Pesticide Fate Research Trends within a Strict Regulatory Environment: The Case of Germany

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Working Paper 92-WP 89
February 1992

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Journal Paper No. J-14721 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa; Project No. 2872. The U.S. Environmental Protection Agency and the German Marshall Fund provided financial assistance. Appreciation is also expressed to Mr. Wolfgang Britz, Institut für Agrarpolitik der Universität Bonn, Bonn, Germany and to Brigitte Gassman for their assistance as translators. All views remain those of the author.

Abstract

Germany has adopted tough regulations to prevent environmental contamination from agricultural chemicals. This is exemplified by strict standards for drinking water that limit chemical concentrations to 0.1 part-per-billion (ppb), regardless of toxicity.

Current German regulatory and research trends are described, with an emphasis on basic pesticide fate research. Several key trends are identified: (1) protection of ground water, surface water, and the atmosphere are all important regulatory priorities, (2) computer models, soil lysimeters, and monitoring play critical roles in regulation and research, (3) increased emphasis is being placed upon multidisciplinary studies to address complex research problems, and (4) solutions are being sought to meet the regulatory goal of absolute protection of drinking water, especially ground water.

Keywords: pesticides, regulations, drinking water, computer models, soil lysimeters, monitoring

1. Introduction

Stringent environmental standards are being adopted in Europe in response to environmental degradation from the use of agricultural chemicals. Some of the strongest regulations are being implemented in Germany, especially for ground water, because 73 percent of the people rely on ground water for drinking water (20). Water resource managers, environmental and agricultural agencies, and farmers in Germany are under tremendous public pressure to ensure protection of drinking water sources (14).

This paper examines the trend of pesticide fate research in Germany given this strict regulatory environment. The discussion is based on visits with German scientists and regulatory officials (Table 1) in the fall of 1990. This research does not encompass all pesticide fate research in Germany but does include several key trends in current German practice. Basic research is emphasized rather than specific research performed in support of the pesticide registration process for the Umweltbundesamt (German Environmental Protection Agency). Emphasis is also placed on regulation and research related to ground water.

Several key points emerged: (1) regulation and research is performed by the Umweltbundesamt to protect ground water, surface water, and the atmosphere from pesticide contamination, (2) absolute protection of ground and drinking water supplies has been implemented, (3) computer models, soil lysimeters, and monitoring play critical roles in regulation and research, (4) increased emphasis is being placed on multidisciplinary efforts to address complex research problems, and (5) current aquifer restoration procedures may be inadequate to ensure total protection of ground water as defined by German standards.

Direct references to conversations with the researchers listed in Table 1 are noted in the text by name and superscript[T1]. The discussion is ordered as follows: (1) regulatory environment, (2) soil lysimeter and pesticide monitoring studies, (3) multidisciplinary efforts, (4) applications of computer models, (5) assessment of current German aquifer restoration strategies, and (6) conclusions.

2. Regulatory Environment

Current German drinking water standards, based on 1983 European Community (EC) standards, were established in 1989 (14). These standards set a maximum concentration level of 0.1 parts per billion (ppb) for a single contaminant and 0.5 ppb for all pesticides detected, including metabolites. These criteria are applied across all chemicals, irrespective of chemical toxicity. In 1990, 20 percent of all German water works could not comply with these stringent drinking water standards (14).

Albrecht Klein[T1], a member of the German delegation to the EC environmental protection initiative, stresses that German law is designed for absolute ground water protection. Thus, ground water detections of pesticides and biologically relevant metabolites must be below the drinking water tolerances (0.1 and 0.5 ppb) and also meet ecological requirements. Günter Klein[T1] is a strong supporter of this objective and insists that no one has the right to "inject" chemicals into ground water at any concentration. While acknowledging that typical pesticide levels detected in drinking water supplies are probably of little human health consequence, he emphasizes that the natural balance of the entire ecosystem must be considered when water quality is defined.

A key German directive is the establishment of protection zones around drinking water supplies. A protection zone for pesticides is the area that is required to obtain the annual ground water recharge volume equivalent to the maximum annual pumping volume licensed to an individual water work. The application of a pesticide within a protection zone can be restricted or forbidden if it possesses "ground water endangering" properties (e.g. very persistent and/or very mobile).

An important clause within the directive is that the tolerance levels (0.1 and 0.5 ppb) can be exceeded for up to two years by a water work, provided that concentrations do not exceed health standards based upon toxicity data for the chemicals in question (Leuchs[T1]). The decision to grant exceedance, and the length of the exceedance period, is decided by the German Health Agency (Bundesgesundheitsamt). Within this period, an aquifer restoration plan or modification of management practices (or both) must be implemented. If the restoration attempts and/or management modifications prove successful, further extension of the exceedance period can be granted to a water work.

To further reduce agricultural impacts on drinking water, some Länder (states) such as Baden-Württemberg are buying out producers in vulnerable watersheds and permanently retiring the land from intensive agricultural production (Teutsch[T1]). Filter strips are also being purchased by some Länder along all key surface water bodies to minimize agricultural impacts upon surface water (20).

The use of many pesticides has been restricted or eliminated in Germany. For example, in 1988 application of the herbicide atrazine was eliminated in protection zone areas due to its potential to contaminate ground water (21). The German government then went one step further and canceled all atrazine agricultural use starting with the 1990 season (Albrecht Klein[T1]). In total, the number of active ingredients permitted for agricultural use has declined from 308 in 1987 to 216 in 1990, a reduction of nearly 25 percent (7).

2.1. The Pesticide Registration Process

The amended German Plant Protection Act of 1986 stipulates that a pesticide can become licensed if it satisfies criteria established by the Umweltbundesamt that no damage will occur to ground water, to surface water, or through atmospheric pathways to terrestrial systems (16). To assess potential damages from pesticide use, exposure analyses are performed for these environmental compartments by the Umweltbundesamt. Only the ground water exposure analysis is discussed in detail here.

The Umweltbundesamt uses three levels of decision making to determine whether a chemical will leach to ground water (11). The first is a screening procedure that considers the following criteria: (1) water solubility > $2.8(10^{-4})$ ounces/gallon, (2) organic carbon sorption constant (K_{oc}) < 500, (3) sorption coefficient (K_d) < 10, and (4) soil half life > 21 days. If a pesticide satisfies any one of these conditions, the next level of assessment must be performed.

The second level of decision making uses computer models to simulate pesticide leaching by accounting for chemical parameters, application amount and timing, total number of applications, soil properties, and climatic conditions. Since 1987, the Umweltbundesamt has used a modified version of the Pesticide Root Zone Model (PRZM) (3), developed by the United States Environmental Protection Agency (USEPA) (Albrecht Klein[T1]). The modified model has been extensively tested with long-term data and compares favorably with output produced by similar models. The modified PRZM is used to perform a standard set of simulations for four soil types (sand, clay, and two intermediate) and three climatic scenarios (dry, normal, and wet). If PRZM indicates the root zone leachate for any of the simulation scenarios contains 0.1 ppb or more of pesticide active ingredient then the third level must be performed--outdoor soil lysimeter tests.

The lysimeter tests require undisturbed soil cores, illustrated in Figure 2, 39.4 to 51.2 inches deep with a minimum area of 5.4 square feet (10.8 square feet is preferred). The combined clay and silt content of the soil cannot exceed 30 percent for the entire soil profile (the remainder being sand), with the added stipulation that the clay content must be under 10 percent. The organic carbon content of the soil cannot exceed 1.5 percent. The yearly precipitation should be at least 31.5 inches per year (the average amount for Germany) to approximate representative water movement and leaching. If local precipitation is less than 31.5 inches per year, then irrigation water must be applied through monthly adjustments determined from long-term monthly means of the representative conditions.

The applied pesticide must be radioactively labeled and applied at the highest label rate during the recommended application time. If more than one application period is possible, then the worst case situation based on simulation results with PRZM or similar models should be used. Typical management practices for fertilization, tillage, and planting time are also required. The total amount of radioactive material in the leachate and in the soil column must be accounted for at the end of the test, which normally takes about two years. If a second application is required one year later then the experiment will run for three years. Again, the Umweltbundesamt criteria of unacceptable water contamination are applied to determine whether the chemical can be marketed. If a pesticide registration is denied on the basis of lysimeter tests, then the registrant can challenge the decision by performing representative field studies to determine if the conclusions reached from the previous levels are valid (16). However, interim registration is not allowed while the field studies are performed.

3. Lysimeter Research and Pesticide Monitoring

Lysimeters play a critical role in the registration of pesticides in Germany. Lysimeter research is being conducted at a variety of German institutes, universities, and pesticide manufacturers. The most intensive work is conducted at the Institute for Radioagronomy, a division of the Nuclear Research Center in Jülich. The Institute conducts both lysimeter and field studies and is engaged in basic research and contractual work for chemical companies attempting to register pesticide compounds. Currently the Institute possesses the largest lysimeter station of its kind in the world (12), with a total of 50 outdoor lysimeters (Figure 2) distributed among 10 experimental beds of five lysimeters each over a total area of 27,000 square feet. The Institute also possesses more pesticide movement and degradation data than does any other research group in the world (Führ[T1]).

To construct the lysimeters, undisturbed soil cores 43.3 inches deep with an area of 5.4 or 10.8 square feet are obtained from an 18.5-acre field located 9 miles from Jülich and from a 2.5-acre field near Kaldenkirchen. The cores are encased in stainless steel cylinders embedded within control areas cultivated with the same crop. Two soil types are used: (1) Parabraunerde (orthic luvisol), a fertile soil widespread in Germany and used extensively in agriculture and (2) a sandy soil (gleyic cambisol) with less than 1.5 percent organic carbon and more than 70 percent sand permitting greater leaching.

Pesticides radio-labeled with ^{14}C are applied to the lysimeters as illustrated for the herbicide metamitron in Figure 2. This labeling allows for processes of plant metabolism and uptake, leaching and soil translocation, and binding of residues to soil to be studied at a level of detail impossible by conventional means. Instrumentation has also been recently developed to measure volatilization losses. Figure 3 shows the general fate of organic chemicals in the soil as determined by 20 years of lysimeter research with nearly 50 different pesticides at Institute for Radioagronomy. In general, the amount of bioavailable chemical able to leach below the root zone declines greatly with time. Chemicals can also become bound within the soil matrix for relatively long periods. Extensive discussion of these processes can be found in the literature (8,9,10,12).

3.1. Pesticide Monitoring

One of the earliest pesticide monitoring studies of German ground water was performed in Baden-Württemberg in 1983 (13). The herbicide atrazine was the most frequently detected chemical in this study, at a maximum concentration of 0.5 ppb. Monitoring of pesticides in ground water and surface water has since become increasingly important because of the stringent German drinking water standards. Increased emphasis is also being placed on monitoring of air and rain water.

For example, monitoring studies have been conducted by the State Agency for Water and Waste, North Rhine-Westphalia, to quantify the extent of pesticide contamination of North Rhine-Westphalia ground water (18) and surface water (19). In 1987, 190 wells representative of vulnerable ground water situations, e.g. shallow ground water table, soils with weak adsorption capacity, and intensive agricultural practices, were sampled throughout North Rhine-Westphalia (18). In 1988, 186 wells were sampled in Münsterland, a subarea of North Rhine-Westphalia implicated as a particularly vulnerable area in the 1987 study (18).

Of the samples, 61 percent and 74 percent yielded no detectable pesticides in 1987 and 1988, and only 11 percent in both years contained concentrations greater than 0.1 ppb. But in ground water partly recharged by surface water, more than half of the samples contained detectable residues, of which 42 and 39 percent exceeded the tolerance limit of 0.1 ppb in 1987 and 1988. Atrazine was the most frequently detected chemical in both monitoring studies.

Surface water monitoring in 1989 of three small rivers in Northwest Münsterland revealed the presence of several herbicides (19). Of greatest importance were elevated levels of isoproturone in April and atrazine in June, resulting from different application periods and precipitation events. The highest concentration of any detected chemical was atrazine at 12 ppb. In general, pesticide concentrations detected in North Rhine-Westphalia surface water, especially small rivers in rural watersheds, are higher than those detected in ground water.

Atrazine has also been detected in the range of 0.1 to 1.0 ppb in North Rhine-Westphalia rainwater, even after its cancellation in 1990 (Leuchs[T1]). Continued detection of atrazine could be due to use in the neighboring Netherlands or from illegal application in North Rhine-Westphalia. The atrazine substitute terbuthylazine has also been detected in rainwater since the cancellation of atrazine. Atrazine, terbuthylazine, and five other pesticides have also been detected in Baden-Württemberg rainwater by researchers at the University of Hohenheim (30).

4. **Multidisciplinary Efforts**

The complexity of agricultural environmental problems has resulted in increased emphasis upon multidisciplinary studies in Germany. A prime example is a project initiated at the Horkheimer Insel (Horkheimer Island) environmental research field site, located 44 miles north of Stuttgart in Baden-Württemberg (26). Researchers include agricultural engineers, hydrogeologists, civil engineers, chemists, computer scientists, and soil scientists, who together represent several institutes from three universities in Baden-Württemberg.

The Horkheimer Insel is located between the Neckar canal on the east and the Neckar river to the west and covers a total area of about 4.9 acres. The site has been extensively instrumented with monitoring wells, piezometers, and other related equipment to monitor the movement of agricultural chemicals below the soil surface. It is divided into two fields so that two different agricultural systems representing conventional and sustainable agriculture can be compared. On one field, conventional farming practices using standard amounts of pesticides and of fertilizers are used with a corn/winter wheat crop rotation. On the second field, a sustainable system with reduced tillage and fewer chemical inputs is used with the same rotation.

Ultimately, the goal is to develop a sustainable agricultural system that is environmentally sound and maintains the economic welfare of the producer. Initial results show greater reductions in nitrate leaching (pesticide leaching results are not available yet) below the sustainable field, than below the conventional field, with only slightly reduced crop yields for the sustainable system. It is hoped that crop yields will be maintained over the long term for the sustainable system.

A second multidisciplinary project has been initiated north of Munich in Bavaria on a 371-acre agricultural site (6). Again, the goal is to develop sustainable agricultural systems that are both economically and environmentally sound. The project is designed to be completed in three phases covering the period 1990-97. Participants in the project represent 12 institutes from the Technical University of Munich, six institutes from the National Center for Environmental Sciences in Munich-Neuherberg, the Bavarian State Ministry of Geology, and the Bavarian State Ministry of Soil Culture and Plant Production. A total of 25 separate subprojects will be carried out within the context of the study.

5. Applications of Computer Models

Stringent German drinking water standards have generated interest among many researchers in developing or applying pesticide leaching models predicting the amount of chemical that will leach to ground water. This is an important component of many field research projects such as the Horkheimer Insel, by which extensive data has been collected to construct and to test both unsaturated and saturated zone models. Much of the current interest focuses on testing models developed in the United States.

Teutsch[T1] is testing the USEPA Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations (RUSTIC) model (4), a linked modeling system incorporating unsaturated and saturated zone (ground water) models within a Monte Carlo framework, with data from the Horkheimer Insel. He hopes to determine which parameters influence pesticide leaching the most and to apply RUSTIC, or a similarly constructed model, to larger regions within Baden-Württemberg. Huwe[T1] is also developing similar models to predict pesticide and nutrient fate based on data from the Horkheimer Insel.

Three unsaturated root zone models developed in the United States--PRZM, the Leaching Estimation and Chemistry Model (LEACHM) (31), and the Ground

Water Loading Effects of Agricultural Management Systems (GLEAMS) model (17)--have been tested with soil data obtained from the upper two soil horizons at the Horkheimer Insel and from a site near Braunschweig (14). For this test, atrazine, terbuthylazine, and bromide (a conservative tracer) were applied to four different soils packed in steel columns. Simulated results for the three models were generally within a factor of two as compared with measured values. Estimates by PRZM and by LEACHM were more accurate than those by GLEAMS.

Model testing is also being performed with lysimeter data. At the Institute for Plant Protection, Hohenheim University, PRZM and LEACHM simulations are being compared against lysimeter leaching data (Häussler[T1]). The PRZM is also being tested with lysimeter data by researchers at the Institute for Radioagronomy in Jülich (Brumhard[T1]) and in its modified form at the Fraunhofer Institute for Environmental Chemistry and Ecotoxicology in Schmallenberg[1].

5.1. **Multimedia Pesticide Fate Modeling**

Increased emphasis on protecting surface water and the atmosphere, as well as ground water, from pesticide contamination has motivated the development of a multimedia pesticide fate modeling system called Simulation Network Atmosphere-Plant-Soil (SNAPS) (24). It is partially based on the Exposure and Ecotoxicity Estimation for Environmental Chemicals (E4CHEM) modeling system that was developed for exposure and hazard assessment of new and existing chemicals (22). Probably the most intensive pesticide fate modeling effort currently being attempted in Germany, the system uses six different models (Table 2) to describe the processes of chemical transport in the atmosphere, unsaturated soil zone, plants, ground water, and surface water. Both parent

[1]Klein, A. 1991. Personal communication. Umweltbundesamt, Berlin, Germany.

compounds and metabolites can be simulated in all environmental media in SNAPS. Model interactions are accomplished through data exchanges among the various modules depicted in Figure 4. Particular attention is paid to the compatibility of the different models and their interfaces due to differences in spatial structure and transport dynamics in the various environmental media.

The SNAPS is menu-driven and can be executed on any standard IBM personal computer. An extensive chemical database has also been developed for use with the system. Modeling validation studies have now been performed for several components of the system. The SNAPS is only partially completed and is being further developed within the multidisciplinary project in Bavaria described previously. Additional information on specific modules can be found in the literature (22,23,24,27,28,29).

5.2. Integrated Ecological/Economic Modeling Systems

Pesticide fate models are also being applied within integrated economic/ecological modeling systems in Germany (Jarosch[T1] and Werner[T1]). The catalyst for these systems is the growing awareness that many complex policy and management questions can be answered only within a modeling framework. These integrated systems link environmental models used to simulate leaching or runoff of pesticides and nutrients with economic optimization models such as linear programming models. In general, the systems are designed for farm-scale applications and optimize farming and land use systems for both economic and ecological criteria. The conceptual aspects and modeling systems are described in greater detail elsewhere (15,32).

An emerging trend is that of applying integrated economic/ecological modeling systems within a multidisciplinary framework for regional analyses.

An example is a system configured to provide economic and ecological optimization for all 3,000 farms covering 236 square miles within one Landkreis (county) in the state of Lower Saxony (1). Currently, both leaching and ground water models are used within the system to simulate nitrate movement to ground water drinking supplies. Pesticide movement will be simulated in future applications.

6. Assessment of German Ground Water Restoration Procedures

Both computer simulation and field (aquifer) research were used in a unique study by Leuchs[T1], Obermann[T1], and colleagues to assess the effectiveness of a two-year aquifer restoration strategy (18). The study embodies many of the previously discussed research trends and regulatory issues and provides critical insight into the problems associated with ensuring absolute ground water protection.

6.1. Aquifer Injection Study

For the initial phase, water contaminated with atrazine, chlortolurone, isoproturone, simazine, and terbuthylazine each at 1 ppb was injected at a constant rate over 80 days into a quartenary (gravel and sand) aquifer in the Niederrhein region of North Rhine-Westphalia (18). Transport and retardation behaviors of the pesticides were studied for travel distances of 32.8 and 164 feet (5).

The retention capacity of the aquifer was very restricted, and continuous injection of pesticides eventually overwhelmed the retention capabilities of the aquifer material. Moreover, pesticide degradation did not seem to take place, because no major metabolites were detected for any of the five chemicals during the study. The results suggest that once the retention capacity of the aquifer material has been surpassed, there is no buffer mechanism to impede pesticide movement. The investigators stress that this is especially important when considering inhomogeneities in aquifer properties such as variation in organic carbon concentration. For example, "hot spots" of high organic carbon concentrations that contain correspondingly high pesticide concentrations could result in continued release of pesticide after an aquifer is declared restored. This would have major implications for any aquifer restoration program in which total purity is required.

6.2. Ground Water Simulation for a Hypothetical Water Supply

The second phase of the analysis used a ground water flow model and a chemical transport model to simulate pesticide movement to a hypothetical water supply representative of conditions in North Rhine-Westphalia (18). Spatial and hydrologic parameters used for the simulation are given in Table 3. Both homogeneous distribution of the sorptive substances and hydraulic conditions were assumed for the simulated aquifer. Based on the aquifer injection experiment, a linear adsorption K_d value of 0.3 was assumed and chemical desorption and decay were not simulated.

The simulation was performed for 25 years using three-month time increments. Ground water contamination was simulated for two point sources (Figure 5) for one three-month time step during each year of discharge. The first source was an 11.6-acre field located 1870 feet from the well gallery assumed to discharge leachate contaminated with 10 ppb chemical over a five-year period. The second source was a creek assumed to discharge leachate contaminated with 15 ppb chemical over a 13-year period. Concentrations were simulated for one ground water monitoring well (M) and for two water supply wells denoted as W1 and W2 (Figure 5).

The legal limit was exceeded for well M in year two and for well W1 in year three as depicted in Figure 5. Maximum concentrations were predicted to occur approximately two years after the leaching inputs from the field stopped, as a result of chemical retardation in the aquifer. Following the peak, another four to five years were required for the concentrations in wells M and W1 to fall below the legal limit. Continued leaching input from the creek over 13 years eventually reached well W1 in year 15, several years after the restoration had taken place. The concentrations then continue to rise and nearly exceed the legal limit by year 25, again as a result of chemical retardation. In contrast, the concentrations for well W2 never came close to exceeding the legal limit, a fact demonstrating how much variation can occur if the pollution originates from a point source.

6.3. Recommendations for Protecting Water Supplies

Leuchs[T1], Obermann[T1] and colleagues maintain that it could take years or even decades until pesticide restrictions or bans lead to decreased well chemical concentrations in sensitive areas, based on the modeling and aquifer injection studies. These researchers believe it is unlikely that an aquifer restoration program would be successful within the trial period of two years and view the trial period as an extraordinary right that most likely will be prolonged several times.

They advocate a series of measures that should be taken in water supply recharge areas to protect potable water sources (18). Some of these measures are as follows: (1) only pesticides possessing properties of high soil adsorption and fast degradation should be used in recharge areas, (2) regular monitoring should be conducted upstream of supply wells at a distance of six months flow time to provide early warning of chemical movement (and to allow prediction of chemical movement to wells with computer models), (3) best management practices and buffer zones should be adopted to prevent surface water pollution, and (4) no or extremely reduced pesticide use should be enforced in tile drained areas.

7. **Conclusions**

There is a wealth of pesticide fate research information available from German sources, much of it published only in German. This information is particularly useful for those interested in protecting drinking water in the United States, because the German goal has been to establish absolute ground water protection. Indeed, perhaps the most important lesson to be gleaned from the German experience is that absolute protection may be impossible with current agricultural practices and aquifer restoration procedures, as shown by the work of Leuchs et al. (18).

Another important point are differences between the Umweltbundesamt and USEPA leaching evaluation procedures[2]. These organizations use similar screening approaches in their initial evaluation of a chemical's propensity to leach. But the USEPA uses standardized modeling and lysimeter tests only for pesticides such as sulfonylureas that are applied at very low rates. Instead, the agency relies heavily upon two-year field studies requiring soil, soil water, and ground water monitoring. In general, this distinction holds for other environmental compartments.

The regulatory applications of lysimeters and computer models in Germany warrant close inspection. Lysimeter research forms the basis of the leaching evaluation procedures used by the Umweltbundesamt. This approach could be useful for regulatory counterparts in the United States. In general, the data

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[2]Behl, E. 1991. Personal communication. Office of Pesticide Programs, United States Environmental Protection Agency, Washington, D.C.

generated from these lysimeter studies is a valuable source of information for anyone studying the fate of pesticides in the environment.

The application of PRZM (and other models) for pesticide registration requirements is also important. Some German researchers express doubt that PRZM (or any other model) is sufficiently accurate for this purpose even though its use by the Umweltbundesamt is standard procedure. Albrecht Klein acknowledges that the modeling procedures are not as precise as desired[3]. However, he emphasizes that from the perspective of ensuring groundwater protection, the modeling results have not generated any false decisions in requiring lysimeter tests. American researchers and regulatory officials would benefit from reviewing the pros and cons of using PRZM this way and examining how its application has impacted the German pesticide registration process.

Some of the trends identified are similar to research trends in the United States. For example, integrated economic/ecological modeling systems are also being developed in the United States (25). However, major differences exist between these systems, such as the spatial scales that are being applied. Increased interaction between American and German counterparts could yield better insight on how spatial scaling and other differences impact the results of these systems. Similar collaboration in other research areas would also be beneficial. Such interaction becomes more and more important as environmental problems grow increasingly complex. This is especially true if the United States adopts similar environmental standards that have been implemented in Germany and other European countries.

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[3]Klein, A. 1991. Personal communication. Umweltbundesamt, Berlin, Germany.

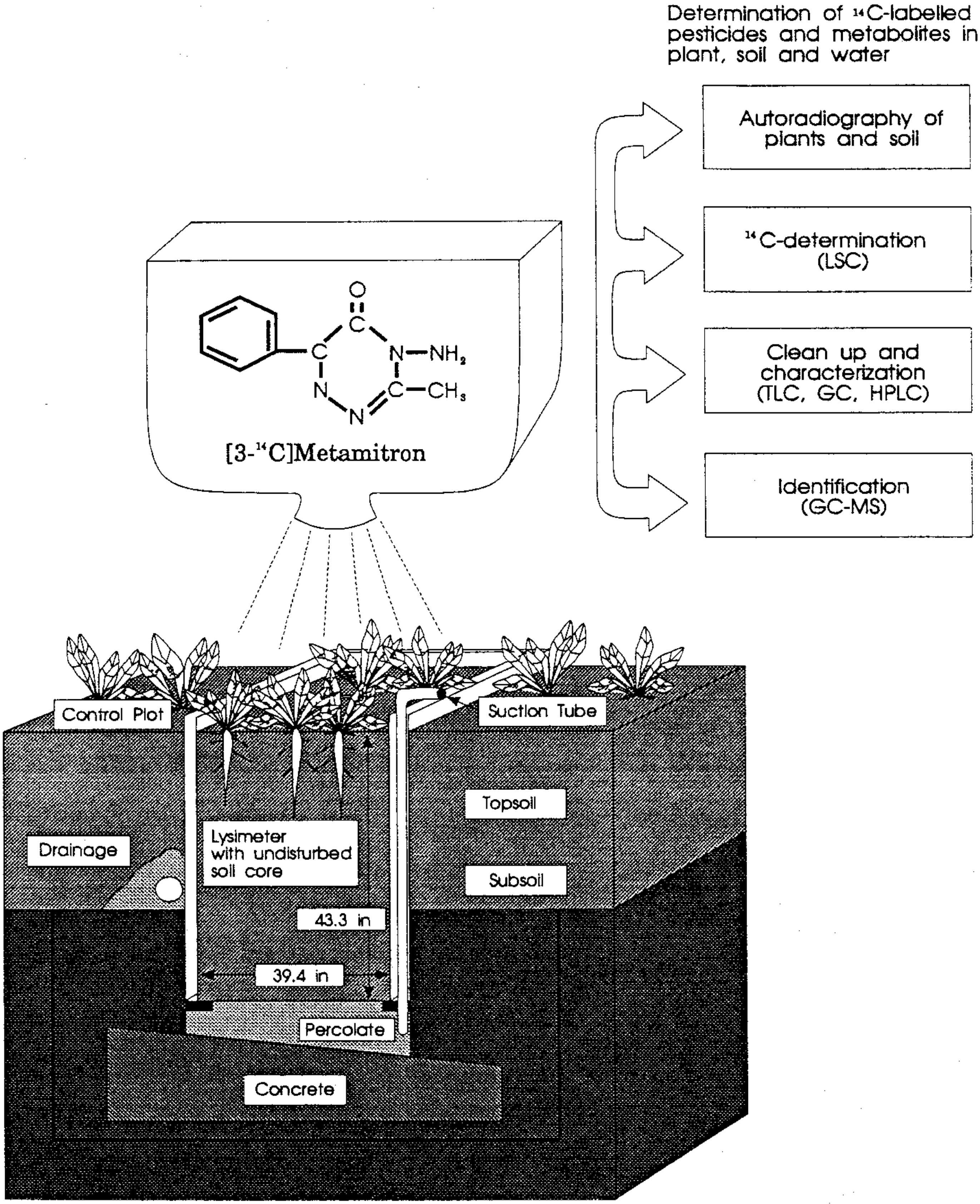

Figure 1. Standard lysimeter configuration for analyzing movement and degradation of ^{14}C-labeled pesticides (Führ et al. 1990)

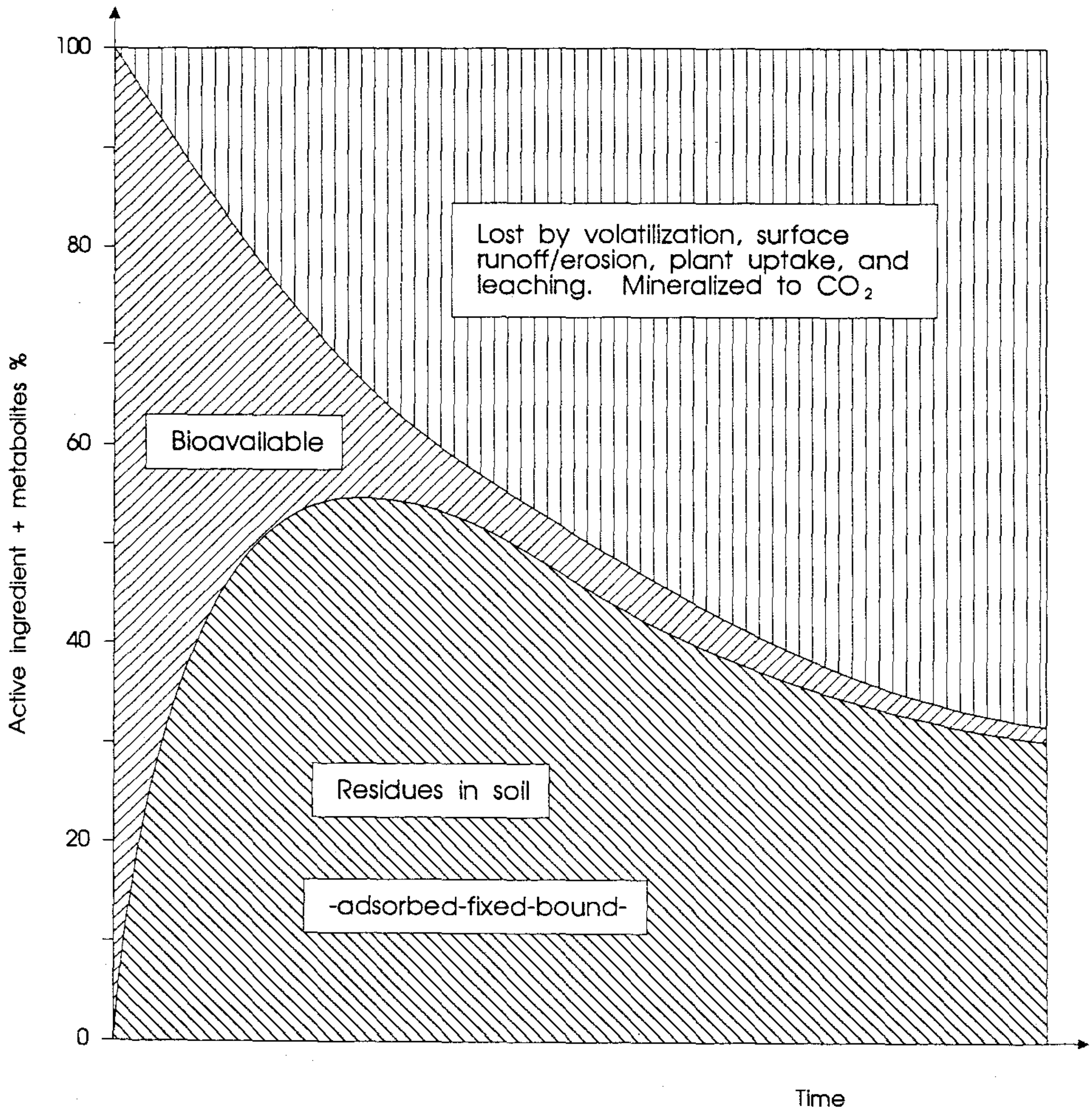

Figure 2. The general fate of organic chemicals in soil (Führ 1991)

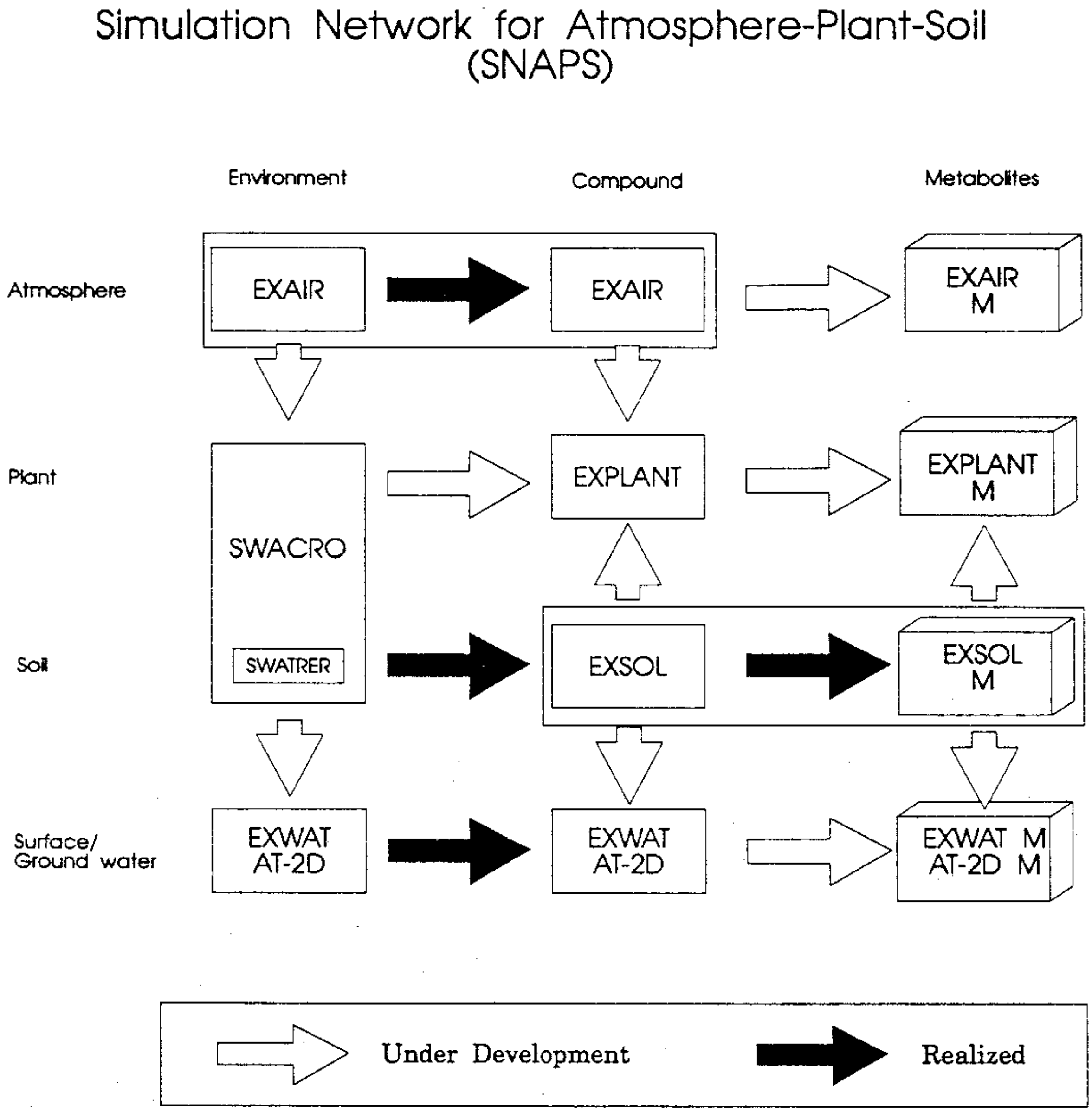

Figure 3. Simulation model network atmosphere-plant-soil-water (Matthies et al. 1990)

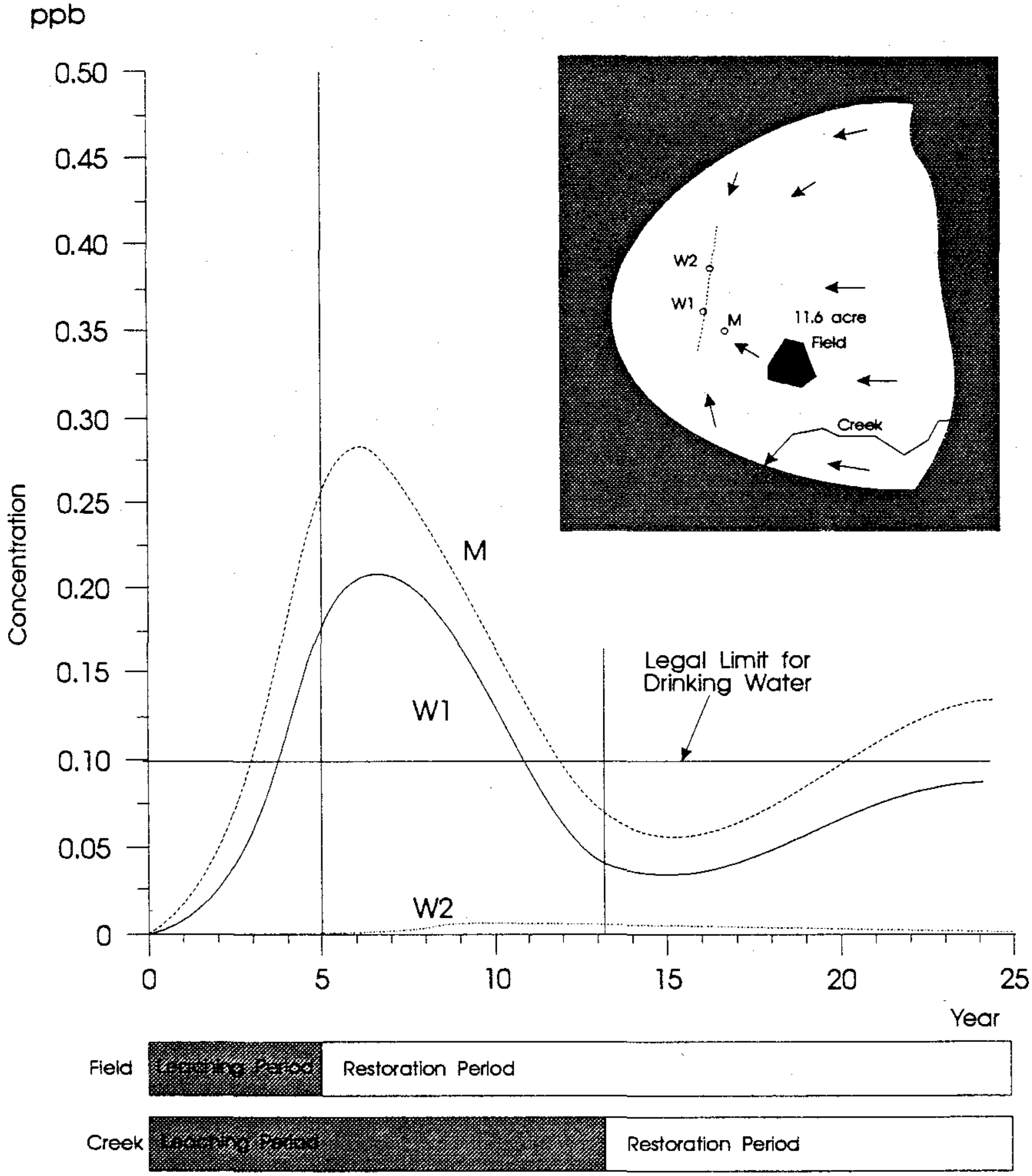

Figure 4. Simulated chemical concentration breakthrough curves for two water supply wells (W1 and W2) and one groundwater monitoring well (M) for a hypothetical recharge area (100 time steps = 25 years). The pollutant sources were the 11.6 acre field and the creek. The arrows show the direction of groundwater and creek flow (Leuchs et al. 1990)

Table 1. German institutes and researchers visited; major topics discussed*

Institute or Agency/Location	Researcher	Topic
Institute for Radio Agronomy, Nuclear Research Center/Jülich	Prof. Dr. Fritz Führ Dr. Björn Brumhard	•Lysimeter studies; applications of models
Environmental Protection Agency/Berlin	Dr. Albrecht Klein	•Regulation of pesticides
Institute for Water, Soil and Air Hygiene/Berlin	Dr. Günter Klein	•Water quality; regulation of pesticides
National Center for Environmental Sciences/Munich	PD. Dr. Michael Matthies PD. Dr. Friedrich Beese	•Environmental modeling •Large-scale field study
Department of Hydrogeology, Ruhr University/Bochum	Prof. Dr. Peter Obermann	•Monitoring, aquifer, modeling stuides
State Agency for Water and Waste (North Rhine-Westphalia)/Düsseldorf	Dr. Wolfgang Leuchs	•Monitoring, aquifer, modeling studies
University of Hohenheim/Stuttgart		
- Institute for Soil Science	Dr. Bernd Huwe	•Horkheimer Insel field study, application of models
- Institute for Soil Chemistry	Dr. Harald Giessl**	•Pesticide monitoring studies
- Institute for Agricultural Economics	Dr. Rolf Werner Dr. Jürgen Jarosch**	•Coupled environmental/economic models
- Institute for Plant Protection	Mr. Wolfgang Häussler Mr. Von Ch. Oberwalder	•Monitoring and lysimeter studies; application of models
Hydraulic Engineering Department, University of Stuttgart/Stuttgart	Prof. Dr. Georg Teutsch	•Horkheimer Insel field study; application of models

*Appreciation is expressed to Dr. Jürgen Jarosch for setting up the Stuttgart meetings and to Mr. Hans Kretschmer, formerly of the Institute for European Environmental Politics in Bonn, for arranging the other meetings.

**No longer working at listed institute.

Table 2. Model characteristics and major input data categories for the different modules of SNAPS (24)

Model	Characteristics	Input Data Categories
EXAIR	analytical box model for atmospheric transport	physicochemical data, meteorological statistics, deposition rates
EXSOL	multilayer soil model for transport and fate in the unsaturated soil zone	physicochemical data, soil characteristics, climatological data
EXWAT	steady-state compartment model for transport and fate in surface waters	physicochemical data, hydrological characteristics, meteorological data
EXPLANT	fugacity based uptake model via roots and foliage	physicochemical data, plant and soil data, air flow
SWACRO/ SWATRER	soil water dynamics in the unsaturated zone, biomass development for crops	soil hydraulic functions, max. root water uptake distribution, rooting depth, crop development stages
AT-2D	analytical transport model, two dimensions	convection, dispersion, sorption, degradation

Table 3. Parameters used in modeling study (18)

Parameter	Value
Aquifer thickness	39.4 ft
Hydraulic conductivity	$1.64(10^{-3})$ ft/sec
Recharge rate	11.8 in/yr
Total recharge area	1.60 mi^2
Annual inflow from surrounding aquifer	$10.8(10^6)$ ft^3/yr
Infiltration from creek	$0.57(10^6)$ ft^3/yr
Annual water withdrawal (from 23 wells)	$53.0(10^6)$ ft^3/yr
Longitudinal dispersivity	98.4 ft
Vertical dispersivity	1.0 ft

References Cited

1. Arbeitsgruppe Systemforschung. 1991. Nitratversickerung im Kreis Vechta: simulationen und ihr Praxisbezug. Endbericht zum Projekt: Intensivlandwirschaft und Nitratbelastung des Grundwassers im Kreis Vechta. Universität Osnabrück. Forschungszentrum Jülich GmbH, Jülich, Germany.
2. Behrendt, H., M. Matthies, H. Gildemeister, and G. Görlitz. 1990. Leaching and transformation of glufosinate-ammonium and its main metabolite in a layered soil column. Envr. Toxc. and Chem. 9:541-549.
3. Carsel, R.F., L.A. Mulkey, M.W. Lorber, and L.B. Baskin. 1985. The pesticide root zone model (PRZM): a procedure for evaluating leaching threats to groundwater. Ecological Modelling 30(1985):49-69.
4. Dean, J.D., P.S. Huyakorn, A.S. Donigian, Jr., K.A. Voos, R.W. Schanz, and R.F. Carsel. 1989. Risk of unsaturated/saturated transport and transformation of chemical concentrations (RUSTIC), volume II: user's guide. EPA/600/3-89/048b.
5. Denzig, D. 1989. Retardations- und Abbauverhalten von Planzenbehandlungs-mitteln (PBM) in einem Porengrundwasserleiter. Unveröff. Diplomarb., Ruhr-Universität Bochum, Germany. 107 p.
6. FAM (Forchungsverbund Agrarökosysteme München). 1991. Erfassung, Prognose, und Bewertung nutzungsbedingter Veränderungen in Agrarökosystemen und deren Umwelt. FAM-Sekretariat, GSF-Forschungszentrum für Umwelt und Gesundheit GmbH, München-Neuherberg.
7. Finney, J. F. 1991. Where do we stand--where do we go?. In: Pesticide Chemistry; Advances in International Research, Development, and Legislation. H. Frehse (ed.). VCH Verlagsgesellschaft mbH, Weinheim, Germany. pp. 555-576.

8. Führ, F. 1984. Agricultural pesticide residues. In: Isotopes and Radiation in Agricultural Sciences; Volume 2: Animals, Plants, Food, and the Environment. M.R. L'annunziata and J.O. Legg (eds.). Academic Press, London, England. pp. 239-270.

9. Führ, F. 1985. Application of ^{14}C-labeled herbicides in lysimeter studies. Weed Science 33(Suppl. 2):11-17.

10. Führ, F. 1986. Non-extractable pesticide residues in soil. In: Pesticide Science and Biotechnology. R. Greenhalgh and T.R. Roberts (eds.). Blackwell Publ., Oxford, England. pp. 381-389.

11. Führ, F., M. Herrmann, A.-W. Klein, C. Schlüter, F. Herzel, W. Klein, R. Kloskowski, H.-G. Nolting, and K. Schinkel. 1990. Richtlinien für die Prüfung von Pflanzenschutzmitteln in Zulassungsverfahren; 4-3: Lysimeteruntersuchungen zur Verlagerung von Pflanzenschutzmitten in den Untergrund. Biologische Bundesanstalt für Land- und Forstwirtschaft der Bundesrepublik Deustchland, Braunschweig, Germany.

12. Führ, F., W. Steffens, W. Mittelstädt, and B. Brumhard. 1991. Lysimeter experiments with ^{14}C-labelled pesticides--an agroecosystem approach. In: Pesticide Chemistry; Advances in International Research, Development, and Legislation. H. Frehse (ed.). VCH Verlagsgesellschaft mbH, Weinheim, Germany. pp. 37-48.

13. Giessl, H. and K. Hurle. 1984. Pflanzenschutzmittel und Grundwasser. Agrar- und Umweltforschung in Baden-Württemberg 8.

14. Harter, T. and G. Teutsch. 1990. Pesticide transport models: comparison and validation with soil column leaching experiments. In: Pesticides in the next decade: The challenges ahead, proceedings of the Third National Research Conference on Pesticides. Weigman, D.L. (ed.). Virginia Water Resources Research Center, Blacksburg, Virginia.

15. Jarosch, J. 1990. Economic and ecologic evaluation of environmental policy strategies in agriculture. Presented at the International Conference on Environmental Cooperation and Policy in the Single European Market. Venice, Italy, April 17-20.

16. Klein, A.-W., L. Fiedler, P. Muhs-Bonte, C. Schluter, W. Klein, and W. Kordel. 1988. Environmental assessment of pesticides--a conceptual approach. Chemosphere 17(8):1391-1410.

17. Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. Trans. ASAE 30(5): 1403-1418.

18. Leuchs, W., M. Niessner, W. van Berk, C. Skark, and P. Obermann. 1990. Vorkommen von Pflanzenbehandlungs- und Schädlingsbekämpfungsmitteln in Grundwässern Nordrhein-Westfalens und Folgerungen für Sanierungskonzepte (Origin of pesticides and herbicides in groundwater in Northrhein-Westphalia and conclusions for rehabilitation schemes). Wasser und Boden 3(1990): 131-137.

19. Leuchs, W., E. Plöger, H. Friege, U. Vogt, and P. Obermann. 1991. Pestizide in Oberflächengewässern Teil 2: Belastungsursachen und ihre Wirkungen auf das Grundwasser--Situation im nordwestlichen Münsterland (Pesticides in surface waters part 2: sources of contamination and their effects on groundwater--situation in the northwest district of münsterland). Vom Wasser 76(1991): 39-50.

20. Manale, A. P. 1991. European community programs to control nitrate emissions from agriculture. International Environmental Reporter 14(12): 345-354.

21. Manale, A. P. 1991. Status of atrazine in the federal republic of germany. CEEPES Atrazine Project Research Memo 2. Center for Agricultural and Rural Development, Department of Economics, Iowa State University, Ames, Iowa.

22. Matthies, M., R. Brüggemann, B. Münzer, G. Schernewski, and S. Trapp. 1989. Exposure and ecotoxicity estimation for environmental chemicals (E4CHEM): application of fate models for surface water and soil. Ecol. Model. 47(1989):115-130.

23. Matthies, M. and H. Behrendt. 1991. Pesticide transport modeling in soil for risk assessment of groundwater contamination. Toxc. and Envr. Chem. 31-32:357-365

24. Matthies, M., H. Behrendt, and S. Trapp. 1991. Modeling and model validation for exposure assessment of the terrestrial environment. In: Pesticide Chemistry; Advances in International Research, Development, and Legislation. H. Frehse (ed.). VCH Verlagsgesellschaft mbH, Weinheim, Germany. pp. 433-444.

25. Shogren, J.F., A. Bouzaher, S.R. Johnson, and A.P. Manale. 1991. CEEPES: an evolving framework for agri-ecological economic analysis. CARD Working Paper. Iowa State University, Ames, Iowa.

26. Teutsch, G. and H. Kobus. 1990. The environmental research field site "Horkheimer Insel": research program, instrumentation and first results. Journal of Hydr. Res. 28(4):491-501.