5 Models in the Courtroom

E. SCOTT BAIR
Department of Geological Sciences, Ohio State University, USA

5.1 INTRODUCTION

Most scientists and engineers will never enter a courtroom as a party in a lawsuit. Most of us may never provide expert testimony in a trial. Yet trial by jury is one of the most valued and highly defended rights guaranteed to citizens of the United States by the US Constitution. It is the hallmark of the US system of justice. Although the Anglo-American system of jurisprudence is rooted in the 'inquisitions' ordered by William the Conqueror in 11th century England to determine the countryside's wealth and population (Van Dyke 1987), the appearance of hydrologic models in courtrooms is obviously a late 20th century phenomenon.

Modern hydrologic models founded on solving partial differential equations using numerical methods also can be traced to England. Shaw and Southwell (1941) may have been the first to use a finite-difference model to address a groundwater seepage problem. Advances in numerical methods and in our theoretical and applied knowledge over the past 30 years combined with continuous improvement in the ease, cost and power of computers have enabled hydrologists to address problems previously considered intractable. The ability to model complex hydrology combined with federal and state environmental laws promulgated in the latter part of the 20th century to protect water supplies, manage waste handling, and improve waste disposal have caused US hydrologists to participate in various types of litigation. As expert witnesses, we may testify in lawsuits filed under violations of environmental statutes or tort laws (laws relating to wilful or negligent damage or injury). In 1995, US District Courts began over 45 000 new cases dealing with tort actions and environmental matters (US Department of Commerce 1997, p. 216). Although most of these cases do not involve hydrologic issues or require testimony from hydrologic experts, and only 5% actually go to trial (Grossman and Vaughn 1999), the statistics reveal the zeal we Americans have for resolving conflict by litigation.

In court, as in other applications, hydrologic models are used to evaluate historic hydrologic events or conditions, and are used to predict future hydrologic events or conditions. In both cases, the credibility of the model rests in the subjective judgment of a jury or a judge. Ideally, we, the scientists and engineers, would like the jury or judge to first decide whether the model is a reasonable representation of the real hydrologic system and then determine whether the predictive simulations are reasonable based on the ability of the model to reproduce known (measured) physical states of the flow system. It is unlikely, however, that this type of sequential, critical evaluation will occur. It is more likely that the jury or judge will simply assess the overall believability of the scientific testimony. Terms such as *validate* and *verify* that suggest or imply realism or truth are used to paint righteous images of models for the jury or judge. As a consequence, these common modelling terms and the procedures hydrologists use to substantiate their conclusions are often highly contested by the opposing party.

Model Validation: Perspectives in Hydrological Science. Edited by M.G. Anderson and P.D. Bates.

It has been said that cross-examination is the most powerful tool in the US legal system for eliciting truth from witnesses. It has also been said that cross-examination by harassment is one of the greatest impediments to truth (Gerber 1987). For a hydrologic modeller, cross-examination is guaranteed to be a challenging experience regardless of the degree of validity, amount of veracity, or the number of confirming observations supporting the model and its predictions.

My objectives in writing this chapter are to describe issues, some substantive and some philosophic, that arise in the courtroom and bear on (1) the use and presentation of hydrologic models by expert witnesses, and (2) the evaluation of these models and their results by a jury or judge. In so doing, I will use the events surrounding a famous federal trial (*Anne Anderson et al. v. W.R. Grace & Company and Beatrice Foods, Inc.*) and the testimony of three expert hydrologists who participated in that trial to examine the interface between science and the US legal system.

5.2 SCIENTIFIC METHODS IN COURT

Hydrologists, like most other witnesses, are visitors in the legal arena. The vocabulary and rules used by lawyers may seem foreign to us, but the legal procedures that can eventually place a plaintiff's complaint before a jury are similar to the general scientific methods we use to develop and test hypotheses. As a result, the path a lawsuit takes through the American legal system is not unlike the path hydrologic research takes through the scientific community. Although scientists do not necessarily agree on all the components that comprise the scientific method, most agree that the scientific method is a set of informal rules for formulating concepts, conducting experiments, making observations, developing inferences, and then testing these inferences by further experimentation and observation (Peters 1996). Hydrologic modellers commonly follow a similar set of procedures in constructing and testing their mathematical models.

Figure 5.1 shows the general steps in the scientific method, procedures followed by hydrologic modellers, and their similarities to the path a civil lawsuit follows through the American legal system. In the latter scheme, a perceived injustice leads to identification of possible causation and the filing of a legal complaint by a plaintiff. In the scientific method, this is analogous to initial observations leading to the formulation of a question and the development of a hypothesis. The scientific hypothesis and the legal complaint both represent queries that have been framed but need to be tested and resolved. In a parallel sense, they are similar to the statement of purpose of a hydrologic model and the development of a conceptual framework of the flow system.

Pre-trial discovery, the phase of a lawsuit when information is acquired and solicited, legal strategies are formulated, and professional opinions are developed, stated and queried, corresponds to the steps in the scientific method where experiments are planned and executed, observations recorded, and the results analysed to see whether the experimental data support or refute the hypothesis. In a hydrologic model, these steps are analogous to the calibration of the model, wherein measured water levels and/or discharges are compared to simulated values to determine how well the model reproduces the measured physical state of the system.

In a trial, discovered evidence is presented by lay witnesses and expert witnesses during direct examination and then is scrutinised by the opposition during cross-examination. A jury or judge makes the final deliberations regarding acceptance or rejection of the legal complaint. At the end of the trial process, evaluation of the testimony by the jury or judge is immediate and the final decision to accept or reject the plaintiff's complaint is made by non-experts and is reached quickly.

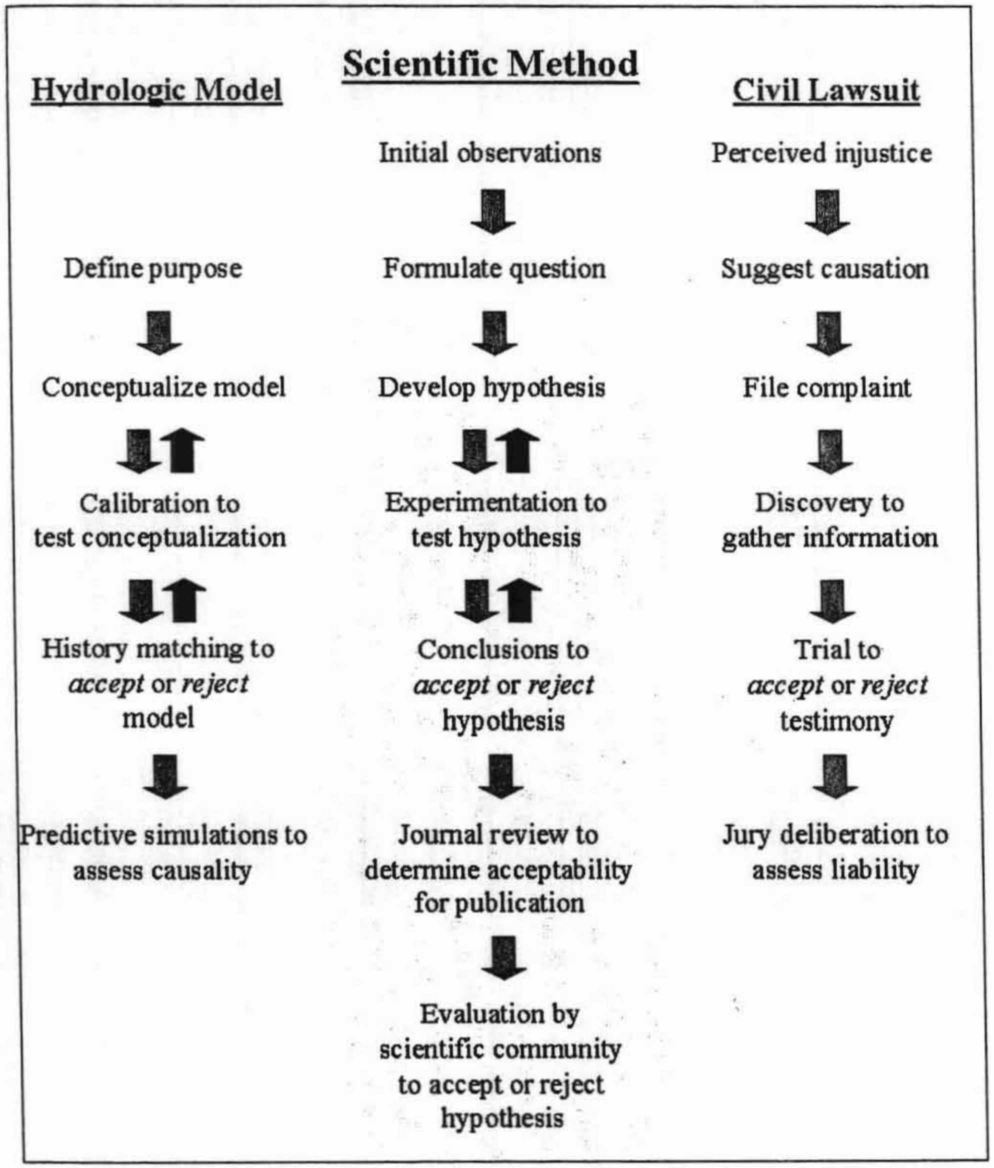

Figure 5.1 Similarities among the scientific method, trial procedures and hydrologic model construction

In the scientific arena, the experimental data are analysed and conclusions (inferences) are drawn whether to accept or reject the hypothesis. If the hypothesis is accepted, the work is commonly submitted for publication in a professional journal where it is scrutinised by peer reviewers to assess its acceptability for publication. If the work is accepted for publication, the greater scientific community makes the final acceptance or rejection of the hypothesis. In

contrast to the legal process, evaluation of professional opinions through the scientific process is slow, is made by fellow experts, and the final decision may not be reached for years as other scientists try to replicate the work (Bair and Wood 1999).

Although there are similarities between science and law, there are also differences. A major difference is in the time spent evaluating whether to accept or reject the hypothesis, the testimony and the model (Figure 5.1). Deliberations by a jury over testimony presented in a trial may take hours, sometimes days, on rare occasions weeks. Evaluation by the greater scientific community of new concepts published in a journal may take months to years, sometimes decades. Another difference is that the jury is made up of non-experts whose common knowledge is relied upon to render an impartial judgment, whereas the scientific community is comprised of competing scientists whose expertise is relied upon to repeat the experiments and validate or reject the work. A third difference is that the scientific method facilitates feedback between hypothesis development, design and execution of experiments, and formulation of conclusions. The path of a civil lawsuit is one directional (see Figure 5.1), although it can be stopped by settlement or the verdict overturned on appeal.

Federal Judge Lynn N. Hughes expressed the differences as follows:

> Scientific investigation is a long-term pursuit focused at understanding our experiences, whereas jurisprudential investigation is a short-term pursuit focused at resolving a conflict between two or more parties. Science has the freedom of the eventuality of finding answers and the generality of application, whereas the law has the constraints of the immediacy of resolution and the particularity of each case. . . Courts are a societal mechanism for resolving disputes in which the concepts of truth and justice are significant but secondary. Although both science and the law seek the truth, both also must rely on incomplete data and both also must operate under uncertainty. Science and law do not, then, have competing visions of truth. Rather, knowledge competes with resolution. . . We need to fit the product of science into the task of courts.
>
> (Hughes 1999)

5.3 SCIENTISTS IN AN ADVERSARIAL LEGAL SYSTEM

Hydrologists, like most applied scientists, are accustomed to constructing models with inherent uncertainty (Voss 1998). It is highly unusual for us not to deal with sparse and/or noisy data. The general public looks to scientists to unravel and explain the physical, chemical and biological processes that operate day-to-day within our realm. The public, however, is accustomed to scientists describing these processes in terms of laws – Newton's Laws of Motion, the Laws of Thermodynamics, Ohm's Law, Snell's Law, Darcy's Law, etc. In allowing this perception of science to prevail, scientists have unwittingly encouraged the public to believe in the certainty of science. After all, science, deals with definitive laws that are tested, proven, and repeatable. As a consequence, the general public, which is sampled to form the jury pool, is unaccustomed to the methods routinely used by applied scientists to deal with uncertainty.

For hydrologists, the most uncertain aspects of model construction – the ones that often make an expert witness squirm on cross-examination – are sparse and noisy data. Using a shallow, transient contaminant transport model as an example, the following types of sparse and noisy data commonly confront the expert witness (Prickett and Pettyjohn 1995).

- surface-water/groundwater interaction
- heterogeneity, anisotropy and assigned hydraulic conductivity distributions
- spatial and temporal variations in recharge rates
- historic pumping rates and schedules of wells

- non-synoptic water-level and contaminant concentration measurements
- contaminant source history and contaminant release rates

In most cases involving site-specific application of hydrologic models, many factors are simply unknown and hence uncertain. Because of uncertainties, most hydrologists, if pressed, might admit to accepting model results that are, in a loosely quantitative sense, 75 to 90% accurate (see Figure 5.2). This assumes that a model cannot be constructed that is 100% accurate (Bredehoeft and Konikow 1993). Given a probability range from 0 to 1.0 that a hydrologic model accurately represents the flow system and accepting that no hypothesis or model can be 100% accurate, then a range of 0.75 to 0.90, or 75 to 90%, for a hydrologic field problem would demonstrate a relatively high degree of correspondence between model results and measured values. In the example of a contaminant transport model, this would be a relatively high degree of correspondence between simulated and measured values of hydraulic head, streamflow change and solute concentration. Over the past several decades, hydrologists have come to expect a higher degree of accuracy because modern finite-element and finite-difference techniques require fewer simplifying assumptions about the hydrogeologic setting and can address more difficult boundary conditions than the closed-form calculus-based analytical techniques developed in the middle of the past century.

In a civil trial, the jury bases its verdict on a preponderance of the evidence. For the jury to find for the plaintiff, a majority of the evidence must indicate that the defendant is liable. To

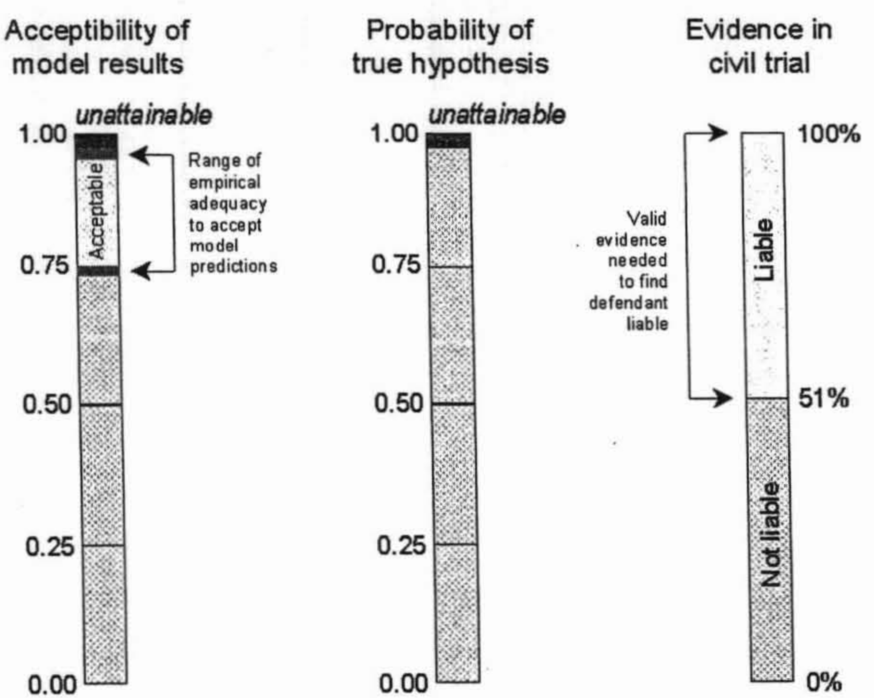

Figure 5.2 Comparison of standards between a civil trial, the probability of a correct hypothesis, and the acceptability of results from a hydrologic model

scientists and engineers accustomed to using modern numerical and computational techniques, a 51% criterion may seem low. It may seem so low that it affords some creativity for experts to use analysis techniques that produce results more favourable to their client's case. This approach is not unethical. It may be employed for a variety of reasons – scientists may approach problems differently, parties often cannot afford the most rigorous scientific approach, legal strategies may not call for a complex analysis. An overly simplistic approach can lead to as much criticism on cross-examination concerning inappropriate use of isotropic and homogeneous parameter values as can use of inappropriate ranges of heterogeneous parameter values in a complex analysis. Simplifying assumptions are always good fodder for cross-examination. It is up to the expert, in consultation with his/her lawyer, to decide whether a simple, one-dimensional analytical model is sufficiently representative of the flow system, or whether a complex, three-dimensional numerical model is required, or whether a laboratory demonstration using a sand tank is appropriate. It is difficult to predict whether, in the minds of the jurors, a simple elegant but fundamentally flawed construction will be more or less believable than a complex arcane truth.

5.4 EXPERT WITNESSING

Expert witnesses, unlike lay witnesses, can present opinions. An expert witness possesses knowledge through experience, training or education of a particular subject in greater depth than the general public (Matson 1994). As society's reliance on specialised knowledge has expanded, so too has the use of expert witnesses (Weinstein 1986). In recent years, several articles and books have been written about the proliferation of junk science in the courtroom. In these essays, expert witnesses are commonly depicted as prostitutes, who, for the right fee, will testify to any farfetched theory in an attempt to win sympathy and a huge award from a scientifically challenged jury selected from a techno-terrified society (Huber 1990; Jost 1991). Peter Huber, author of Galileo's Revenge: Junk Science in the Courtroom (1991), argues that the admission of junk science is in response to the easing of standards for admissibility of expert testimony. It is a problem that may be further heightened by judges and lawyers who are not adequately trained to assess the veracity of the scientific evidence placed before them (Blauvelt 1999).

For much of the 20th century, courts maintained that if the scientific theory or reasoning was sufficiently reliable to attain the *general acceptance* of the scientific community, then the evidence was sufficiently reliable to be admitted in court. Known as the Frye Rule, this general acceptance test was established in 1923 (*Frye v. United States*) and governed the admissibility of scientific evidence in US courts for decades. The main criticism of the Frye Rule was that it excluded new scientific advances that were too new to have established general acceptance by the scientific community (Foster et al. 1993). In the latter part of the 20th century, many states adopted the Federal Rules of Evidence, which included a broadly discretionary set of guidelines for the acceptance and restriction of scientific testimony. Rule 702, the most important of these rules, provides that expert testimony is admissible 'if scientific, technical, or other specialised knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue' (Weinstein 1986). Although the 'assistance to the trier of fact' standard liberalised the admissibility of scientific evidence, it led to the admission of various types of novel expert testimony and a blurring of the distinction between expert testimony and lay testimony (Weinstein 1986).

The US Supreme Court in *Daubert v. Merrel Dow Pharmaceuticals, Inc.*, a 1993 case alleging birth defects as a result of taking the anti-nausea drug Bendectin, held that under Rule 702 scientific knowledge presented as testimony must be derived by the scientific method. The Supreme Court also held that evidentiary reliability is to be based on scientific validity. Under the Daubert ruling, the trial judge is assigned the responsibility of gatekeeper to make preliminary evaluation of whether the reasoning and methodology underlying the testimony is scientifically valid or reliable and whether it is applied properly to the facts at issue (Foster et al. 1993; Blauvelt 1999). The gatekeeper's role is not to determine which expert opinion is correct. Rather, it is to determine whether each expert used valid scientific reasoning and principles to reach his/her conclusions and to screen out professional opinions based on conjecture and speculation (Blauvelt 1999). The Supreme Court established that the initial determination regarding the admissibility of an expert's scientific testimony is to be based on (1) whether the expert opinion is founded on reliable data, (2) whether the expert opinion is supported by valid scientific reasoning and methodology, and (3) whether the expert opinion is based on information relevant to the case (Blauvelt 1999).

5.5. EXAMPLE OF *ANNE ANDERSON ET AL. v. W.R. GRACE & COMPANY AND BEATRICE FOODS, INC.*

The 1986 Woburn Toxic Trial, the informal name referring to *Anne Anderson et al. v. W.R. Grace & Company and Beatrice Foods, Inc.*, is an excellent example to demonstrate the analogy between scientific hypothesis testing and the civil trial process using a case that centres on the interpretation of hydrologic data and the predictions of hydrologic models. In this lawsuit, which is the focus of the award-winning book *A Civil Action* (Harr 1995) and the 1999 Touchstone Pictures movie of the same name, eight plaintiffs, who lived in eastern Woburn, Massachusetts, filed suit against two large corporations that operated a local manufacturing plant, the Cryovac Division of W. R. Grace & Company, and a local tannery owned by Beatrice Foods, Inc. The plaintiffs' 1982 legal complaint alleged that improper handling and disposal of five industrial chemicals, including trichloroethene (TCE), dichloroethene (DCE) and tetrachloroethene (PCE) at the two properties, entered the groundwater system, flowed to two municipal wells, and prolonged ingestion and exposure to the toxic chemicals caused leukaemias, central nervous system disorders, and other health problems.

The two municipal wells, known as wells G & H, began operating in 1964 and 1967, respectively. The wells are 2-feet in diameter, 88-feet deep, and 600 feet apart. Both wells have 10-foot screens and, when operating, pumped at average rates of 700 and 400 US gallons per minute, respectively. Wells G & H were used together only 23% of the time and primarily were used only during periods of drought to augment water produced by six other municipal wells in another part of town. The wells were built on earthen mounds within the floodplain of the Aberjona River. At normal stage, the river flows within 300 feet of well G and 100 feet of well H (Figure 5.3). At elevated stages, the river floods across a wetland and flows within a few feet of the municipal wells. The wells are constructed in highly permeable glacial outwash deposits filling a buried bedrock valley composed of fractured granodiorite (Figure 5.4). Wells G & H were closed in May 1979, by order of the Commonwealth of Massachusetts, after water samples revealed concentrations of TCE and PCE exceeding public health standards. US EPA (1985) considered TCE and PCE to be probable human carcinogens. Samples taken from wells G & H prior to this date were not analysed for volatile organic compounds.

Because of the complex nature of the case, the judge, in accordance with federal procedures, divided the case into three phases. Each phase contained a trial that focused on a specific issue. The resolution of each issue, in sequence, would progress to the determination of the ultimate issue – whether prolonged consumption of dilute concentrations of TCE, DCE and/or PCE caused the specific types of leukaemia contracted by the plaintiffs. The first of these trials was to determine which, if any, of the contaminants entered the groundwater system on the defendants'

properties and, if so, whether the contaminants flowed to the municipal wells within the time the wells operated. If either defendant was found liable in this phase, then the subsequent two phases would proceed to determine whether the contaminant(s) reaching the wells could cause leukaemias and the other health effects. In trifurcating the trial, the judge produced a series of sequential subordinate hypotheses. If the jury rejected the subordinate hypothesis for a particular defendant, the lawsuit ended at that phase. If the jury accepted the subordinate hypothesis for a particular defendant, the lawsuit continued to the next phase.

From a hydrologist's perspective, the unique aspect of this trifurcated case is that the first phase focused entirely on surface-water and groundwater hydrology. From the jury's perspective, the unique aspect of the first phase is that the plaintiffs did not testify and almost all the testimony presented by lay and expert witnesses dealt with scientific issues related to contaminant source areas and concentrations, geologic characterisation, physical properties of sediment and rock, induced streambed infiltration, flood frequency, surface-water and groundwater interaction, flowpaths, retardation factors, organic chemistry, and the prediction of contaminant arrival times at the wells using hydrologic models. As a result, the trial provides an interesting view of the interface between science and the law.

Pre-trial discovery began in October 1982. No field data, including groundwater levels or monitoring well samples, were collected prior to closure of the two municipal wells in May 1979. As a result, during discovery it was necessary to design and perform field tests to reproduce the configuration of the water table when the wells were periodically operational between 1964 and 1979, and to determine the degree to which the wells were hydraulically connected to the Aberjona River and wetland. Independent of the trial, the US Geological Survey and US EPA conducted a 30-day pumping test using wells G & H. The test began in December 1985 and was done in support of federal Superfund cleanup activities at known sources of contamination near wells G & H. During the test, wells G & H were pumped at their average rates.

The plaintiffs' and defendants' experts were provided the groundwater level and streamflow measurements made during the 30-day test. These data helped them develop their professional opinions for the trial concerning the role of induced stream infiltration, flowpaths from the defendants' properties to the wells, and travel times of contaminants to the wells. Based on these and other data, the hydrologic experts developed conceptual models of the hydrogeologic setting and constructed mathematical models of the flow system that became the foundation of their opinions. The experts' opinions represent inferences drawn from the experimental data. Figure 5.3 shows the configuration of the water table after pumping wells G & H for 30 days. Water levels in the 45 monitoring wells used to construct Figure 5.3 had not quite attained steady state at the end of the pumping period (Myette et al. 1987). After the first day of pumping, periodic stream discharge measurements made at Olympia Avenue, north of the wells, and at Salem Street, south (downstream) of the wells (see Figure 5.3), showed that water in the river and wetland was being induced to flow downward into the aquifer to supply the two municipal wells. By the end of the 30 day pumping period, there was 565 US gallons per minute less stream discharge measured at Salem Street than Olympia Avenue (Myette et al. 1987).

5.5.1 Experts' Opinions on the Hydrologic System at Woburn

During the 78-day trial, the jury heard opening remarks by a lawyer representing each of the three parties, direct testimony and cross-examination from lay and expert witnesses, and closing arguments from the lawyers. The jury also visited the wells G & H area. During direct examination, the geologic experts hired by each party described the aquifer in which wells G & H are completed as a heterogeneous sequence of transmissive glacial sediments (see Figure 5.4). The main points of controversy in the opinions of the hydrologic experts concerned (1) the

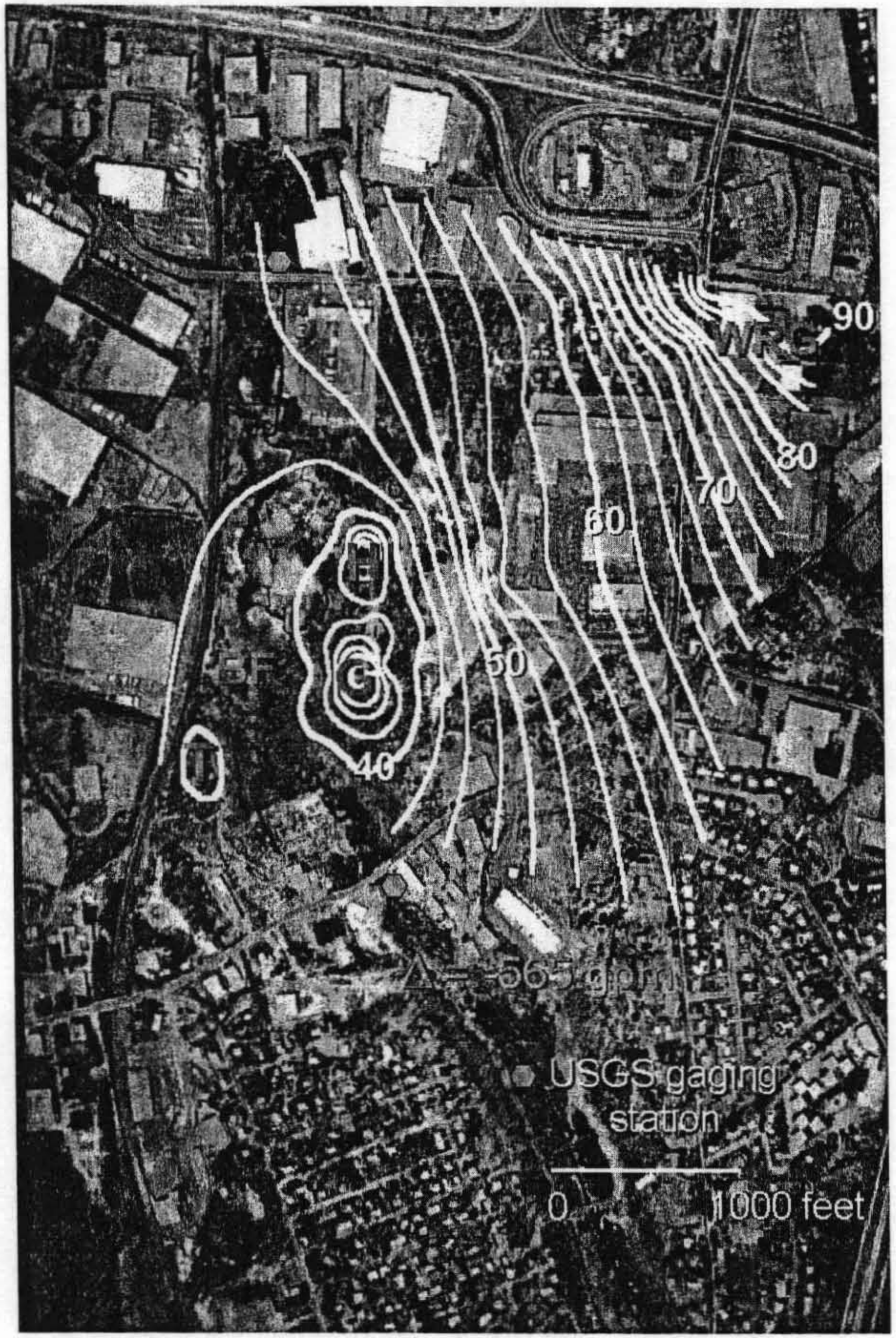

Figure 5.3 Water-table map of the Aberjona River valley near wells G & H after 30 days of continuous pumping, 3 January 1986 (contours from Myette et al. 1987). WRG = W.R. Grace property. BF = Beatrice Foods property. G & H = municipal wells. T = tannery well

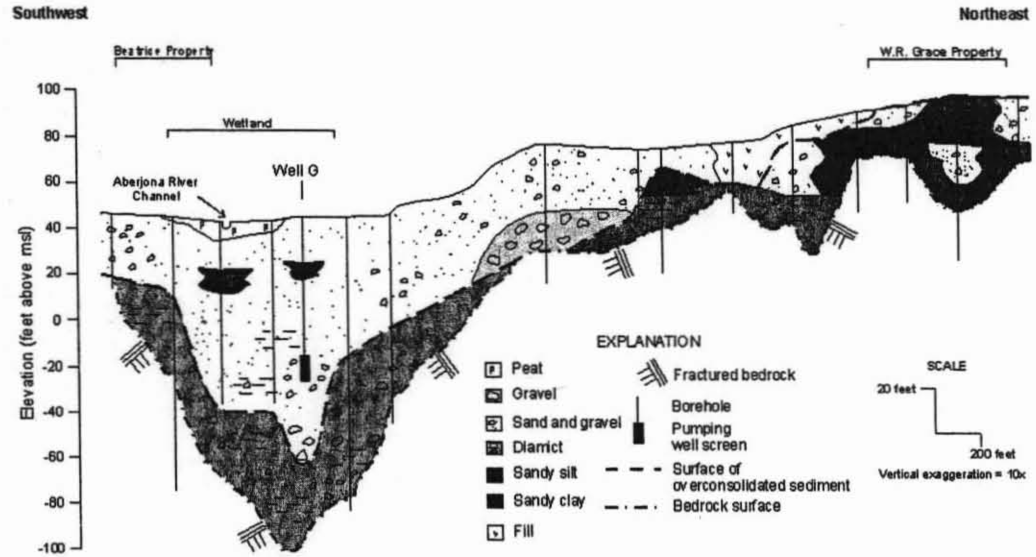

Figure 5.4 Generalized geologic cross-section from the Beatrice property, through well G, to the W.R. Grace property (after Metheny 1998)

degree to which the Aberjona River and wetland were hydraulically connected to the aquifer, (2) the hydraulic properties of interbedded peat and fine sand underlying the river and wetland, outwash sand and gravel in the buried valley, and silty clay (lodgement) till underlying the uplands (see Figure 5.4), and (3) the configuration of the water table beneath the river and wetland when wells G & H were pumping (see Figure 5.3). The opinions of the three hydrologic experts differed substantially on pathlines and travel times of contaminants to the wells, the capture zones of the wells, and whether induced infiltration of surface water entered the aquifer and flowed to the wells during pumping. Following are descriptions of the testimony of the three hydrologic experts in the case. A summary of their opinions and the bases of their opinions are given in Figure 5.5.

5.5.2 Plaintiffs' Expert

The defendants' lawyers deposed the plaintiffs' hydrologic expert on three separate occasions for a total of 16.5 hours (Grossman and Vaughn 1999). His direct testimony occurred on days 39, 40 and 41 of the trial, which was followed by seven days of cross-examination and two days of re-direct examination and re-cross examination.

The plaintiffs' expert constructed a three-dimensional flow and transport model synthesising data from well logs, soil borings and slug tests into a heterogeneous geologic framework. The numerical model was used to develop a 'cosmopolitan view' of the aquifer and flow system. However, because the model was not calibrated in a rigorous manner against measured values of head, streamflow change or solute concentrations, it was never introduced into evidence at trial and was used solely to illustrate his opinions drawn from other analyses. According to the plaintiffs' expert, the model did simulate the overall patterns of groundwater flow measured during the 30-day pumping test (Deposition #4, 13 February 1986, p. 130). The plaintiffs' expert

	Plaintiffs'	Beatrice's	W.R. Grace's
Field data	Water levels, well logs, f_{oc}, slug tests	Water levels, stream flows, well logs	Water levels, stream flows, well logs, f_{oc}, slug tests, recharge
Basis	Flow vectors, plus 1-D analytical transport model	Potentiometric maps and flowlines	3-D numerical flow and transport model
Geologic Heterogeneity	Uniform in 1-D K_{GRACE} = 75 ft/day $K_{BEATRICE}$ = 2300 ft/day	Not addressed directly	Heterogeneous 3 layers K_{RANGE} = 0.75 - 113 ft/day
River infiltration (wells pumping)	Limited infiltration due to peat, reaches wells in 10 to 20 years	Infiltration creates groundwater divide, reaches wells in 3 to 4 months	Substantial infiltration 50% of well discharge, reaches wells in 2 to 4 months

Figure 5.5 Summary of hydrologists' expert opinions in *Anne Anderson et al. v. W.R. Grace & Company and Beatrice Foods, Inc*

held the following opinions with respect to the interaction of the wetland and river with the groundwater flow system.

> ... if I were to try and bracket the time of travel of contaminants from the river to the wells, it could be as long as 10 to 20 years.
>
> (Trial Day 43, p. 67)

> I think very little [water], if any at all was pumped out of the river during the pumping test of wells G and H].
>
> (Trial Day 43, p. 71)

The negligible amount of induced infiltration, he stated, was due to the very low hydraulic conductivity of the peat underlying the river and wetland.

As the basis of his opinion, the plaintiffs' expert used a one-dimensional analytical flow and transport equation (Ogata-Banks equation, see Domenico and Schwartz 1998, p. 373) to estimate travel times of contaminants from the W.R. Grace and Beatrice properties to the municipal wells. This one-dimensional analytical model necessitated use of uniform values of hydraulic conductivity, hydraulic gradient and porosity, and limited hydrodynamic dispersion to the longitudinal direction of groundwater flow. Based on this one-dimensional analysis, the plaintiffs' expert made the following testimony regarding contaminant travel times.

> ... a travel time for TCE of 3 years from Grace... the travel time in terms of the Grace site to the wellfield would be for [DCE] – 1.03 years, [PCE] – 9.67 years ...
>
> (Trial Day 41, pp. 108–109)

> ... in terms of Beatrice, I would like my testimony to read that TCE was 3 months, [DCE] – 1.03 months, [PCE] – 9.67 months ...
>
> (Trial Day 41, p. 109)

In this analysis, the plaintiffs' expert used a porosity of 0.20, a dispersivity of 67.5 feet, and different retardation factors for each contaminant that ranged between 1.5 and 8. For the calculations pertaining to contaminants at W.R. Grace, he used a hydraulic conductivity of 75 feet/day, a hydraulic gradient of 0.001 and a distance of 2840 feet, whereas he used a hydraulic conductivity of 2300 feet/day, a hydraulic gradient of 0.018 and a distance of 525 feet for the Beatrice calculations (Trial Day 41, p. 109). In his opinion the chemicals originating at Beatrice reached wells G & H within a few months, and TCE and DCE originating at W.R. Grace were present at the future locations of wells G & H before the wells were actually built, assuming the chemicals entered the flow system in 1960, the year the plant opened. The Aberjona River, in his view, was neither a source of additional contamination to the wells nor a source of dilution because of the poor hydraulic connection between the river and the aquifer.

5.5.3 Beatrice's Expert

The other parties never deposed the expert hydrologist hired by Beatrice. His entire testimony occurred during days 58, 59 and 60 of the trial. His opinions were based on his conceptualisation of the hydrogeologic setting using well logs, and groundwater level and streamflow gain/loss measurements made during the 30-day pumping test. He presented a conceptual model of the flow system, but did not construct an analytical or numerical flow model, or compute travel times. With respect to the interaction between the Aberjona River and the pumping wells, he made these statements during the trial.

> I would say that river water could flow to Wells G and H in a period of 3 to 4 months.
>
> (Trial Day 58, p. 127)

> ... the river creates this ridgepole effect, and it is the high point on the water table surface with the tarpaulin that slopes away on both sides. This is caused by the pumpage of G actually inducing water to leave the river. As the water goes out of the river channel, it forms a mound on the water table, and the mound is this ridge-shaped affair ...
>
> (Trial Day 59, pp. 22–23)

> ... the cone of depression from G and H, which is what we've depicted on this map, can only go up to the river. It does not cross the river. So the effect of [wells] G and H will not cross the river but will be contained and be stopped from leakage by the river itself.
>
> (Trial Day 59, pp. 31–32)

The Beatrice expert made no calculations of contaminant travel times to wells G & H because his analysis showed that groundwater under the Beatrice property would not flow under the river to the east and downward to the well screens. He made the following statement.

> What we found out was that groundwater [at Beatrice], on the contrary, moves away from Wells G and H when they were pumping. Therefore, the fact of having chemicals in that water during the 1964 to 1979 period may really be secondary because even if they were there – and I'm not saying they were – but even if they were, they would not move to Wells G and H.
>
> (Trial Day 59, p. 57)

In his opinion, contaminants, if present on the Beatrice property, would not flow eastward toward municipal wells G & H, but would flow westward, away from the wells due to the groundwater mound formed beneath the Aberjona River by induced infiltration of river water. Hence, contamination measured in wells G & H in May 1979 could not be derived from 55-gallon drums dumped on the Beatrice property because induced infiltration from the Aberjona River formed a barrier to groundwater flow from that direction.

5.5.4 W.R. Grace Expert's Testimony

The plaintiffs' attorney deposed the expert hired by W.R. Grace for 1.5 hours. His direct examination occurred on days 66, 67, and 68 of the trial, and was followed by cross-examination on days 68, 69 and 70, and re-direct examination on day 71. The W.R. Grace expert used well logs, seismic surveys, and soil borings from the area to construct a conceptual framework of the geologic setting. He used historic pumping records, historic streamflow data, and water-level and streamflow measurements from the 30 day pumping test to develop a conceptual model of the hydrologic system and the interaction between the river and wetland with the groundwater flow system. The data were incorporated into a three-dimensional numerical flow and transport model that was used to simulate transient water level and streamflow conditions, and chemical transport in the flow system from 1960 to 1979. The model incorporated spatial variations in hydraulic conductivity, spatial and temporal variations in recharge, bedrock leakage, partial penetration of the wells and river, and historic pumping rates of the municipal wells. Hydraulic conductivity values in the three-layer model varied from 0.75 feet/day for the lodgement till underlying the bedrock uplands to 113 feet/day for the glacial outwash filling the buried valley. The flow model was calibrated to data collected for the 30 day pumping test using water levels measured immediately before wells G & H commenced pumping, transient water levels measured during the 30 day pumping period and streamflow gain and loss measurements made before and during the test. The transport model was not calibrated because of the lack of historic TCE, DCE and PCE data. A sensitivity analysis was performed using ranges of transport parameters and a conservative assumption was made placing the contaminants at the water table the day the plant opened in 1960.

In his testimony, the W.R. Grace expert made the following statements regarding the interaction between the river/wetland and wells G & H:

> But under conditions where a man-caused hydrologic stress, that is pumping of a production well for water supply, and that well is located close to the Aberjona River, it will induce water to flow out of the river into the aquifer and be a source of the supply of water to those wells.
>
> (Trial Day 67, p. 73)

> . . . on a long-term period . . ., the water that comes out of the river gets to the wells within two months, and that is equal to about half the well pumpage.
>
> (Trial Day 67, p. 73)

The W.R. Grace expert viewed the river as a probable source of contamination to wells G & H because of abundant induced infiltration and periodic flooding of the wetland bringing volatile organic compounds and heavy metals from known historic sources of contamination upstream in the basin into the capture zones of the municipal wells.

With respect to simulated travel times of contaminants from the W.R. Grace property to the wells, he made the following statements

> . . . for TCE the three periods of time that I calculated were 11 years, 19 years, and 25 years . . . At the end of 11 years, TCE would have moved a distance of 750 feet. For 19 years, the distance would be less than 1000 feet. And for 25 years, the distance is less than 1100 feet.
>
> (Trial Day 68, pp. 2–3)

> The distance (1,2) trans (DCE) would have moved in 11 years is less than 800 feet; in 19 years, less than 1300 feet; and in 25 years, less than 1600 feet.
>
> (Trial Day 68, pp. 2–3)

Based on these model simulations, his opinion regarding the movement of organic solvents at the W.R. Grace property, which were dumped on the land surface and placed in 55-gallon drums in a shallow pit, was that even if the TCE, DCE and PCE were released into the groundwater flow system on the day the plant opened in 1960, the chemicals would not have reached wells G & H, over 2500 feet away, by May 1979 when the wells were shut down (Trial Day 68, pp. 2–3).

5.5.5 Jury Verdict

At the end of the trial, the judge described to the jury the legal statutes that applied to the case and read two sets of special interrogatory questions, one set of four questions pertaining to each defendant, which would elucidate their verdict. The judge in concert with the lawyers composed the special interrogatory questions. Obviously, the judge believed the jury could answer the questions based upon the testimony presented at the trial. The first special interrogatory question, shown below for W.R. Grace, asked the jurors to determine which, if any, of the contaminants substantially contributed to the contamination of wells G & H during the period of time the wells operated.

> #1. Have the plaintiffs established by a preponderance of the evidence that any of the following chemicals were disposed at the Grace site after October 1, 1964 and substantially contributed to the contamination of Wells G & H by these chemicals prior to May 22, 1979?

(a)	trichloroethylene	yes______	no______
(b)	tetrachloroethylene	yes______	no______
(c)	1,2 transdichloroethylene	yes______	no______

The second interrogatory question, shown below, asked the jurors to determine the year and month when each contaminant selected in #1 first reached the wells.

> #2. If you answered 'Yes' in question 1 as to any chemical(s), what, according to the preponderance of the evidence, was the earliest time that such chemical(s) disposed of on the Grace site after October 1, 1964 made a substantial contribution to the contamination of Wells G & H?

(a)	trichloroethylene	mo.____________	yr.______
(b)	tetrachloroethylene	mo.____________	yr.______
(c)	1,2 transdichloroethylene	mo.____________	yr.______

According to Pacelle (1986), the jury was dumbfounded by the specificity of the special interrogatory questions, especially having to identify a date (year and month) that each contaminant made a substantial contribution to the contamination of the wells. Prior to receiving instructions from the judge, the jurors believed they would answer a singular question concerning the simple liability of each defendant, not a series of complexly worded questions about each chemical named in the lawsuit (Pacelle 1986). The third and fourth interrogatory questions addressed the legal issue of negligence and were framed and worded in a manner similar to the first two interrogatory questions.

After nearly ten days of sometimes heated deliberations (Pacelle 1986), the jury reached answers to the special interrogatory questions. W.R. Grace was found liable of contaminating wells G & H with TCE beginning in September 1973, but not with DCE or PCE. Beatrice Foods was found not liable of contaminating the wells with any industrial chemicals. The answers to the special interrogatory questions serve as the verdict and represent the final acceptance or rejection of the first subordinate hypothesis. The trial, however, did not proceed to a second phase with the remaining defendant, W.R. Grace & Company. Several months later, a settlement was reached between the plaintiffs and W.R Grace, shortly after the judge indicated he would grant the defendant's motion for a mistrial based, in part, on inconsistencies in the responses to the special interrogatory questions (Pacelle 1986).

5.5.6 Discussion of Woburn Verdict

Based on the accounts of Pacelle (1986), Kennedy (1989), and Harr (1995), it is apparent that many of the participants and observers of the Woburn Toxic Trial felt that the US legal system operated at a level below its best. A common criticism of the US legal system is its reliance on lay juries in exceptionally technical cases. Arguments are made that highly technical cases should be tried before a judge because judges are more highly educated and experienced in resolving technical issues than a lay jury. Arguments are made that technical cases should be tried before an expert jury – one comprised solely of experts whose technical disciplines are germane to the case.

Although these arguments have merit, so do the counter-arguments. Prentice H. Marshall, a US District judge, argues that

> . . . in most civil and criminal cases a carefully selected jury which has received coherently submitted evidence and accurate and succinct instructions is superior to a judge in making decisions. The jury's collective comprehension of the facts is more complete than the judge's. The jury renders its decision more quickly than the judge can. The jury's independence and integrity are superior to the judge's. The jury's cross-sectional makeup brings community values to the decision-making process.
>
> (Marshall 1990)

Lynn N. Hughes, also a US District judge, argues that it would be nearly impossible to empanel a jury of experts, who individually did not develop biases as a result of their professional experiences, whereas a lay jury, while naïve, is unbiased and can usually understand the pertinent technical issues (personal communication, October 1999).

As a society, we trust that the collective wisdom of the jury will produce the correct verdict (Marshall 1990). However, the process by which the jury derives the verdict is inherently passive (Friedland 1990). Jurors may or may not be allowed to make notes during the trial. They cannot read supplemental materials or reference books. They probably are not allowed to review the testimony transcribed by the court recorder. They cannot discuss the case with others, or among themselves except during formal deliberations following the trial. Students are active learners; jurors are not. Jurors, unlike students, do not get to benefit from homework assignments, term papers, laboratory reports, and exams that reinforce concepts covered in class.

A list of the hydrologic topics the jurors in the Woburn Toxic Trial were asked to comprehend includes geologic mapping, glacial history and glacial stratigraphy, physical properties of rocks and sediments, drawdowns and cones of depression produced by pumping wells, stream gauging, flood recurrence intervals, induced stream infiltration, aqueous and organic chemistry,

regional groundwater flow, contaminant transport with retardation, and analytical and numerical models of groundwater flow and transport. The topics are nearly equivalent to the content of courses a graduate student is required to take for a master's degree in hydrology. Only one of the six jurors in the Woburn Toxic Trial attended college and none had any specific scientific training or background (Pacelle 1986).

The crux of the jury's decisions in the Woburn Toxic Trial centred on their understanding the hydrogeologic setting and its influence on groundwater pathlines and contaminant travel times, the interaction between the groundwater flow system and the wetland when the municipal wells were pumping and when they were not, and the processes affecting the fate and transport of chlorinated solvents. As a society, we hope the jury had a sufficient level of understanding of the field data and an appreciation of the necessary theory and concepts to differentiate among the divergent opinions held by the hydrologic experts. As scientists, we hope the jury was able to differentiate among the technical approaches used by the hydrologic experts. As hydrologic modellers, we hope the jury was able to decipher the limitations of each expert's predictive model. We have high hopes.

In January 1999, Harvard Law School held a conference called *Lessons from Woburn*. Many of the lawyers, several of the plaintiffs' mothers, some of the expert witnesses, and one juror from the trial participated in the conference. Many of these people led focus sessions dealing with specific aspects of the trial. (Videotapes of the sessions can be viewed on the conference website at *www.cyber.law.harvard.edu/acivilaction*.) The juror who spoke mentioned growing up on a cotton and tobacco farm where chemicals were routinely sprayed on the crops and that her family used a spray bottle of DDT in the house to kill flies. To this juror, exposure to toxic chemicals was a common, non-deleterious occurrence. The juror also mentioned that water from the Beatrice property could not flow *through* the Aberjona River to the municipal wells. To me, sitting in the audience, it sounded as if the juror considered the hydrologic system to consist of streams of water that could not pass *through* each other, as do beams of light. The juror's comment suggested that the jury may have seen the flow system in only two dimensions and did not understand the importance of the partially penetrating wells, induced infiltration out of the river and wetland downward to the wells, and the three-dimensional character of the capture zones of the wells. If this is true, as a teacher, I find it terribly disappointing – all three hydrologic experts, especially the plaintiffs' and W.R. Grace's, took several hours in their direct testimony to educate the jury on the local geology and the general concepts of surface-water and groundwater hydrology.

Hydrologists invariably are dismayed at the degree of scientific certainty the judge and the lawyers expected of the jury in order to answer the contaminant arrival time questions in special interrogatories #2 and #4 with a precision of one month. However, one of the hydrologic experts stated contaminant travel times in terms of hundredths of a month, seemingly expressing his certainty in the arrival time of the contaminants within plus or minus eight hours. This may have been the precedent for the judge and the lawyers to request the unrealistic degree of scientific certainty stated in special interrogatories #2 and #4. As potential expert witnesses, we should ask ourselves whether the unrealistic degree of scientific certainty requested in special interrogatories #2 and #4 demonstrates a general lack of scientific understanding by the courts, or does it demonstrate our disregard for acknowledging to the general public the uncertainty of our work? Outside the courtroom, we acknowledge that even the most complete model analysis of an actual field problem has limitations and contains uncertainty. Inside the courtroom, uncertainty is usually revealed on cross-examination in attempts by the opposing party to counteract and damage testimony presented during direct examination.

It is interesting to contrast the degree of scientific sophistication employed by the three hydrologic experts to develop their opinions compared with the verdict rendered by the jury.

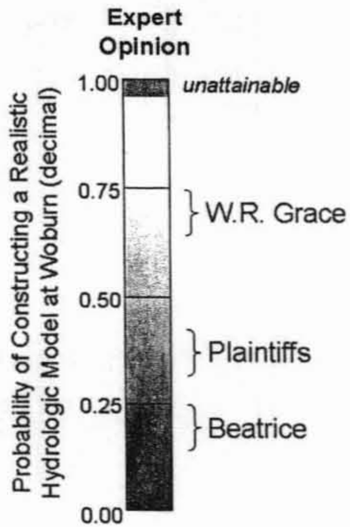

Figure 5.6 Probability of constructing a realistic model of the hydrologic system at Woburn.

Having read over 1800 pages of testimony presented by the three hydrologic experts and having helped construct three-dimensional numerical flow and transport models of the wells G & H area (see Metheny 1998), I rank the degree of sophistication of their approaches according to that shown on Figure 5.6.

The plaintiffs' expert analysed well logs from the valley and uplands, grain-size analyses and slug tests and portrayed the geology as a heterogeneous assemblage of glacial materials. He used this geologic framework to construct an uncalibrated three-dimensional numerical flow and transport model used for illustrative purposes. The one-dimensional analytical equation he used to compute contaminant travel times inadequately incorporated the heterogeneous nature of the glacial materials, converging three-dimensional flow to the pumping wells, induced infiltration from the river and wetland, leakage from bedrock, hydrodynamic dispersion, spatial and temporal variations in recharge, and temporal variations in pumping rates. Based on these limitations, I believe the probability that this analysis realistically represents the flow system when wells G & H were in use to be no more than 40% (Figure 5.6).

The Beatrice expert plotted and analysed the water level and streamflow data from the 30-day pumping test. He constructed no models and made no travel time calculations. This analysis inadequately incorporates the complexity of the interaction between the surface-water and the groundwater flow systems. It ignores the three-dimensional nature of the groundwater flow system created by the partial penetration of the wells and the river. By relying solely on limited field data and not incorporating historic data into a model of any kind, his analysis inadequately accounts for bedrock leakage, aquifer heterogeneity, temporal and spatial variations in recharge, and temporal variations in pumping rates. I believe the probability that this conceptual analysis realistically represents the flow system between 1964 and 1979 to be less than 25% (Figure 5.6).

The W.R. Grace expert used the available geologic, hydrologic and pumping data to construct

a transient three-dimensional numerical flow and transport model of the area that accounted for the heterogeneous character of the glacial materials, partial penetration of the pumping wells and the river, bedrock leakage, spatial and temporal variations in recharge, historic variations in pumping rates, hydrodynamic dispersion, and chemical retardation. It was the most comprehensive analysis and the most sophisticated model. The flow model was calibrated using two sets of measured water level and streamflow gain/loss data. The transport model was not calibrated, although a sensitivity analysis was performed to determine possible ranges of contaminant arrival times at wells G & H. This model incorporated many more of the hydrologic factors affecting surface-water and groundwater flow over the 15-year period wells G & H operated. The model also included more parameters and processes and fewer unrealistic assumptions than the other approaches. I believe the probability is about 75% that this analysis represents the actual behaviour of the flow system during the period when wells G & H were operating (Figure 5.6).

The major difficulties each of the hydrologic experts faced in constructing a reliable hydrologic model that could predict water levels, streamflows and contaminant concentrations were the lack of historic source concentration values of the contaminants and the lack of historic water level, streamflow change, and chemical concentration measurements that could be used as calibration targets. The same difficulties exist today for researchers trying to further understand the hydrology of the site (Myette et al. 1987; de Lima and Olimpio 1989; Metheny 1998). Even though a sophisticated model may calibrate reasonably well to the available data, there are simply inadequate historic data to enable the probability of a reliable analysis to be much better than 70 to 80%. It is the lack of historic data and the uncertainty produced thereby that makes working in the legal arena so challenging.

From the viewpoint of scientific sophistication, the jury's verdict is the inverse of the ranking shown on Figure 5.6 – Beatrice was found not liable and W.R. Grace was found liable. The nagging questions for lawyers and hydrologists studying the Woburn Toxic Trial is whether the science itself was too complicated for the judge and jury, and/or whether the presentation of the science was too confusing.

5.6 CONCLUSIONS

Testimony from the Woburn Toxic Trial shows that predictions from hydrologic models were central to the expert opinions presented to the jury, whereas model calibration was not a major issue brought before the jury (although it was discussed heatedly in depositions and during the trial at several side bars between the lawyers and the judge). Now, fifteen years after the trial, I believe model calibration would be an important part of the direct examination and the cross-examination of each expert hydrologist. Today, the methods of model calibration are much better established and known by the hydrologic community than they were then. Textbooks (Anderson and Woessner 1992) and standards (Brown and Laase 1995) have been written and their influence on modelling studies is pervasive. Philosophic, pragmatic and guidance articles also have been written about model calibration (Bredehoeft and Konikow 1993; McCombie and McKinley 1993; Bair 1994; Oreskes et al. 1994; Woessner and Anderson 1996) and the essential procedures used in hydrologic modelling have become part of the fabric of our discipline. In the interim, expert witnesses have passed this knowledge on to their lawyers, who appear to understand the terms and the methods. This was not true in 1986 when the Woburn Toxic Trial took place. Today, model calibration would be a critical part of the scientific methods applied to the construction of a predictive model used by a hydrologic expert witness. As such, the methods used to calibrate the model would probably be evaluated by the trial judge under the Daubert ruling and model calibration would undoubtedly be highly scrutinised under cross-examination.

Models will always be attractive tools for lawyers and experts to convey information to a jury. Continued advances in image processing and visualization will bring digital animation of model simulations into the courtroom with increasing frequency (Stafford 1998). Models synthesize field data and incorporate physical, chemical and biological processes in a manner that addresses the causal relations that most legal disputes seek to resolve. Models can simulate the unobserved conditions that occurred at the crux of the conflict. The ability of hydrologic models to make reasonable predictions of these conditions, however, will always be dependent on the accuracy of the conceptual hydrogeologic framework and on having sufficient historic data to assure the jury that the model is a realistic representation of reality. Without historic data, rigorous calibration of the model is not possible and the opinions of experts are vulnerable to attack by the opposition – as well they should be. The following statement by Hugh Greenwood (1989) is worth remembering when formulating expert opinions based on model results, 'A model that has no predicted testable consequences is unverifiable and, if not useless, is sterile.' Presentation of a sterile model in the court, before a judge and jury, with the spectre of vigorous cross-examination, is not a prudent legal strategy.

Scientists and engineers need to recognise that the legal system in the United States, unlike the scientific method, is not designed to find the truth. It is designed to resolve conflicts. The primary purpose of a civil trial is to end a dispute. Many hydrologists who testify in court are disappointed by the experience, perhaps this is because their experience demonstrates that the legal system cannot attain the same goal as the scientific method. As stated by Federal Judge Lynn N. Hughes (1999), 'When our legal system works at its best, the court solves the problem by a process that respects the legal conventions, honors the ideal of truth, incorporates the force of reason, recognizes the dignity of the participants, and accepts the necessity of a decision.'

REFERENCES

Anne Anderson et al. v. Cryovac, Division of W.R. Grace & Company; W.R. Grace & Company; John J. Riley Division of Beatrice Foods, Inc.; Beatrice Foods, Inc.; United States District Court for the District of Massachusetts, Civil Action No. 82–1672-S, 1982, Boston, MA.

Anderson, M.P. and Woessner, W.W. 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport.* Academic Press, San Diego, CA.

Bair, E.S. 1994. Model (in)validation – a view from the courtroom. *Ground Water*, **32**(4), 530–531.

Bair, E.S. and Wood, W.W. 1999. *A Civil Action* – what will be the legacy of wells G & H? *Ground Water*, **37**(2), 161–162.

Blauvelt, S. 1999. Expert scientific testimony examined: part 1. PA GEOTECH, *Newsletter of the Pennsylvania Council of Geologists*, **9**(4), 2–6.

Bredehoeft, J.D. and Konikow, L.F. 1993. Ground water models: validate or invalidate. *Ground Water*, **31**(2), 178–179.

Brown, D.E. and Laase, A. 1995. *Standard Guide for Calibrating a Groundwater Flow Model Application C–7*, ASTM Standards on Ground Water and Vadose Zone Investigations, Philadelphia, PA.

Daubert v. Merrel Dow Pharmaceuticals, Inc., 61, U.S.L.W. 4805 (1993)

de Lima, V. and Olimpio, J.C. 1989. Hydrogeology and simulation of groundwater flow at Superfund-site Wells G and H, Woburn, Massachusetts. *US Geological Survey Water-Resources Investigations Report* 89–4059.

Domenico, P.A. and Schwartz, F.W. 1998. *Physical and Chemical Hydrogeology.* John Wiley, New York.

Foster, K.R., Bernstein, D.E. and Huber, P.W. 1993. Science and the toxic tort. *Science*, **261**, 1509, 1614.

Friedland, S.I. 1990. The competency and responsibility of jurors in deciding cases. *Northwestern University Law Review*, **85**(8), 190–220.

Frye v. United States, 293 F. 1013 (D.C. Cir., 1923)

Gerber, R.J. 1987. Victory vs. truth: the adversary system and its ethics. *Arizona State Law Journal*, **19**(1), 3–26.

Greenwood, H.J. 1989. On models and modeling. *The Canadian Mineralogist*, **27**(1), 1–13.

Grossman, L.A. and Vaughn, R.G. 1999. *A Documentary Companion to* A Civil Action. Foundation Press, New York.

Harr, J. 1995. *A Civil Action.* Random House, New York.

Huber, P. 1990. Junk science and the jury. *University of Chicago Legal Forum, The Role of the Jury in Civil Dispute Resolution*, **1990**, 273–302.

Huber, P. 1991. *Galileo's Revenge: Junk Science in the Courtroom.* Basic Books, New York.

Hughes, L.N. 1999. Clients, cogency & candor: the complications of consulting in court. *Abstracts with Programs, Geological Society of America Meeting*, **31**(7), A181.

Jost, K. 1991. Weird science. *American Bar Association Journal*, October.

Kennedy, D. 1989. Death and Justice: Environmental tragedy and the Limits of Science. *The Boston Phoenix*, copyrighted, www.dankennedy.net/woburn_trial.html

Marshall, P.H. 1990. A view from the bench: practical perspectives on juries. *University of Chicago Legal Forum, The Role of the Jury in Civil Dispute Resolution*, **1990**, 147–160.

Matson, J.V. 1994. *Effective Expert Witnessing*, 2nd edition. CRC Press, Boca Raton, FL.

McCombie, C. and McKinley, I. 1993. Validation – another perspective. *Ground Water*, **31**(4), 530–531.

Metheny, M.A. 1998. Numerical simulation of groundwater flow and advective transport at Woburn, Massachusetts, based on a sedimentologic model of glaciofluvial deposition, unpublished Master's thesis, Department of Geological Sciences, Ohio State University.

Myette, C.F. Olimpio, J.C. and Johnson, D.G. 1987. Area of influence and zone of contribution to Superfund-Site wells G and H, Woburn, Massachusetts. *US Geological Survey Water-Resources Investigations Report* 87–4100.

Oreskes, N., Shrader-Frechette, K. and Belitz, K. 1994. Verification, validation, and confirmation of numerical models in earth sciences. *Science*, **263**(February), 641–646.

Pacelle, M. 1986. Contaminated verdict. *American Lawyer*, December, pp. 75–80.

Peters, E.K. 1996. *No Stone Unturned – Reasoning About Rocks and Fossils.* W.H. Freeman, New York.

Prickett, T.A. and Pettyjohn, W.A. 1995. Groundwater modeling and litigation. In: El-Kadi, A.I. (ed.), *Groundwater Models for Resources Analysis and Management.* Lewis Publishers, Boca Raton, FL, 137–145.

Shaw, F.S. and Southwell, R.V. 1941. Relaxation methods applied to engineering problems; VII Problems relating to the percolation of fluids through porous media. *Proceedings Royal Society*, **A178**, 1–17.

Stafford, J.M. 1998. Geoscience and the law. *Geotimes*, May, pp. 18–22.

US Department of Commerce, 1997. *Statistical Abstract of the United States – The National Data Book*, 117th Edition. Economic & Statistics Administration, US Bureau of Census, Washington, D.C.

US Environmental Protection Agency, 1985. National Primary Drinking Water Regulations: Volatile Synthetic Organic Chemicals. 40 CFR 141–142, Federal Register 50 (219).

Van Dyke, J.M. 1987. Trial Courts and Practice. In: Janosik, R.J. (ed.), *Encyclopedia of the American Justice System*, vol. 2, 734–752.

Voss, C.I. 1998. Groundwater modeling: simply powerful. *Hydrogeology*, **6**(4), A4–A6.

Weinstein, J.B. 1986. Improving expert testimony. *University of Richmond Law Review*, **20**(3), 473–498.

Woessner, W.W. and Anderson, M.P. 1996. Good model – bad model, understanding the flow modeling process. In: Ritchey, J.D. and Rumbaugh, J.O. (eds), *Subsurface Fluid-Flow (Ground Water and Vadose Zone) Modeling*, ASTM STP 1288, American Society for Testing Materials, Philadelphia, PA, 14–23.