to the limited number of available samples. The best estimate recovers the two main peaks of the actual source release history, but the uncertainty is

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167. Snodgrass & Kitanidis, *supra* note 147 (reporting the results of this study).

168. Michalak & Kitanidis, *Dover AFB, supra* note 148 (reporting the results of their study).

169. Snodgrass & Kitanidis, *supra* note 148.

such that the third smaller peak (centered around time 150) is not recovered.

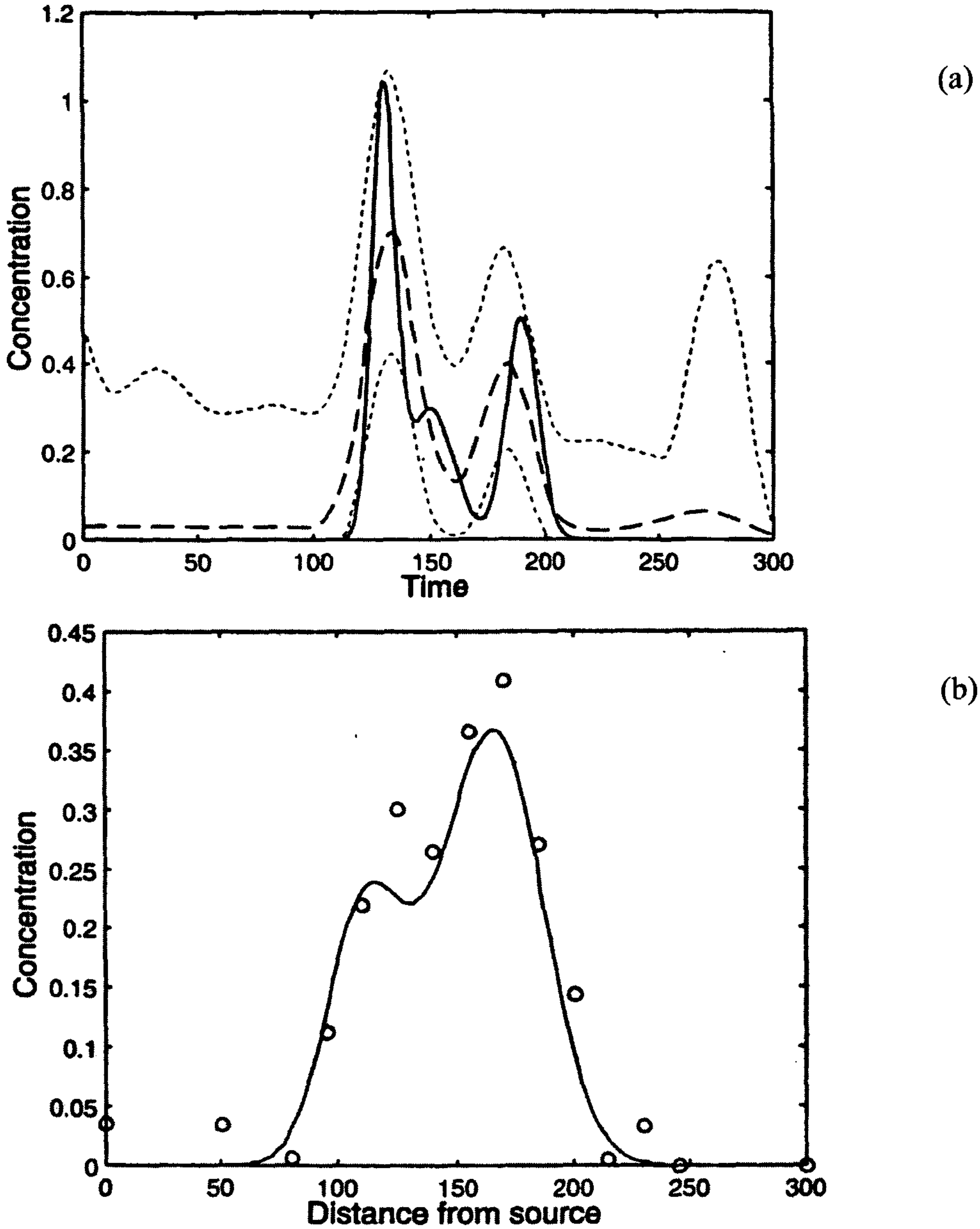

Figure 2. (a) Actual release history (solid line), recovered best estimate of release history (dashed line), and approximate 95% confidence interval (dotted lines). (b) Contaminant plume with sparse data and large measurement error, with measurement locations denoted by circles.

The next set of figures demonstrates the effect of the availability of better data, which could be obtained if more sophisticated instruments were used to analyze samples, or, more likely, if multiple samples were taken at each location in an attempt to average out random errors. Clearly, this corresponds to a case where the transaction costs would have been higher. Whether such an expenditure would have been worthwhile would have depended on how much the parties in conflict stood to gain from better definition of their property rights. Figure 3b shows the same plume, with the same number of observations, but the measurement error has been reduced. Figure 3a shows the release history recovered from these new data. As can be seen from the figure, the confidence intervals are dramatically narrower, showing that better data yield more precise results. Once again, both a best estimate and 95 percent confidence intervals are presented, along with the actual release history, which would be unknown in a real case. In this case, the best estimate and the actual release history are almost identical. Furthermore, all three peaks of the actual distribution are captured.

This methodology offers many advantages over methods used in the presented court cases. It allows one to compute the statistics of all possible contamination histories, given the available data and any assumptions that were made. Therefore, one can obtain a best estimate of the contamination history, which is an average of all possible individual histories. This best estimate will be smoother than individual possible scenarios, because it will represent the features that are common to all of the possible realizations. Furthermore, one can compute confidence intervals about the best estimate. In this case, the 95 percent confidence intervals mean that, at any point in the past, there is a 95 percent chance that the release concentration was between the upper and lower 95 percent confidence interval levels.

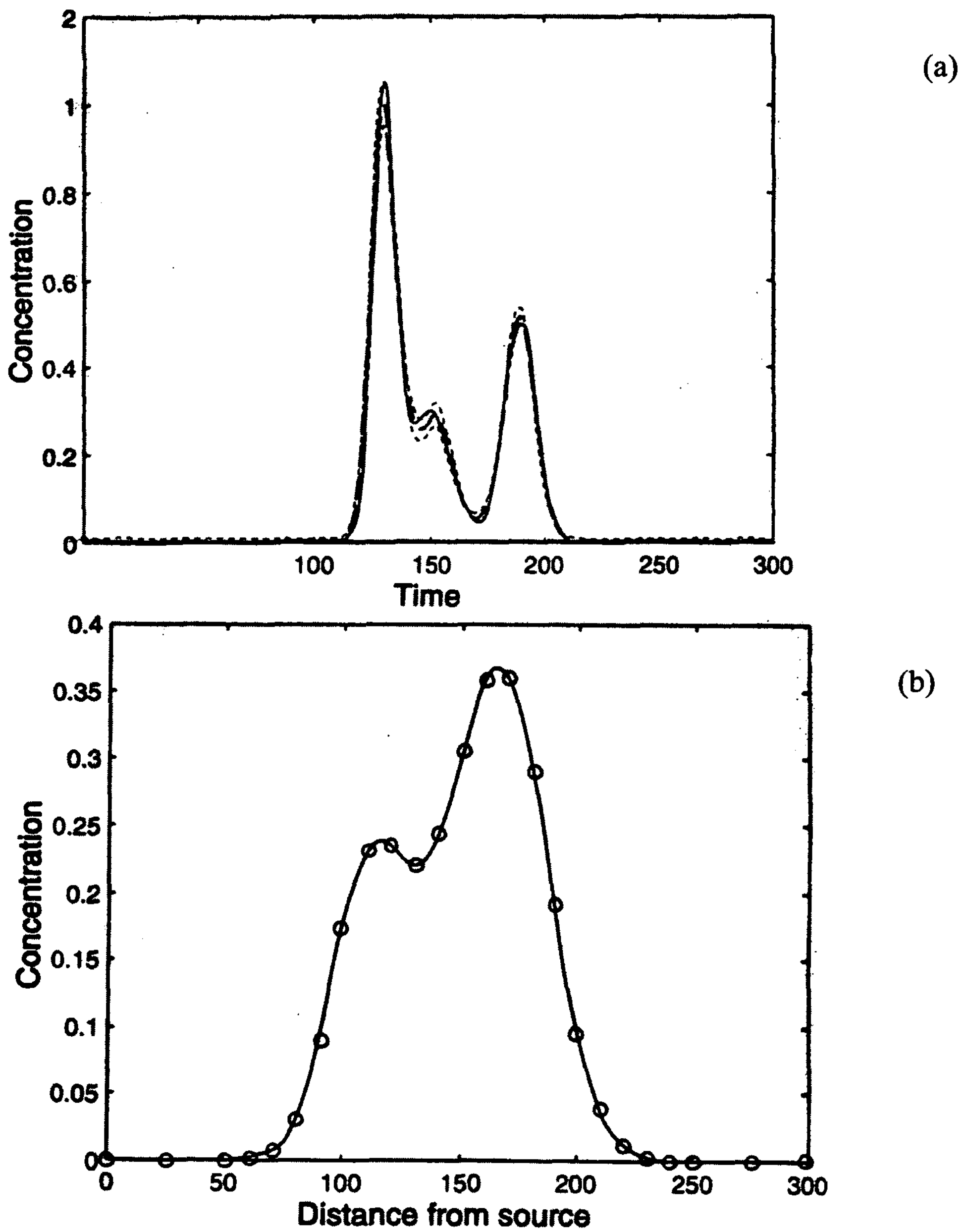

Figure 3. (a) Actual release history (solid line), recovered best estimate of release history (dashed line), and approximate 95% confidence interval (dotted line). (b) Contaminant plume with sparse data and low measurement error, with measurement locations denoted by circles.

2. Recovery Of History Of Contamination At Dover AFB, Delaware

Michalak and Kitanidis[170] presented the first application of Bayesian inference methods based on the geostatistical approach to contaminant source identification using field data.

In this case study, cores were taken from an aquitard at the Dover Air Force Base in Delaware. These cores were analyzed to infer the contamination history in the overlying aquifer. At the site, an unconfined sand aquifer[171] is underlain by a two-layer aquitard. Tetrachloroethene (PCE) and trichloroethene (TCE) are two principal chemical contaminants of the overlying aquifer contaminant plume, and concentration profiles for both these chemicals were obtained in the underlying aquitard at several locations.[172] The data sets used for the analysis presented in this work are at locations referred to as PPC11 and PPC13.[173]

The soil core samples were also used to independently determine other properties of the aquifer, such as sorption properties[174] and porosity[175] of the two aquitard layers.[176] The measurement error and

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170. Michalak & Kitanidis, *Dover AFB*, *supra* note 148.

171. An unconfined aquifer "is an aquifer in which the water table forms the upper boundary." FREEZE & CHERRY, *supra* note 133, at 48.

172. Michalak & Kitanidis, *Dover AFB*, *supra* note 148.

173. A detailed description of the site geology and hydrogeology can be found in D. M. MACKAY ET AL., FIELD AND LABORATORY STUDIES OF PULSED PUMPING FOR CLEANUP OF CONTAMINATED AQUIFERS, (Final Rep. AL/EQ-TR-1997-0017, Armstrong Lab. Environics Dir., Tyndall AFB, Fla., 1997); *and* William P. Ball et al., *A Diffusion-Based Interpretation of Tetrachloroethene and Trichloroethene Concentration Profiles in a Groundwater Aquitard,* 33 WATER RESOURCES RES. 2741 (1997). *See also* Chongxuan Liu & William P. Ball, *Application of Inverse Methods to Contaminant Source Identification from Aquitard Diffusion Profiles at Dover AFB, Delaware,* 35 WATER RESOURCES RES. 1975 (1999) (describing the sampling at the site).

174. Sorption parameters determine the factor by which contaminant transport is retarded relative to water transport.

175. Porosity corresponds to the fraction of space in the medium available for water transport and storage.

176. Ball, et al., *supra* note 173.

structural parameters defining the shape of the contamination history were also estimated from the data.[177]

Results for TCE for the two sampling locations are presented in Figures 4 and 5. Figures 4a and 5a show the estimated boundary concentration with 95 percent confidence intervals. Figures 4b and 5b show two possible contamination history scenarios, called conditional realizations, which can be used as an aid in visualizing what the concentration history in the overlying aquifer may have been. Figures 4c and 5c show the actual concentration profiles in the aquitard cores taken at these locations and represent the data that were used to derive the contamination history. These figures also show the concentration profile as reproduced by the best estimate of the contamination history.

In this case, unlike in the previous application, the actual contamination history is unknown. Results from both sampling locations suggest that the TCE concentration in the aquifer peaked around 1989. The magnitude of this peak is also similar for the two datasets.

Once again, the methodology offers many advantages over existing methods. As can be seen from these figures, the method reproduces the measurements well. It provides not only a possible scenario for what the contamination history may have been in the aquifer, but can provide a range of such scenarios. Each of these scenarios will be different, but will be consistent with the data, and share certain common source features, which are those that the data clearly identifies. Furthermore, the methodology allows one to compute the statistics of all possible contamination histories, given the available data and any assumptions that were made. Therefore, one can obtain a best estimate of the contamination history, which is an average of possible histories. This best estimate will be smoother than individual scenarios because it will represent the features that are common to most possible source history scenarios. Furthermore, one can compute confidence intervals about the best estimate. In this case the 95 percent confidence intervals mean that, at any point in the past, given the assumptions that were made, there is a 95 percent chance that the concentration in the overlying aquifer was between the upper and lower 95 percent confidence interval levels.

177. Michalak & Kitanidis, *Dover AFB*, *supra* note 148.

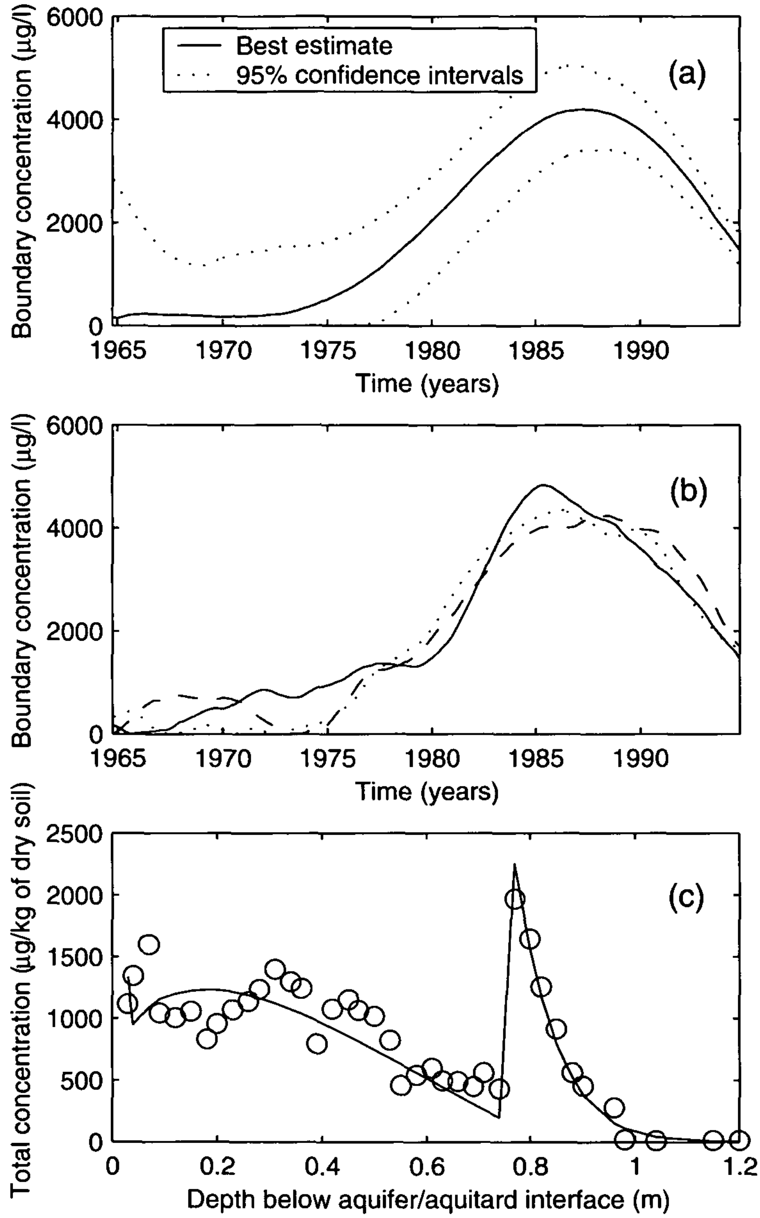

Figure 4. Results of source estimation from TCE data at location PPC11. (a) Estimated time variation of boundary concentration at the interface between the aquifer and aquitard. The end time represents the sampling date (October 27, 1994). (b) Conditional realizations of boundary concentrations. (c) Measurement data and fitted concentrations resulting from the estimated boundary conditions.

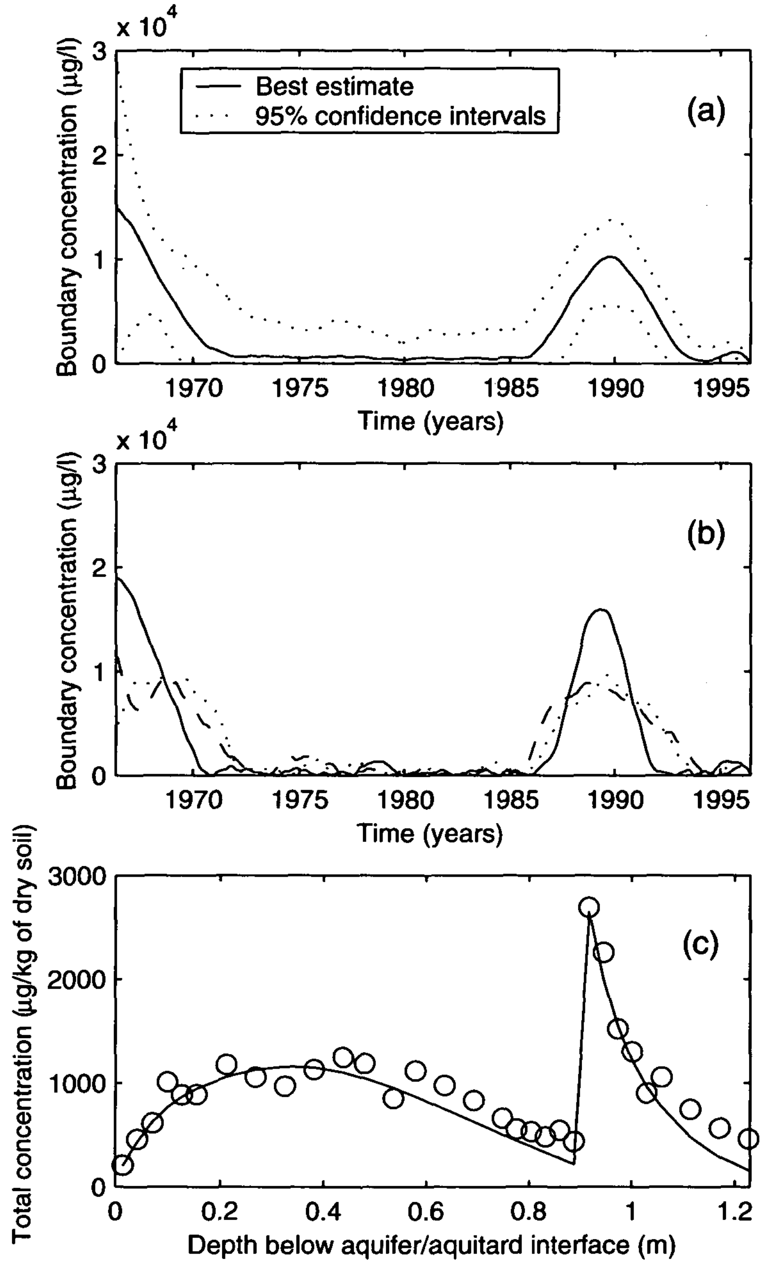

Figure 5. Results of source estimation from TCE data at location PPC13. (a) Estimated time variation of boundary concentration at the interface between the aquifer and aquitard. The end time represents the sampling date (June 6, 1996). (b) Conditional realizations of boundary concentrations. (c) Measurement data and fitted concentrations resulting from the estimated boundary conditions.

V. CONSIDERATIONS FOR THE APPLICABILITY OF NEW METHODS

Considerations that will affect how and when the new stochastic source identification methods can become part of the legal landscape are briefly discussed in this last section. These issues are the admissibility of evidence based on these methods, the burden of proof that they can provide, and other possible legal forums for their application.

A. *Admissibility of Evidence*

A fundamental requirement for the applicability of the methods described in the previous section is that they be admissible in a legal setting. Various American courts have different evidentiary rules that dictate the types of evidence that are admissible. Furthermore, these evidentiary rules and their interpretations have changed over time. The nature and status of the described methods must be examined in this light.

In general, scientific evidence is any demonstrative and testamentary information that uses the techniques of science to assist the trier of fact in deciding which of two or more theories explain what, why, who, and when something happened which is the object of contention in a trial.[178] A special test for competence is required with scientific evidence. The question is whether the science or the scientific tests employed are of such a level of validity as to be allowed into evidence. The legal setting within which scientific evidence is to be presented affects the types of evidence that can be presented and the manner in which it is presented.

Historically, the test was whether the science was "generally accepted" as being valid. This test of general acceptance was first enunciated in 1923 in *Frye v. United States of America,*[179] a criminal case in which the United States wished to introduce polygraph evi-

178. William G. Eckert & Ronald K. Wright, *Scientific Evidence in Court*, *in* INTRODUCTION TO FORENSIC SCIENCES 69 (William G. Eckert ed., 1997).
179. Frye v. U.S., 293 F. 1013, 1014 (D.C. Cir. 1923).

dence. Evidence of validity included published reports in peer-reviewed journals.[180]

The *Frye* rule came under attack in the 1960s and the 1970s. Some critics viewed it as delegating legal decisions to scientists. *Frye*, they argued, imposed an unfair burden on plaintiffs. General acceptance, other critics argued, had substituted for real analysis of the reliability and validity of proffered testimony.[181] Furthermore, in rapidly advancing fields such as DNA testing, the delay between the development of novel methods and the publication of results often threatened to limit truly valid science from trial.[182]

Partly as a result of this controversy, the Federal Rules of Evidence were developed.[183] These rules were codified in 1975 and are the rules of evidence that federal judges apply today. Many, though not all, state courts revised their rules along similar lines.[184] Three federal rules bear directly on scientific evidence in court:

> Rule 403 permits the exclusion of otherwise relevant evidence if its probative value is substantially outweighed by dangers of prejudice, confusion, misleading the jury, or wasting time.
>
> Rule 702 states that trial testimony is admissible from any qualified scientific expert who possesses "scientific, technical, or other specialized knowledge [that] will assist the trier of fact [the jury] to understand the evidence or to determine a fact in issue.
>
> Rule 703 provides that experts may base their opinions on data that might not be admissible as evidence, if those data are "reasonably relied upon by experts in the particular field in forming opinions or inferences upon the subject." This rule allows a scientific expert to rely on "hearsay evidence," which is not admitted when offered by ordinary witnesses." [185]

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180. Eckert & Wright, *supra* note 178; *see also* KENNETH R. FOSTER & PETER W. HUBER, JUDGING SCIENCE KNOWLEDGE AND THE FEDERAL COURTS 11-16 (1998) (hereinafter FOSTER & HUBER).

181. FOSTER & HUBER, *supra* note 180, at 11-6.

182. Eckert & Wright, *supra* note 178.

183. FOSTER & HUBER, *supra* note 180, at 11.

184. FOSTER & HUBER, *supra* note 180, at 11.

185. FOSTER & HUBER, *supra* note 180, at 11.

For a time, some federal judges interpreted the 1975 rules as allowing almost any scientific testimony to be presented to a jury.[186] Criticism mounted from those who argued that courts were issuing decisions based on pseudo-scientific testimony having little basis in reality.[187] Some courts gradually moved back toward stricter scrutiny of scientific evidence.[188]

In 1993, the U.S. Supreme Court handed down a landmark ruling on scientific evidence in *Daubert v. Merrell Dow Pharmaceuticals*.[189] "Faced with a proffer of expert scientific testimony," Justice Blackmun wrote for a seven-Justice majority, "the trial judge must determine . . . whether the expert is proposing to testify (1) scientific knowledge that (2) will assist the trier of fact to understand or determine a fact in issue. . . . Many factors will bear on the inquiry, and we do not presume to set out a definitive checklist or test. But some general observations are appropriate."[190]

In *Daubert*, the U.S. Supreme Court introduced a four-part test to replace *Frye*:

1. Has or can the evidence be tested by scientific methodology?
2. Has the underlying theory or technique been subjected to peer review and been published in the professional literature (although this is not a *sine qua non*)?
3. How reliable are the results in terms of potential error rate?
4. Finally, general acceptance (the old *Frye* test) can have a bearing on the inquiry.[191]

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186. FOSTER & HUBER, *supra* note 180, at 11.

187. *See* PETER WILLIAM HUBER, GALILEO'S REVENGE: JUNK SCIENCE IN THE COURTROOM 13-17 (1991); *see also* FOSTER & HUBER, *supra* note 180, at 11-13; Kenneth R. Foster, DAVID E. BERNSTEIN & PETER W. HUBER, PHANTOM RISK: SCIENTIFIC INFERENCE AND THE LAW (1993).

188. FOSTER & HUBER, *supra* note 180, at 11-13. *See, e.g.*, Christopherson v. Allied Signal Corp., 939 F.2d 1106 (5th Cir. 1991).

189. Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 U.S. 579 (1993).

190. FOSTER & HUBER, *supra* note 180, at 1.

191. Eckert & Wright, *supra* note 178. "But only federal courts are bound by *Daubert*; state courts frame their own rules of evidence,

Consider the stochastic approaches discussed in the previous section in terms of these four tests. The fact that they have been tested by scientific methodology is supported by publications in peer reviewed literature. The source estimates obtained using these methods can be used in generally-accepted numerical models to show that the source estimates do reproduce available data. The results obtained by these methods are thereby verifiable (although not obtainable) using generally accepted modeling methods, and the reliability of their results can therefore be verified. Finally, although these methods are not yet generally applied in consulting and legal settings, which one might argue indicates that they are not yet generally accepted, they are based on the same mathematical formulation of contaminant transport as that underlying currently used methods for modeling contaminant transport.

Although there may be some initial resistance to the stochastic approaches because they may not yet be generally accepted, especially in the legal community, they appear to pass the *Daubert* test. In fact, the stochastic methods should be more admissible than older methods, which simply demonstrate the possibility of a given source being responsible for observed harm, because the stochastic methods assign a probability to the source estimate. The limitations associated with expert opinions discussing only possibilities was at the heart of the *Daubert* remand decision.[192]

B. *Standard Of Proof To Be Met*

As already mentioned, certain factors affect the standard of proof that needs to be met in the court and other legal settings, and these factors need to be considered when evaluating the applicability of the proposed methods. Although the standard in various legal settings can be defined in a theoretical sense, factors such as the nature of the statistical evidence and the size of the stakes can raise the required standard of proof.

The law refuses to honor theoretical statistical standards of proof when the evidence is coldly statistical. A court would not, for example, hold the government liable to a farmer for injuries inflicted

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and a good number still follow Frye." FOSTER & HUBER, *supra* note 180, at 228.

192. Daubert v. Merrell Dow Pharmaceuticals, Inc., 43 F.3d 1311 (9th Cir. 1995).

on him by his mule frightened by a "buzzing" airplane if the only evidence that the pilot was a member of the Air Force (rather than a civilian) was that most of the pilots flying in the area that day were Air Force personnel.[193]

Furthermore, the court might be swayed in its demand for evidence by the size of the stakes, although, according to the rules of a court setting, the stakes are irrelevant. A more elaborate presentation would naturally be expected if the farmer was claiming $100,000 in damages than if he was claiming $100.[194] The allowable risk is lower when the stakes are higher.

The first point above could alter the standard of evidence required of the proposed methods if the method used to describe the prior information used in the model is based purely on statistics. For example, if it is assumed, *a priori*, that a certain party is more likely to be responsible for observed contamination because he or she operates a larger fraction of the potential sources, then the bias created by such an assumption may be unjustified. Two remedies exist in this situation, however. First, one can select a statistical model that introduces little or no prior bias to the solution. Secondly, one can specify the prior information based on, for example, preliminary but not entirely conclusive results obtained using other source identification techniques, such as compositional analysis or tracer studies. If care is taken in selecting the statistical model, then the evidence offered by the proposed methods cannot be dismissed as "coldly statistical."

The second point above is highly relevant to the application of the methods proposed here, because the cost associated with liability for a contaminated site can be very high. Furthermore, the risk posed by contaminants will vary dramatically based on the nature of the contaminant, the exposure levels, and the vulnerability of the exposed population. Therefore, if a property owner were to use statistical methods to assign responsibility in a common law setting for contamination on his or her property, the standard of proof to be met may be higher than those discussed earlier. This will be especially true in high risk cases and in high remediation cost cases. However,

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193. Henry M. Hart, Jr. & John T. McNaughton, *Evidence and Inference in Law, in* EVIDENCE AND INFERENCE: THE HAYDEN COLLOQUIUM ON SCIENTIFIC CONCEPT AND METHOD 48 (Daniel Lerner ed., 1959).

194. *Id.*

in cases for which potentially responsible parties have much to gain by indemnifying themselves against responsibility, a higher cost associated with source identification may not be unreasonable.

C. *Potential Applications Of Probabilistic Methods In Other Settings*

The discussion of probabilistic (or stochastic) methods for identifying the most probable sources of observed contamination has been presented from the point of view of the requirements of the common law. The nature of the contaminant transport process, however, is clearly independent of the approach used to ensure adequate protection of environmental attributes. Therefore, the stochastic source identification methods currently being developed are also applicable in a statutory setting, as well as in other non-court based environmental conflict resolution settings.

1. Statute Law

The basic purpose of a statutory approach to environmental contamination is to control potential contaminant sources that may cause harm. As such, statute law is not concerned with the relative risk posed by individual sources, but simply with whether the contaminant load associated with these sources is beyond a given acceptable threshold. This load is decided on the basis of the actual or perceived potential risk posed by the contaminant.

Although, in this light, identifying contaminants that are emitted from individual sources is not central to the statutory approach, determining the exact source of contamination can become part of the statutory process in some cases. When contamination that is suspected of being in violation of existing environmental statutes is observed, its source must be determined. Furthermore, the EPA can defend the promulgation of novel environmental regulation by demonstrating that the targeted sources are responsible for observed harm. For example, in *Ethyl*[195] and *Central Arizona Water Conservation District,*[196] source identification was applied to support the introduction of regulations that targeted certain sources, to show that the EPA's actions were not arbitrary and capricious. Lastly, a few

195. *Ethyl Corp.*, 541 F.2d 1 (1976).

196. *Central Arizona Water Conservation District,* 990 F.2d 1531 (1993).

environmental regulations, such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)[197] and the Oil Pollution Act (OPA),[198] impose liability for harm instead of specifying limits on allowable discharges if a contributing source can be identified. This makes source identification necessary.

Although contaminant source identification is not as central to statutory law as it is to common law, opportunities for improved technologies, such as the stochastic approaches discussed in this paper, do exist. In fact, scientific methods of contaminant source identification have already been applied in support of environmental regulations. Using a stochastic approach would allow the courts to take into account the uncertainty intrinsic in this process.

Stochastic methods of contaminant source identification also can be used to modify environmental regulations. Because these methods can assess the effect of individual sources, they can be used to

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197. CERCLA imposes liability for releases of hazardous waste. For off-site contamination, the court's interpretation of CERCLA requires proof of causation if parties responsible for a contaminant source are to be held liable for observed damage. *See, e.g.*, Dedham Water Co. v. Cumberland Farms, Inc., 689 F.Supp. 1223 (D. Mass. 1988). All responsible parties are generally held jointly and severally liable for costs recoverable under the National Contingency Plan (NCP). The courts, however, have allowed parties to recover costs from other responsible parties for that portion of expenses that exceeds their equitable share, if the responsibility can be shown to be divisible. *See* Gaba, *supra* note 72; *see also* Thomas C. L. Roberts, *Allocation of Liability Under CERCLA: A "Carrot and Stick" Formula*, 14 ECOLOGY L.Q. 601 (1987).

198. OPA imposes liability for oil spills on the party responsible for the spill. *See* NANCIE G. MARZULLA & ROGER J. MARZULLA, PROPERTY RIGHTS UNDERSTANDING GOVERNMENT TAKINGS AND ENVIRONMENTAL REGULATION 105 (1997). A responsible party is liable for all cleanup costs, unless it can show that a certain fraction of the oil originated from a different source. For example, in 1993 a geochemist successfully used gas chromatography and mass spectrometry, which are compositional analysis methods, to trace oil in Prince William Sound to a 1964 oil spill, bolstering Exxon's contention that the 1989 Exxon Valdez disaster was not responsible for all of the oil fouling the sound. *See* BRUBAKER, *supra* note 11, at 132.

mandate a cap on the impact of specific probable sources instead of regulating all possible sources.

2. Science Court

The idea of a "science court" was originally proposed by Arthur Kantrowitz in 1967.[199] The basic idea is to separate scientific issues from non-scientific ones in a given conflict. The scientific questions would then be addressed in a setting similar to a traditional court, but where the discussion could be mediated and decisions would be made by a group of scientific experts.[200] The proceedings would be presided over by a magistrate and judges, all of whom would be scientists.[201]

In such a setting, the stochastic methods proposed for contaminant source identification could be used to determine whether there is sufficient information to determine the likely source of the contamination. A traditional court setting could then deal with the liability associated with the contamination.

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199. Arthur Kantrowitz, *Proposal For An Institution For Scientific Judgment,* 156 SCIENCE 763 (1967)

200. There has been much discussion and debate over the merits of such an approach. *See e.g.*, Albert R. Matheny and Bruce A. Williams, *Scientific Disputes and Adversary Procedures in Policy-Making, An Evaluation of the Science Court,* 3:3 LAW & POLICY QUARTERLY 341 (1981); *see also* Thomas G. Field, Jr., *The Science Court is Dead; Long Live the Science Court!*, 4:2 RISK 95 (1993); Arthur Kantrowitz, *Elitism vs. Checks and Balances in Communicating Scientific Information to the Public,* 4:2 RISK 101 (1993); Carl F. Cranor, *Science Courts, Evidentiary Procedures and Mixed Science-Policy Decisions,* 4:2 RISK 113 (1993); Itzhak Jacoby, *Consensus Development at NIH: What Went Wrong?,* 4:2 RISK 133 (1993); Sheila Jasanoff, *Procedural Choices in Regulatory Science,* 4:2 RISK 143 (1993); Allan Mazur, *The Science Court: Reminiscence and Retrospective,* 4:2 RISK 161 (1993); Jon R. Cavicchi, *The Science Court: A Bibliography,* 4:2 RISK 171 (1993).

201. Matheny and Williams, *supra* note 200, at 343-44.

3. Alternative Dispute Resolution, Arbitration, Mediation

In many cases, the costs of litigation as opposed to attribution can represent a significant fraction of clean up costs. According to Church,[202] only 20 percent to 50 percent of total expenditures for contamination are expended on clean-up costs, with the rest being expended on the litigation process. A significant fraction of the litigation cost is attributable to proving whether a given source is responsible for contamination.

The possibility for resolving a case outside of the court setting can result in savings for all parties in a conflict. The presented stochastic methods of contaminant source identification can be a useful tool in such situations. One of the advantages of settling a case without litigation is that no set standard of proof needs to be met by any party. Therefore, as long as the uncertainty associated with an estimate of each party's liability can be obtained, the parties can identify the optimal degree of precision with which to define the contaminant source. This level of definition will be higher for cases where the costs associated with liability are higher. Overall, however, the costs will be lower than those of litigation, because the parties will be able to decide what level of definition they wish to obtain, instead of being bound by the standards of proof applicable in a court setting.

For example, the stochastic methods can be used to assign a probability to each source, and each party can pay a proportional fraction of any expenses associated with the liability. As a second example, if several sources may have contributed to the contamination, the parties can share the liability according to the best estimate of the source distribution based on available evidence, even though the uncertainty associated with this estimate may be too great to be useful in a court setting. For both these examples, the parties are not only avoiding legal fees, but also the costs associated with more extensive characterization that would be required for more precise delineation of the unknown source.

These alternative forms of conflict resolution are becoming more popular and the aim of the majority of participants is specifically to find a solution outside of the courtroom. For example, in a survey of

202. Tom Church, *The Relationship of Law, Sciences and Environmental Policy*, 3 SCI. EVIDENCE REV. 1 (1997).

160 mediated disputes, Bingham[203] found that 133 disputants specifically stated that their objective was to reach an agreement; of these, 78 percent of the disputants were successful in reaching agreement. The old science and the old negotiation strategies, however, will not serve the new field of environmental dispute well.[204]

In short, the stochastic approach to source identification would allow parties to lower the costs of arbitration by allowing parties to quantify and control the uncertainty associated with source estimates. As such, these methods can help avoid litigation, by making out-of-court settlements significantly more flexible and cost-effective.

VI. CONCLUSIONS

Environmental contamination issues result from competition for scarce resources. Both the polluter and the person affected by the contamination are trying to derive gain (whether financial or otherwise) from a given resource. The common law can resolve such conflicts by assigning and enforcing the property rights associated with the affected environmental amenities. The common law theories of trespass, nuisance and strict liability have been broadly applied for this purpose. The costs associated with defining and enforcing these rights, however, must be manageable if the common law is to be applicable. When the level of uncertainty associated with the delineation of property rights can be quantified, parties can identify the optimal level of definition by weighing the potential gains from better definition against transaction costs associated with it.

In the case of environmental contamination, identifying the source of contamination is critical to determining who is liable for observed harm. Conflicts over environmental contamination, however, often involve cases with multiple potential sources. Various scientific methods have been applied in an attempt to identify sources. These methods, however, do not identify the uncertainty associated with the source estimate, and the degree to which the liability associated with contamination is defined is therefore unclear. This shortcoming

203. G. BINGHAM, RESOLVING ENVIRONMENTAL DISPUTES: A DECADE OF EXPERIENCE (1986).

204. *See* Painter, *supra* note 140.

leads to increased transaction costs as each party attempts to convince the court that its estimate of the source is exact. The availability and application of contaminant source identification methods that quantify the uncertainty associated with source estimates would reduce the transaction costs associated with defining and assigning liability.

Methods that take into account the uncertainties associated with contaminant source identification are becoming available, and the usefulness of these methods has been demonstrated for a variety of problems, including source identification for sample field-scale problems.

The applicability of these new methods in legal settings is also promising. The methods fit in well with the rules governing the admissibility of scientific evidence. Furthermore, the standard of proof required in various court settings can be met, assuming that the anticipated benefit to the parties involved in the conflict are sufficiently large.

Although this paper has focused on the common law approach to contamination, these new stochastic methods are also potentially applicable in a variety of other settings. For example, they could be useful both in the design and implementation of environmental statute laws, or in the determination of whether a statutory approach is required in a given setting. These methods can also be applied to non-court-based forums for resolving environmental conflicts, such as mediation and arbitration.

Finally, the issue of risk assessment, although explicitly ignored in most of this work, must also be considered. Science governing the determination of the effect of various chemicals is also statistical or stochastic in nature. The exact effect of a compound cannot be determined with certainty. Furthermore, even if the possible effects are quantified, the probability of a given individual's ailments being a result of the contaminant can never be determined with certainty. The science of epidemiology strives to incorporate this uncertainty by identifying confidence intervals about their estimates of chemical effects. Furthermore, the courts recognize the uncertainty related to the cause of individual incidences of a given ailment by requiring that expert witnesses demonstrate a factor of 2 increase in the risk associated with a given ailment in order to hold a party liable for damages.[205] Therefore, it is important to note that, although this paper has dealt almost exclusively with the stochastic nature of contaminant source identification, the effects of the contaminants are also not perfectly delineated, and this uncertainty also plays a major role in environmental litigation.

VII. APPENDIX: DETAILS OF EXAMPLE ILLUSTRATING LOSS OF INFORMATION DUE TO MIXING

The concentration profiles resulting from the two possible release scenarios were generated using the analytical solution for solute transport in a 1-dimensional homogeneous domain from a time-variant point source. The equation relating the source release history to the concentration profile is thus:

$$c(x,T) = \int_0^T s(t) f(x, T-t) dt$$

where s is the source concentration at time t, c is the observed concentration at point x, T is the time of the observation, and

$$f(x, T-t) = \frac{x}{2\sqrt{\pi D (T-t)^3}} \exp\left[-\frac{(x - v(T-t))^2}{4D(T-t)}\right]$$

where v is the advective (flow) velocity, D is the dispersion (mixing) coefficient, and π is a constant approximately equal to 3.14159.

In this case, the final time T was taken to be 1200 in arbitrary time units, and both the velocity v and the dispersion coefficient D were taken to be equal to 1 in arbitrary but consistent length per time and length squared per time units, respectively.

The sample measurements were generated using the concentration profile resulting from Scenario 2, with the addition of a normally distributed measurement error with a variance of 2.5×10^{-5}.

205. *See, e.g.*, *Daubert v. Merrell Dow Pharmaceuticals,* 43 F.3d 1311.