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EDITORIAL

ENVIRONMETRICS

This special issue of *Environment International* is devoted to the application of quantitative techniques to the study of the environment. I use the term environmetrics for this (Beer 1988). Others prefer the term envirometrics, or environometrics. There are few rules in neology. The ending -metrics is based on the greek *metron*, and the latin *metrum*, both of which mean to measure. The ending can therefore be placed on both Greek and Latin prefixes. It is also used on more recent prefixes—as in galvanometric. Most words that end in -metrics have a prefix that ends in a vowel. The reasoning behind the anomalous choice of environmetrics is this: in the word environment, the English language appears to have decided that the prefix is environ- which is then followed by -ment. This then determines the prefix to which to add -metrics.

The scope of environmetrics is large. It draws on materials, concepts, and skills from many different fields of knowledge. Each speciality brings to the study of the environment analytical techniques which, syncretically, provide a more comprehensive picture of the total environment. This situation has been faced by various disciplines in the past, with geography being the most notable example. Geography unashamedly draws on a wide range of supporting fields—as depicted in Fig. 1 on the following page—to fulfill its role as a synthesizing discipline.

Notice from Fig. 1 that the tools combining economics and mathematics are called econometrics. By an analogous process, the areas of environmental studies, field methods, and quantitative methods (and possibly even statistics and probability) may be amalgamated. They form the core of environmetrics. To illustrate its spread and its scope, a group of prominent authors, who are involved in the study of some aspect of the environment, were invited to contribute articles reviewing or illustrating the application of quantitative methods to their own area of speciality. This special issue is therefore wide-ranging, in keeping with the multidisciplinary nature of *Environment International*. It covers biology, resource economics, air and water pollution, as well as an overview of some of the new mathematical tools that hold promise for the quantitative study of the environment.

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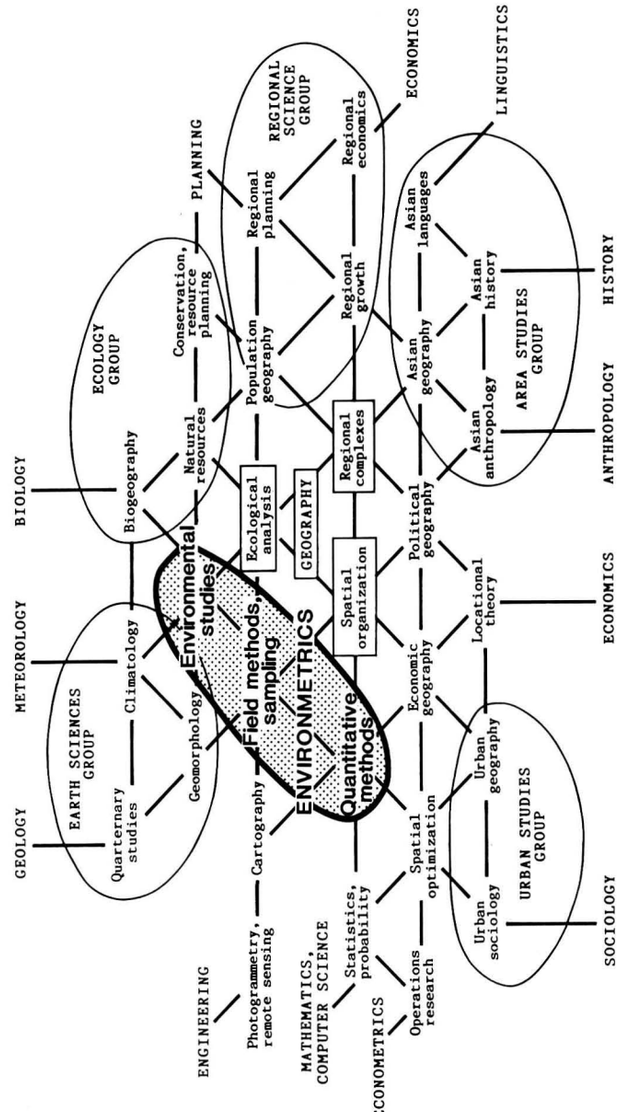

Fig. 1. The role of environmetrics (adapted from Haggett et al. 1977).

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AN IDIOSYNCRATIC ASSESSMENT OF THE ROLE OF MATHEMATICAL MODELS IN ENVIRONMENTAL SCIENCES

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This paper summarizes a number of studies in two disciplines of particular interest to environmental scientists and managers: academic ecology and academic economics. These studies suggest that too often in the past we have been extremely cavalier in our acceptance and use of some theoretical mathematical models purporting great importance and generality. Of particular concern is that on a number of occasions, data have been presented as substantiation of certain theoretical models while in fact, on closer examination, they are not. In many cases, the use of these formulations have led to unnecessary environmental destruction and illogical economic decisions. I conclude that, although there are many good reasons to continue to formalize our knowledge about systems through explicit model development, we must not continue to confuse mathematical rigor with scientific rigor, and we must subject our theoretical formulations to more rigid tests vis-a-vis nature than we have in the past.

INTRODUCTION

This paper addresses problems pertaining to the relation of mathematical models to scientific knowledge based on several previous papers (Hall and DeAngeles 1985; Hall 1988; Hall 1990). As such, it is a caveat to the justifiable celebrations of our accomplishments and prospectus in using mathematics as applied to environmental issues. There is a wealth of good, specific quantitative studies in ecology and economics. The proper use of mathematics is to formalize, quantify and explore, through modeling, what we think we know about nature, human societies and human perturbations of nature (e.g., Hall and Day 1977; Detwiler and Hall 1988). But many models are connected to nature in only the vaguest way, and the scientific community has not been sufficiently adroit or vocal in separating wheat from chaff in modeling. Thus the arguments that follow are more about specific historical abuses of modeling rather than irreconcilable methodologies. They are aimed at specific models and modeling approaches rather than models per se. Many scientists and managers have been led to believe that the development of these models has been objective and consistent with commonly accepted procedures in science. However many such models, and their testing, have been used as tools of advocacy, including the "proving" of previously arrived at conclusions, and the advancement of personal and predetermined philosophies. Sometimes this has been little different from the more blatant use of advocacy in the development of general principles in law, advertising, politics, and other nominally less objective fields (see Kingsland 1985 for a similar conclusion based on the earlier history of theoretical development in ecology).

ECOLOGY

Basically the problem is that a fairly large portion of basic ecology, and especially theoretical models in ecology, both in our textbooks and in many papers, has little to do with how nature works. Even more disturbing is that we appear to lack the tools for discriminating among theories that are good, in the sense that they can be used, at least eventually, to make useful and accurate predictions, and those that are merely intricate and interesting. Professional ecologists have accepted many theories as truth based on inappropriate and occasionally poor evidence. This concern is aimed principally at the relation between mathematical theory and theoretical ecology, at the relation between theoretical ecology and empiricism, and especially at the relation of all this to how we teach these disciplines. The goal is, eventually, better ecological theory, and there are some relatively simple procedures that, if followed, will allow considerable house cleaning.

One might think that theory in ecology would be developed by examining data on nature, seeking patterns, and then developing constructs that might explain those patterns. Instead, many theoretical ecologists often have used theoretical physics and mathematical induction as a model. A considerable amount of theory is generated simply by borrowing mathematical ideas from other disciplines: information theory, stability analysis, catastrophe and chaos theory, economics etc.) that have little relevance to real populations and ecosystems, at least as it is formulated using purely mathematical analysis. The majority of theoretical ecological models do not provide any validation, but instead repeat or build upon commonly accepted, but actually completely undocumented, mathematical starting points. Some of many possible examples are found in Fretwell (1972), May (1974), Maynard Smith (1974), Vandermeer (1981), and Nisbet and Gurney (1982). Although these books develop ideas that are important, and some add appropriate (although underemphasized) caveats, there is essentially no investigation as to whether the equations developed therein represent actual populations in nature, or whether there might be a different approach to the classical models that might have more powerful explanatory or predictive power. In fact, there is essentially no data at all that demonstrate that some of our most basic equations in ecology have ever been validated for any real population in nature despite examples given to the contrary (Hall 1988). And the theoretical ideas so generated tend to be repeated such that even the most recent basic textbooks present them, often without any particular caveats (Begon et al. 1990; Nebel 1990; Ehrlich and Roughgarden 1987; Hall and Cornell 1991).

Furthermore, a large portion of the research in theoretical ecology has not added a great deal to the science of ecology. Despite some obvious cases to the contrary, theory in ecology too often has been presented with almost complete disregard for necessary empirical assessment. This is also evidenced by the failure of most theoretical papers to suggest means by which the theory could be demonstrated true or false—or at least consistent with nature—within the limits of science to do that difficult task. And in the relatively few cases where empirical science has attempted to test mathematically-derived theories (McNaughton and Wolf 1970; Rader and Ward 1989), the result is generally that widely held theories are not supported; thus, mathematically-developed theory has often misled and retarded the growth of defensible knowledge (McIntosh 1985; Kingsland 1985). Such speculation also has diluted and sometimes demeaned the large number of publications based on careful and appropriate field observations and experimentation that should serve at least equally as the basis for the development of theory. Many other ecologists have expressed similar concerns (Peters 1980a and 1980b; Simberloff 1982; Weins 1984; James and McCulloch 1985; Hall and DeAngeles 1985; Hairston 1986). A few theoreticians have risen to the defense (Levin 1980; Caswell 1988), but these efforts seem insufficient and, in some cases, such as the former of these two, seem to end up making the same case made here. Meanwhile the production of untested theory continues at a pace far exceeding our winnowing of existing theory. Some theoreticians have recently shown more interest in linking theory and experiment (Kareiva 1989), but even Kareiva concludes that the testing of theory has been rare.

One fundamental problem is that there has been a considerable confusion between mathematical rigor and scientific rigor (Hall and DeAngeles 1985). While many theoretical papers in ecology are internally consistent and mathematically rigorous, they are frequently based on inappropriate and untested starting assumptions—such as an overdependence on linear density-dependence relations—that are quite divorced from how nature works. More generally, they are inappropriately or inadequately tested (Hall 1988). Many of the most commonly accepted mathematical starting points (as developed below) have no evidence to support that they have ever operated in nature, let alone operate routinely. Yet these models have been

used relentlessly for the development of additional theory and for management, sometimes with results that are destructive to the resource (Hall 1988).

Examples of inappropriate validation

The following examples, derived largely from Hall (1988), give examples of the inappropriate validation of three commonly accepted and utilized theoretical models:

The logistic model. Purported examples of data supporting the logistic model of population growth exist in many textbooks. Although all of these data appear superficially attractive, a closer examination of all examples shows that either:

1) The data are from the laboratory, where there is little doubt that the logistic curve at least occasionally represents the growth of monocultures of some organisms such as yeast or daphnia (See Fig. 3a and 3b; the figures mentioned in these examples are found in Hall 1988 and are derived from Hutchinson 1978, and Allee et al. 1950; They are also found in many other textbooks).

2) The growth curve is for a population (e.g., barnacles) with a distinct temporal larval stage, after which there are no additional recruits possible (Fig. 3c).

3) The data (for collared turtledoves) are plotted on semilog paper to give the appearance of the logistic. This appearance disappears when the same data are plotted on a linear scale (Fig.18 in Hutchinson 1978).

4) The lines fit to the data (on bees and antlions) reflect far more the scientist's eye and prejudices than the data themselves (Fig. 3d and 3e). The same (mis)fits to the data are reproduced, in this case, from one publication to another nearly 30 years later.

5) The data are for a human-managed population (e.g., sheep in Tasmania). Why the sheepherders of Tasmania chose to limit the population of sheep as they did is unknown, but it certainly does not reflect any natural control.

6) The majority of the logistic curves in ecology books had no data points at all associated with them.

Predator prey models. Another widely used, but inappropriately validated model is the Lotka-Volterra system of coupled equations. Such coupled equations of predators and prey are commonly used in theoretical ecology (Maynard Smith 1974; Vandermeer 1981). These equations show strong and regular oscillations of prey growth, followed by predator growth, overconsumption of prey, and decline, which then allows another cycle. A very similar-appearing predator-prey pattern exists in nature. Long-term trapping records from the Hudson Bay Company show a series of about a dozen remarkably strong and regular cycles of both hares and lynx, which normally has been interpreted as predators and prey causing each other to cycle as occurs in the mathematical equations, since lynx eat hares (Begon et al. 1990). But, a closer examination of this data does not support the concept that the hare and lynx are interacting in the same way as the mathematics. First, the changes in the lynx populations sometimes precede those of the hares (Gilpin 1973; incidentally, an ecological theorist), something that is mathematically impossible unless hares eat lynx. Second, a closer look at the original data showed quite clearly that the two sets of population data were not from the same region: the hares were from Eastern Canada near Hudson Bay and the lynx were from Western Canada (Finerty 1979). The skins of the hare were not valuable enough to ship very far to the Hudson Bay Company's collecting centers, although those of the lynx were. Finally, there is evidence that the hares on Anticosti Island, in the Gulf of St. Lawrence, go through cycles similar to hares on the mainland, but there are no lynx on Anticosti Island (Elton and Nicholson 1942). Although it seems reasonably clear that some kind of cycles do exist for both lynx and hare populations (Finerty 1980), the reasons for those cycles are not clear. There seems to be some relation of the cycles to sunspot activity, but no one has proposed any connecting mechanism. Weinstein (1977) offered an interesting possible explanation for the cycles seen in the Hudson Bay's records as a result of sociological factors affecting trappers. Hall (1988) and Romesburg (1981) provide additional examples of how these unsubstantiated models are taught and used in management sciences such as fisheries and wildlife.

Competition models. The overacceptance of the importance of competition in ecology and the many papers critical of that overacceptance are beyond the scope of this review (see Simberloff 1982; Weins 1984; Hairston 1986). But it is interesting to examine the evidence that has been used in the past to support the supposed importance of competition in structuring communities.

An influential idea in ecology is that competition among similar species will force them into different physical and functional habitats. A classic diagram used to support this is from Diamond (1973), which is reproduced in various places, including MacArthur (1977). The diagram shows an elevational gradient along a mountain in New Guinea and the distribution

patterns of two species of warblers over that gradient. The original title for the figure as used by MacArthur (given here as Fig. 1a) says that "note that the two species replace each other sharply at 5 400 feet and that each species reaches its maximum population density just above or just below this altitude". MacArthur's figure is a replica of the right half of the figure in Diamond's original publication (Fig. 1b here), but leaves out the left hand diagram, which shows the raw data on the number of observations of each species. In fact, the raw data given in Diamond show that the two species reach their maximum respective density at a difference of at least 2 000 feet (610 m) in altitude. The density distribution of each species (as far as we can tell from this data) is similar to a normal curve, one with a maximum abundance at about 3 600 feet (1080 m) and the other at about 5 900 feet (1770 m), a difference of 2 300 feet (690 m). The absolute abundance of both species tails off independently as they approach 5 400 feet (1620 m). The apparent sharp replacement of one for the other is an optical illusion; it occurs only because in the right-hand figure each species is plotted as a percent of the number of individuals of all bird species. The apparent sharp replacement of one for the other occurs because, for some unexamined reason, the total avifauna is low at 5 400 feet (1620 m), an interesting observation unrelated to the

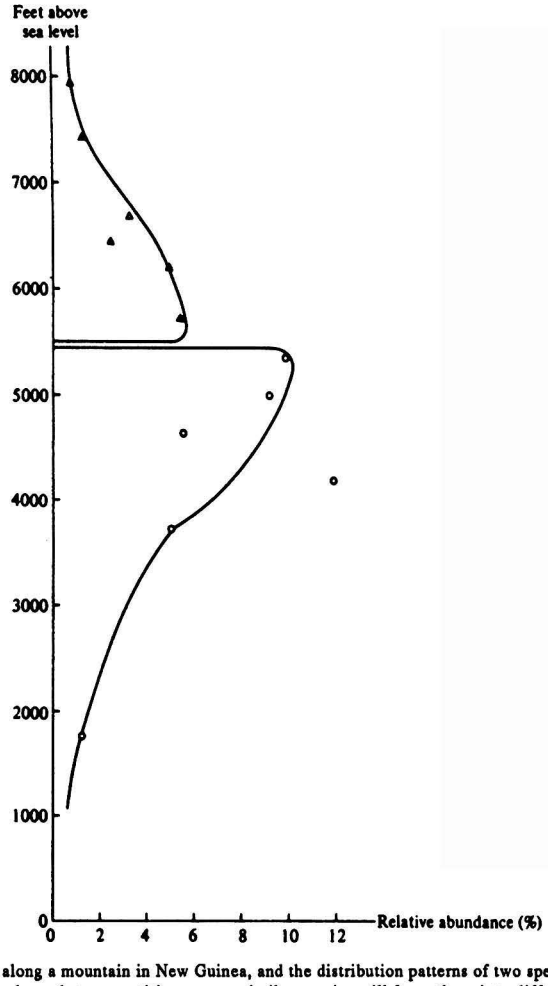

Fig. 1a. An elevational gradient along a mountain in New Guinea, and the distribution patterns of two species of warblers, data used to support the influential idea in ecology that competition among similar species will force them into different physical and functional habitats (Diamond 1973).

question at hand. Thus an inappropriate analysis was used to support an apparently predetermined position of the authors, that "competition structures communities of plants and animals". Competition and competitive exclusions may be several of the most powerful intellectual ideas in ecology over the past two or three decades, but the data that has been used to support them are often suspect.

Realism in modeling

For some reason, probably due to the earlier success of such techniques in physics and the mathematical rigor made possible by their use, most theoretical models have been developed using analytic mathematical approaches. But the number of mathematical problems that can be solved by routine analytic techniques are small (Hall and Day 1977). One might argue that we are after the essence of a problem, and by its very nature the essence is rarely multifactorial, so that the limits of few equations is irrelevant. On the other hand, it seems that to perceive that natural populations are importantly influenced by only one or two factors, and hence modellable using relatively few equations, is an absurd proposition, for there are so many interacting variables that influence each component, and then each component influences others. One can understand the difficulties and frustrations of attempting to put all of an ecosystem within a model, for then an error in parameter measurement

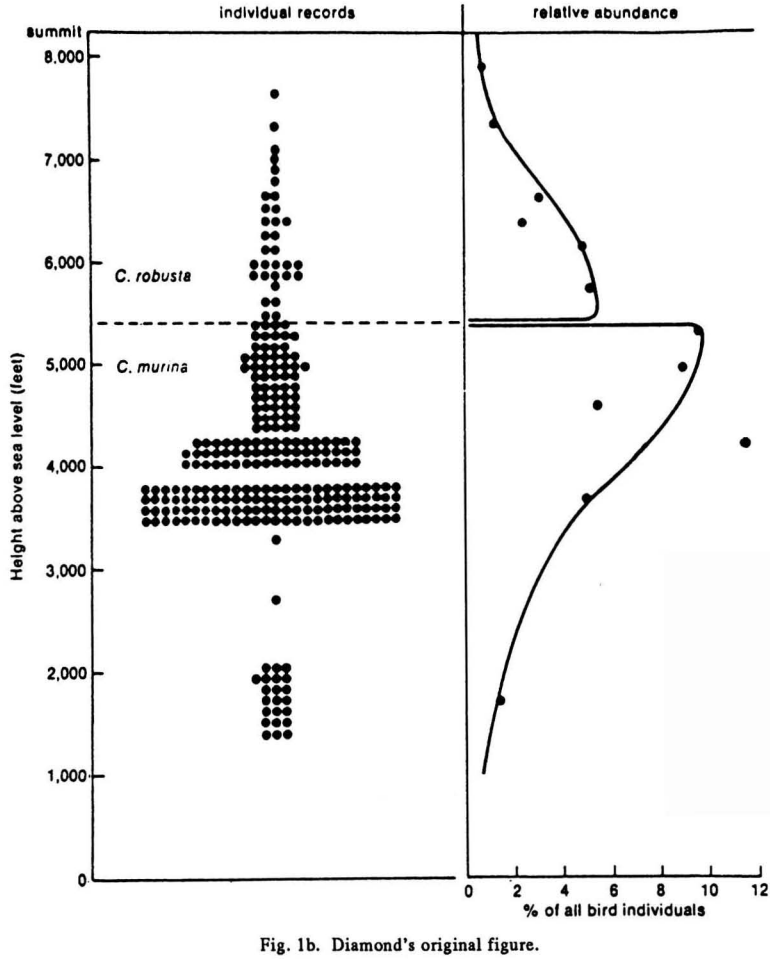

Fig. 1b. Diamond's original figure.

may negate the gains of greater inclusiveness. But to avoid the genuine complexities of nature by building an artificial world that must ignore complexities due to limitations of the chosen tools seems to be hopeless with respect to constructing models of real nature, where nature is indeed complex. The need to include sufficient components and an avoidance of too-heavy parameter dependence is readily dealt with in case by case analysis, as echoed by Botkin's (1977) editorial "in praise of medium-sized models".

The analytical models most often used to develop theory are selected for mathematically solvability, and as such give predictions as a function of included mechanisms and input variables. It is an implicit assumption that these mathematical solutions are equivalent to ecological solutions. If the model predicts something, nature of necessity must do the same, at least in a general way. If nature does not, and the problem is correctly formulated, then the formulation must be incomplete, or the input or validation data must be wrong. But there is no reason why nature should follow our equations, and with the exception of the exponential equation (one of the few truly mechanistic theoretical formulations in ecology, at least when applied to very limited and unnatural conditions in the laboratory) the fundamental premise that mathematical results are of necessity ecological results has not been tested.

As previously concluded (Hall 1988), we as a discipline have been far too eager to grasp at data that appear superficially to support our most cherished beliefs, and we often have not paid sufficient attention to data that have been trying to tell us something quite different. Somehow these models have taken on a life of their own, unrelated to empirical reality. Yet perfectly valid alternative theoretical approaches with a better fit of data to theory have existed since at least Hjort (1916). As someone with an ecosystem perspective, I believe that this overacceptance of certain simple models with inappropriate or very weak mechanisms has led us to pay insufficient attention—in fisheries and elsewhere—to more complex, or at least larger-scale, ecosystem- or climate-oriented models that have much greater predictive value (Hall et al. 1986; Sharp and Csirke 1983; Magnuson 1991).

Why are theoretical models chosen so often even when they have obviously been failing ? Much of the problem has to do with the complexity of the real processes of nature and our desire to find simple patterns. Eventually, approaches based on thermodynamics should be much more powerful in addressing some of the issues presented here (Ware 1982; Kitchell 1983; Smith and Li 1983; Watt 1986; Hall et al. in press) but a stronger case must be made than has been done so far. And it should be subject to at least the same rigorous criticisms leveled at other approaches. Certainly, intensive scrutiny is essential here, for the human mind is far better at providing simple, elegant models than is most of nature.

ECONOMICS

The same situation occurs in economics, at least in the "contemporary neoclassical" branch that dominates western economic theory and practice today (Hall 1990; Christensen 1989; Hall in press, a).

The first fundamental problem is that neoclassical analysis gives importance to resources principally, or perhaps only, in terms of their market price, and the collective contribution of prices to national wealth as measured by GNP. The value of something is measured by its price, so that something contributes to people's welfare as a function of value as measured by price. But prices can be a very poor, or even inverse, measure of wealth. To give an example of how market prices incorrectly value commodities as development proceeds, consider the price of shrimp in Ecuador, or nearly any tropical country. Fifty or even twenty years ago shrimp were cheap and a common part of local diets. Nature did most of the work of producing shrimp, and they could be harvested readily with simple methods. Now the natural fisheries have been heavily industrialized, and the shrimp are overfished . Many of the natural mangrove areas that serve as natural shrimp nurseries have been converted to fossil-energy intensive shrimp maricultures (Olsen in press).

Because the purchased inputs, such as fuel, required to catch or grow the shrimp have increased dramatically, the price retailers must pay also has increased a great deal. Hence they are worth more as measured by their market price. However, the total shrimp catch of Ecuador has declined while their worth, as valued in the market, has increased dramatically (Olsen in press). The average Ecuadorian can no longer afford shrimp, nor do most Ecuadorians gain any benefits from the commercial aquaculture which provides shrimp to North American supermarkets. The GNP from the shrimp has increased, but the value to almost all Ecuadorians has declined a great deal. This appears to be the common pattern during development, and it makes a mockery of the neoclassical approach of measuring value to humans by price.

The second problem is that there appear to be little empirical testing of basic hypotheses in economics, and a lack of interest, or even disdain, for that testing. We were unable to find in about a dozen basic

to intermediate economics textbooks: 1) any basic economic theory stated as a testable hypothesis, 2) any explicit test of a theory or hypothesis, or 3) any data by which the theories presented could be tested. In fact, such empirical testing as does exist often tends to contradict basic theory (Hall 1990; Schoemaker 1982; Knetsch and Sinden 1984; Smith 1989). Although there are many empirical studies in economics, the majority are fitting parameters to, rather than testing the validity of, assumed equations. For example, a superficial review of 127 papers in the American Economic Review in 1989 found a surprising degree of empiricism; 41% had some kind of data and 10% did attempt to test explicitly some hypothesis. But only 3% could be considered in any way specific tests of basic economic theories (e.g., rational expectations, efficiency of market, the assumption that decisions are made for profitability). Of these explicit tests, two theories were not supported and the other two were ambiguous. Thirty-two percent of the papers were models or theory with no data, and 27% were editorials. Thus, there was considerable theory without any empirical test, much data of a purely descriptive nature, and only a little testing of basic theory. And, where basic theory was tested it was at least as likely to be found wanting as not. What percent of such experiments would support the hypothesis based on chance alone?

Additional problems with the neoclassical model are advanced by investigators who are more oriented towards the failure of the neoclassical model to meet social or environmental goals. Some particular components of the neoclassical approach that have been examined and found wanting, and other examples of the supposed virtues of economic theory that is belied by the actual operation of economies, can be found in Goodland and Ledec (1987), Makgetla and Sideman (1989), Hildyard (1989) and Hall (1990). But this general problem is stated best by economists themselves. The interested reader is referred to Hall (1990) and Hall (in press, a) for quotes from economists.

The third problem is that economics as a profession and most economists as individuals seem to discount the importance of resources almost totally except, perhaps, as they influence prices. Solow (1974), in an article emphasizing the substitution of resources, suggests that at the extreme "the world can, in effect, get along without natural resources".

A similar, but less extreme, view is found in the ongoing discussion based on Barnett and Morse (1963) (i.e., Smith 1979). Nevertheless, later analysis (i.e., Hall and Hall 1984) has shown that Barnett and Morse's analysis, and later revisions, totally missed the critical importance of resources to the United States economy because Barnett and Morse's analyses were conducted for a time period of increasing availability and use, and decreasing price, of petroleum. Thus they neglected to consider the role of the massive increase in use of energy to compensate for the ongoing exhaustion of high grade resources by allowing for the use of lower grade resources. Whether imported oil, coal or some other fuel can continue to substitute for resource degradation is an open question.

A fourth failure of neoclassical economics to guide intelligent long-term decision making is its formalized reliance on the use of discount rates (a mathematical procedure to weigh the time value of money, so that economic production today is valued a great deal more than economic production some years in the future). The U.S. government discount rate reflects primarily the interest rates charged by the nation's largest banks, and thus the cost of borrowing money from commercial banks. It changes as a function of Federal monetary policy and other factors that are irrelevant or even antagonistic to wise resource decisions.

The use of a discount rate means that a one time gain of a thousand dollars today will be weighed more heavily than tens of thousands of dollars gained slowly over a long time. Thus a forested watershed may provide a city with important flood control and water quality services. These services are not sold in markets, so they have no defined price and are not a part of GNP accounting. If they were monetarized, the services are probably worth less in a given year—although perhaps much more over decades—than the market (monetary) value of the timber that can be extracted. In a standard neoclassical economic analysis, the services of the watershed ten years from now would be discounted to only about 10% of their value today, and in 50 years. they would be discounted to essentially nothing. So neoclassical analysis will always argue for the destruction of nature when short-term profits can be made, even at the expense of much greater gains over long time periods. Government policies based on such economic techniques will deprive its citizens and their children much future economic well-being.

THE SOCIAL CONSEQUENCES OF THIS EPISTEMOLOGICAL DILEMMA

Thus in two disciplines of particular importance to the environment, ecology and economics, a fair number of the most influential theories and concepts are

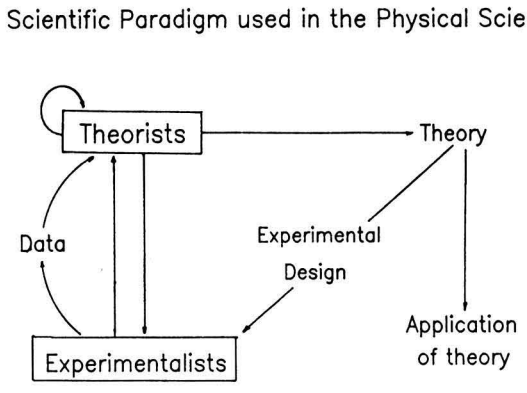

Fig. 2a. The interaction of theory and observation/experimentation, at least ideally, in the physical sciences. In physics, the theorists generate ideas that are, at least in principle, routinely subject to experimentation by which the theory can be rejected or not. There is a continuous flow of information from experimentalists to theorists and vice versa.

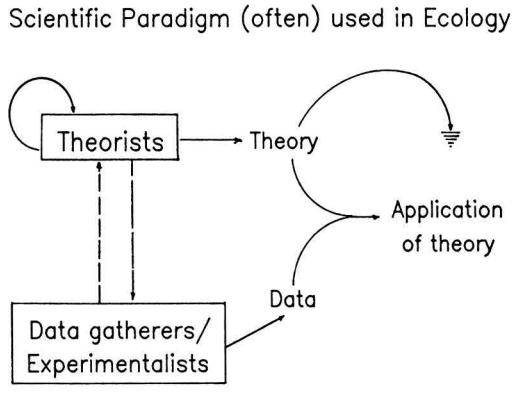

Fig. 2b. Such a flow is often lacking in theoretical development in some other disciplines.

more devised than real, or, at least, one cannot tell whether the theories are valid. Figure 2 shows how theory and empiricism should interact vs. how they appear to interact in these two disciplines. It would be interesting to know if other disciplines suffer from similar problems.

If indeed the perspective given above is true, or even partly true, one important consequence is that our faith in the veracity of the central tenets of two important sciences is greatly undermined. This, in turn, makes it more difficult and possibly less moral to apply these disciplines to important real world problems that use their ideas for analysis or expected resolution. For theoretical ecology this is perhaps not so critical, for this discipline has had relatively little impact to date on what decisions are made in society (beyond some applications to fish (Hall 1988), and wildlife (Romesburg 1981), and the appropriate and common sense dictum to preserve nature. On the other hand, it does seem that ecology should be important to how we make decisions in the larger world.

The implications associated with the application of economics, however, are enormous, both on people and on nature. Most of the decisions that are made by individuals and governmental agencies tend to be made according to one economic criteria or another.

The use of economic decisions as guided and sanctioned by neoclassical economic theory allows people to escape, or to think that they are escaping, some real and important limits and constraints imposed by physical reality, including the dependence of people on the environment.

For example, in agriculture, most would agree that Malthus has been demonstrated wrong; that agricultural production as fueled by technology can keep up with human population growth. While this has been true in the recent past (although starvation remains widespread), it has been done almost entirely through the industrialization of agriculture through the use of cheap fossil fuels. This certainly cannot last indefinitely, as we are reminded by three "oil crunches" in the past two decades. As one example of the finitude of fossil fuels, the energy cost of obtaining our most important domestic U.S. fuels is increasing rapidly, and in some cases is approaching the energy obtained by their exploitation. While there is a great deal of oil left elsewhere in the world, the vast majority is within the borders of only four countries: Saudi Arabia, the Soviet Union, Kuwait and Iran. There seems to be no question but that the agricultural production of most of the world will be increasingly beholden to the policies and economics of these four nations. And the increased use of petroleum-derived fertilizers, which is occurring in virtually every country of the world, is masking other serious problems, such as large-scale soil erosion (which undermines the ability of soils to produce food in the absence of fertilizers) and maldistribution of land. A proper system of economics needs to give far more weight to the importance of resources in general, and fossil fuel in particular, if it is to reflect the future accurately (Hall et al. 1986).

In the developing nations, investment policies based on neoclassical economic analyses encourage borrowing from developed countries, and hence growing indebtedness. Pressure to service this debt in turn encourages the mining of resources to get a quick return on the investment, so that the lending banks get their hard cash return (Repetto 1988). In the meantime, the long-term productivity of the region may be destroyed, and the possibly greater utility of the resources for local use is lost by this mining. But those assessments are not included in the original analyses or, in the rare cases where they are, their value is heavily discounted. In effect, such policies encourage the short-term mining of natural resources with the cost falling on the majority of the citizens who often have little say in the matter.

Many investigators have questioned many aspects of the validity of the application of neoclassical economics and capitalism to those industrial countries where it was derived because much of the theory appears essentially untested or unsupported when tested. But even less is known about its validity to issues of development. The basic concepts of neoclassical economics are being dispersed and promulgated throughout the world under the guise of development with very little examination as to whether or when it works. And, where free market economies have worked, it is rarely asked why. Has this been due to the intrinsic nature of the neoclassical economics that supposedly guides them, or rather to a high ratio of domestic resources to population number (e.g., the U.S.), high imports of oil (e.g., Japan, Italy), or high rates of exploitation of the resources of other countries (U.S., Europe, Japan)? And what about market economies that are far less successful (e.g., Brazil, Chile, and the poor subcultures of many countries)? Is the principal virtue of neoclassical economics that it assists economies in exploiting their and other nations' resources as rapidly as possible?

Thus, the application of untested and even arbitrary economic models to development and environmental decision-making results in the destruction of nature in a way that is often actually uneconomic to the people of a region (Hildyard 1989). This is done routinely, is encouraged by unregulated or insufficiently regulated free markets, and works against the supposed efficiency of free markets. These arguments should not be construed in any way as supporting centrally-planned approaches which have some of the same and additional problems, but rather to suggest a system of economics that is more firmly based in resources.

Energy use and development

Neoclassical economics focuses on demand, not production. But it is clear that issues of economic development are essentially issues of production and especially the industrialization of production (Hall 1990). Thus it seems that the principal issue of development is the physical or economic availability of fuel resources, or the willingness to incur debt to obtain the needed energy. My colleagues and I have examined the quantitative behavior of the economies of the United States, Argentina, France, England, Germany, Japan, and Honduras over the past 50 to 100 years. These studies found extremely high correlations between GNP and fuel energy use, especially when corrections are made for energy quality (e.g., electricity vs. fossil fuel) and for the proportion of

energy used directly by consumers vs. that used in manufacturing (Cleveland et al. 1984; Gever et al. 1985; Paruelo et al. 1987; Kaufmann 1990). Similar strong correlations are found between energy and labor productivity, energy and inflation, energy and sectorial productivity, and indeed energy and nearly all economic activity (Hall et al. 1986). Yet despite many such analyses, and the obvious economic impact of the oil price changes of 1973, 1979 and 1990, academic economics has not shown any particular interest in restructuring either basic theory or particular applications to incorporate the importance of the constraints imposed by basic physical laws such as thermodynamics. Neoclassical economics remains completely a social science, and as such will continue to represent only part of reality. Both classical economists (Christensen 1990) and some ecologists (Hall et al. 1986) have attempted to build economic models more explicitly related to the physical and biotic reality of the world, but the impact on most neoclassical economists and on most applied economics is minuscule at best.

CONCLUSION

There has been great confusion among average ecologists between mathematical rigor and scientific rigor. One result is that ideas that clearly have at least some kind of rigor, even if of an inappropriate kind, have been given far greater credibility than they deserve. This is not to belittle the importance of good mathematical rigor in the development of theory in ecology and elsewhere (Caswell 1988), but it, like any tool, has its place.

The theoretical underpinnings of both ecology and economics can be made much more rigorous by attempting to work from the same first principles of energy and matter that are used in, for example, physics, biochemistry, and the modeling of water movement (Ayres and Nair 1984; Hall et al. 1986; Hall 1991). These ideas are explicitly testable (Cleveland et al. 1984), and are quite capable of revision or rejection based on the results of empirical analysis. But whether the solutions that I offer are useful or not it seems clear that we must be very careful about accepting such conventional wisdom in these disciplines.

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FRACTALS, LATTICE MODELS, AND ENVIRONMENTAL SYSTEMS

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Lattice models, as used in statistical physics, exhibit self-similarity. They are related to fractals which also exhibit self-similarity. Percolation models are the most relevant of these lattice models to environmental systems. Some applications in resource ecology, fire spread, groundwater intrusion, and rainfall are reviewed. Despite the qualitative appeal of the percolation theory and the ability of certain laboratory experiments to reproduce its results, quantitative attempts to apply it to real environmental systems have not yet been successful. The reason for this seems to be that only the simplest interaction rules have been used because the correct solutions for these are known. Realistic use, in environmental science, of models from statistical physics will require more detailed knowledge of the fundamental processes involved in the phenomenon of interest, coupled with greater computer power.

INTRODUCTION

In two extremely influential books (and numerous publications) Mandelbrot (1977, 1983) proposed fractal geometry as a description of a wide range of natural systems. The persuasiveness of his work led scientists in many areas, including a number in environmental sciences, to exploit these concepts. Because of the newness of these ideas, Mandelbrot avoids giving a precise definition of fractals but rather emphasises their properties, one of which is self-similarity (and another of which is the presence of power laws). In fact, according to Feder (1988), Mandelbrot has retracted his original tentative definition and proposes merely that "a fractal is a shape made of parts similar to the whole in some way". For our purposes, we shall concentrate on the property of statistical self-similarity as being the defining characteristic of the systems and the models that we consider.

Many environmental systems exhibit self-similarity as indicated by the fact that a photograph generally needs to be marked with a length scale (e.g., geologists often use a coin or their geological hammer). It has recently been realised that certain physical systems, especially during phase changes, also exhibit self-similarity. Recent developments in statistical physics have successfully applied lattice models to these systems. The idea of using these same models to describe environmental systems is attractive and this article reviews progress in this area. Firstly, by explaining self-similarity and fractals and showing how they are related to lattices. Then, discussing

some environmental applications of lattice models. Finally, there is a discussion of some of the mathematics used to characterise various lattice models and to find important properties of the lattice; percolation on a square lattice being one example in which the value of the percolation probability p_c would be one of the important properties to be determined. Our examples mainly use the square lattice. The reason for this is that when self-similarity occurs on the square lattice it should occur, with the same fractal behavior, on all two-dimensional lattices (Stauffer 1985).

Power laws and self-similarity

Richardson (1961) pondered the question: How long is a coastline? Some estimates of the Australian coastline are given in Table 1 and it can be seen that the answers differ. The smaller one's scale of measurement, the longer the measured length. If you measure the length with dividers and an atlas, you will get a low value that increases as you decrease the spacing of the dividers. If you decide to pace it out, you will get a very much longer value because you will have to walk upstream of rivers until you can ford them. On an atlas, you would draw an imaginary line across the mouth of the river, but in reality the coast, being the demarcation between land and water, extends up every stream. If an ant walked the same route, it would get an even longer length. Your paces treated the stones as flat surfaces, but an ant would need to climb up every stone and grain of sand, and include their lengths in its total.

Table 1. Some estimates of the length of the Australian coast.

Yearbook of Australia	36 735 km
Australian Encyclopaedia	19 658 km
Australian Handbook	19 320 km
Australian Landforms	8 000 km

Source: Galloway, R.A., 1987, Maritime Studies, No32

Richardson (1961) showed that the length of a coastline does not reach any final value but increases to infinity as the scale of measurement decreases. He drew curves relating the length of a coast to the length of the ruler used to make the measurement and found that these curves were straight lines on double logarithmic graph paper (log-log paper). Straight lines on log-log paper indicate that the two quantities are related by a power law with the slope of the line determining the power which is appropriate. To Richardson, the slope of these lines had no theoretical interpretation, but to Mandelbrot, a coastline is a fractal curve and the slope of the curve, s, is related to the fractal dimension d by $s = 1 - d$.

At a more technical level, Mandelbrot relates d to the Hausdorff dimension of geometry. Nevertheless, a certain amount of care is needed in identifying the value of a power-law exponent with the fractal dimension. In lattice percolation systems discussed below, Stanley (1986) identifies ten "fractal dimensions" based on different measurement methods. Some, if not all, of these techniques will lead to differing estimates of the fractal dimension. In fact, Hentschel and Procaccia (1983) showed that fractals in general, and strange attractors (which arise in the theory of chaos) in particular, are characterized by an infinite number of generalized dimensions. In the case of homogeneous fractals, they all have the same value. The term multifractals is now used to cover the general situation.

NOTATION

A	catchment area
$B(x)$	number of broken bonds
d	fractal dimension
$E(x)$	number of connected bonds
g_n	arbitary lattice property
j	integer variable
l	length scale
L	main stream length
m	arbitary exponent
n	integer index
N	Number
p	probability variable
p_c	critical (percolation) probability
$P(u)$	percolation probability
r	distances
s	slope of line on log-log paper
t	time
u	$= 1 - p$ in percolation models
U	flow speed
$V(x)$	number of vertices
x	cluster number
α	constant in length-area relations
β	critical exponent for P(u)
γ	exponent of rainfall times
δ	exponent in length-area relationship
η	kinematic viscosity
ν, τ	critical exponents as defined by Albinet et al.

The Koch snowflake (Fig. 1) provides an example of a geometric coastline. Start with a triangle and a rule for generating a new figure. The rule is: Make copies of the original triangle and shrink them so that their sides have a length 1/3 of that previously. Now paste them onto the midpoint of each straight side of the figure. The first time that you do this, you get the Star of David; the second time (and the length of the side of each paste-on triangle is now only 1/9), a somewhat more complicated star. Continue this process to infinity and not only do you generate a geometric coastline, but it exhibits self-similarity. Self-similarity means that if you enlarge a photograph of a small end section of this curve, the result is indistinguishable from a photograph of a larger section of the curve. A great virtue of the Koch snowflake is that one can calculate its fractal dimension exactly. The perimeter of the original triangle has a length of 3 units, being the sum of three sides each of length one. The Star of David is made up of 4×3 sides each of length $(1/3) \times 1$. The length scale (the size of the ruler being used to measure around the coastline) is now 1/3 of the original length scale of one. At a length scale of 1/9 there are 4×12 sides each of length 1/9. The total length as a function of length scale is drawn in Fig. 2. The slope of the line is -0.26, indicating that the Koch snowflake has a fractal dimension of 1.26 or, to be exact, a fractal dimension of log(4)/log(3).

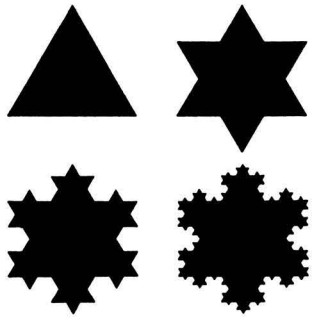

Fig. 1. The Koch snowflake.

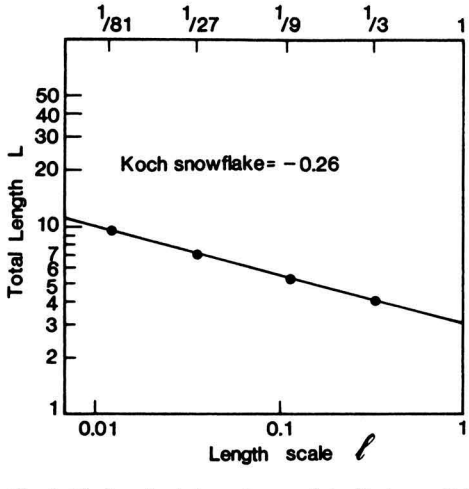

Fig. 2. The length of the perimeter of the Koch snowflake as a function of the length scale used to measure the perimeter. The slope of the curve is -0.26.

SELF-SIMILARITY AND ENVIRONMENTAL SYSTEMS

Self-similarity and fractals have been applied to a number of environmental systems. Scholz and Mandelbrot (1989) edited a special volume on fractals in geophysics that includes discussions on the fractal nature of turbulent flows, the sinuosity of stream channels, and topographic data sets. There is a rapidly growing literature, which started with Lovejoy and Mandelbrot (1985), attempting to identify the self-similar structure of rainfall. Kedem and Chiu (1987) pointed out that this original model, which sought a fractal structure for rain rate, could not possibly be correct. Lovejoy and Schertzer (1989, 1990) countered by claiming that rain rate was multifractal whereas Beer (1990) has suggested that it is the time between rainfall events that has a fractal, self-similar nature.

Mandelbrot (1983) noted that in hydrological systems main stream length, L and catchment area, A are observed to have a power-law relationship such that $L = \alpha A^{\delta}$. If the catchment area were a circle, with the main stream corresponding to a diameter of the circle, then $\delta = 0.5$ and $\alpha = (4/\pi)^{0.5}$. In this case, the units do not matter because the equation is dimensionally consistent. Numerous field determinations indicate that δ is close to 0.6, and α has a value of 1.4 (for length measurements in miles and area measurements in square miles) or 1.27 (for measurements in km and km^2). The fact that natural channels, when ordered a certain way, have bifurcation and length ratios that are power laws was discovered by Horton (1945), an influential hydrologist. Modern-day hydrologists have therefore been keen to find a theoretical basis for these relationships (Tarboton et al. 1988; Barbera and Rosso 1989). In the past, the discrepancy has been ascribed to basin shape. Robert and Roy (1990) show that this may, to some extent, still be true. The fractal dimension estimated from measuring the river lengths as a function of length scale

agreed with that estimated from the length-area relation at the largest map scales, but at the smallest map scales (i.e., lowest resolution maps) the estimates of the two fractal dimensions differed, presumably because of the effects of the basin shape.

It was mentioned that rainfall has been studied in terms of its self-similarity. The shapes of rain areas and the shapes of clouds have also been studied in detail as has the nature of smoke puffs. Much of this work is reviewed by Gifford (1989) and we shall return to it in the discussion of the lattice percolation models. Kaye (1989), in his entertaining and readable book on fractals, discusses the fractal (and hence self-similar) nature of smoke and dust particles.

Self-similar and self-affine

Much of the early work on fractals and self-similarity was characterized by semi-quantitative arguments. If a phenomenon could be characterized by a power law with an exponent different to that suggested by regular geometry, then this was sufficient to characterize it as a fractal, and hence self-similar. Eventually, the limitations to this approach were realised. We have already mentioned the problem of different definitions of the fractal dimension. To make it more specific, consider again the problem of estimating the fractal dimension of the coastline of Australia. The traditional method is to use different length scales and look at the power-law relation between estimated total length and length scale. An alternative method is to measure both the area and the perimeter at different length scales and to examine the area-perimeter relation. Hentschel and Procaccio (1983) introduced a method by which squares (of side l, where l is the length scale) are overlaid over an area (such as continental Australia). If $N(l)$ is the number of squares that include the coastline, then the fractal dimension could be estimated by the slope of the log $(N(l))$ versus log(l) line.

There are occasions when these different methods of estimating the fractal dimension lead to different results. One solution was to extend the concept of self-similarity to self-affinity. If an object has different scaling factors in two different directions, then it is self-affine rather than self-similar. In this respect, clouds would appear to be self-similar in the horizontal, but self-affine when the vertical direction is included. In this case, a box-counting method of estimating fractal dimension would need to use rectangles rather than squares (Mandelbrot 1985; Lovejoy et al. 1987).

Lattices

In some of the examples that we have mentioned, the analyses have been supplemented by attempts to build statistical models that reproduce the observed self-similar behaviour. In all of the continuum models that we know, such modelling has had the self-similar scaling behaviour built-in, either explicitly through some imposed power-law distribution of the geometrical components or else implicitly through a recursive definition. While such an approach can lead to interesting models, it provides little insight into the way in which such statistical self-similarity can arise.

There are, however, known classes of statistical models where self-similar behaviour arises spontaneously from simple local interaction rules. These are the various lattice models of phase transitions that have been extensively investigated in statistical physics. Since the lattice imposes a lowest length scale, any self-similarity that occurs can not be exact but can only apply asymptotically in the limit of large distances. An important property of some of the lattice models described below is that when such large-scale self-similarity occurs, it is often accompanied by isotropy so that the lattice axes no longer play a privileged role. In this case, the details of the lattice no longer matter and theoretical results obtained on a square lattice will be as equally valid as those obtained on triangular or other lattices.

The applications of these concepts to environmental phenomena is still relatively new. To illustrate these concepts, consider the case of the mathematical fire-propagation model (Stauffer 1985). Imagine a large array of squares—such as that provided by wire mesh. Physicists call such an array a square lattice. Imagine further that a fraction, p, of the squares of this lattice are randomly filled with a burnable element; a matchstick with an ignitable head stuck vertically in the wire mesh springs to mind. The remaining fraction u, which equals $1\text{-}p$, is left empty. Now define an interaction rule that governs the spread of fire. The simplest interaction rule is one in which a burning site ignites its first neighbours (i.e., nearest neighbours) on the next time step. First neighbours are the adjacent non-diagonal elements. Burnable clusters are then defined as a group of burnable elements joined by first neighbours. The notation for neighbouring elements is shown in Fig. 3.

A fire is then started by igniting the row of burnable sites at the top of the lattice. At the next time step, the nearest neighbours to these burning sites are ignited and simultaneously the original burning sites are extinguished. This process is continued until either there are no more nearest neighbours, or the fire

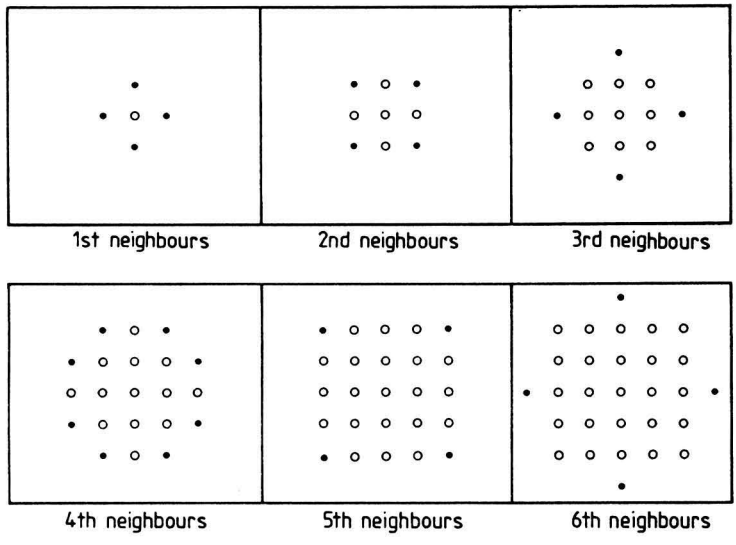

Fig. 3. Notation used for sites on a square lattice.

reaches the bottom row of the lattice. The time at which this occurs, the termination time, is noted. Fig. 4 depicts the general shape of the curve that links the mean termination time with the value of p.

For this particular interaction rule, it turns out that if p is less than about 0.59 (0.59275 to be more exact), then the clusters are discrete groups within the bounds of the lattice. If p is well above this value then there will be at least one cluster that spreads from one end of the lattice to the other, and is thus capable of supporting a propagating fire. Such a cluster is called a percolating cluster. At low values of p, the times are low because the fire burns in only a few small clusters. At high values of p, the times are low because the fire propagates directly from one end of the lattice to the other. There is, however, a value at which the termination time of the fire is a maximum, because the path of the fire is tortuous. The value of p at which this occurs is known as the percolation threshold, or the critical probability. We denote it by p_c. It turns out that the potentially burnable clusters in this model are self-similar. Or, expressed another way, the fire-front is a fractal in the same way that a coastline is a fractal. Stauffer (1985) informs us that when $p = p_c$, then the fractal dimension of the percolating cluster (and hence the fractal dimension of the set of burnt trees) is 1.896.

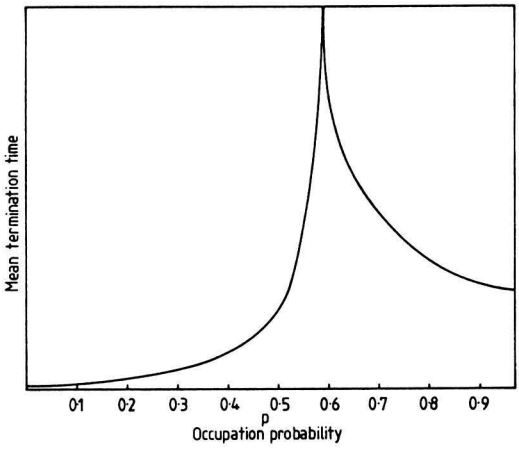

Fig. 4. Idealised representation of the curve of mean termination time as a function of the probability of site occupation.

PERCOLATION

Mathematical description

The approach to mathematical fire propagation uses percolation theory to predict the expected fire behaviour. There are two types of percolation models, bond percolation and site percolation. The

example in *Lattices* deals with site percolation (i.e., each available site has a specified probability of occupation). Bond percolation considers the edges or bonds of the lattice to be connected with probability p and broken with probability $u = 1 - p$. (The terminology 'open' and 'closed' is often used, but this can be confusing because these words have opposite connotations when applied to taps as opposed to switches.) If you imagine a sheet of graph paper, then site percolation deals with the points at which the lines cross (the vertices); whereas bond percolation deals only with the lines joining the vertices.

Site and bond models are related. All one needs to do is to replace each potential bond by a new site situated at the center of the bond (with a more complicated rule for joining neighbours), and one has converted a bond model to a site model. The new lattice that is so formed is called the covering lattice. In the case of a square lattice, its covering lattice is also a square lattice, rotated 45° from the original lattice. It is always possible to construct the covering lattice of a given lattice, but not every lattice is a covering lattice. Hence every bond process is a site process on a different lattice, but not every site process is a bond process. Efros (1986) provides a good introductory discussion of this point and its consequences. Site processes are more fundamental and, in general, we restrict attention to them.

An important property is the percolation probability, $P(u)$, which is the probability that an arbitrary site or bond is part of an infinite cluster connected by unbroken sites or bonds. For small u (i.e., large p), $P(u)$ is non-zero, while below some critical probability, p_c, $P(u)$ vanishes. As $p \to p_c^+$, $P(u)$ behaves as $(p - p_c)^\beta$ with $\beta = 7/36$ in two dimensions. This value of β does not depend on the type of lattice, and is true for a wide variety of interaction rules (e.g., it is true for first, second, third, etc. neighbour interactions). The power law suggests self-similarity and this is indeed the case. The clusters are self-similar. In the applications to be described below, $P(u)$ specifies the proportion of trees ultimately burnt in the mathematical forest-fire model and $1 - P(u)$ specifies the proportion of bubbles trapped in the ice-core model described in the following section.

There is an extensive literature on percolation. An accessible account is given by Stauffer (1985). Many technical aspects are described by Essam (1972) and Grimmet (1989). One mathematical technique that can be used to study percolation is series expansion. The percolation probability for a bond percolation model is defined as

$$\begin{aligned} P(u) &= \text{Prob (arbitrary site is not in infinite cluster)} \\ &= \text{Prob (origin is not in infinite cluster)} \\ &= 1 - \text{Prob (origin is in finite cluster)} \\ &= 1 - \Sigma\, \text{Prob (origin is in cluster } x) \end{aligned}$$

where the sum is over all clusters, x, containing the origin. Thus

$$P(u) = 1 - \sum V(x) p^{E(x)} u^{B(x)}$$

where the sum is over all translationally distinct clusters, x, $V(x)$ is the number of vertices in cluster x, $E(x)$ is the number of connected bonds in cluster x and $B(x)$ is the number of broken bonds that form the boundary separating cluster x from the rest of the lattice. These quantities are depicted in Fig. 5 and Table 2. Listing clusters in increasing size, and using the values in Table 2 gives a series expansion in powers of u beginning

$$P(u) = 1 - u^4 - 2 \times 2 \times (1 - u) u^6 \ldots$$

which enables $P(u)$ to be calculated.

Fig. 5. Notation for series expansion methods for clusters of 1, 2, and 3. The solid lines show the connected bonds, the dots show the number of vertices, and the dashed lines show the broken bonds that form the cluster boundary.

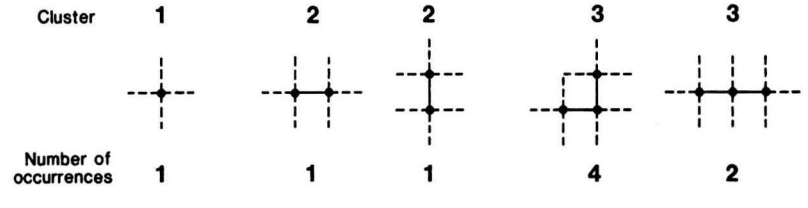

Table 2. Numerical values for quantities used in series expansion methods as shown in Fig. 5.

Cluster (x)	number of occurrences	$E(x)$ - solid lines	$B(x)$ - dashes	$V(x)$ - dots	weight
1	1	0	4	1	u^4
2	2	1	6	2	$4(1-u)u^6$
3	6	2	8	3	$18(1-u)^2u^8$

Bubble trapping in ice

An environmental problem that has assumed importance recently is that of the carbon dioxide content of the atmosphere in the past. One method of determining this is to collect air samples from bubbles that have been trapped in polar ice. As snow falls and then coalesces into grains, the lower layers of ice become compressed and the channels between the grains gradually close. Air can be trapped in the larger cavities between grains, forming small visible bubbles. These bubbles can be extracted from old ice. Their composition gives a record of the levels of greenhouse gases in the atmosphere at past times (e.g., Pearman et al. 1986). The ice can be dated by a variety of techniques but it is clear that the bubbles are trapped some time after the deposition of the original snowfall. Furthermore, the bubbles in a sample are not all trapped simultaneously—rather there is a distribution of trapping times relative to the time of snowfall. Interpretation of changing gas concentrations in ice cores requires a knowledge of the mean trapping time obtained from this distribution.

The percolation model has been applied to the trapping of air bubbles in polar ice by Enting (1985, 1987) and Stauffer et al.(1985). The system was represented as a percolation model on a lattice with the sites representing the trapped bubbles and the bonds representing the randomly closing channels. The proportion of trapped bubble sites thus corresponds to $1\text{-}P(u)$ where u is the probability of a channel being closed.

In the ice core modelling, it is of considerable interest to know the degree of statistical variablity that arises from the randomness of the trapping process. This problem can be addressed by Monte-Carlo simulations. The bubble density in ice samples analyzed in our laboratory is of the order of 2.5×10^5 bubbles per kg of ice. It is feasible to simulate samples

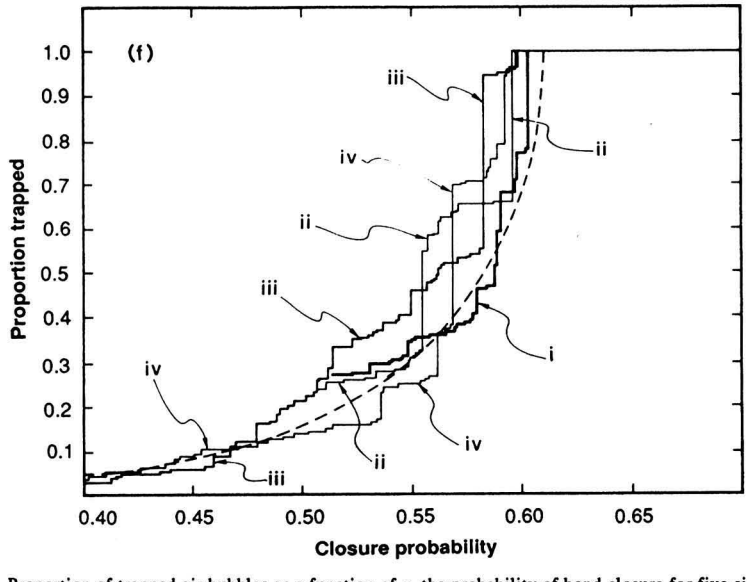

Fig. 6. Proportion of trapped air bubbles as a function of u, the probability of bond closure for five simulations.

of this size. Figure 6 shows some results from five such simulations. Each curve shows the proportion of trapped bubbles as a function of u, the probability of bond closure. The difference between the five simulations shows the large degree of statistical variability that occurs near the critical probability.

Modelling fire spread

The possibility of using percolation to model the spread of fire through a random medium, as described in Section *Lattices*, was suggested by Stauffer (1985) and the detailed mathematical development was undertaken by Albinet et al.(1986). We have used the term "mathematical forest-fire" for this process. There is little doubt that the percolation model offers some qualitative insights in that there are three regimes of wildfire spread; namely, the fire propagates ($p > p_c$), the fire fails to propagate ($p < p_c$), and the fire is marginal ($p = p_c$). In addition, as in the ice core model, there is a large amount of statistical variability associated with the case $p = p_c$ indicating that marginal fires will be unstable, with a tendency for sporadic flaring and extinction. However, it seems clear from laboratory experiments that the quantitative information derived from the simple interaction rules of Albinet et al.(1986) is incorrect when applied to actual combustion processes (Beer and Enting 1990).

The ability of a percolation model to propagate a numerical fire depends on the percentage of burnable sites on the lattice, the characteristics of the sites, the intensity and range of the interaction between sites, and also the physical size of the lattice used in the simulation. Albinet et al. (1986) examined the above model in detail (mainly by Monte-Carlo simulations) and confirmed the result that for the simple interaction rule where first neighbours ignite, $p_c = 0.593$. If a burnable site can ignite both first and second neighbours then the value of p_c drops to 0.407. Conversely, if the interaction rule is such that two burning sites are needed to ignite a first or second neighbour, then the percolation threshold is shifted upwards, to a value of about 0.67.

Beer and Enting (1990) tested this with some laboratory simulations using random arrays of matches. They obtained a curve of termination time versus occupation probability that has the same general shape as Fig. 2. However, when the experiment was set up to reproduce first-neighbour interactions (the requisite separation distance having been estimated from burning lines of matches), the percolation probability, p_c, was at a value of 0.39—which is much lower than the 0.59 predicted by naive application of the theory.

Of greater concern was the fact that the critical exponents of the laboratory experiments could not reproduce the critical exponents predicted by Albinet et al. (1986). This is shown in Table 3 for a small array of 512 sites and a larger array of 2048 sites. The reason seems to be that the experiment was set up so that a single burning match (a cluster of one match) would ignite only its nearest neighbours. However, once the fire had gotten under way and a large cluster was burning, the matches at the edge of this cluster could ignite other distant matches. This illustrates the well-known phenomenon that a small fire is difficult to keep alight, but a large fire is difficult to suppress. It would appear that the following revised interaction rules may explain the laboratory results:

Table 3. Comparison of theoretical critical exponents predicted by simple percolation theory compared to laboratory observations of matches burning in random arrays. The exponent d represents the fractal dimension of the burnt areas. The other critical exponents are as defined by Albinet et al. (1986). The exponent ν/τ indicates deceleration ($\nu/\tau < 1$) or acceleration ($\nu/\tau > 1$) of the fire front.

Exponent	Theory	Small array	Large array
ν/τ	0.87	1.4	5
$(\nu-\beta)/\tau$	0.78	1.2	1.9
τ	1.55	0.4	0.1
β	0.12	0.1	0.4
d	1.88	1.9	1.4
ν	1.3	0.6	0.6

Rule 1: First neighbours ignite simultaneously.

Rule 2: Each match can ignite other matches within a distance $N^{1/2}$, where N is the number of matches in the burning cluster.

Rule 3: The ignition of distant matches (i.e., second and higher neighbours) is controlled by radiation. There is a time delay in ignition which depends on the number of burning matches and their distances (r) and is proportional to

$$\ln\left(1-\left\{\sum\frac{N}{r^2}\right\}^{-1}\right)$$

Resource ecology

O'Neill et al. (1988) apply the results of percolation theory for an infinite square lattice to the problem of ecological resource utilization and point out that it means that an organism can move freely if its critical resource or habitat occupies 59.28% (i.e., a fraction equal to p_c) of the landscape. They claimed that if an organism can traverse j grid points per unit time then the critical percolation probability drops and is given by:

$$p_c = 1-(1-0.5928)^{1/j} = 1-0.4072^{1/j}$$

This expression indicates that p_c equals 0.3619 for $j = 2$. The ability to move two steps allows an organism to reach 12 sites (1st, 2nd and 3rd neighbours—see Fig. 3). Essam (1972, Table 2.2) quotes $p_c = 0.292$ for this case. The discrepancy appears to reflect a neglect in the analysis of O'Neill et al. (1988) of the existence of multiple paths of length 2 to some of the sites. The discrepancy in O'Neill et al.'s result is substantial in mathematical terms, but may not be that important in ecological terms for two reasons. Firstly, the exact value of p_c depends on the lattice being used. (Remember, however, that the critical exponents and the fractal dimension are independent of the lattice that is used). Thus on a triangular lattice $p_c = 0.5$ when $j = 1$. This is related to the second reason which is that lattice models, near criticality, group into equivalence classes of models with identical critical exponents. These have different values of p_c, but because the critical exponents are the same they exhibit the same behaviour. In such cases, there is no one true model with which to describe the system.

Percolation and fractals

Stauffer (1985) points out that it is possible to define a fractal dimension for the clusters occurring in the percolation model. The value of this fractal dimension for site percolation on a two-dimensional lattice is 1.56 for $p < p_c$, it is 91/48 = 1.896 for the percolating cluster at $p = p_c$ and is 2.0 for $p > p_c$. Feder (1988) defines the backbone of the percolating cluster. This is the shape obtained by pruning all the parts of the percolating cluster that are connected to it by only a single site. The backbone has a fractal dimension of about 1.61 (Oxaal et al. 1987).

The backbone is important in explaining the flow of fluids in porous media. Groundwater would be an example. The backbone consists of all sites visited by all possible random walks that do not intersect their previous path—called self-avoiding random walks. Consider a situation encountered in petroleum mining where a fluid, such as water, is used to extract the oil by injecting it through the porous medium. The driving fluid (water) cannot enter the dangling ends (i.e., those parts of the percolating cluster that do not form part of the backbone) because the trapped oil is incompressible and has no escape route.

Oxaal et al. (1987) set up a laboratory simulation of this phenomenon—called viscous fingering—which confirmed the theoretically expected results. They explain that the reason for this is that both the random walk and flow in porous medium satisfy the same differential equation, which is known as Darcy's law in groundwater hydrology. Despite these encouraging laboratory results, it turns out that these models cannot be used in the field. Lenormand (1989) points out that there are three reasons for this:

Cross-over regimes

Statistical models are valid when one type of force is dominant; for example, either capillary forces or viscous forces. In real fluids, viscous forces are proportional to the length of the injected pattern, and they increase with the size of the sample. Realistic simulations of viscous forces are limited to lattices smaller than 1000 × 1000.

Fractal geometry

Reservoir engineers are reluctant to use fractal geometry for a basin because they do not, in general, know its fractal dimension.

Need for macroscopic equations

Large-scale reservoir simulations are based on the convective-diffusion equation. Consequently, even if a fractal approach is valid it has to be written in a suitable form for reservoir engineers (Neuman 1990). This problem is the modern equivalent of the one

faced earlier this century of proving that a one-dimensional random-walk problem is formally equivalent to the convective-diffusion equation; it is (Wax 1954). The convective-diffusion equation predicts that the variance of the concentration of a tracer varies with time as t. Again, the converse is not true. Beer and Young (1983) show that other processes also have a variance that grows linearly with time. Random walks on a fractal percolation cluster will exhibit anomalous dispersion such that the variance of the concentration of a tracer varies with time as t^m. (Torelli and Scheidegger 1971). However, other effects such as lateral inflows can also cause such behaviour.

Self-similarity and the renormalization group

The site percolation model can be used to illustrate the way in which renormalization group approaches are intimately related to the self-similarity properties. Consider dividing the square lattice into square cells of $N \times N$ sites, and analyse f_N, the probability that a cell will be sufficiently densely occupied, that it is connected internally, and that it can connect to all four neighbouring cells. We have:

$$f_1 = p$$

$$f_2 = p^4 + 4p^3(1-p)$$

$$f_3 = p^9 + 9p^8(1-p) + 36p^7(1-p)^2 + 52p^6(1-p)^3 + 25p^5(1-p)^4$$

The form of f_2 reflects the fact that one of the four sites can be unoccupied without breaking the connectivity; but if two or more sites are unoccupied, then the connectivity must be broken. The form of f_3 reflects the fact that the connectivity breaks down if five or more sites are unoccupied but cannot break down if seven or more sites are occupied. A tedious enumeration of cases shows that connectivity is preserved in 52 of the 84 arrangements of six occupied sites and in 25 of the 126 arrangements of five occupied sites.

The renormalization group approach is based on the concept that if self-similarity occurs, then the connectivity properties should, asymptotically, cease to depend on cell size and so the critical point, p_c, is estimated by looking for points at which this occurs. In our simple example, this corresponds to estimating p_c from $f_i(p_c) = f_j(p_c)$ using two different length scales i and j. Using f_2 and f_3 (i.e., our larger two cases since we expect only asymptotic self-similarity) gives the estimate $p_c \approx 0.6782$. This is a crude approximation to $p_c = 0.5928$, but it does illustrate the basic principle of the renormalization group approach. Renormalization group techniques can be extended to calculate the power law exponents from the way in which probabilities such as the f_i change as a result of changes in length scale.

CLUSTER GROWTH

The example of a mathematical fire igniting nearest neighbours, as presented above, has emphasized the analogy with site percolation. An alternative view is to see it in terms of lattice growth. In this case, start with a single burning point (generally known in this context as a seed site). Then examine each of the neighbouring sites (remember there are four on the square lattice) and either ignite it, with a probability p, or declare it unignitable (with a probability $u = 1 - p$). When expressed in this form, the mathematical fire model is known as an epidemic process (Grassberger 1983). The same mathematical treatment can be used to model epidemic infections in trees; in which case, burnable sites correspond to those susceptible to infection, burning sites correspond to those actively infected, and unignitable sites are those resistant to infection.

There has been a large amount of recent interest in models of clusters that are formed by stochastic growth from one or more seed sites. In particular, Herrmann (1986) reviews models such as the Eden model (Eden 1961) and the DLA (diffusion-limited aggregation) model. The Eden model is similar to the growing mathematical fire model of the previous paragraph, except that particles are never declared unignitable. At every instant of time, all unoccupied neighbours of a burning site are examined and set alight with a probability p. The DLA growth model starts with a seed particle. A particle is then released from the perimeter of a large circle centered on the seed particle. The released particle executes a random walk until it either leaves the circle (and vanishes) or reaches a neighbouring site of an occupied site, in which case it becomes part of the growing cluster. The viscous fingering described in Section *Percolation and fractals* is an example of a DLA process (Oxaal et al. 1987; Daccord and Lenormand 1987). Figure 7 illustrates the shapes generated by the above three processes.

TURBULENCE AND LATTICE GAS HYDRODYNAMICS

The onset of turbulence in a flowing homogeneous fluid is determined by the Reynolds number, Re given by

$$\mathrm{Re} = U\,l\,/\,\eta$$

where U is the flow speed, l is the length scale, and η is the kinematic viscosity. At very low values of Re, the flow is laminar. At very high values of Re, it is turbulent. The transition for flow in smooth pipes is at a value of about 2000. Mandelbrot (1983) asserted that the theory of fractals must be applicable to turbulence. Attempts to systematically investigate this by determining the self-similarity of turbulent flow fields (Sreenivasan and Meneveau 1986) show the situation to be more complicated. Though several aspects of turbulence have some fractal (or multifractal) structure, it loses its fractal-like behaviour when viewed on very long timescales.

Frisch (1989) describes attempts to use lattice models to describe macroscopic fluid flows. He calls these lattice gas models. The problem is to find both a lattice and an appropriate set of interaction rules such that the collective behaviour of particles moving on the lattice is equivalent to the Navier-Stokes equation of hydrodynamics. A close approximation is the two-dimensional square lattice with the simple rules:

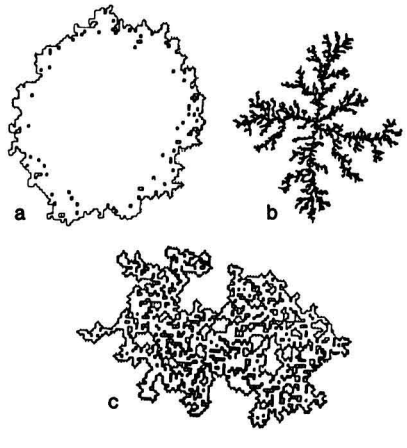

Fig. 7. Examples of shapes generated by growth processes from a single seed site on a square lattice. (a) Eden cluster of 1500 occupied sites. (b) DLA cluster of 11260 particles on a square lattice. (c) Epidemic cluster of 1800 sites at $p_c = 0.59273$ [based on Herrmann (1986)].

1. Each particle moves one lattice constant in a direction determined by its momentum.

2. If two particles collide head-on, then they rotate their momenta through 90°.

It turns out that the momentum flux tensor is not isotropic on such a square lattice, and a triangular lattice (i.e., each point has six connections) with more complex interaction rules is needed to maintain its isotropy.

There are qualitative similarities between the flow patterns generated by lattice gas models, and those observed in laboratory simulations at Reynolds numbers in the range of 100 to 200. Realistic environmental flows, such as those of the atmosphere, oceans, and rivers are all turbulent and have higher Reynolds numbers. These cannot yet be simulated. The size of the lattice gas that is used determines the Reynolds numbers, and sufficient computing power is not yet available to permit lattice gas models to be applied to flows with Reynolds numbers in the thousands.

These lattice gas models are purely deterministic as opposed to the stochastic models considered in the rest of this review. The volume edited by Wolfram (1986) collects a number of papers describing such systems.

LATTICE ANALYSIS METHODS

Most studies of lattice models, such as percolation, suffer from the disadvantage that the spatial structure has not been the main topic of investigation. Rather the concern has been with calculating the various moments of the distributions. Because most lattice applications have been in solid state physics, these moments correspond to various thermodynamic quantities.

Typically, these take the form

$$\Phi = \Sigma g_n p^n$$

where g_n denotes some configurational property of the lattice and p is a probability defining the stochastic aspect of the model. In the original applications to modelling phase transitions, the stochastic input comes from temperature effects and p is replaced by an appropriate function of temperature. A second problem is that many of the analyses lack mathematical rigor. The emphasis has been on developing workable computational tools rather than constructing a fully-blown mathematical theory. Whether this is an advantage or a disadvantage is partly a matter of taste.

There are five main ways of treating lattice models:

1. Exact solutions.
2. Closed form approximations (Burley 1972). These are not suitable for examining self-similarity.
3. Monte-Carlo simulation.
4. Series expansions.
5. Renormalization group analysis.

Examples of some of these approaches are given in the discussion below.

Exact solutions

Exact solutions can only be obtained in very special cases, mainly on low-dimensional lattices. Baxter (1982) described many of the known solutions. For some models it is not possible to solve for any of the thermodynamic functions of the type $\Phi(p)$, but it may still be possible to determine exactly the critical point at which the singularities and the self-similar behaviour occur. This can be done for bond percolation on the square and triangular lattices and for site percolation on the triangular lattice.

Monte-Carlo simulation

One of the most useful techniques is the Monte-Carlo simulation. This can be used to study a wide range of lattice models. It is, however, inherently restricted to finite systems, and so careful extrapolations are needed when this technique is used to study the critical point (p_c) at which the characteristic length scale of the system diverges. Furthermore, near the critical point, the standard sampling procedure leads to successive samples being correlated with a decay time that diverges (for an infinite system) as the critical point is approached. Thus, long computations and careful statistical analysis are required in order to obtain satisfactory statistical estimates of the critical behavior. An introductory account is given by Binder and Heermann (1988).

Series expansions

Series expansions were briefly introduced in Section *Mathematical description*. They provide an alternative way of extrapolating towards the critical point. For many lattice models the coefficients g_n can be determined for small n. Typically, the effort required to determine each successive g_n grows exponentially with n. This places severe limits on the number of coefficients that can be obtained. Since the critical point will be at or beyond the radius of convergence, special series extrapolation techniques are needed to estimate the critical behaviour (Gaunt and Guttmann 1974).

Renormalization group

Renormalization group techniques are based on a consideration of how the probabilities defining a lattice model change under a transformation of the length scale. Model probabilities, $p(L)$, appropriate to a length scale, L, are related to probabilities, $p(L')$, that would give the same statistical behavior for a model defined at some other length scale, L'. The transformation is written $p(L') = R[p(L)]$. Self-similarity occurs at the fixed points of the mapping $R(\,.\,)$. The difficulty of this approach is that the transformations can only be obtained approximately. While approximate transformations often give good approximations to the critical behaviour, there is usually no way of estimating the errors, and successive refinement of the approximation does not always lead to a steadily converging set of estimates (Domb and Green 1976). Refinement of the approximation involves increasing the number of model parameters, leading to a rapid growth in the complexity of the calculations needed to determine $R(\,.\,)$. The technique has been applied by Gabriel et al. (1990) in their study of the radiative transfer through fractal clouds.

FIELDS

The main feature of the site percolation model that was described in Section *Percolation* is that the occupation probability, p is independent of the neighboring sites or bonds. In other words, there is no correlation between the sites. The growth models of Section *Cluster growth* introduced simple correlated systems in which the behaviour of a lattice site depended in some way on the neighbouring site. In the simple site model, a site has only two states: occupied or vacant. The mathematical fire model introduces a third state (burning) which can only be triggered by a neighbour changing state from occupied to burning.

In this section, we describe a simple correlated lattice model. There are numerous, more complicated, correlated lattice models that can be defined, but we are not aware of any that have been successfully applied to environmental systems.

Correlated rainfall model

Beer (1990) attempted to link the percolation model with his observations that the time interval between raindrops followed a power-law distribution (and hence had a fractal structure). The problem, as illustrated in Fig. 8, is one of finding an interaction rule to generate rain patches that have the known fractal dimension of clouds, and have the observed

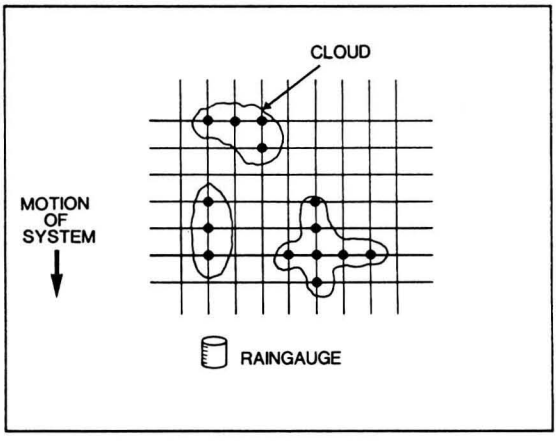

Fig. 8 A lattice statistical model for rainfall treats 0.5 mm tips of the rain gauge as occupied vertices of a two dimensional lattice that translates along one of its axes, and collects rain from the occupied vertices.

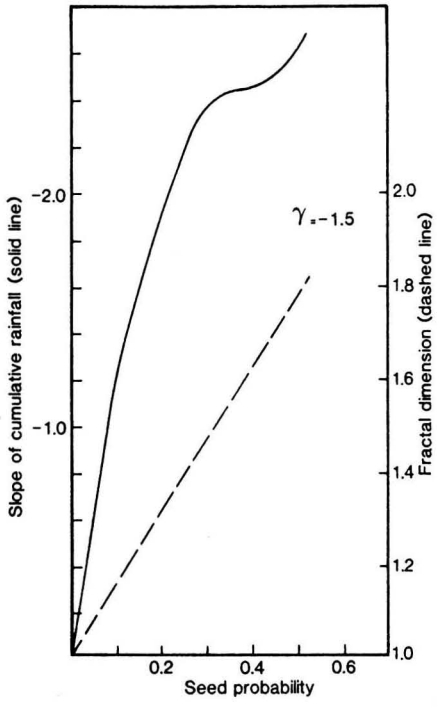

Fig. 9 Results of the simple correlated lattice model of rainfall in which sites are grown from a seed such that the probability of growth varies as $n^{-\gamma}$ where $\gamma = 1.5$.

fractal structure of the time between tips of a tipping bucket rain-gauge.

The probability distribution for the time interval between raindrops as generated by the simple lattice model of uncorrelated sites is an exponential distribution, rather than the observed hyperbolic distribution. This indicates that random placement of sites on the grid of Fig. 8 will not produce results that agree with observations, which is a rather tortuous way of determining the result, known to all cloud physicists, that clouds do not form as uncorrelated stochastic processes.

Beer (1990) suggested that it may be possible to describe the observed results by generating correlated sites with an interaction rule such that the cumulative distribution of n-occupied sites in a cluster is n^{γ} so that the probability distribution is

$$P(T > n) \sim n^{\gamma+1}/\gamma + 1$$

where γ has a value of about -1.54. A growth model was developed as follows. A square lattice was seeded with particles with a probability p_s. Points adjacent to a cluster were designated as growth points and added to the growing cluster with a probability p_g where

$$p_g = \left\{ \sum_{i=1}^{4} n^{-\gamma} \right\} p_s$$

The results of this model (Fig. 9) indicated that the observed slope of the cumulative rainfall distribution in time could only be obtained for $p_s = 0.1$; in which case, the resulting fractal dimension of the spatial structure was 1.2—a value that is much lower than any published observations of the fractal dimensions of clouds or rain areas. This result indicates that an interaction rule that successfully describes rain-cloud formation is going to be more complex than this one.

DISCUSSION AND CONCLUSIONS

Many environmental systems possess fractal-like properties. Where these fractal properties extend to their spatial structure, lattice models have great potential for modelling the spatial statistics of environmental data. This potential arises because both systems deal with the problem of self-similarity. The idea is fundamental to the notion of a fractal. Under certain conditions, e.g., $p = p_c$, lattice models also exhibit self-similarity.

Based on experience in statistical physics, some important aspects of lattice models can be summarised:

1. Simulation is the most general way to analyze them. However, because self-similarity implies divergent length-scales in a lattice model, careful extrapolation to large lattices is needed.
2. Most lattice models have specific sets of critical exponents and thus specific fractal dimension, except to the extent that different definitions of the fractal dimension lead to different numerical values.

One reason that lattice simulations have remained a specialized tool is the large amount of computational power required. The storage requirements for a two-dimensional lattice increase as the square of the lattice size. Furthermore, all methods of analysis of lattice rules are computationally intensive. Monte-Carlo simulations, renormalization group techniques, and series expansions all need a lot of computation.

Fractal simulations to date, such as computer realizations of the Mandelbrot set, rely on exhaustive iteration through decreasing size scales. Lattice simulations manage to generate fractal behavior naturally from simple local interaction rules. In addition, there are equivalence classes of models, defined by the action of the renormalization group, so that simple lattice models can exhibit behavior that characterizes many more complex models. Some results, particularly critical exponents, are the same for all members of a universality class and so can be obtained from analysis of a simple model.

However, qualitative self-similarity is not enough. The critical exponents of the lattice model and the environmental phenomenon of interest need to be the same. There are very few environmental systems in which this has been tested, bubble trapping in ice cores and the propagation of fires being some of the few. In other environmental systems, detailed analysis of existing data indicates that a fractal model is applicable, but the appropriate lattice model has yet to be determined. The nature of rainfall (Beer 1990) and the drainage area of streams (Robert and Roy 1990) fall into this category. The problem of groundwater flow that was discussed in Section *Percolation and fractals* has been more intensively studied, yet also seems to have similar problems. Tyler and Wheatcraft (1990) have shown how the measured pore-size distribution index of soils is related to their fractal dimension. Nevertheless, attempts to apply the percolation theory to the problem (Golden 1980; Torelli and Scheidegger 1971) did not produce quantitative results that have been used in hydrology.

We have mentioned that the critical exponents of the lattice model and the environmental phenomenon of interest need to be the same. However, the converse is not necessarily true. Stanley (1986) points out that both percolation and diffusion-limited aggregates in three dimensions have a fractal dimension of 2.5; yet one can immediately see that these two fractals look completely different to each other. The reason is that the other critical exponents differ.

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VEGETATION AND CLIMATE

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Over the last two centuries, man's activities have caused a 30% increase in the atmospheric concentration of CO_2, with continued increases seeming inevitable. This change in CO_2 concentration will act on vegetation, both directly and indirectly through global climatic change. It is well established that, on a global scale, patterns of vegetation and climate are closely correlated. Such correlations indicate that climatic change will cause the distribution of vegetation to change. However, the use of correlations for predicting vegetation responses to climatic change is fundamentally unreliable because correlations have no mechanistic underpinning of causation. This paper outlines a mechanistic model for predicting the equilibrium state between current climate and vegetation. It is also used to indicate the sensitivity of global vegetation to the changed climate associated with a doubled CO_2—greenhouse scenario. The interpretation of this static model is discussed in terms of rates and patterns of vegetation change.

INTRODUCTION

Comparisons between global maps of vegetation and climate indicate many close correlations, such as between the latitudinal changes in vegetation and temperature, the occurrence of desert and shrub vegetation, and low rainfall. Indeed, it is possible to define the climatic envelopes of most types of vegetation on the basis of correlations between their distribution, annual temperature, and precipitation (Holdridge 1947, 1964; Whittaker 1970; Lieth 1974; Box 1981). If this approach is recognised as just a correlation, and not an indication of cause, then the approach is acceptable.

Two problems arise when the approach is pushed beyond its capacity. The first is a naive interpretation of the correlation in mechanistic terms. For example, tundra vegetation is found in areas where the mean annual temperature falls to at least -10°C (Whittaker 1970). This incorrectly implies that plants of the tundra can grow at this temperature.

The second problem with the approach emerges when the correlations are used to predict the responses of vegetation to scenarios of climate change (Emanuel et al. 1985). The predictions are shown graphically (Figs. 1 and 2) as correlation plots between annual temperature and precipitation, with the climatic envelope of a particular vegetation type shown as an ellipse. In the simplest case (Fig. 1), the correlation implies that an increase in temperature and precipitation will cause the geographical regions vegetated by type 1 to change to type 3 vegetation. However, such a prediction fails when crucial mechanisms, which are not considered in the correlation, are effective. For example, if atmospheric CO_2 increases along with the change in climate, then plant-water use efficiency may increase (Morison and Gifford 1984). This response may be broadly equivalent to more effective annual precipitation, and so another vegetation type may develop (Fig. 1, type 2). The annual total of precipitation hides the seasonality of

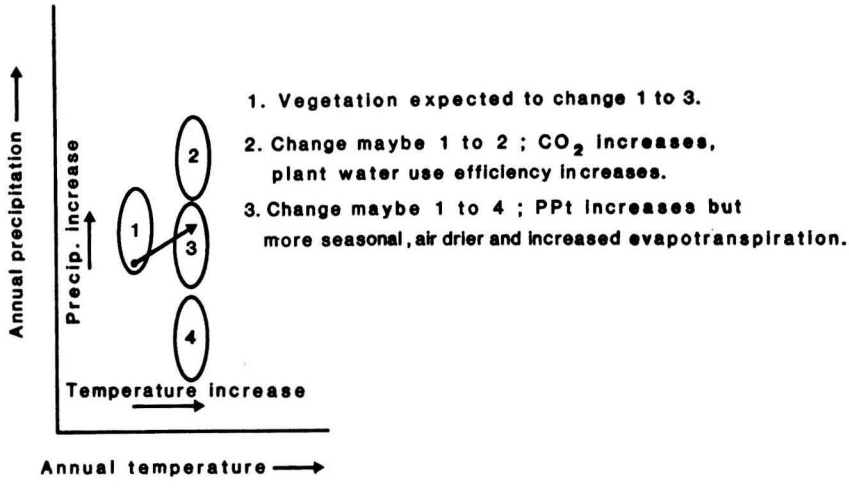

Fig. 1. Problems with correlation approach to climatic change. I.

precipitation. It may be that climatic change alters the seasonal patterns of precipitation, perhaps with dry and wet seasons. In this situation, high rates of water loss by evapotranspiration in the dry season may lead to leaf abscission through drought (Woodward 1987). As a result, the vegetation may become drought deciduous (Fig. 1, type 4), perhaps making less-efficient use of the bi-phasic supply of water.

More complex issues emerge in using the correlation approach, between present day vegetation and climate, to predict future vegetation. It is highly likely that a novel vegetation type may emerge (Fig. 2, type 5), a response expected from palaeoecological evidence (West 1964). Another problem likely to be encountered is that soil characteristics, such as nutrient supply and water holding and infiltration capacity, may also change, perhaps diminishing the availability of precipitation to the vegetation (Fig. 2, type 4).

A final and crucial question is how quickly will the vegetation respond to the changing climate. Although the functioning of the individual plants in the

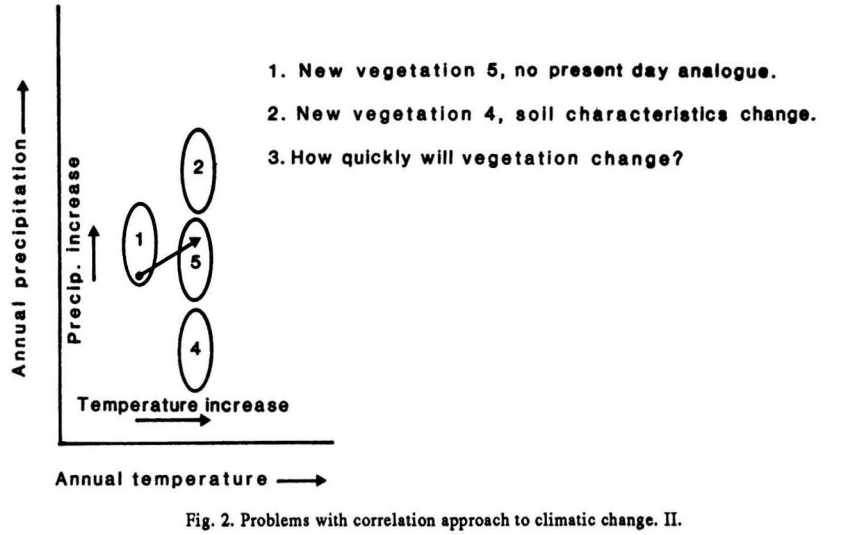

Fig. 2. Problems with correlation approach to climatic change. II.

vegetation may change rapidly, it may be many years before the structure of the vegetation changes. The correlation approach presented here can not answer this question. However, if the correlation was presented in three dimensions with a time axis, such as could be derived from palaeoecological data (Huntley and Birks 1983), then rates of change could be derived. The problem with such an approach is that of reconstructing those historical climatic axes which are relevant to a mechanistic model.

MECHANISMS IN THE CLIMATIC CONTROL OF VEGETATION

A more reliable method for predicting the effects of climatic change on vegetation should be based on mechanisms of responses. The actual driving force for both functional and structural change of vegetation may then be investigated directly. The search for mechanisms is not easy. However, Woodward (1987) defined three mechanisms which may be investigated experimentally and which are of major importance in the climate-related control of vegetation distribution. The three mechanisms are 1) minimum temperature resistance, 2) growing-season length and temperature for life-cycle completion and 3) precipitation supply for developing and maintaining a canopy of transpiring leaves.

The experimental and modelling data for deriving these mechanisms are described in Woodward (1987). Their relationships with climatic data, as recorded at meteorological stations, are shown in Figs. 3 to 5.

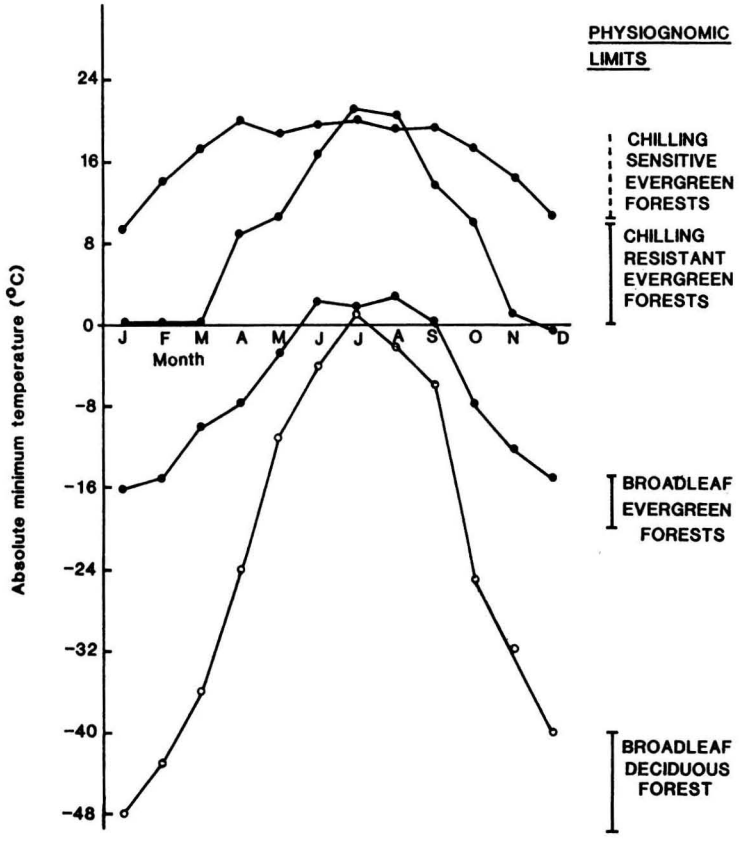

Fig. 3. Relationship between absolute minimum temperature for meteorological stations (from Müller 1982, in chilling sensitive, chilling resistant, (frost) broadleaf evergreen and broadleaf deciduous regions, in order of decreasing absolute minimum temperature) and observed killing temperatures (from Woodward 1987) for different physiognomic classes of vegetation.

Minimum temperature resistance

Experimental observations show that particular physiognomic classes of vegetation have particular limits of low temperature endurance. The limits for four major physiognomic classes are shown (Fig. 3) with typical climates. In climates where the absolute minimum temperature is greater than 10°C, there is no physiological limit to survival. If water is in sufficient supply, then the vegetation is expected to be a broadleaved and evergreen forest but sensitive to chilling (when the minimum temperature falls between 0°C and 10°C). Vegetation, which occurs in regions where the temperature falls in the chilling range, must be chilling resistant and is again expected to be a broadleaved and evergreen forest.

When the minimum temperature falls below 0°C, the vegetation must be capable of enduring some degree of tissue freezing. In general, it appears that for the cells within a leaf, for example, water may freeze in the cell walls and the leaf will survive, given a sufficient capacity to tolerate the high solute concentrations which develop when some of the water freezes (Woodward 1987). However, once water freezes within the cells and the cell membranes are disrupted, then cell death is inevitable (Sakai and Larcher 1987). Vegetation, which occurs in areas where the minimum temperature falls to about -15°C, is also expected to be broadleaved and evergreen. However, a number of mechanisms have evolved to endure frost, including the severe frost-drought which occurs when water freezes extracellularly. As a consequence, leaves are thick and tough to the touch and plants are characteristically slower growing than those of chilling resistant forests (Woodward 1987).

Species of the broadleaved but winter deciduous forests can endure minimum temperatures to about -15°C and -50°C. These species have summer leaves which are rather sensitive to even mild frosts, but have dormant buds which are more frost tolerant (Woodward 1987). No temperate broadleaf forests

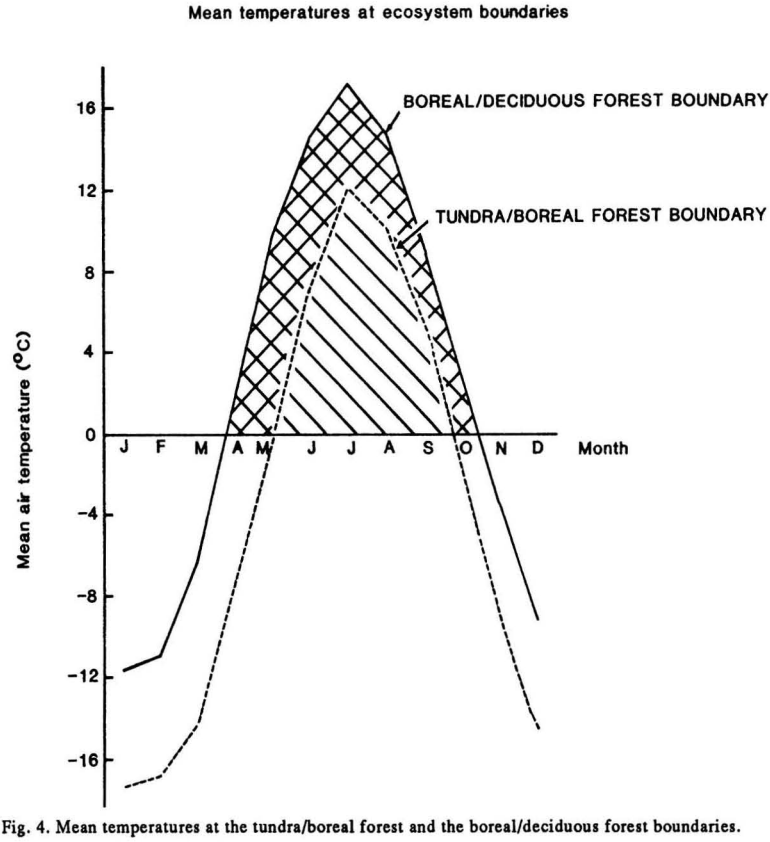

Fig. 4. Mean temperatures at the tundra/boreal forest and the boreal/deciduous forest boundaries.

are found in climates with minimum temperatures below about -50°C. These climates are occupied by boreal species, which are primarily coniferous, although this includes a small group of early successional and deciduous broadleaf species. These boreal species can endure temperatures below -90°C (Sakai and Larcher 1987) and so minimum temperature, per se, is not evidently a crucial factor in controlling their distribution.

Growing season duration and temperature

Although the absolute minimum temperature does not appear to limit the distribution of boreal trees, the length and temperature of the growing season is an important limit. Growth of boreal trees and the adjacent tundra shrubs and herbs occurs above a threshold temperature of about 0°C (Bliss 1956; Black and Bliss 1980). If the integral of time and temperature above 0°C is calculated (Fig. 4), then the boundary between the treeless tundra and the forested boreal forest occurs at 1000 day-degrees (Woodward 1987). The boundary between the boreal forest and the broadleaf deciduous forest (Fig. 4) occurs at 2000 day-degrees (Woodward 1990).

Whereas leaves of the tundra and boreal forests may develop once the temperature exceeds 0°C, the same cannot be true for plants in vegetation types of warmer climates, such as in chilling sensitive forests (Fig. 3) where plants may be killed by temperatures as high as 10°C. However, there are as yet insufficient data to define this threshold.

The hydrological budget

Observations on the relationship between precipitation and vegetation indicate that stature increases with precipitation (Fig. 5, Woodward and Williams 1987; Woodward 1989). In addition, for natural vegetation there is a relationship between canopy leafiness and vegetation stature (Woodward 1987). Leafiness is measured as the leaf area index (LAI), the area of leaf over a unit area of ground. These features are correlations for which mechanisms are still being defined. However, Woodward (1987) has established a clear mechanism for defining LAI. Given this mechanism, it is possible to assign a probable vegetation type to the predicted LAI, in the manner described on Fig. 5.

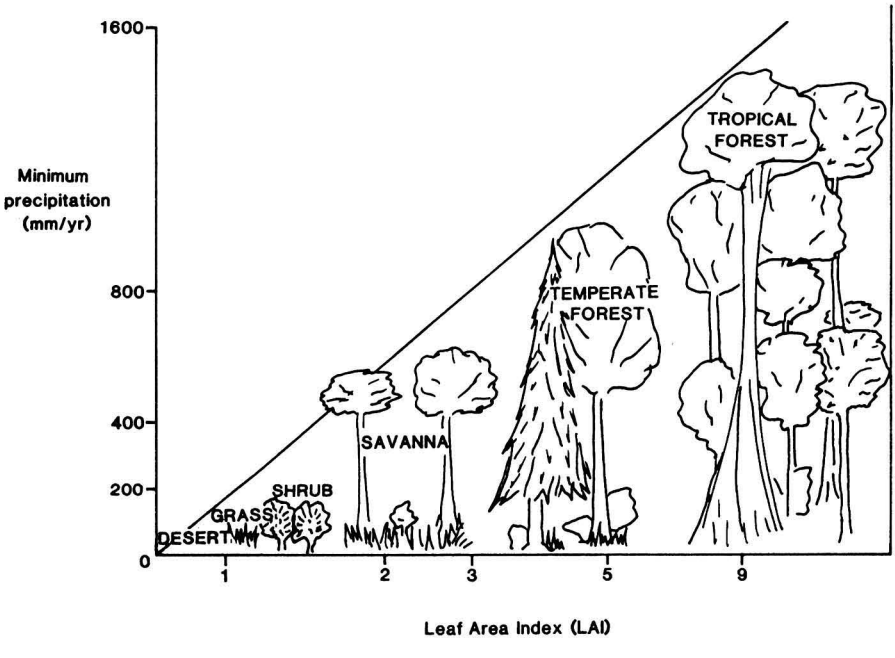

Fig. 5. Relationships between global averages of minimum annual precipitation, leaf area index and ecosystem stature (from Woodward 1989).

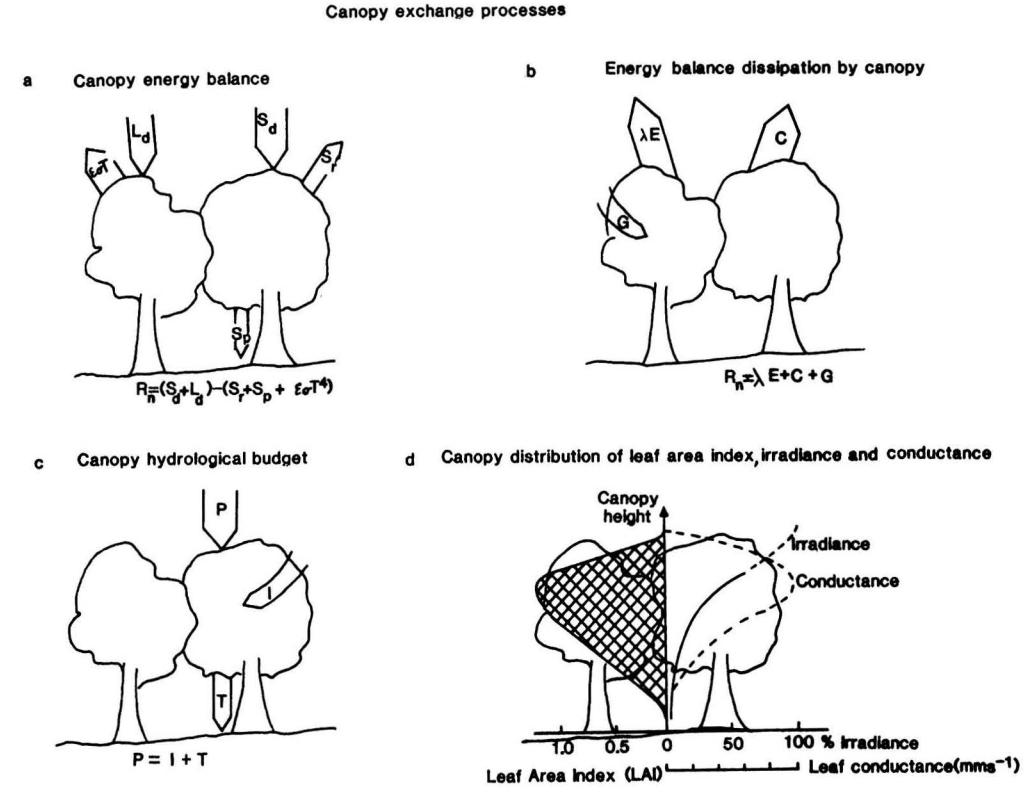

Fig. 6. Scheme for calculating canopy evapotranspiration. a) Canopy energy balance, b) energy balance dissipation by the canopy, c) canopy hydrological budget, d) canopy distribution of leaf area index, irradiance, and conductance.

The method for defining LAI from climate is shown in Fig. 6. In general terms, the energy gained by a canopy (measured as the net radiant balance) must be dissipated by energy loss in convection and evapotranspiration. The rate of evapotranspiration (evaporation is the evaporation of rainfall intercepted by leaves, transpiration is the evaporation of water through the stomata of the leaf) is controlled by the degree of opening of the stomata, the boundary layer thicknesses of the individual leaves in a canopy, and the canopy as a whole, the dryness of the air and the net radiant balance.

Figure 6 shows a scheme for calculating canopy eva-potranspiration. Section a indicates the canopy energy balance where R_n is the net radiant balance, S_d is the downward flux of solar radiation, L_d is the downward flux of long wave (terrestrial) radiation, S_r is the reflected solar radiation, S_p is the penetrating solar radiation, and $\varepsilon\sigma T^4$ is the emitted long wave radiation at canopy temperature T (K), canopy emissivity ε and with σ the Stefan-Boltzmann constant. Section b provides for the energy balance dissipation by the canopy, where λ is the total latent heat transfer by transpiration and evaporation, C is the sensible heat transfer and G is heat storage. Section c is the canopy hydrological budget, where P is precipitation, I is intercepted precipitation and T is throughfall. Finally, section d is the canopy distribution of leaf area index, irradiance and conductance (from Woodward 1987). The diagram shows the reduction in irradiance (solar) through the vegetation canopy, the resultant canopy conductance to water vapour (equal to the product of the mean stomatal conductance at height z in the canopy and the leaf area index at height z) and the distribution of leaf area index with height. This distribution of leaf area index is

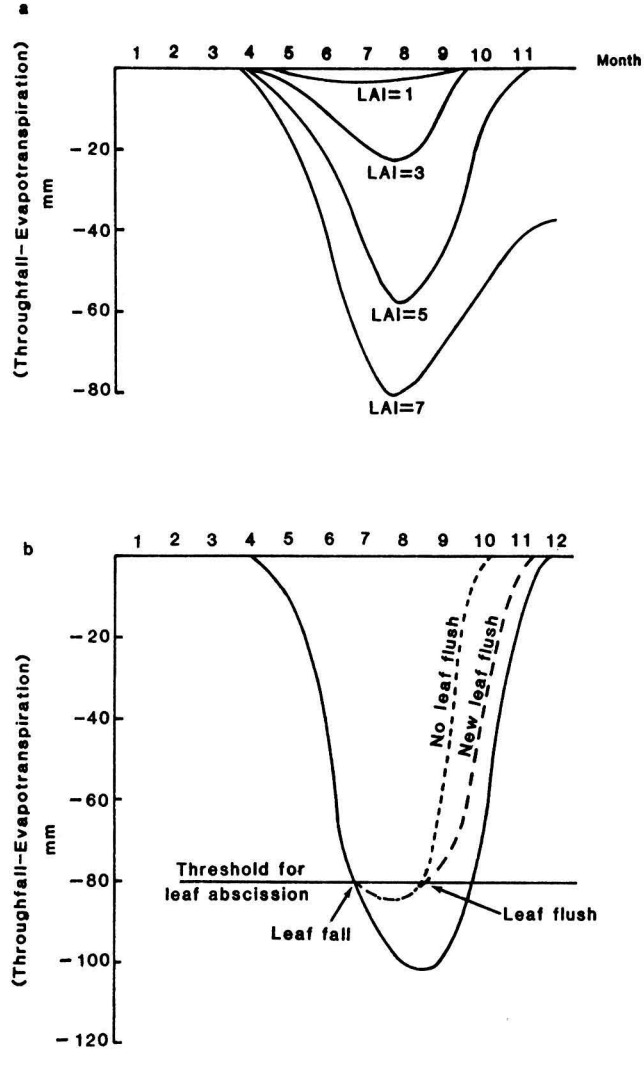

Fig. 7. Predicting leaf area index. a) Changes in soil water content (throughfall - evapotranspiration) for different leaf area indices. b) Predicting a drought deciduous response for vegetation, when the soil water content falls during a dry season to the threshold deficit of -80 mm, and the changes in soil water during the subsequent wet season, with and without leaf flushing.

applied to all canopy leaf area indices. The irradiance at any height z is defined as $S_z = S_0 \cdot \exp(-k \cdot L)$, where S_0 is the irradiance at the top of the canopy, L is the total leaf area index above height z and k is the extinction coefficient for irradiance, taken to be 0.5. The effect of irradiance on stomatal conductance g_z is defined from the empirical relationship (Woodward 1987) between the irradiance S_z and the maximum conductance, g_m, $g_z = (g_m \cdot S_z) / (S_z + (29500 \cdot g_m))$.

The method for predicting LAI is shown in Fig. 7. For any site, the balance between the throughfall of precipitation to the roots of the vegetation and the evapotranspiration rate of the canopy is calculated

for one year. Total evapotranspiration increases with LAI, whilst throughfall decreases (Woodward 1987). Consequently, in the model, as LAI increases, the soil-water content will be diminished by an amount calculated as throughfall less evapotranspiration (Fig. 7a). This drying of the soil proceeds to such an extent that at high LAI (e.g. LAI = 7 in Fig. 7a), there is a net annual drying of the soil, i.e., the soil water content is not recharged during the wet periods of the year. In such a case, it is expected that leaf abscission will occur, causing a reduction in LAI to a level where there is no net change in the annual mean soil-water content (Woodward 1987). In Fig. 7a, this state is satisfied when the LAI is 5, therefore, predicting that the appropriate LAI for a site is the maximum for which there is no annual loss of water held in the soil. In contrast, the canopy of LAI 3 fails to make maximum use of the available rainfall and so LAI should increase.

The maximum LAI predicted in this way may be exceeded if the vegetation is drought deciduous (Fig. 7b). In a simple model (Woodward 1987), it is predicted that once the soil water is depleted to some threshold (80 mm of rainfall equivalent in Fig. 7b), then leaf abscission occurs. The soil water content may increase following subsequent rains, and if the temperatures are adequate for growth, a new flush of leaves is developed. Drought deciduous vegetation, with high LAI in the wet season, may have a competitive advantage over evergreen vegetation, which will have a lower sustainable LAI.

PREDICTING THE GLOBAL DISTRIBUTION OF VEGETATION FROM CLIMATIC DATA

The information described above (Figs. 3, 4, 5, 6, and 7) and in Woodward (1987, 1989) can be distilled into a table of rules for predicting vegetation types (Table 1). The rules enable a prediction of vegeta-

Table 1. Rules for predicting vegetation type from climate.

VEGETATION TYPE	
1. Tundra	Day-degrees <1000
2. Boreal Forest	Day-degrees >1000
3. Broadleaf deciduous (winter) forest	Day-degrees >2000 Minimum -15 to -50°C
4. Broadleaf evergreen (frost resistant) forest	Minimum 0 to -15°C
5. Brodleaf evergreen (chilling resistant) forest	Minimum 10 to 0°C
6. Broadleaf evergreen (chilling sensitive) forest	Minimum 10°C
VEGETATION STATURE	
1. Forest	LAI = >4
2. Shrub and grass	LAI = 2 to 3
3. Sparse vegetation	LAI = <1
DROUGHT PHENOLOGY	
1. Drought deciduous forest	Soil water <80 mm deficit

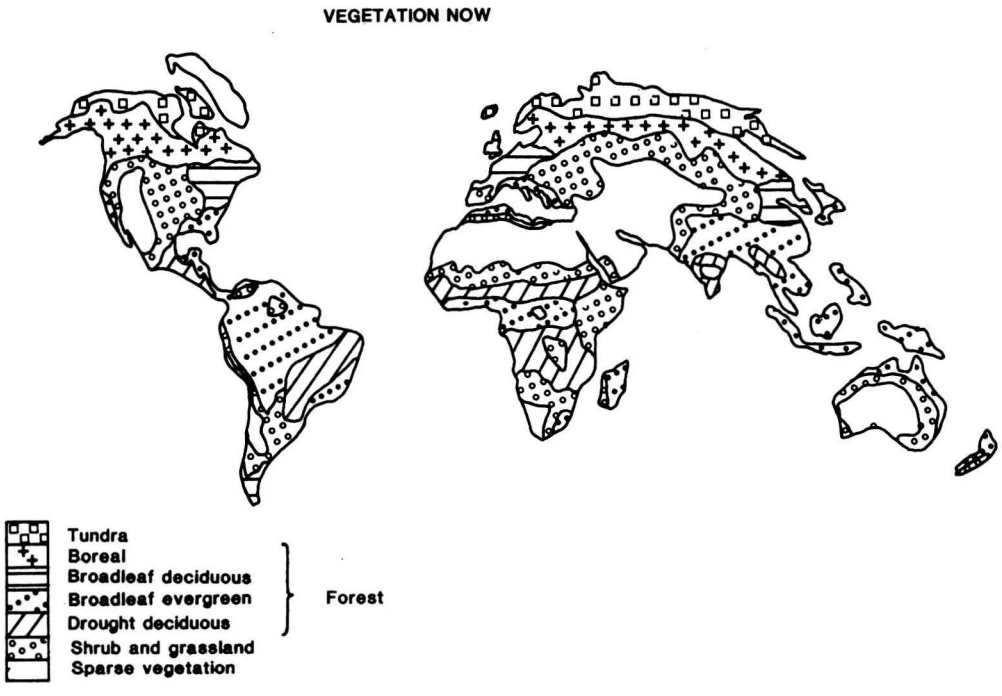

Fig. 8. Predictions of present day vegetation from climate data (Müller 1982).

tion from meteorological data (such as presented in Müller 1982). The present-day distribution of vegetation, predicted in this way, is presented on Fig. 8. The fit is very close between these predictions and observations (e.g., Polunin 1960; Whittaker 1970; Woodward 1987; Woodward and Williams 1987), implying that the rules, which were developed from experimental information (and not from correlations), provide an adequate description of reality. In addition, the predictions imply that present-day vegetation is close to an equilibrium state with climate.

PREDICTING VEGETATION DISTRIBUTIONS IN A GREENHOUSE CLIMATE

The rules for predicting present-day vegetation from present-day observations of climate can also be applied to climates predicted for the future, under the general head of a "greenhouse climate". Such a prediction will be attempted for the General Circulation Model (GMC) developed at the Goddard Space Centre (GISS) for a doubling of CO_2 concentration (Hansen et al. 1984), and is similar to other attempts at prediction (Woodward 1989, 1990).

The predicted extent of future vegetation can be readily achieved (Fig. 9). It suffers from two obvious problems. The first is due to the GCM itself, which may be a poor predictor of the future climate. Although this is not a fault of the biology, it must not be forgotten. The second problem with the prediction is the assumption that the geographical distribution of the vegetation is in equilibrium with the changed climate. That this may not be the case, has been discussed (e.g., Emanuel et al. 1985; Woodward 1990) and will be followed further in the next section.

Given these problems with the equilibrium vegetation map, it is, nevertheless, instructive to compare the two maps for investigating particular sensitivities to climate by vegetation. The most obvious change is in the diminished extent of tundra for the future. Emanuel et al. (1984) and Woodward (1989, 1990) show similar expectations of a northward spread of the boreal forest as the growing season warms. The reduced extent of the tundra would have a marked

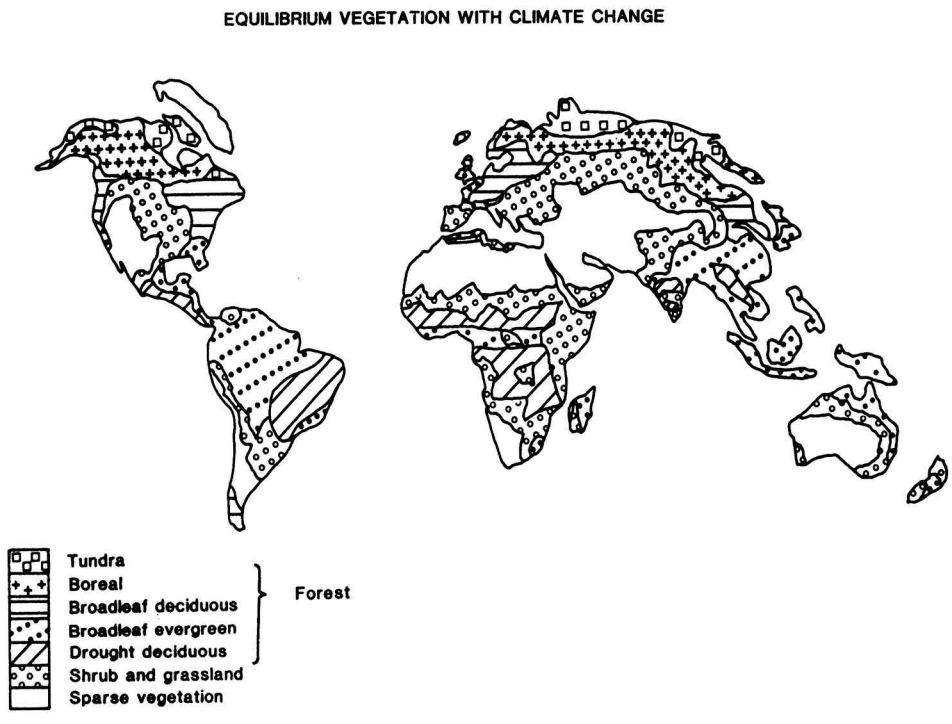

Fig. 9. Predictions of the equilibrium vegetation under a GISS climate-change scenario.

effect in reducing the available sites for summer migrant birds and mammals.

Other areas expected to be most sensitive to the changed climate predicted by GISS, are the reduced extent of forest in southern Europe, the increased area of sparse vegetation in south and north America, Africa and eastern Asia, the spread of drought-deciduous forest in south America and the spread of shrub and grassland in New Zealand and south Yemen.

Overall, the greatest expected global response to the GISS simulation is tundra, which is predicted to reduce its areal extent by about 50%. On a more regional basis, sparse vegetation is expected to increase in area by about two fold in south America and New Zealand, whilst the rain forest of central Africa is predicted to decline by about 30%.

MIGRATION

The map which predicts the responses of global vegetation types to a changed climate provides a sensitivity analysis of vegetation. Since it is the equilibrium state which is described by this static model, then it is incomplete. This incompleteness will be markedly so for ecologists, agriculturalists, economists, and politicians who need to know the dynamics of the predicted change, i.e., how long will it be before an area of vegetation can no longer survive in situ and how long will it be before new species move into the vegetation?

The migration maps generated by Huntley and Birks (1983) could imply that during the last significant period of global warming (which ended the Devensian glaciation of northern Europe and America), the rate of climatic change outstripped the rate at which temperate forest trees were able to colonise new, climatically suitable areas. If this is true for CO_2-induced climate change, then the dynamics of vegetation responses must be considered. A simple dispersal model is introduced to illustrate this feature.

The particle dispersion model (from Solomon 1975) is defined as follows:

$$N_x = N_o \cdot \exp - \frac{(q \cdot X)}{u \cdot H} \quad (1)$$

where
N_x is the number of particles deposited at distance X from a source, of height H, N_o is the number of particles deposited at the source, q the particle fall speed (terminal velocity), and u the mean wind velocity.

If the particles in question are seeds and the source is a single tree, then the migration rate (R) would follow the crude relationship:

$$R = - \frac{u \cdot H}{T \cdot q} \cdot \ln F \quad (2)$$

where
F is the proportion of deposited seeds necessary to cause an individual tree to regenerate, (discounting seed viability and extra-source deposition), and T is source longevity.

The following approximate figures for spruce (Harper 1977) have been inserted into Equation 2 to estimate R:

$u = 5\ m\ s^{-1}$, $q = 0.6\ m\ s^{-1}$, $F = 0.0001$

$T = 20\ y$, $H = 30\ m$

In this case the estimated rate of migration is $115\ m\ y^{-1}$, a value which falls in the lower range of estimates derived by Huntley and Birks (1983) from the analysis of pollen in peat cores.

The model is, however, deceptively simple and it fails, principally, because it ignores the effects of wind turbulence. Turbulence may significantly decrease the fall speed (q) of a seed; in addition, turbulence in the troposphere can move particles over great distances. This process is notoriously unpredictable and so, the modelling of often rare, long-distance events is likely to prove difficult (McIntosh and Thom 1978).

The colonisation of the Aleutian Islands (Woodward 1987) since the last glaciation illustrates some of the problems involved in predicting migration. The inter-island distances are too great for short-range dispersal to be relevant. The belt of islands spans from the extreme east of the USSR to the west of Alaska, USA. Palaeoecological evidence clearly indicates that colonisation of these islands occurred from both the east and west. Therefore, a model based on the prevailing wind direction is inappropriate.

The simple models described in Equations 1 and 2 do indicate that species' specific properties, such as fecundity, propagule size, and aerodynamics (or succulence for attracting animal dispersers), the height of the source plant and the species generation time, are all important in defining the rates of migration. Therefore, migration will need to be first considered at a species level.

Migrations in response to future climatic change will occur across man-managed landscapes. Over large regions the extent areas of natural and semi-natural vegetation have been reduced to small pockets. Since the geographical locations of these reserves are unlikely to be allowed to migrate (Peters and Darling 1985), the movement of species in this context may follow an island-hopping pattern. In addition to reducing the areal extent of natural vegetation, man has also introduced alien species for a variety of purposes. The progressive naturalisation of these aliens may provide an early indication of ecological change.

CONCLUSION

Equilibrium models such as that presented here may be of direct use in planning for future forestry and agriculture. The requirements for ecologists and conservationists are more complex. Where the rate of climate change exceeds the rate at which species can adapt, and historically this appears to be the general case (Cox and Moore 1985), the subsequent survival of a species and a specific vegetation type will depend on migration. Depending on the stage of the life cycle or the phenology of the vegetation which is most sensitive, in situ extinction may proceed concurrently with climate change, or it will follow within a few generations. In either case, important questions concerning species and vegetation conservation will need to be addressed.

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A SURVEY IN APPLIED ENVIRONOMETRICS: THE HEDONIC VALUING OF ENVIRONMENTAL AMENITIES

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This paper surveys recent advances in determining the value for environmental amenities through considering the application of hedonic pricing models. These values may be used in benefit/cost analyses by decision-makers to assist in the evaluation of policy alternatives. Because environmental amenities are not marketed commodities (ones that are bought and sold directly), establishing their value is a difficult proposition, but one which may be addressed through resort to implicit pricing models. These are the basis for establishing the so-called "hedonic prices." The implied values are derived by way of statistical inference, through reliance upon multivariate regression analysis of marketplace transactions of a composite good that incorporates, as an attribute, the environmental amenity in question. Since any particular facet of the composite good is not in itself being individually traded; e.g., durability, quality, prestige, quiet, etc., an inferential approach utilizing environometric methods provides the mechanism for evaluating the buyer's "willingness to pay" for the specific features which cannot, logically, be marketed separately. The statistical analysis provides for the establishment of a metric for the values being sought.

INTRODUCTION

The term "environometrics" makes reference to the quantitative, scientific analysis of questions relating to a multiple-disciplinary study of the environment; accordingly, this inquiry involves the application of methods that employ statistical procedures. (The word "environometrics" is proffered as a composite of "environs" and "metric." Because the practice has been to use a Greek grammatical composition, e.g. therm-o-meter, the basic structure would come out to be, according to that idiom, "environ-o-metrics." The term is constructed so as to encompass the broad range of quantitative, multiple-disciplinary research requisite in environmental analysis and so as to convey the understanding that the emphasis is not monodisciplinary as would be implied by the use of a term such as econometrics, sociometrics, poliometrics, psychometrics, or biometrics adopted from another of the "metrical sciences". See Berlinski [1976] for a discourse on some of these disciplines, particularly as they pertain to the development of statistical techniques in the social sciences.) Statistical techniques have an impressive legacy for both the physical sciences and social sciences relying upon the tools of scientific inquiry which require the formal presentation of assumptions, the specification of relationships in a theoretically coherent manner, and the empirical testing of the models posited; and, the analysis must be applied to the entire system if rational policies are to evolve. For example, understanding the chemistry of ozone depletion in the troposphere is essential in

* The views expressed do not necessarily represent those of the Health Care Financing Administration or the U.S. Department of Health and Human Services.

determining the causes of the seasonal hole recently confirmed to exist in the ozone layer of the atmosphere over the Antarctic; but the socioeconomic ramifications of the changes that may be required to ameliorate the problem must also be comprehended, or the appropriate solutions will not become manifest and therefore realized. Environmental analysis represents a holistic approach to problems, and environometric techniques are being developed so as to provide the quantitative tools that will allow implementation of the analysis. It is important that integration of the analytical apparatus concerning environmental matters be furthered. This paper is directed toward promoting the goal of greater communication among scientists concerned with the environment.

This survey paper is concerned only with the economic valuing of environmental amenities. The presentation is divided into a review of the theoretical underpinnings of the analysis for valuing environmental amenities, including a survey of the past decade's literature. Next, a review of the statistical techniques involved in hedonic modeling is presented, wherein the approaches and inherent problems in such models are explored. Finally, some areas suitable for future research are suggested.

THEORETICAL FOUNDATIONS

A body of literature has developed in distinct segments of the theoretical and applied social sciences—including demography, economics, environmental management, real estate finance, regional science, and urban studies, among others—on the evaluation of amenities that are not themselves directly traded (e.g., Smith 1990; Palmquist 1988; Hyman 1981). This relates to the concept of "willingness to pay" in economic theory. Various techniques for inferring willingness to pay have been developed, including contingent valuation, opportunity costs, and hedonic price indexes (Anderson and Bishop 1986; Cummings et al. 1986; Brookshire et al. 1982). (A thorough discussion of the meaning of the word "value" is beyond the scope of the present paper; herein, value is synonymous with the term "willingness to pay.")

Contingent valuation involves the sampling of individuals' opinions through questionnaires and is subject to strategic behavior on the part of the survey respondents. One aspect of this, as it relates to environmental goods, is the "free-rider" dilemma of public goods; namely, a respondent sets a high value on the amenity in question, such as clean air, while knowing that, as an individual, he/she will never be required to pay the price that is given. A public good, vis à vis a private good, is one from which individuals cannot be excluded from the act of consuming. Thus, with a public good, there is no incentive for anyone to pay the use value of the good. For example, an individual can use the Common to any extent that person desires without paying for this privilege or contributing to its maintenance. This is referred to as "the tragedy of the Commons". The second strategy of valuing a good is by way of posing the question regarding the "next best alternative" use to which it may be put. This concept of opportunity costs is attractive, but imperfect, as it is implemented in the case of non-marketed amenities, because of the jointness of consumption. An example is the use of "travel costs"; i.e., attributing the travel costs of a vacation that includes a visit to a National Park to be the value solely of that particular facility does not gauge the amount or portions of those costs which should be ascribed to other sites viewed or activities engaged in along the way to the park.

The hedonic-price methodology represents a means of addressing in a scientific fashion the issues of "strategic behavior" and "jointness of consumption" through considering the willingness to pay of consumers (Palmquist 1991; Epple 1987; Edmunds 1984). It does not, however, confront the "public good" question adequately; but, by providing a statistical decomposition of the actual purchase decisions of consumers, it interprets the observed marketplace behavior in such a way so as to identify the relative values of the component parts of the good. While these amenities are associated with the consumption of private goods, they are still externalities for which the consumer does not pay directly and over which the individual cannot exercise property rights. The hedonic approach merely provides inferences as to the implicit value being ascribed to the amenity by the purchaser. This information is obtained without the necessity for any suppositions having been formed by the individuals being sampled, and without neglecting the value of the other important attributes of the complex good. (There is some controversy in the literature as to whether or not willingness to pay is actually being evidenced in hedonic models [Smith 1977]. In the ensuing discussion, the consumer's revealed preference as to willingness to pay, as evidenced in hedonic pricing models, is accepted as a maintained hypothesis.) The hedonic approach is considered through a survey of the 1980's literature specifically, as this pertains to the valuing of environmental amenities; and a non-exhaustive bibliography of the literature of the decade is provided. Several papers (Smith et al. 1988; Bartik and Smith

1987; Freeman 1979a, 1979b, 1985; Hufschmidt et al. 1983; Miller 1982; Smith 1977) survey the earlier research in this field.

The first application of the implicit pricing strategy approach is that of Court (1939), who relates the selling price of automobiles to distinct attributes of the vehicles, e.g., size, weight, horsepower, etc., and refers to this relationship as a "hedonic price index". The adjective "hedonic" is chosen as a reference to the satisfaction that an individual derives from consuming a good. This interpretation of utility-seeking behavior on the part of consumers is premised upon the assumption that consumption decisions are the result of individuals employing an optimizing strategy.

A subsequent interest in hedonic pricing arises in the effort toward developing a methodology for the construction of price indexes to be used in adjusting national accounts to a consistent base-year value. The process of developing deflators such as, a consumer price index, a gross national product deflator, or a health-care cost deflator, necessitates the isolating of price changes from changes in: 1) the composition of the basket of goods purchased, 2) the characteristics of the good, 3) the quantity of the good, and 4) the quality of those goods. For example, people in 1990 purchased a greater number of personal computers than in 1980; the hardware components of the machine, its durability, and its capabilities have all changed, along with the price. If the real change of price in computers is of interest, then, the effects of these other changes, i.e., quantity, quality, and composition, must be isolated and eliminated from the total change that is observed to have occurred. Griliches (1971) proposes that Court's hedonic approach provides a solution, and he adopts this modeling strategy in the development of more meaningful indexes. Griliches provides a decennial retrospective of works following the initial researches into the problem. An alternative term for hedonic is the "characteristics approach" wherein a commodity that includes a multitude of models and varieties may be understood in terms of a much smaller number of basic attributes. This approach greatly reduces the magnitude of the problem (Griliches 1971). However, these early works of Court and Griliches are largely ad hoc with no firm theoretical foundation having been established for the approach. The theoretic basis of utility-maximizing behavior for hedonic models is not articulated, although it might perhaps be inferred in their work.

It is S. Rosen (1974) who explicates an economic rationale as the conceptual basis for the hedonic technique. This work provides the basis for the approach to become established as a scientific tool and, therefore, one suitable for evaluating implicitly-marketed goods. Therein, the case of the "economic person" in a market-oriented society is posited as that of an individual who seeks to equate "the outlay of monies on the margin to the utility obtained from the next unit of the good purchased". In behaving in this manner, the person is characterized as being a hedonist in the attempt to maximize utility. Yet, while environmental amenities themselves are not separately purchased aspects of complex goods, the hedonic pricing technique may be used to statistically infer from the overall purchase price the value that the buyer ascribes to the environmental component. Berndt (1983) details the argument of this economic paradigm which relies upon the utility-maximizing behavior of decision-makers positing that choices are made on the margin through the comparison of incremental benefits with incremental costs. It is a well-known fact that utility maximization is achieved at the point where marginal benefits equal marginal cost—a heuristic explanation should suffice. A person will continue to purchase more of a product as long as the benefits derived from the additional increment exceed the additional amount that must be paid. As soon as the cost of the increment exceeds the added benefit, purchase stops. That is the point of maximum utility for the consumer. Essentially, the explanation involves the concept of the individuals pursuing a decision strategy that is designed to achieve the greatest possible personal satisfaction. If, in the aggregate, consumption behavior is accurately described by such a model of the "economic person", then inferences may be drawn concerning the implicit values that consumers place upon the component parts of any complex good.

Since the decision to purchase a house is a major one in anyone's life and involves a complex good, that particular decision may be presumed to elicit as much of the consumer's attention to the calculus of the evaluation process as is required in the theory of utility-maximization. The implementation of the optimizing behavior involves the consumer in deriving information concerning the nature and extent of the market and in incorporating this with his/her own values for the unique attributes associated with the specific good under consideration. The features of a house being valued thusly include, not only those structural characteristics that are readily measured, such as size and number of rooms, but also subjective attributes, such as the quality of construction, the design of the house, the merits of the neighborhood

and its environs, and its proximity to the workplace. It is also the case that financial arrangements and contractual contingencies affect the selling price (Shilling et al. 1989), but the information concerning those details of housing sales transactions is rarely available to the analyst, so they have been largely disregarded. Case and Shiller (1989, 1987) are notable exceptions. (The SREA [Society of Real Estate Appraisers] Market Data Center in Atlanta, Georgia, has more than twenty years of data for selected regional markets containing financing information and property characteristics obtained from appraisers' reports submitted to them. Also, the National Association of Realtors in Washington, DC, has recently made available survey data covering the years 1985 through 1989, which includes financing variables, buyer demographics, and property characteristics. But these data sources have yet to be employed in environmental analyses.)

S. Rosen (1974) theorizes that all of this information is implicit in the observed transactions price (sales price) of the commodity, and that the values attributed by the individual to the tangible and intangible component parts of the property may be statistically derived. In a market-oriented economy, the sales price is a confirmation of the willingness to pay of the successful purchaser. But what specific aspects of a property affect the sales price of a house poses an empirical question. The objective design variables relating to the dimensions of the property are important without doubt; however, if the neighborhood offers little access to public facilities, has a high crime rate, is located near a potential environmental hazard (e.g., location within an earthquake zone, a floodplain, or in proximity to a volcano, a nuclear power plant, an airport flight path, or a chemical plant); and, if this is a factor which must be expected to be evidenced in the selling price, then statistical analyses are required in order to evaluate the degree of impact. Research has been directed toward understanding some aspects of each of these factors.

GENERAL FORMULATION

The general hedonic model is postulated where the value of a property, V, is a function of the physical attributes of the property, X; the environmental attributes associated with it, Y; and the financial exigencies of the market, the buyer, and the seller, Z; namely:

$$V = f(X, Y, Z) \qquad (1)$$

There is no a priori reason to expect Eq.1 to assume any particular mathematical form, although the majority of the research to date has adopted the pure linear or linear-in-logarithms form because of the ease with which these functional forms may be statistically estimated. And, it has been demonstrated that often these simple forms provide reasonable representations of the relationships under a wide range of cases. Specifically, the linear functional form is:

$$V_j = \beta_0 + \sum_{i=1}^{n} \beta_i X_{ij} + \sum_{k=n+1}^{n+m} \beta_k Y_{kj} + \sum_{l=n+m+1}^{n+m+o} \beta_l Z_{lj} + \epsilon_j \qquad (2)$$

where

- V = value of property j
- X = physical characteristics i
- Y = environmental attributes k
- Z = market and financial conditions l
- ε = $N(0, \sigma^2)$ error term
- n = number of physical measures i
- m = number of environmental aspects k
- o = number of financial variables l

(The various aspects relating to the overall market conditions have received attention in the finance literature, but the general lack of transactions details has largely precluded these from the broader consideration of environmental impacts. For this reason, the determinants contained in the Z vector are omitted from the remaining discussion.)

Equation 2, in this linear formulation, is estimated using multiple regression analysis; with the estimated parameters, the β's, representing the marginal effect of the specific variables on the observed transactions-value of the property. The analysis entails collecting data on selling prices, the physical characteristics of the properties, and other variables to reflect the environmental aspects that might be supposed to influence price. These environmental variables might include the decibel level of noise, the volume of vehicular traffic, or the level of air pollution that is observed nearby. Whether or not the property is in an earthquake prone zone or a designated floodplain might constitute others. Specific statistical issues that relate to the estimation of the relationship and the interpretation of results are discussed in the section on environometric methods.

LITERATURE REVIEW

Air pollution is a disamenity that has received considerable attention in the literature, and was one of the first applications of the hedonic model in assessing an environmental impact. Ridker and Henning (1967) rely upon a linear model structure to assess the effects of air pollution on owner-occupied property values in St. Louis, using 1960 census-tract data that relate to the median-values of the housing stock. (A "census tract" is the smallest geographic enumeration unit from which data are collected and upon which summary statistics are reported by the U.S. Bureau of the Census. The average population of a census tract is roughly 4000; therefore, these may be considered to be one approximation of a neighborhood.) The owner's estimate of value, rather than an actual selling price or a professional appraiser/assessor's valuation, is the dependent variable, V. Since the authors are interested in identifying individual equation parameters and are concerned with the degree of multicollinearity present in the data, they propose a simple transformation, residualization, in the collinear variable of interest—sulfation levels (an index of SO_2, SO_3, H_2S, and H_2SO_4)—with which to deal with the problem. Collinearity is the measure of the correlation among the explanatory variables in a regression model. "Residualization" involves regressing the problematic variable in the model against all of the other explanatory variables and then utilizing the resulting error term from this auxiliary regression (instead of the actual observed sulfation level) in the originally specified hedonic equation. The issue of collinearity is endemic to hedonic models, since in the "bundles" of attributes there are often structure and meaning—large houses have more bedrooms and bathrooms, etc. After applying the transformation, Ridker and Henning obtain a statistically significant negative relationship between the index of sulfation and median property values. These findings are supported by Harrison and Rubinfeld (1978) in an analysis of similar 1970 Boston Standard Metropolitan Statistical Area (SMSA) data. (An SMSA represents a collection of counties, parishes, or townships for which data are regularly published. These political sub-areas are included in a larger geographic region because of the economic ties that the areas have one with the other.) They conclude, in addition, that marginal air pollution damages "increase with the level of air pollution and increase with the level of household income" (Harrison and Rubinfeld 1978). Murdock and Thayer (1988) suggest that the mean levels of air pollution measures that are used in the aforementioned models should be replaced with more accurate site-specific ones, illustrating a case wherein a probabilistic measure is demonstrably superior to support the argument. The appropriate quantifying measures for amenities are difficult to obtain, and the relative ordering in terms of priority of amenities (and disamenities) is income-sensitive.

Bayless (1982) also considers the air quality question in the hedonic framework, but evaluates its impact on an area's salaries instead of on house prices. The results reinforce those of Harrison and Rubinfeld, in that the value of good air quality is found to be positively related to income levels. The approach is extended by Izraeli (1987) who uses both earnings and housing values to calculate hedonic indexes for amenities. His "results confirm the hypothesis that a tradeoff exists between the quantity and the quality of environmental goods, earnings levels, and house values" (Izraeli 1987, p. 373). Since much of the contemporary environmental literature is concerned with the eutrophication of lakes as caused by the acid rain, it is perhaps surprising that Rich and Moffitt (1982) are the only authors who attempt to establish a hedonic index for water quality by considering the impact of improvements in its quality on housing prices. This is a potentially fruitful area for further research.

Another class of hedonic price analyses has concentrated on natural hazards, such as flooding, earthquakes, and volcanos, and how the market may value these infrequent and unpredictable events. Skantz and Strickland (1987) consider two neighborhoods: one affected by severe flooding, and the other, a control group of houses wherein no flooding occurred. The authors test the hypothesis that an efficient housing market capitalizes the probable flood costs, a view that is not generally held by real estate professionals, i.e. agents, appraisers, and/or assessors. These groups, if pressed for an opinion, often argue that buyers are forgetful, and that while housing prices will decline immediately after the occurrence of an event, the prices return relatively quickly to the pre-event levels. Skantz and Strickland observe capitalization of an insurance-cost increase in a decline in house values to the extent of roughly 3.5% of the selling price. Shilling et al. (1985) similarly identify capitalization in selling prices of the present value of the flood insurance premiums amounting to approximately 50% of this discounted payment stream. Lee and Donnelly (1989) analyze house sales during the mid-1980s for a city that experienced its last major flood event in 1965 (with some minor localized flooding in 1978). They find that an implicit discount of $5300 is applied to each house located in the

U.S. National Flood Insurance Program designated floodplain. Since the last major event was more than twenty years prior to the sales being studied, the results derived do not indicate consumer myopia. Donnelly (1989, 1988) establishes that the market discounting is directly proportional to the value of the property (a US$5.50 per US$100 of assessment discount applies), and concludes that buyers capitalize an amount that exceeds the flood insurance premium payments, postulating that mere compensation for flood damage incurred is not sufficient for property owners who may be requiring an additional "hassle premium" by way of recompense. The discount in selling price that is observed is roughly 12%. MacDonald et al. (1987) observe that selling prices of houses located in another floodplain imply a discount rate of about 3%. Earlier studies by Park and Miller (1982) and Thompson and Stoevener (1983) use much smaller sample sizes, yet reach similar conclusions to the ones mentioned above. The Park and Miller analysis finds a statistically significant effect of the floodplain location on selling price, and Thompson and Stoevener argue that the observed differential in capitalized assessed value reflects the value which the market places upon a flood mitigation project.

Brookshire et al. (1985) evaluate the value of "safety" in constructing a hedonic price gradient for the Los Angeles and San Francisco areas, reflecting the discounts in selling prices of houses located in earthquake prone zones; and, the authors' results are consistent with actuarial estimates of potential damage. Bernknopf et al. (1990) similarly document that the threat of earthquakes and volcano damage result in a perceived loss in market values of houses of between 8 and 11%. These study results support the hypothesis that buyers evaluate amenities (in this instance negatively, therefore these are disamenities) in establishing the price that they are willing to pay for a house.

Another group of locational and site disamenities, as these pertain to man-made environmental hazards, has also seen broad consideration (e.g., Michaels and Smith 1990). Several studies have considered the price effect of a nuclear power plant sited near to subject properties (e.g., Webb 1980). Nelson (1981) and Gamble and Downing (1982) investigate house prices in the vicinity of the Three Mile Island (TMI) power plant. Nelson's analysis of county assessor's data finds no statistically discernable effect of the accident on the selling prices; whereas Gamble and Downing consider single-family house sales nearby TMI and farther away, and discover an unexpected positive relationship between the selling price and proximity to the TMI plant. Gamble (1980) investigates the impact of "line of sight" proximity and distance from a nuclear plant on house prices without identifying any statistically significant effect. These anomalous results are interpreted by Bjornstad and Vogt (1984) as evidence of the capitalization of the revenue benefits provided by the facility through lowered local property taxes. They suggest that the lower local taxes that are observed for houses located in the power plant's property-tax jurisdiction vis à vis the situs disamenity of the potential hazard are merely offsetting effects. What Bjornstad and Vogt suggest is that these models have been misspecified, and/or the results misinterpreted, in that an important determinant of value is omitted from the relationship. Whenever local infrastructure is financed by a property tax, this poses an additional problem in the analysis because the tax imposed on the property will necessarily be related to the level of local infrastructure provided. The government services are benefits to the property owner while the property tax is the cost; the former would be expected, *ceteris paribus*, to increase the value of the property while the latter would, *ceteris paribus*, reduce the value. It is not necessary that these effects be exactly offsetting in the determination of value. In fact, it is imperative that the analyst not regard them as such. A larger proportion of the local infrastructure's cost in the TMI area is carried by businesses than by anyone else, supporting the Bjornstad and Vogt argument relating to increasing housing values. Conversely, where areas have a disproportionate share of property that is tax exempt, such as church, nonprofit, or government-owned properties; a decrease in housing values would be expected to be observed, because a larger relative burden is being borne by those remaining owners of taxable parcels.

Social scientists also investigate the effects of voluntary social groupings and government regulation on property values (Bartik 1988; Blumqist and Worley 1981). (A saying in real estate is that there are three things that affect the selling price of a house: location, location, and location.) Asabere et al. (1989), Pogodzinski and Sass (1989), Ford (1989), Fischel (1985), Lockard and Hinds (1983), and Schwartz et al. (1981) establish that pro-active government regulations, such as zoning laws which stipulate the acceptable use of property, have the desired effects of maintaining or increasing values. General neighborhood effects on housing prices that have been identified include: general locational differences

(Dubin and Sung 1990; Parsons 1990; Bond and Coulson 1989; Manning 1989); the quality of the schools and level of crime (Clark and Cosgrove 1990; Dubin and Goodman 1982); the access to transportation facilities (Bajic 1983; Li and Brown 1980); the presence of public housing projects or group homes for the handicapped (Farber 1986; Rabiega et al. 1984); as well as the racial composition of the area (Gabriel 1987; Mann 1982). These, too, are environmental factors in the broadest sense, which includes all of the physical and social aspects of the property. However, the correction of what may be perceived to be consequent problems arising from any of these purely social effects is perhaps even less straightforward when social engineering is to be attempted than when changes to the physical environment are being proposed.

ENVIRONOMETRIC METHODS

Statistical analysis techniques have been extended to answering questions regarding numerous social science disciplines. The "metrical" sciences now include: cliometrics in history, econometrics in economics, polimetrics in political science, and psychometrics in psychology. Each discipline utilizes its own theoretical paradigms for specifying hypotheses that are to be tested and each has adapted the tools of statistics to its own specific needs. The same will doubtless occur in environmental analysis as the needs of the environometrician dictate, but initially, as has been the case in the other disciplines, existing techniques will be adopted whole-cloth before original contributions to metrical analysis may be anticipated. Therefore, being a new metrical science, some established statistical techniques and modeling strategies that are suitable for environmental analysis will be discussed here.

The linear functional form as depicted in Eq. 2 has been extensively used in much of social science research, as it is simple to specify and estimate, and it has proven robust in its results. It is often persuasively argued that the true underlying function in question is linear, or linear-in-logarithms, within the relevant range of the data. This argument appears in many of the environmental studies cited. However, it may be also argued that the inherent structure that is present in complex goods serves to dictate against a simple linear specification.

An additional concern raised by Jones (1988) is that, since a bundle of goods is being traded, linearity of prices may not hold in technical terms; this somewhat esoteric argument relates to the marginal utilities not being equal to the marginal rates of substitution. This aspect, when combined with the nature of a hedonic price model being an inherently nonlinear one because of jointness in consumption (i.e., the bundling of attributes), would seem to preclude simpler linear specifications (McConnell and Phipps 1987). That is to say, newer large houses have many bedrooms, several bathrooms, and other associated amenities; are situated in better neighborhoods that have lower crime rates; and exhibit a more pristine environment. These issues may be handled by the addition of cross-product terms to Eq. 2 such that the number of bathrooms and other attributes in those houses are allowed to affect the manner in which floor space contributes to the property's value. That is, the partial derivative of value with respect to floor space is not a simple constant, β_i, where i is the floor space variable, but also includes other terms that depend upon the bathrooms and other attributes that are present in the property. Equation 2 therefore might be extended in the following manner:

$$V_j = \beta_0 + \sum_{i=1}^{n} \beta_i X_{ij} + \sum_{k=n+1}^{n+m} \beta_k Y_{kj} + \sum_{i=1}^{n} \sum_{l=1}^{n} \beta_{il} X_{ij} X_{lj} + \sum_{i=1}^{n} \sum_{k=1}^{m} \gamma_{ik} X_{ij} Y_{kj} + \epsilon_j \quad (3)$$

Herein, the impact of a marginal change in the i^{th} attribute, floor space, on value in this instance would be defined as:

$$\frac{\partial V_j}{\partial X_i} = \beta_i + 2\beta_{ii} X_{ij} + \sum_{\substack{l=1 \\ l \neq i}}^{n} \beta_{il} X_{lj} + \sum_{k=1}^{m} \gamma_{ik} Y_{kj} \quad (4)$$

If the analysis concerns the effect of a change in floor space on value, the $\beta_{il}X_{lj}$'s might include the contribution of a floor space/bathroom interaction variable, among others, and the $\gamma_{ik}Y_{kj}$'s might include a floor space/floodplain term. In addition, the quadratic term, $\beta_{ii}X_{ij}$, will influence this calculation, and the algebraic sign of this term would be expected to be negative, i.e., $\beta_{ii} < 0$, so as to provide for the eventual onset of diminishing marginal utility. In this example with the two other characteristics, the former might be hypothesized to make a positive contribution, i.e., $\beta_{il} > 0$, while the latter might be expected to make a negative contribution, i.e., $\gamma_{kj} < 0$, to value

as floor space increases. That is to say, the evaluation of the second derivative of the marginal contribution Eq. 4 will indicate in what manner and to what degree these other factors combine with the i^{th} factor in establishing the value of the good. Naturally, each of these variables, bathroom and floodplain, would have its own partial derivative that might include terms relating to other attributes as well. This is considered by Diamond and Smith (1985, p. 291) specifically: "the simultaneity arises from the nonlinearity of the hedonic price function for housing, since the nonlinearity implies that the marginal price paid for a unit of a characteristic is a function of the amount consumed or produced of that characteristic and other characteristics."

The specification in Eq. 3 accounts for pairwise interactions of variables and includes a quadratic influence of the variable itself, the $X_{ij}X_{ij}$ term. But this formulation also exacerbates any level of collinearity that is present in the simpler linear relationship, since X_{ij}^2 is an obvious function of X_{ij}. The greater the level of collinearity in the model the less the certainty that the parameters of the model can be statistically identified —see Belsley et al. 1980 for a comprehensive discussion of techniques for identifying the presence of problematic collinearity. This problem of parameter identification always exists as a trade-off against model realism (and therefore complexity). If the objective of the exercise is merely to forecast the dependent variable (as is the case in a preponderance of the literature concerning housing markets which concentrates upon developing a model that will explain the observed selling price of the property), then the issue of collinearity may be ignored.

That forecasting objective is distinct from the attempt to identify the contribution of the individual components of the property to its value. Models can serve two distinct objectives, forecasting or parameter estimation. Although these are not mutually exclusive goals, they do raise different problems in model construction. Development of a good forecasting model does not require parameter identification, and models with statistically significant parameters may not forecast well. Conversely, if one wishes to know the size of the β's and γ's, then greater levels of collinearity in the specification pose an obstacle to this end. This simply means that the concerns of the modeler must be directed to other issues when evaluating the suitability of a forecasting model vis à vis one designed to identify implicit prices.

A second form of the problem is the "classical" identification issue of demand/supply as it is addressed in the econometric literature. Economic theory posits that the levels of production and consumption are functions of the price of the good, the price of other goods, tastes, and technology, among other factors. An estimated relationship between quantity and price could, therefore, theoretically relate to either supply or demand—the only difference being the à priori expectation as to the algebraic sign to be observed. Since the reported marketplace values of prices and quantities used in the statistical estimation are transactions values, these represent points on both the supply and demand curves for the product. One thus needs information or assumptions in addition to price and quantity to be able to "identify" the specific relations as representing either supply or demand. Naturally, some of the parameter estimates in demand and supply relationships will necessarily have different algebraic signs; therefore, understanding which relationship is being estimated is important to the analyst.

Another issue concerns the most appropriate functional form to be specified; yet economic theory is largely mute on this point. The functional relationship might be linear or some nonlinear form, for example; linear-logarithmic, logarithmic-linear, quadratic, etc. (Milon et al. 1984). The predominance of research has quite pragmatically involved the simpler-to-estimate linear formulations. Nonlinear model estimation is more demanding both in terms of human and physical capital. Fortunately, the latest microcomputer hardware and software readily facilitate much more sophisticated analytical approaches than have been commonplace in the literature to date. The issues of whether a demand curve or a supply curve is being observed and of what functional form, as well as the sensitivity of parameter estimates, are addressed by Graves et al. (1988) and Bender et al. (1980). If the data can provide insights into these questions—since theory does not—so much the better. Brown and H. Rosen (1982) recognize the extent of the identification problem inherent in S. Rosen's specification, arguing that segmented market models or ones with specific functional forms, e.g., inelastic supply or nonlinear models, may overcome this problem (see also Murray 1983). The indentification problem is one that Horowitz (1987) explores in the context of bid-and-offer curves (see also McConnell and Phipps 1987)

The nonlinear modeling approach is pursued by Bartik (1987, p. 83) who observes that "the nonlinearity of the hedonic price function allows the consumer to endogenously choose both quantiles and marginal prices". Mendelsohn (1985, pp. 27-31) agrees that

the solution to the identification problem is that "analysts should turn to the multiple market examples, either intertemporal or cross-sectional" or, alternatively, to nonlinear modeling.

Whereas Eq. 3 provides for the introduction of nonlinearities into the estimation process, it is not a very general formulation. A more flexible functional form, one incorporating the Box-Cox (Box and Cox 1964) transformation procedure, is applied by Harrison and Rubinfeld (1978) to the concentration of nitrogen oxide variable in their model—the indication is that the variable should be squared. The Box-Cox transformation itself is:

$$A_{ij}^{(\lambda_i)} = \frac{A_{ij}^{\lambda_i} - 1}{\lambda_i}, \quad \text{for } \lambda_i \neq 0 \qquad (5)$$

$$= ln A_{ij}, \quad \text{for } \lambda_i = 0$$

The Box-Cox transformation can be applied to the dependent and independent variables appearing in Eq. 3 yielding the quadratic Box-Cox (QBC) functional form which allows the data itself to assist in determining the most appropriate form. The QBC is one of a class of flexible functional forms. A formal definition of flexible as provided by Lau (1986, p. 1540) is:

"An algebraic functional form for a unit cost function $C(p;\alpha)$ is said to be flexible if at any given set of nonnegative (positive) prices of inputs the parameters of the cost function, α, can be chosen so that the derived unit-output input demand functions and their own and cross-price elasticities are capable of assuming arbitrary values at the given set of prices of inputs subject only to the requirements of theoretical consistency".

The QBC for property j is of the form:

$$V_j^{(\theta)} = \alpha_0 + \sum_{i=1}^{n} \alpha_i A_{ij}^{(\lambda_i)} + \frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n} \alpha_{ik} A_{ij}^{(\lambda_i)} A_{kj}^{(\lambda_k)} \qquad (6)$$

In this formulation the impact of a marginal change in an attribute i of the property j on its value is then

$$\frac{\partial V_j}{\partial A_i} = V_j^{[1-\theta]} A_{ij}^{[\lambda_i - 1]} \left[\alpha_i + \sum_{k=1}^{n} \alpha_{ik} \left(\frac{A_{kj}^{\lambda_k} - 1}{\lambda_k} \right) \right] \qquad (7)$$

Table 1. Parameter restrictions on the QBC for standard functional forms.

Functional Form	α_0	θ	λ's
1. quadratic Box-Cox	-	-	-
2. translog	-	0	0
3. generalized Leontief	-	1	0
4. quadratic	-	1	1
5. generalized square-root	-	2	1
6. linear Box-Cox	0	-	-
7. linear (lin)	0	1	1
8. linear-in-logarithms (log-log)	0	0	0
9. semi-logarithmic (log-lin)	0	0	1
10. exponential (lin-log)	0	1	0
11. inverse (1/V)	0	-1	1
12. reciprocal ($1/A_i$)	0	1	-1

The quadratic Box-Cox transformation provides a specification that is a flexible functional form such that different values for α_0, θ, and λ will yield different mathematical relationships. Evaluating these parameters, which are derived simultaneously in a maximum likelihood estimation procedure, will allow the data to suggest the most appropriate mathematical form of the relationship (Donnelly 1991; Cropper et al. 1988; Goodman and Kawai 1986; Halverson and Pollakowski 1981). Table 1 provides some of the alternative functions that result from different values for the three parameters. The QBC modeling strategy imposes additional burdens upon the data, as these now must not only identify the impact of characteristics on the value, but also must suggest the functional form of the model.

Although functions 7 through 9 are the most commonly specified and estimated forms for hedonic price indexes, Cassell and Mendelsohn (1985) consider the quadratic Box-Cox form, and they identify potential problems in specification, in estimation, and in forecasting that need to be addressed. The BC form requires strictly positive values for variables or else imaginary numbers will result. The large number of parameters to be estimated will necessarily reduce the accuracy of any single coefficient, and bias will result in forecasts because of the nonlinearity of the model form. These concerns can all be addressed; e.g., the bias in the transformation of a log-log or semi-log model's forecast that results in providing the conditional median instead of the mean value are simply corrected (Stynes et al. 1986; Goldberger 1968; Meulenberg 1965). Halvorsen and Pollakowski (1981) consider this issue of functional form and conclude that neither the linear, linear-in-logarithms,

nor the semi-log forms of the relationship are the most appropriate in their data. Whereas Bender et al. (1980) and Graves et al. (1988) use this modeling strategy and conclude that the general QBC form, wherein α_0, θ, and $\lambda_i = \lambda_j$ can assume any values, along with the transcendental logarithmic (translog) form (Christensen et al.1975), where α_0 can take any value and $\theta = \lambda_i = \lambda_j = 0$, are the most acceptable forms. These authors show that the values established for air quality are quite sensitive to the specification; and, thus, the estimation of the simpler, more convenient linear or linear-in-logarithm hedonic model will result in biased estimates due to misspecification. Conversely, Edwards and Anderson (1984) find that the linear Box-Cox form is the most acceptable specification, rejecting the quadratic form because of its high degree of collinearity.

Great demands are imposed upon the data by the QBC specification; for example, as has been discussed, collinearity increases as more variables and their cross-product terms are added to the model. In addition to collinearity, other problems with the model's error term may be obscured by the QBC estimation. Specifically, the problem of heteroscedasticity should be anticipated in hedonic models. The expression "heteroscedasticity" refers to a changing variance in the regression error term. In the instance of housing, the variance of the error might be expected to be related to the value of the house. That is to say, generally, there will be observed to be greater variation in the selling prices of comparable expensive homes than there will be in the sales prices of comparable low-priced homes. The estimation of the Box-Cox θ and λ parameters can be shown to be biased in the direction required for a more nearly homoscedastic result without having actually addressed the problem (Judge et al. 1985; Seaks and Layson 1983; Savin and White 1978). (The details of the diagnostic testing of regression assumptions, e.g., homoscedasticity or serial correlation, is beyond the intended scope of this paper and therefore is not discussed. However, such testing of regression models should be undertaken as a matter of course by the analyst.) Judge et al. (1985, pp. 839-841) provide a good description of the Box-Cox estimating procedure, and Spitzer (1982) details several alternative approaches to deriving the Box-Cox parameters. Estimation of the QBC can be programmed in most multiple regression packages—SHAZAM, a program written by Ken White at the University of British Columbia provides a BOX command that automates the estimation process (White et al. 1990).

SUMMARY

It is difficult to establish values for environmental factors that are not regularly bought and sold in the market place. Multiple regression analysis provides the means of testing hypotheses concerning the valuing of component parts of a complex good in the context of a theory which relates individual decision-making behavior to observed consumption. The theory of hedonic price indexes can be usefully applied to defining a range of values for environmental amenities that then may used in assessing various policy alternatives. This inferential approach to establishing values eliminates problems associated with survey and other indirect techniques, but it does pose difficulties with respect to model specification. Hedonic price theory is mute on the question of the functional form of the relationships. It has been demonstrated that recourse to a flexible functional form, such as the quadratic Box-Cox, may provide assistance here. Unfortunately, the information so derived is not costless, since the estimation process is more complicated than for simpler functions and other computational questions also may arise.

The extension of the research in the application of hedonic pricing models to new issues relating to the environment must proceed. This will entail developing better data sources and measures of the phenomena to be analyzed and incorporating these with existing information. The direction has been suggested by the studies discussed here. Unfortunately, each of these studies has been forced to rely upon its own specially collected and/or constructed dataset for the analysis. It would be hoped that future analyses may benefit from the development of comprehensive geographic information systems that include not only detailed physical, but also socio-economic and demographic data. Priority should be given to such projects.

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A PROCEDURE TO ESTIMATE WORST-CASE AIR QUALITY IN COMPLEX TERRAIN*

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Using a straightforward synoptic climatological analysis scheme, it is shown that the potential for an area to experience air quality degradation due to local sources is highest under polar subtropical highs. With respect to polar highs, the problem is most severe when the sun angle is low and snow covers the ground, and the polar high persists for a long period of time. A simple algorithm is introduced which is designed to estimate worst-case impact in a trapping valley. The potential for the accumulation of air pollution in such valleys due to the persistence of a polar high in a region, is ignored in current regulatory air quality assessments. Trapping valleys and synoptic flow stagnation often occur in wilderness areas. Refined air quality assessments are shown to be possible using a mesoscale meteorological model and a pollution dispersion model. These tools permit quantitative assessments of pollution build-up from local sources as a result of the recirculation of the local air. This tool, along with the synoptic climatological classification scheme, also permits an evaluation of the fractional contribution of long range versus local sources in the air quality degradation in a region. Areas near the center of a polar or subtropical surface high pressure system, for instance, appear to be dominated by local sources, if they exist, whereas in the vicinity of extratropical cyclones, long-range transport is usually much more important.

INTRODUCTION

One of the reasons for formally establishing wilderness areas is to preserve regions in which the impact of man is minimal. This is the rationale for the goal to ban motorized vehicles, permanent structures, and roads in such areas. Unfortunately, however, man can impact these purportedly pristine areas in a direct fashion through the movement of air pollution. In United States National Park areas, Everhart (1983), concludes that air pollution is the single most important threat to the quality of the National Park system.

The purpose of this paper is two-fold:
(1) To identify those synoptic meteorological conditions in which the impact of air pollution would be most pronounced. As will be shown in the next section of this paper, the frequency with which specific synoptic conditions occur will be shown to vary across the United States and from season to season. This suggests that the potential for air quality degradation in wilderness areas will depend on where they are located, in addition to the magnitude of emissions from nearby pollution sources.
(2) Since existing observations in and adjacent to wilderness areas are invariably insufficient to adequately characterize the wind flow and turbulence within these areas, mesoscale meteorological models, as dis-

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cussed in Section *Mesoscale analyses* of this paper, represent an alternative tool for needed meteorological assessments. The atmospheric conditions are generated by the interaction of meteoro-logical circulations driven by differential gradients in the terrain surface with synoptic features in the overlying atmosphere.

The need to adequately characterize the meteorology in and near wilderness areas is paramount if accurate estimates of air pollution effects are to be achieved. As discussed in Section *Mesoscale analyses* of this paper, current regulatory tools used to assess worst case air quality impact in complex terrain, often very inaccurate and misleading, are ten to twenty years behind current technological capabilities.

AIR QUALITY CLIMATOLOGY

Classiflcation of the general circulation

The general circulation of the earth can be schematically conceptualized into major regions, as illustrated in Fig. 1. The regions dominated by persistent subsidence are associated with deserts, while regions with average ascending motion generally have significant precipitation. These regions of average upward and downward motion move poleward in the summer, equatorward in the winter. While the influence of continents, mountains, and other geographic features alter the specific pattern, the general circulation framework illustrated in Fig. 1 is a useful backdrop with which to discuss air quality characteristics.

From Fig. 1, the general ability of air pollution to disperse can be interpreted. Not surprisingly, sinking air creates inversions and stabilizes the atmosphere, thereby inhibiting pollution dispersal while ascending air destabilizes the air. Precipitation cleanses the troposphere through scavenging (e.g., acid rain) in both stratiform and convective precipitation and by ejecting pollutants into the stratosphere by deep convective storms (with a possible climatic effect, Lyons et al. 1986). In clear air, pollution mixing near the ground is enhanced when solar heating is strong, but dispersion is inhibited during the night as long- wave radiational cooling near the ground creates a low-level stable layer.

As suggested in the schematic represented by Fig. 1, pollutant dispersion potential is poorest in the polar regions during the winter. Not only is the region dominated by subsidence associated with the polar surface high pressure system, but there is little or no solar heating. Unless there are strong katabatic flows such as found, for example, in Antarctica, there will be poor dispersal of pollution. In contrast, pollutant dispersion is expected to be very efficient in the intertropical convergence zone where average ascent and strong solar heating occur during the day results in deep thunderstorm systems.

From this brief discussion, it appears that certain areas of the world will be more prone to pollution problems than others. We can estimate the regions

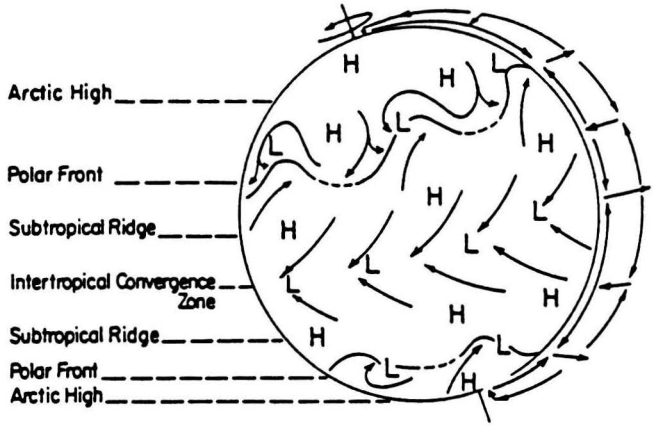

Fig. 1. Schematic of the general circulation of the earth in the northern hemisphere winter. There is average subsidence in the subtropical ridge and arctic high, and average ascent in the intertropical convergence zone and the polar front region (Pielke et al. 1987).

where these problems will be worse by considering their location relative to the large-scale circulation patterns of the atmosphere.

Synoptic classification

The United States, with the exception of Alaska, Hawaii, and a number of territories, is generally influenced by the southern portion of the polar high, the polar front, or the northern side of the subtropical ridge. Along the polar front, extratropical cyclones propagate which have different air quality dispersion characteristics in different parts of the cyclone.

Figure 2 presents an example of a weather map where cold and warm fronts on the polar front are indicated. Five major synoptic categories are defined

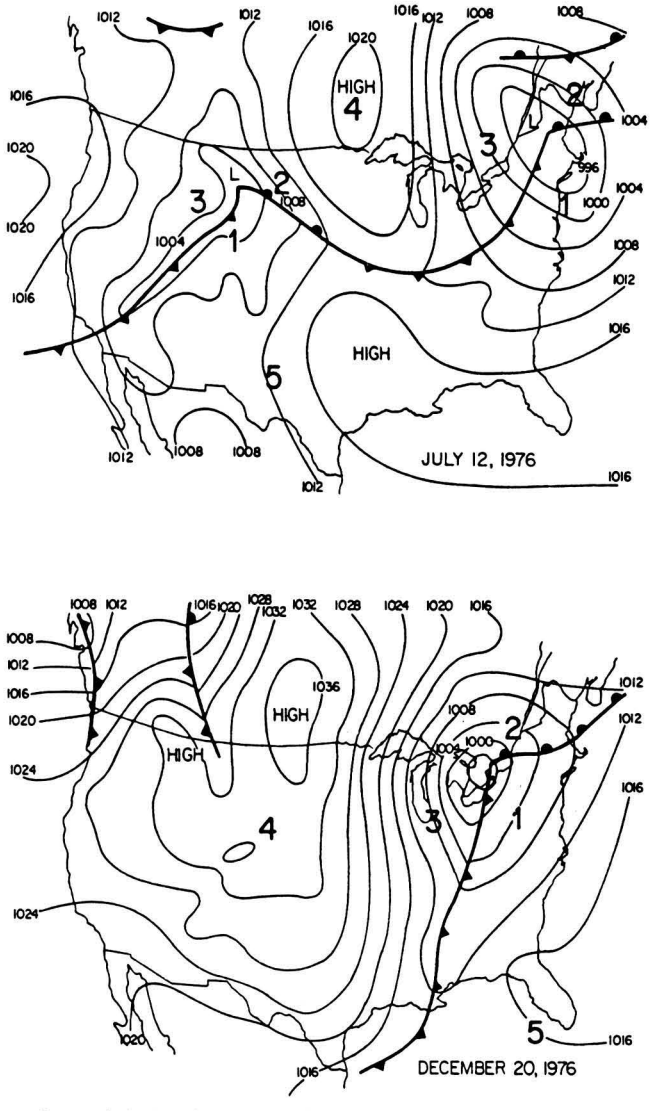

Fig. 2. Example of a surface analysis chart for 12 July 1976 and 20 December 1976 showing the application of the synoptic climatological model for the five synoptic classes listed in Table 1 (Pielke et al. 1987).

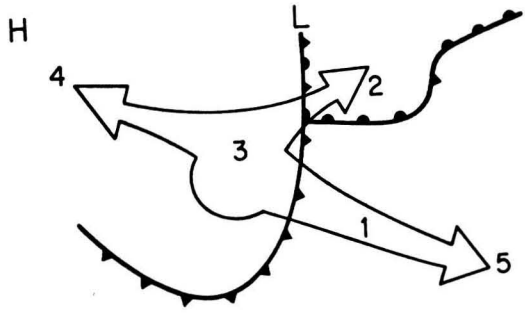

Fig. 3. Schematic illustration of the relative ability of different synoptic categories to disperse pollutants emitted near the ground. The ability of the atmosphere to disperse pollutants decreases away from synoptic Category 3 (Pielke et al. 1985).

in these examples which have the general air pollution dispersion characteristics shown in Fig. 3. The reasons for these dispersion characteristics are summarized in Tables 1 and 2. In the continental United States, Category 4, the region corresponding to an equatorward bulge in the polar high with sinking air through the lower and mid troposphere, has, in general, the poorest dispersion characteristics. When the sun angle is low (e.g., during the winter) and/or snow covers the ground, the dispersion under Category 4 is even worse.

The frequency of occurrence of the different synoptic categories varies during the year and from location to location. Figure 4 illustrates the variation of these categories for Brownsville, Texas; Mobile, Alabama; and Hampton, Virginia. This data was constructed from 10 years of weather maps (1955 to 1964, inclusive), with a 25-day running mean (Pielke et al. 1987).

The seasonal and geographic variation of the categories can be explained from the variations in the general circulation pattern. At Brownsville, for example, the much higher frequency of Category 5 during the summer results because of the movement northward of the subtropical high. In the winter the polar front is farther south, so that polar highs reach the Brownsville area much more frequently. At the more northerly site of Hampton, the polar front is closer during both the summer and winter so that there is less variability in the pattern during the year.

Seasons can also be defined using the frequency of the categories. Winter is defined as that period of the year when a site has the highest frequency of categories which occur poleward of the polar front (Categories 2, 3, and 4). Using this framework, summer corresponds to that time of the year when a location has the highest frequency of categories that lie equatorward of the polar front (Categories 1 and 5). Spring and fall are the transition times when the categories poleward of the front are, respectively, decreasing or increasing in frequency. Using these meteorological definitions of seasons, the length of winter and summer and the time of commencement of spring and fall at the different locations are very similar, despite the different latitudes of the cities in Fig. 4 (Fig. 5).

With these climatological definitions, the sensitivity of an area to air pollution degradation can be estimated. For the reasons listed in Table 2, Categories 2 and 4 are particularly prone to poor dispersion. In addition, since Category 4 often lasts a relatively long time, as exemplified in the next paragraph, pollution often accumulates over time within a region. It is possible to use the synoptic climatological classification scheme along with standard climatological classifications (see inside the cover of Trewartha and Horn 1980) to characterize the annual and geographic variability in air quality dispersion characteristics over the United States.

In order to demonstrate the usefulness of this synoptic classification scheme, the study of air stagnation in the Lake Powell, Utah area reported in Pielke et al. (1985) is used. In that investigation the occurrence of the different synoptic categories were evaluated for the October to May time periods of 1976 to 1981. Category 4, which, as has been discussed, is associated with poor air dispersion was evaluated for its persistence. During a persistent Category 4 event (in which no other categories sweep through to flush out any pollution), air quality is likely to deteriorate if local sources of emission exist.

Table 1. Synoptic classification scheme (Pielke 1982; modified from Lindsey 1980).

Category	Air Mass	Reason for Categorization*
1	*mT*	*In the warm sector of an extratropical cyclone.* In this region, the thickness and vorticity advection is weak with little curvature to the surface isobars. There is limited low level convergence with an upper level ridge tending to produce subsidence. Southerly low-level winds are typical.
2	*mt/cP, mT/cA, mP/cA*	*Ahead of the warm front in the region of cyclonic curvature to the surface isobars.* Warm air advecting upslope over the cold air stabilizes the thermal stratification, while positive vorticity advection and low-level frictional convergence add to the vertical lifting. Because of the warm advection, the geostrophic winds veer with height. Low-level winds are generally northeasterly through southeasterly.
3	*cP, cA*	*Behind the cold front in the region of cyclonic curvature to the surface isobars.* Positive vorticity advection and negative thermal advection dominate, with the resultant cooling causing strong boundary layer mixing. The resulting thermal stratification in the lower troposphere is neutral, or even slightly, superadiabatic. Gusty winds are usually associated with this sector of an extratropical cyclone. Because of the cold advection, the geostrophic winds back with height. Low-level winds are generally from the northwest through southwest.
4	*cP, cA*	*Under a polar high in a region of anticyclonic curvature to the surface isobars.* Negative vorticity, weak negative thermal advection and low-level frictional divergence usually occur, producing boundary layer subsidence. Because of relatively cool air aloft, the thermal stratification is only slightly stabilized during the day, despite the subsidence. At night, however, the relatively weak surface pressure gradient associated with this category causes very stable layers near the ground on clear nights due to long-wave radiational cooling. The low-level geostrophic winds are usually light to moderate varying slowly from northwesterly to southeasterly as the ridge progresses eastward past a fixed location.
5	*mT*	*In the vicinity of a subtropical ridge* where the vorticity and thickness advection, and the horizontal pressure gradient at all levels are weak. The large upper-level ridge, along with the anticyclonically curved low-level pressure field, produces weak but persistent subsidence. This sinking causes a stabilization of the atmosphere throughout the troposphere. Low-level winds over the eastern United States associated with these systems tend to blow from the southeast through southwest.

*This discussion applies to the northern hemisphere.

For the five-year study period, the average maximum duration of Category 4 was found to be 13.2 days with a maximum length of 18 days (Fig. 6). In another study which used the same classification scheme, a rectangular grid area with dimensions of 35° N - 37.5° N and 115° W - 120° W (this includes the Lake Powell area) was classified for the years 1980/1981 through 1986/1987. The first four years involved an analysis of eight months of data per year (October-May), and the last three years involved an analysis of only five months

Category Characteristics	Category 1	Category 2	Category 3	Category 4	Category 5
Category Class	*mT* In the warm sector of an extratropical cyclone.	*mT/cP, mt/cA, mP/cA* Ahead of the warm front in the region of cyclonic curvature to the surface.	*cP, cA* Behind the cold front in the region of cyclonic curvature to the surface isobars.	*cP, cA* Under a polar high in a region of anticyclonic curvature to the surface.	*mT* In the vicinity and west of a subtropical ridge.
Surface Winds	Brisk SW surface winds.	Light to moderate SE to ENE surface winds.	Strong NE to W surface winds.	Light and variable winds near the center of the high.	Light SE to SW winds.
Vertical Motion	Weakening synoptic descent as the cold front approaches.	Synoptic ascent due to warm advection and positive vorticity advection aloft.	Synoptic ascent due to positive vorticity advection aloft (in this region this ascent more than compensates for the descent due to cold advection).	Synoptic descent (due to warm advection and/or negative vorticity advection aloft).	Synoptic subsidence (descending branch of the Hadley cell). Becomes stronger as you approach the ridge axis.
Temperature Advection	Little temperature advection at the surface.	Warm advection above the frontal inversion.	Cold advection at the surface.	Weak temperature advection at the surface.	Weak temperature advection at the surface.
Inversion	Weak synoptic subsidence inversion caps planetary boundary layer.	Boundary layer capped by frontal inversion.	Deep planetary boundary layer.	Synoptic subsidence inversion and/or warm advection aloft create an inversion which caps the planetary boundary layer.	Synoptic subsidence inversion.
Diurnal Variation in Boundary Layer Stability	Moderate diurnal variability in the boundary layer stability.	Little diurnal variability in boundary layer stability because of cloud cover.	Little diurnal variability in the boundary layer stability because of strong winds and destabilizing of boundary layer by cold advection.	In the absence of snow cover because of clear skies and light winds. Large diurnal variability in boundary layer stability.	Moderate diurnal variability in boundary layer stability.
Diurnal Variation in Surface Layer Stability	Moderately unstable surface layer during the day. Moderately stable surface layer during the night.	Stably stratified surface layer day and night.	Near neutral surface layer day and night.	Weakly to moderately unstable surface layer during the day unless snow cover present or low sun angle in which case surface layer tends to be stably stratified. Very stable surface layer at night.	Moderately to strong unstable surface layer during the day. Moderate to strong stable surface layer during the night.
Humidity	Often humid in relative and absolute sense.	Often dry in absolute sense but humid in relative sense.	Dry in the absolute sense. Usually dry in the relative sense.	Dry in the absolute sense. Humid in the relative sense. At night, dry in the relative sense during the day except when ground is snow-covered and/or the low levels are cold.	Humid in the relative and absolute sense.
Cloud Cover	Clear to partly cloudy skies except near squall line.	Mostly cloudy to cloudy.	Clear to scattered or broken shallow convective clouds.	Clear except tendency for fog at night. Middle and/or high level clouds can be transported in by warm advection over the center and to the west of the polar high center.	Scattered fair weather cumulus in the day. Clear during the night except near the mesoscale systems listed below.

Table 2. Overview of meteorological aspects of the five synoptic categories illustrated in Fig. 1 (northern hemisphere) (modified from Pielke et al. 1985).

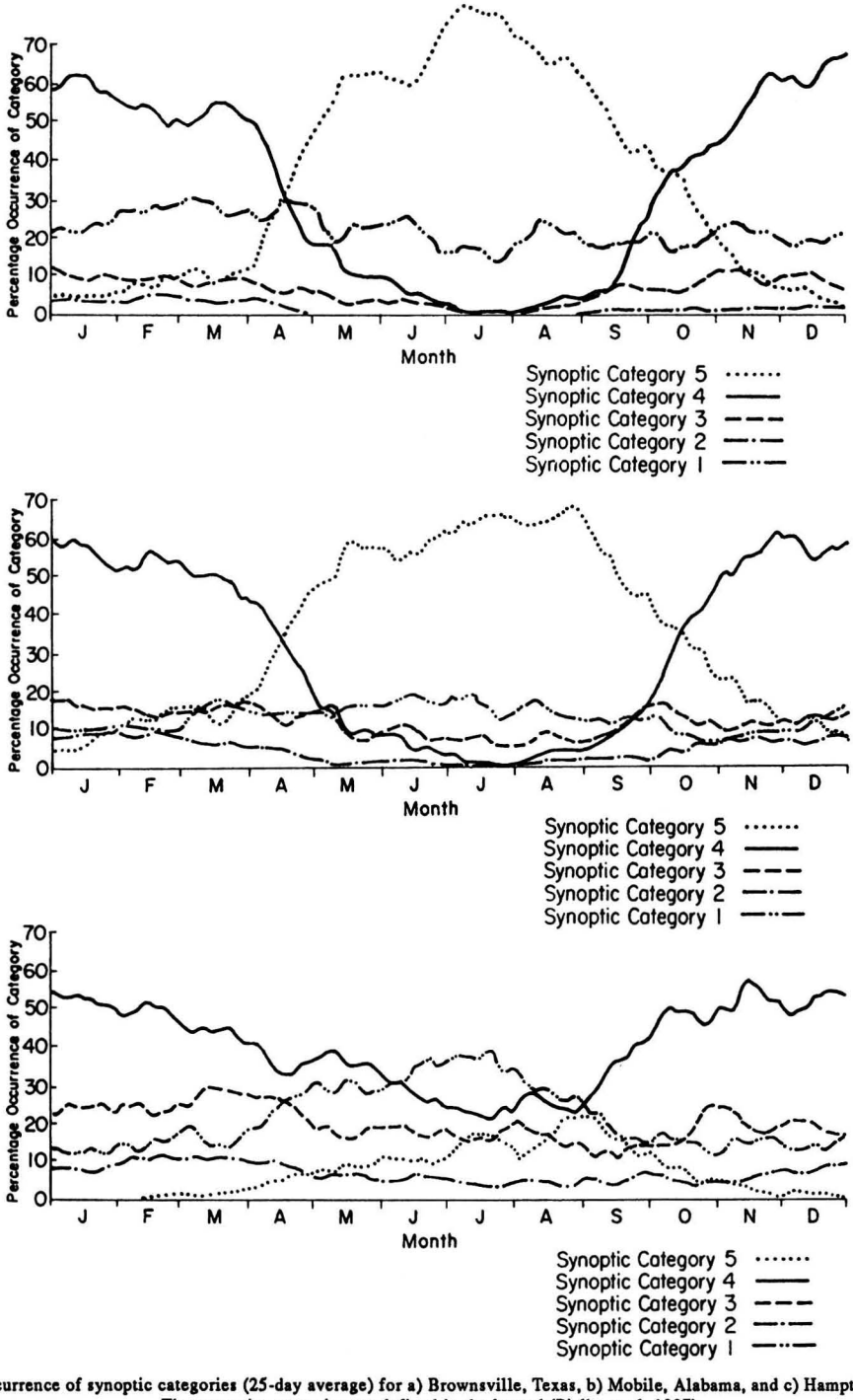

Fig. 4. Occurrence of synoptic categories (25-day average) for a) Brownsville, Texas, b) Mobile, Alabama, and c) Hampton, Virginia. The synoptic categories are defined in the legend (Pielke et al. 1987).

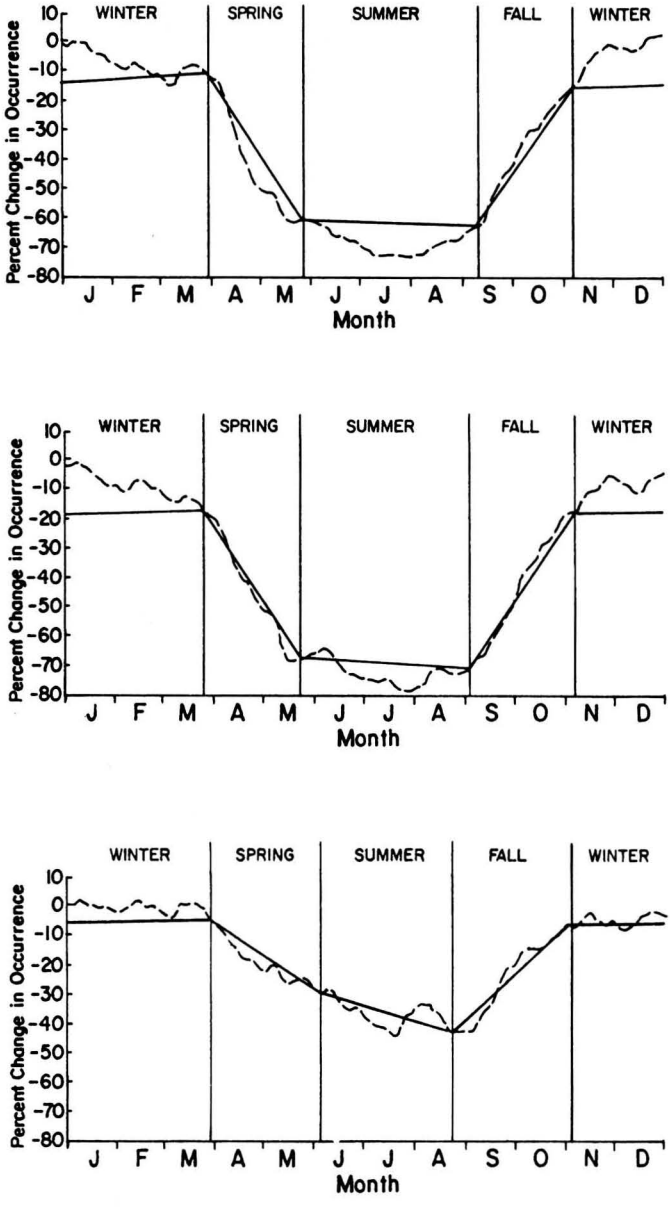

Fig. 5. Changes in frequency of occurrence of categories north of the polar front (dashed line) for a) Brownsville, Texas, b) Mobile, Alabama, and c) Hampton, Virginia. The solid line is the average over seasons which are meteorologically defined as given in Pielke et al. (1987).

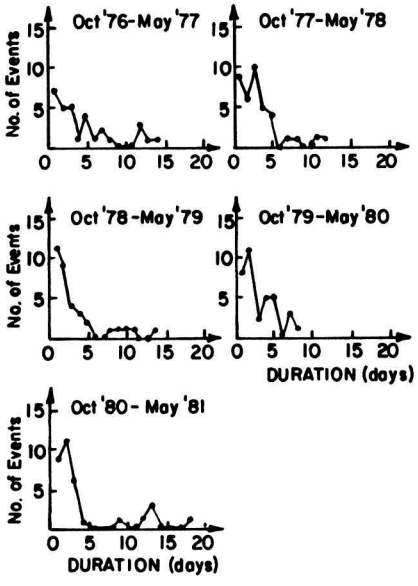

Fig. 6. Duration and number of events of Category 4 for the specified time periods (Pielke et al. 1985).

(November-March) . Since the synoptic classification scheme was applied over an area instead of a point, the possibility of multiple classifications (more than one synoptic category in an area on any given day) were considered in the persistence calculation. To this end, two types of persistence calculations were performed. In the first, if any subportion of the area contained a non-Category 4 region, the persistence event was terminated (these events are defined as conservative in Fig. 7). In the second analysis, if any portion of the area retained a Category 4 region, the persistence event continued (these events are defined as non-conservative events in Fig. 7).

Figure 7 shows the results of these analyses. The average length of a persistence event for the seven-year period (only persistence events longer than two days were considered) was 5.2 and 7.7 days for the conservative and non-conservative calculations, respectively. The longest persistence event was 23 and 43 days for the conservative and non-conservative calculations, respectively. Since the first four-year and last three-year analysis involved different time periods, the average persistence events were also calculated separately for each period. For the first four years, the average persistence event lasted 5.0 and 7.5 days for the conservative and non-conservative calculations, respectively. For the last three years, the average persistence was 5.7 and 9.5 days for the conservative and non-conservative calculations, respectively. This implies that most of the longer persistence events in this area occur between the months of November and March.

In a separate study for western Colorado using radiosonde soundings at Grand Junction, Colorado to characterize days with poor air quality dispersion, Hanson and McKee (1983) found similar results. In their study, during the December to January time period for 1959-1978, stagnation events lasted an average of 9 days with a maximum of 28 days in the 1976-1977 period. According to their study stagnation events 3 days or longer occur on the average nearly 7 times per year. Pielke et al. (1985) concluded that Category 4 conditions correspond, in general, to the situations of persistent stagnation as found by Hanson and McKee (1983).

From the above discussions and the related published studies, it is concluded that the climatological potential for poor (or good) air quality dispersion can be characterized with reference to the general circulation of the earth and to synoptic weather systems. In the next section, tools will be discussed which can assess worst-case air quality impacts in complex terrain.

MESOSCALE ANALYSES

Types of mesoscale systems

There are a wide range of atmospheric systems which are local in scale as discussed, for example, in Pielke (1984). These systems are referred to as being mesoscale. These include features which are associated with extra-tropical storms (e.g., squall-lines, embedded convection) as well as circulations that are forced by terrain irregularities (e.g., land and sea breezes, mountain-valley winds). The latter type of systems, frequently referred to as thermally-forced mesoscale systems, are most often associated with polar and subtropical surface high pressure systems (i.e., synoptic Categories 4 and 5, and the typical mesoscale systems are listed in Table 2). These thermally-forced mesoscale circulations are most well developed when the synoptic flow is weak or absent, such as often occurs in Category 4 and 5. Thermally-forced circulations develop because differential heating or cooling develops between adjacent locations. A circulation develops as the atmosphere responds to the horizontal temperature distribution.

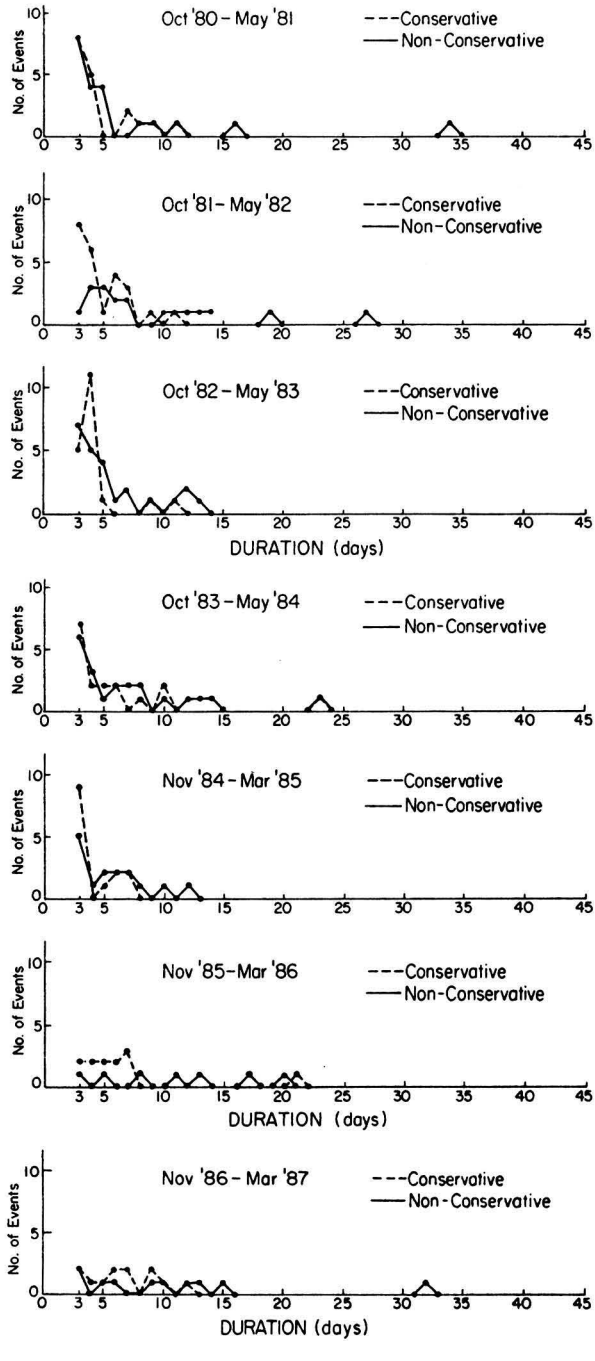

Fig. 7. Duration and number of events of Category 4 for an area representing Lake Powell, Utah. See text for definitions of conservative and non-conservative.

One type of thermally-forced system, the mountain-valley circulation, is particularly important in the air quality budget in irregular terrain. It is well-known that elevated topography acts as an elevated heat source during sunny days and as a heat sink on clear nights. The resultant wind flow is one in which air tends to move uphill during the day and downslope at night. This upslope/downslope flow tends to be confined to below the inversion height associated with the polar and subtropical high pressure systems. In rugged terrain, particularly in the winter and at times of low sun angles, this inversion is often confined below the heights of the higher terrain.

The potential for air quality degradation due to local sources of emission in irregular terrain exists during these meteorological situations. The accumulation of pollution in these mountain-valley circulations is expected to be greatest when the circulation is confined within a basin (as a result of the pooling of cold air), so that none of the effluent exits the region.

As discussed by McKee and O'Neal (1988), there are two types of mountain-valley systems. A trapping valley system is one in which the mountain-valley circulation is too shallow for air to be transported out of the basin, whereas a flushing valley system is one in which gaps and passes exist below the inversion height so that the pooled cold air can flow out. A flushing valley, therefore, has a mechanism to disperse locally generated pollution.

The trapping valley, therefore, represents the potential for the worst case of pollution due to local sources within that valley. Unfortunately, no existing regulatory air quality assessment tool is capable of estimating accumulations of air pollution within a trapping valley. Moreover, even flushing valleys can act as a trapping valley if the synoptic wind flow has nearly the same vertical temperature distribution and is equal and opposite in direction to the outflow of cold air from the valley.

Algorithm to estimate air quality degradation due to trapping

Despite the lack of attention by the regulatory agencies to trapping valleys, a very simple algorithm can be used to estimate potential or actual pollution impacts due to local sources within such a valley. This algorithm can be expressed

$$C = E\,t/(\Delta x\,\Delta y\,\Delta z) \qquad (1)$$

where $\Delta x\Delta y\Delta z$ is the volume into which pollution is input at a rate of E over a time period t and C is the concentration of the pollution (i.e., mass per unit volume). The dimensions Δx and Δy could correspond to the horizontal dimensions of a valley, or to that portion of the valley over which the pollution spreads, while Δz would be the layer in the atmosphere into which the pollution is ejected. In a daytime, well-mixed boundary layer, this layer would correspond to the distance from the surface to the inversion height, whereas in a stable, stratified pool of cold air, this would correspond to some fraction of the inversion height. The time, t, would correspond to the length of time (i.e., persistence) of the trapped circulation, while E is the input of pollution above some baseline (which could be zero). C represents the maximum uniformly distributed concentration of an elemental chemical (e.g., sulfur, carbon) over the volume $\Delta x\Delta y\Delta z$ since deposition to the surface is ignored. While this conceptually simple model needs to be validated, it is a plausible approach to represent pollution build-up in trapping valleys.

In order to illustrate the use of Eq. (1) to assess air quality impacts for a valley which acts to some extent as a trapping valley, the possible effects of a source in the Grand Valley of Colorado near Grand Junction on Colorado National Monument will be assessed for a typical wintertime stagnation event. The variables in Eq. (1) are defined as

$$\begin{aligned} \Delta z &= \beta z_i = \beta(2\text{ km}) \quad \beta \le 1 \\ \Delta y &= 20\text{ km} \\ \Delta x &= \alpha \Delta y \qquad\qquad \alpha > 1 \qquad (2) \\ t &= 9\text{ days} \\ E &= 25\text{g s}^{-1}\text{ of S} \end{aligned}$$

where the sulfur is primarily in the form of SO_2.

In Eq. (2), β represents the fraction of the inversion height into which the pollution is input and diffused. The inversion height is estimated from the climatological analyses of Hanson and McKee (1983), and is below the elevation of the valley sides. The distance Δy is the approximate width of the valley, while α represents the distance of pollution dispersal along the valley with respect to the valley width. The time, t, of an episode is selected as nine days based on the information discussed in Section 2. E is a realistic estimate of SO_2 input from a relatively small industrial facility. Using these values, Eq. (1) can be rewritten as

Table 3. Selected solutions for (3) for various values of α and β.

C	$\beta = 1$	$\beta = 0.1$
$\alpha = 10$	2.43×10^{-6} g m^{-3}	2.43×10^{-5} g m^{-3}
$\alpha = 20$	1.21×10^{-6} g m^{-3}	1.21×10^{-5} g m^{-3}

$$C\left(\text{g m}^{-3}\right) = \frac{(2.43 \times 10^{-5})}{\alpha\beta} \qquad (3)$$

The 24-h primary air quality standard for SO_2 at a Class I air quality area in the United States is expected to be the most sensitive to violation as a result of a nine-day stagnation event. The 24-h standard is 5×10^{-6} g m^{-3}. Thus Eq. (3) indicates a violation if the volume covered by $\Delta x\ \Delta y\ \Delta z$ includes a Class I area and $\alpha\beta < 5$.

Colorado National Monument has been categorized as a state of Colorado equivalent to a Federal Class I area for SO_2. The state nomenclature refers to it as a Category I area. Thus depending on the values of α and β, and the site of the emission with respect to the Monument, a violation could be shown to exist.

Table 3 illustrates values of C for different values of α and β. In a stable layer of pooled air, it is expected that β would be on the order of 10% of the inversion height since a surface non-buoyant emission would tend to be confined close to the ground while an elevated release would stabilize around the effective stack height (as long as the effective stack height remains below the inversion). The along valley direction for the example is more difficult to estimate, however, but a distance of 200 km ($\alpha = 10$) is likely to represent the largest horizontal area covered.

Local versus long-range transport

The discussion in the last section focused on a situation in which only local recirculation and accumulation of pollution is important. In the more general case, transport of pollution into a region is of concern.

Using the synoptic classification scheme presented in Section *Air quality climatology*, it is straightforward to argue that long-range transport becomes important when a significant synoptic flow exists. The synoptic flow in the lower troposphere can be estimated from the 850 mb and 700 mb winds, and from the surface pressure gradient. A unidirectional wind of 5 m s^{-1} at 850 mb, for example, would transport a plume of pollution 384 km after 24 h. A wind of 15 m s^{-1} would result in a movement of 1152 km.

While winds are seldom so uniform, using these relative estimates of the influence of wind speed on transport, it is obvious that pollution releases near regions of moderate or strong synoptic flow will be subject to long-range transport, while lighter synoptic flow will result in less movement and a greater importance of local circulations.

Near the centers of synoptic Categories 4 and 5 (the polar and subtropical highs) are regions with light synoptic flow, while a larger horizontal pressure gradient force, and thus stronger synoptic winds occur near extratropical cyclones. Current tools used to assess transport (e.g., the ARL-ATAD model; see Artz 1982), apply observational data to characterize transport. Unfortunately, due to insufficient measurement data density, these tools are only able to characterize the longer range transport, but not the movement of air associated with local circulations. Table 2 summarizes whether long- or local range transport is expected to dominate for each of the synoptic categories. Stocker et al. (1990) used observed transport patterns of balloons to demonstrate the differences of the ARL-ATAD model.

Use of a mesoscale model to characterize local circulations

Since the existing synoptic observation network is unable to characterize local circulations, such as occur in synoptic Categories 4 and 5, other techniques must be found. In lieu of an extensive measurement network in a local area, the only tools available are models. In this section, one such tool will be discussed.

Since the early 1970's, extensive research has been made into the study of thermally-forced mesoscale systems by our research group (Table 4). With respect to the impact of local circulations on air quality and local transport under synoptic Categories 4 and 5, this mesoscale meteorological model has been used

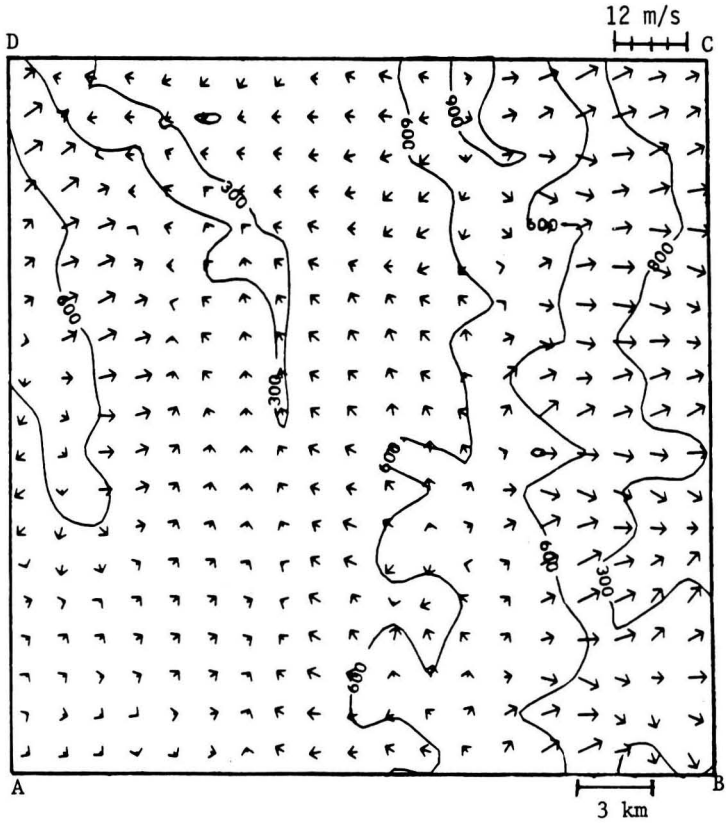

Fig. 8. Simulated horizontal wind velocities at 3.5 m height on 18 July 1977 at 0310 LST. Contours indicate elevation of terrain in meters. The top of the figure is towards the northeast (Pielke et al. 1985).

to simulate wind flow and turbulence characteristics in complex terrain. The output of this model is used to integrate a so-called Lagrangian Particle Dispersion (LPD) model in which releases of a number of particles from elevated or surface locations are used to simulate the dispersion of pollution from actual or planned sources. This dispersion is a result of both turbulent diffusion and differential vertical and horizontal advection. Our approach has been summarized in Pielke et al. (1983).

To illustrate this approach with respect to an existing federally legislated wilderness area, the meteorological model has been integrated in order to simulate the local flows that developed on 18 July 1977 in and near Shenandoah National Park, Virginia. About 79 000 acres of the park are legislated wilderness areas. Figure 8 illustrates the local wind flow at 3.5 m above ground level as predicted by the model. The output from the meteorological model is used to simulate a hypothetical release from an elevated source near Elkton, Virginia (Fig. 9). This location corresponds to the site of a brewery. Existing EPA-approved regulatory tools indicated that the Class I increment for SO_2 would not be violated at any point within the park as a result of this facility. The results in Fig. 9, however, raise serious questions as to the accuracy of the EPA-approved results since the recirculation (and resultant accumulation) of pollution associated with the mountain-valley flow illustrated in Fig. 8 were ignored in the regulatory models. Work is continuing under National Park sponsorship to quantify expected concentration impacts on the park wilderness areas as a result of mountain-valley circulations; it appears that to some extent at

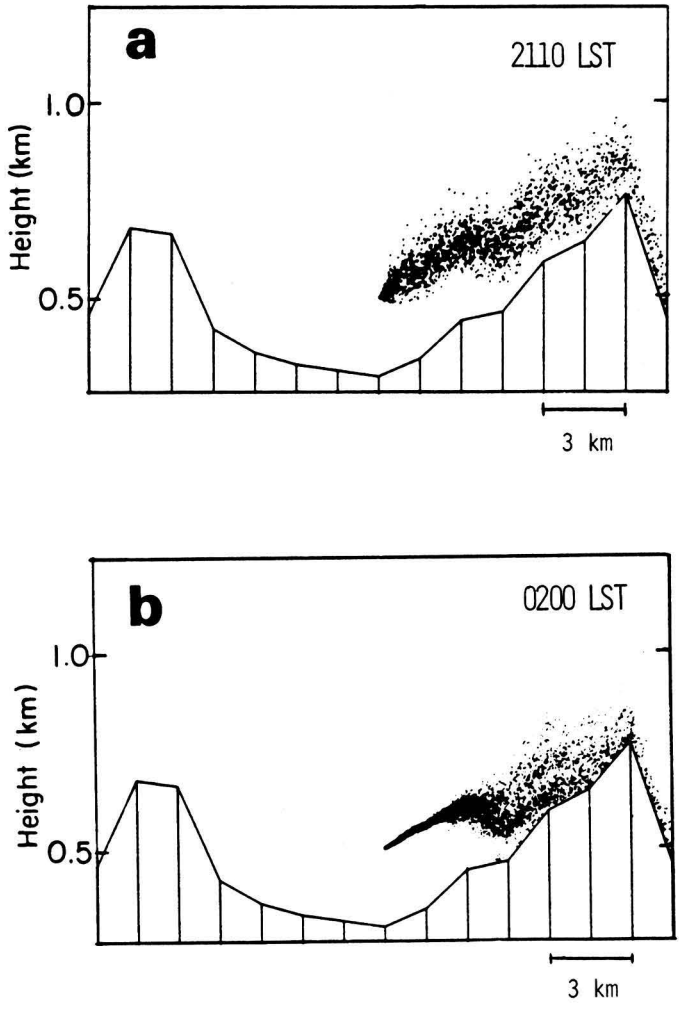

Fig. 9. Plot showing dispersion of particles continuously released at 60-second time intervals during a) two hours following sunset and b) the two-hour period following midnight. Release height is 200 m above ground level. The meteorological model applied to create Fig. 8 was used to generate these dispersion characteristics.

least, Shenandoah Valley can act as a trapping valley. Additional results, including effects on dry deposition, are discussed by Arritt (1988; 1990).

CONCLUSIONS

Using a straightforward synoptic climatological analysis scheme, it is shown that the potential for an area to experience air quality degradation due to local sources is highest under polar and subtropical highs. With respect to polar highs, the problem is most severe when the sun angle is low and snow covers the ground, and the polar high persists for a long period of time.

A simple algorithm is introduced which is designed to estimate worst-case impact in a trapping valley. The potential for the accumulation of air pollution in such valleys due to the persistence of a polar high in

a region, is ignored in current regulatory air quality assessments. Trapping valleys and synoptic flow stagnation often occur in wilderness areas.

Refined air quality assessments are shown to be possible using a mesoscale meteorological model and a pollution dispersion model. These tools permit quantitative assessments of pollution build-up from local sources as a result of the recirculation of the local air. This tool, along with the synoptic climatological classification scheme, also permits an evaluation of the fractional contribution of long range versus local sources since pollution releases near regions of moderate or strong synoptic flow will be subject to long-range transport while lighter synoptic flow will result in less movement and a greater importance of local circulations.

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A METHOD FOR PREDICTING THE FREQUENCY DISTRIBUTION OF AIR POLLUTION FROM VEHICLE TRAFFIC, BASIC METEOROLOGY, AND HISTORICAL CONCENTRATIONS TO ASSIST URBAN PLANNING

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Mathematical models can play an important role in assessing the air quality implications of urban planning by linking the emissions that result from specific land uses to ambient concentrations of those pollutants. Where motor vehicles are a dominant source of air pollutant concentrations, it is necessary to predict the dispersal of air pollutants from road networks under average emission and meteorological conditions. It can also be important to identify extremes or worst case conditions that may occur in any given year, particularly where these extremes relate to health guidelines used for urban planning. This paper examines an approach that can satisfy these requirements for providing air quality advice to the planning of urban areas. A hybrid approach is outlined which combines a deterministic model with statistical techniques for estimating the freqency distribution of concentrations from the model output and the analysis of historical pollutant concentrations. The particular method described is a very simple but useful implementation of the general hybrid approach. The deterministic model component requires only basic traffic and meteorological measurements to infer estimates of mean annual concentrations. The statistical component allows inference of the frequency distribution of concentrations about this mean, including extreme values such as the maximum. Results are illustrated for 24-h average measurements of carbon monoxide over annual periods in Canberra, although the method can be applied to predict seasonal values of shorter term concentrations. The hybrid approach can also be applied with more detailed deterministic models, should there be adequate meteorological and other information to drive them.

INTRODUCTION

The hybrid approach described in Jakeman et al. (1988) has been developed to combine the useful facets of both deterministic and statistical modelling techniques. In essence, the hybrid approach achieves this by using a deterministic model to predict those concentrations which occur relatively frequently (e.g., arithmetic mean), in conjunction with statistical techniques for analysing the parametric distributional form of the air pollutant data in question, to estimate percentiles, including the extreme values (e.g., maximum), of the appropriate distribution. This approach has been based largely on the ability of deterministic models to make causal links between emissions, meteorology and mean ground level concentrations, and the ability of statistical models to predict the distribution of all events about the mean, once the distributional form appropriate can be identified or assumed from historical observations and its parameter value inferred from predictions of some of its properties by the deterministic model.

The hybrid approach can be stated generally in the following four steps:

(1) select an appropriate deterministic model of the phenomena of interest to make predictions over desired periods (e.g., annual averages),

(2) identify, from a range of alternatives, the parametric form of the probability distribution of historical observations taken within individual periods and assess its consistency over all periods,

(3) for each prediction period fit the predictions of the deterministic model in (1) to the parametric form identified in (2) so that its parameters can be estimated,

(4) calculate the percentiles of the probability distribution function (pdf) for each period from a knowledge of the estimated parameter values.

The major assumptions of the approach are:

(A1) within a period the probability distribution can be characterised by simple parametric form,

(A2) the parametric form of the pdf at a site of interest remains consistent from one period to another,

(A3) the deterministic model yields sufficiently accurate properties of the pdf such as the mean.

It should be acknowledged that in general the ability of deterministic models to predict high-percentile extreme events is limited (Jakeman et al. 1988). Also, additional assumptions related to the values of some of the pdf parameters of the statistical model must be made if it has two or more parameters and a deterministic model cannot predict any variability about the mean. This is the case with the deterministic model POLDIF (Anderson 1985), selected here when applied to data from the city of Canberra which is the case study employed to illustrate our techniques.

The analytical tools required for the statistical component of the hybrid approach are: (a) parameter estimation or methods for fitting probability density functions to samples; and (b) identification criteria for discriminating among pdf alternatives. Jakeman and Taylor (1989) represent a review article on the tools required and available and Bai (1990) describes some improvements to these tools.

THE CANBERRA AIRSHED

Canberra lies within the Australian Capital Territory (ACT), 100 km inland from the Pacific Ocean and at an elevation of 600 m. This geographical position places the city within the subtropical high pressure belt. Topographically, the city lies in a valley bounded by hills and ranges in the south, east and west. The city area is approximately 400 km^2. The geography and topography of Canberra combine to establish a poor dispersion climate. The prevalence of high pressure systems and the absence of marked sea-breezes yield low average surface windspeeds. Surface temperature inversions are frequent and subsidence inversions are common and persistent (Daw and O'Loughlin 1972).

THE DETERMINISTIC MODEL

POLDIF is a model that predicts the dispersion of air and noise pollution from urban road networks and has been developed and made commercially available by the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO), Division of Building Research (Anderson 1985). This deterministic model uses a combination of traffic volumes, emission rates and meteorological conditions to determine ground level concentrations of pollutants for a given road network. The specific data required by the model include: date, latitude, time, cloud cover, wind speed and direction, inversion height, vehicle fleet compositions, link volumes and speeds, point source strengths and grid size for the receptor location. Table 1 shows the values for key meteorological data used in this study.

With these data the model calculates the ground level concentration for air pollutants using principles of Gaussian plume dispersion (Turner 1970). Thus the concentration of a gas $\chi(g/m^3)$ at a point (x, y, z), emitted at a rate of Q(g/s) and at a location and height (x′, y′, z′), is dispersed according to vertical $\sigma_z(m)$ and horizontal $\sigma_y(m)$ dispersion parameters and u(m/s), the mean windspeed. For vehicle exhausts z′ can be taken as 1.2 m, the effective height for the mixing area in the wake of the vehicle (Taylor and Anderson 1982).

Each link within the network is treated as a line source where the concentration at any point is found by integrating over the line upstream of the receptor. The contribution of each link to each receptor point is calculated and the contributions of all links to each receptor are then added. The contributions of links at a distance greater than $3\sigma_y$ from any receptor are neglected.

Table 1. Meteorological data used by POLDIF to produce estimates of CO.

Parameter	Year 1982	1983	1984	1985	1986	1987
Wind speed (knots)	3.62	3.70	3.53	3.34	3.75	3.21
Wind direction (° from North)	315	315	315	315	315	315
Cloud cover (10^{ths})	4.6	5.8	5.4	6.3	5.5	6.0
Inversion height (m)	150	150	150	150	150	150

The vehicle emissions are determined by link volumes, average link speeds and emission factors associated with vehicle fleet composition. The vehicle fleet composition has been determined for Canberra based on Australian Bureau of Statistics data for vehicle registrations. The fleet composition is divided into petrol, diesel, 6 cylinder, 4 cylinder, unleaded petrol and gas-fired vehicles.

Link volumes and speeds are determined by a local area traffic model, MULATM (Anderson and Taylor 1988), based on morning peak traffic data and calibrated for 1985-1986. It must therefore be assumed that 1985-1986 volumes are not significantly different to other years for which the model has been run here (1982-1987). Emission models constructed for Canberra by Jakeman et al. (in press) confirm that this is a reasonable assumptions from 1985-88. The assumption has not been tested for prior years.

For this paper, POLDIF has been run with annual average data to provide predictions for an average hour in an average year. It must also be assumed that the morning peak hour selected above is representative of an average hour within an average day of the year. It is commonly considered that the morning peak carries approximately 10% of the daily traffic. If uncorrected, the use of the morning peak traffic data should overestimate the average ambient concentration. A correction factor of 2.4 has therefore been used to reduce the predicted ambient concentration to what would be expected from average hourly traffic conditions. The rationale for this factor is the following: if the morning peak hour carries 10% of the daily traffic over 24 h, then the average traffic per hour is 10/24 of the volume in peak hour.

The dispersion parameters are calculated in POLDIF using the angle of the sun and cloud cover, to determine incident solar radiation and wind speed. It has been assumed that neutral atmospheric conditions (i.e., adiabatic lapse rate equals environmental lapse rate) would best represent the average hour for any given year in Canberra. This is achieved by selecting an average length day (22 March or 22 August). For the calculation of average seasonal concentrations of pollutants the shortest day (22 June) and the longest day (22 December) could be used to produce more stable and unstable conditions respectively.

Temperature inversions are also taken into account in POLDIF as they restrict the vertical distribution of the air pollutants. The model allows the vertical dispersion parameter to vary downwind until $\sigma_z = h_i/2.15$ where h_i is the inversion height (m). It is held constant from then on. The average inversion height varies seasonally in Canberra and some estimates have been reported by MacNicol (1982) for the mixing depth in summer. In winter, however, much lower, stronger, surface temperature inversions can occur during the night and early morning (Ferrari et al. 1986). The average inversion height has been assumed to be a minimum of 150 m, although the sensitivity of this assumption is reported.

We have examined carbon monoxide (CO) as it is of particular concern to air quality in Canberra (NCPA

1989). As can be seen from Fig. 1, the annual average concentrations predicted by the POLDIF model for one-hour concentrations are generally within a factor of two. This is regarded as an acceptable level of accuracy for modelling air pollution (Hanna 1982). The very low observed concentration for 1984 should be discounted because an abnormally low proportion (40%) of observations for computing the mean concentration were recorded in that year.

The observed and predicted concentrations are below levels considered to be of concern to health in the long term. Maximum concentrations of CO over other averaging times, such as an eight-hour period, have nonetheless been found to exceed air quality goals. Recent work (Jakeman et al. 1991) extends the method here to predict the maximum winter concentrations over one-hour and eight-hour averaging times.

PARAMETRIC FORM OF ANNUAL DISTRIBUTIONS OF HISTORICAL CONCENTRATIONS

For each of the calendar years 1982-1987, two and three parameter versions of the Weibull, gamma, and lognormal distributions were fitted by maximum likelihood estimation to these historical pollutant data sets. These shape-scale-location parameter distributions are felt to cover a large range of possible forms from which the historical data could be assumed to be derived (Jakeman and Taylor 1989). The identification results are not given in detail here but show that the two parameter gamma distribution is the most appropriate for the 24-h average CO data and satisfies assumptions (A1) and (A2).

A HYBRID METHOD AND PREDICTIONS

One possible implementation of the hybrid approach is demonstrated for predicting the annual frequency distribution of 24-h average CO concentrations. In selecting a method it must be appreciated that the deterministic model POLDIF, when used in isolation from statistical models predicts only mean values with reasonable accuracy. The results in Table 2 show the accuracy of the mean predictions for the years simulated. Note that the year-to-year variation in mean predictions is small, partly because only static emissions and meteorological data are fed into POLDIF and partly because some of these data are assumed identical for all years (see Table 1 where wind direction and inversion height inputs are the same for each year). In the case of inversion height, this makes little difference. Average annual predictions from POLDIF for 1985 were computed using inversion heights of 150 m, 300 m, and 450 m. The corresponding predictions were 1.48, 1.47, and 1.47 so that there is little model output sensitivity for inversion heights greater than 150 m.

Because the distribution for CO is two parameter (i.e., with positive shape and scale and zero location value), two pieces of information are needed to describe it. Yet no variability of this mean provided by POLDIF is available as model output. A simple strategy used in Jakeman et al. (1990) for predicting water quality extremes where the concentrations conform to a two parameter Weibull distribution can be analogously adopted. The strategy is to use th POLDIF model to provide the mean of the gamma distribution, assume a range of values for its shape parameter, compute

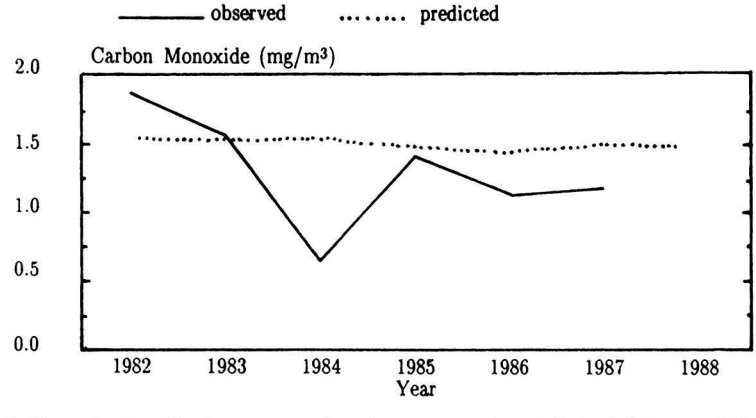

Fig. 1. Observed and predicted average annual one-hour concentration of CO (mg/m³) between 1982 and 1987.

Table 2. Comparison of measured and predicted values of annual 24-h CO concentrations (mg/m^3).

Year	Mean		Maximum				
	Measured	POLDIF	Measured	Hybrid Method Shape Parameter 2.0	2.5	3.0	3.5
1985	1.42	1.48	5.84	6.17	5.52	5.07	4.72
1986	1.11	1.45	3.39	6.20	5.54	5.07	4.63
1987	1.18	1.49	4.91	6.47	5.78	5.29	4.75

the scale parameter from the mean and shape, infer the percentile result of interest, and evaluate the sensitivity of the result to values within the shape range. Table 2 contains the results for the maximum concentration, the most difficult property of the distribution to estimate accurately. The results are reasonably insensitive to the variation in shape value shown as any of the shape values yield sufficiently accurate results by accepted standards (Hanna 1982). Also, the range of shape addressed in Table 2 covers that found from fitting two parameter gamma distributions to historical annual concentrations data sets from 1982-1987.

The levels of 24-h average and maximum CO shown in Table 1, although not directly comparable with the one-hour and eight-hour air quality goals recognised in Australia, are not considered to be excessive. In Canberra, the one-hour maxima are characteristically one-half the recognised goal of 40 mg m^{-3} and during the period 1982-87 the eight-hour goal of 10 mg m^{-3} was only exceeded three times (NCPA 1989).

CONCLUSIONS

A method has been constructed to extend the utility of a traditional and simple physically-based model of pollutant dispersion (POLDIF) from predicting annual averages to the annual frequency distribution of concentrations. The extension requires the use of additional prior knowledge based upon analysis of the parametric form of historical concentrations. The simple physical basis of POLDIF provides a crude but adequate link between a given traffic network and ambient concentrations of, in this instance, CO. This is an essential link for the application of the method outlined in this paper to the planning of urban environments.

The average and extreme estimates, produced by using the hybrid approach to combine the deterministic and statistical models, can then be compared against recognised air quality goals. In this case, predicted levels of CO are not found to be excessive. However, the nature of the method described allows new land use options or modifications to existing traffic networks to be tested in order to minimise the impact of air pollution in urban areas. For planning purposes, it is also necessary to be able to relate the model output to recognised air quality goals. As mentioned earlier, the 24-h mean and maxima are not directly comparable to the air quality goals recognised in Canberra. However, the approach demonstrated here can be equally applied to other averaging times, such as one-hour and eight-hour. A forthcoming paper, Jakeman et al. (1991), examines the use of POLDIF and the hybrid approach to predict one-hour average concentrations of CO during worst case winter conditions.

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HUMAN INDUCED SALINISATION AND THE USE OF QUANTITATIVE METHODS

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Sustainable development of the earth's limited water and land resources is of paramount importance because of rising world population and existing conflicting demands for these resources. Enormous capital investment has been made in developing these resources, but now there is irrefutable evidence that such developments have led to major resource degradation. This includes problems of salinisation and damages to ecosystems. The countries predominantly affected by human induced salinisation are located in arid and semi-arid regions of the world and include Australia, China, Egypt, India, Pakistan, USSR, and USA. This paper describes the processes of salinisation, its impacts and the use of quantitative methods in salinity investigation and management. Australia is used as a case study of typical salinity problems and as a demonstration of the fruitful application of quantitative methods. The paper concludes that quantitative methods such as surface water and groundwater models are powerful design, management and predictive tools in salinity investigation. However, application of some models, such as those for unsaturated flow and transport and groundwater solute transport, are not widespread due to uncertainties in describing the complexity of the processes and the lack of hydrodispersive data.

INTRODUCTION

The accessible fresh water and arable land resources of the world are very limited and unevenly distributed. These resources have been in a state of continuous development to feed the world's increasing population. Development pressures have resulted in the degradation of these resources by a variety of processes including salinisation. Buringh (1979) estimated that the world is losing at least ten hectares of arable land every minute including three from salinisation. Kovda (1983) estimated that soil salinisation, both natural and human induced, claims about 1 - 1.5 Mha y^{-1}. Much of this loss transforms fertile soils in irrigated crop lands with high yield to barren lands.

Human induced salinisation or so-called secondary salinisation is normally caused by agricultural and irrigation activities associated with inefficient use of water. Generally water has been considered a freely available commodity. Therefore, it has been used excessively and inefficiently in irrigation, which uses more than 70% of the total world water consumption. Secondary salinisation is a major problem in arid and semi-arid regions. In non-arid regions, rainfall leaches the substances through the soil and prevents salinisation. Countries predominantly affected by secondary salinisation include Argentina, Australia, China, Egypt, India, Iran, Iraq, Pakistan, Thailand, USSR, and USA.

SALINISATION PROCESSES

In arid and semi-arid regions, a number of processes can cause salinisation. These processes include:
1) The addition of salt to the soil and its underlying strata by irrigation water in proportion to the soluble salt content and the amount of irrigation water used. For example, irrigation with good quality water, containing 200 - 500 mg L^{-1} of soluble salts, adds 2 - 5 Mg of salt per year per hectare for a total irrigation requirement of 10 000 m^3 per year. If natural or artificial drainage is not adequate, percolating water gradually raises the watertable to within 2 - 3 m below the surface. Groundwater then starts to evaporate, concentrating the salt content of the soil and shallow groundwater, causing catastrophic salinisation of irrigated soils.
2) Rising watertables of saline aquifers will increase the seepage of saline groundwater into streams and enhance their salinisation.
3) Land clearing and removal of deep-rooted native vegetation will raise watertables causing land and stream salinisation.
4) Construction of dams, weirs, and locks on rivers in regions where groundwater is saline creates a head of water which causes saline groundwater to flow into rivers and neighbouring lands.
5) Discharge of saline water arising from mining and industrial activities into river systems can also cause their salinisation.

IMPACTS OF SALINISATION

Salinisation has a number of negative impacts on the environment, society and the economy of salt affected areas as well as the economy of the country as a whole. In its early stages of development, salinisation reduces soil productivity. In advanced stages, it kills all vegetation and transforms fertile and productive land to barren land, leading to loss of habitat and reducing biodiversity. Social impacts of salinisation arise from its ability to dislocate farm populations. Economically, salinisation causes tens to hundreds of millions of dollars damage per year in salt affected countries, in production loss and other damages such as damage to water supply systems due to corrosion.

REMEDIAL AND PREVENTIVE MEASURES

Many options are available as remedial and preventive measures. These include:
1) reduction of accessions to the groundwater system via improved surface drainage, improved irrigation techniques, lining irrigation canals, land forming, and establishment of deep-rooted vegetation;
2) provision of subsurface drainage to lower water tables either by groundwater pumping or tile drainage;
3) release of dilution flow from reservoirs to maintain stream salinity below critical levels;
4) adequate conjunctive use of surface and groundwater resources;
5) water pricing to reduce water consumption and increase its efficiency.

Implementation of any option depends on the particular circumstances. While one option may be effective and feasible in one case it may not be valid in another. Generally, a mix of options is required as no one measure is sufficient.

QUANTITATIVE METHODS USED IN SALINITY INVESTIGATION

Mathematical models which describe and quantify the basic hydrological processes and phenomena under a range of conditions are very useful in salinity investigation and particularly assessment of the efficiency of remedial and preventive measures. Jakeman et al (1987) delineate the types of models required and discuss some problems in their construction and calibration.

Groundwater models are useful if a management strategy is required to consider the effects of rainfall, irrigation, cropping activity, groundwater pumping and land use behaviour on groundwater levels and on land and stream salinity..

Hydrologic routing and surface water quality models can be used: to predict downstream salinity concentrations from upstream data for management strategies, such as salinity dilution by release of additional discharge from upstream storages; to provide advance warning of salinity levels which are too high for irrigation usage; and for quantifying saline accessions within a reach of river.

Other models include soil salinity models to predict salinity in the root zone from irrigation application and associated water salinity, infiltration models that predict aquifer recharge rates in combination with water balance models of crop water use and evapotranspiration, and solute transport models.

The success of model development and subsequent simulation depends upon a number of interrelated factors:
1) the objectives of the modelling exercise;
2) the complexity of variables dominantly controlling the behaviour of the system and the level of understanding and knowledge of system structure (the model structure identification problem);

3) the mathematical properties of the derived model (the model parameter estimation problem);
4) the quantity and quality of data available (information content);
5) the modelling approach taken.

The complexity of model development for particular cases and the lack of required field data are major reasons for some models being used more frequently than others. For example, groundwater, stream routing, and surface water quality models are used more than complex groundwater solute transport models and unsaturated flow and transport models.

HUMAN INDUCED SALINISATION IN AUSTRALIA

Australia has about 1.7 million ha of irrigated land, out of which 530 000 ha have water tables less than 2 m below the groundsurface. Salinity has also severely reduced crop and pasture production from about 470 000 ha of non-irrigated farm lands. The discharge of saline groundwater into surface water bodies is a major factor affecting the quality of rivers and lakes in most states (Peck et al 1983, Peck and Allison 1988). Two regions have severe salinity problems due to human activity. One in the southeast and the other in the southwest of the continent.

Salinity problems in southeast of Australia

In the southeast of the Australian continent, the Murray-Darling Basin has a major salinity problem. This basin covers 1.06 M km^2 or one seventh of the surface area of Australia. The basin extends over a wide range of climatic zones: subtropical in the north, cool and humid in the Eastern Highlands, temperate in the south and hot and dry in the west. The mean annual rainfall for the Murray-Darling catchment is 430 mm but varies from 250 mm in South Australia to 1500 mm in the upper catchment. The mean annual runoff of the basin is about 24.3 Gm^3 and the water resources of the basin are intensively regulated.

River salinity and land salinisation are particularly severe in the lower part of the basin. Along the Murray River average salinity increases from around 40 $\mu S\ cm^{-1}$ with 25 mg L^{-1} Total Dissolved Solids (TDS) in the headwaters to about 800 $\mu S\ cm^{-1}$ (480 mg L^{-1} TDS). The main reason for the increase in salinity is the discharge of saline groundwater to the river.

In hydrogeologic terms the lower part of the Murray-Darling Basin, the Murray Basin, is a shallow sedimentary basin about 600 m in depth and covering an area of 300 000 km^2. This Basin contains a number of major aquifers in Pliocene, Pleistocene, and Quaternary Formations. Hydrogeologic features and salinity problems in the basin are documented by a number of authors (Brown 1989; Evans and Kellett 1989). A brief account of these features is now given.

Recharge zones for confined aquifers in the Murray Basin are generally around the margins of the basin. Shallow unconfined aquifers are recharged from the margins as well as from rainfall and stream flows (Fig. 1). Discharge from the deep aquifers is by upward leakage through confining layers to the watertable aquifers. The major proportion of discharge from the watertable aquifers is either to the lower reaches of the Murray River and its tributaries or by direct evaporation from the capillary zone.

European settlement in the basin has gradually changed the hydrological balance of the basin. The main change has been the removal of the previous existing forest cover and replacement by crops and pastures, the modification of grasslands by heavy grazing and cultivation, and the introduction of major irrigation schemes. The removal of trees from highlands and the plains has increased recharge as a consequence of decreased evapotranspiration. This has led to the gradual filling up of regional aquifer systems. Rising groundwater levels are bringing salt stored in the aquifers to the surface, are polluting streams, and are causing destruction of soil and vegetation. Therefore, there is widespread community and Government concern at the extent of land degradation, deteriorating water quality, rising groundwater, and loss of native flora and fauna troughout the basin.

Monitoring of groundwater levels shows that they have been rising rapidly. Rate of rise has been of the order of 10 to 20 cm per year with the most significant rise during periods of heavy rainfall. In fact, as a result of high rainfall in the mid 1970s, the associated rise in regional groundwater pressures resulted in expansion of the regional groundwater discharge zones and caused major damages due to waterlogging and salinity. Unfortunately, the present trend towards increasing salinity continues with little evidence that equilibrium is yet in sight (Macumber et al 1988).

The extent of salinisation in the Murray Basin is indicated in Victoria where shallow watertables threaten about 385 000 ha of Australia's largest irrigation area. Already 140 000 ha of land in the region are damaged by salt. Outbreaks of dryland salting are scattered throughout Victoria. A total of 55 000 ha of dryland farming land is affected and an equivalent area is incipiently salted. Dryland salinisation is expanding at an average rate of 2% per year. The majority of this increase occurs during abnormally

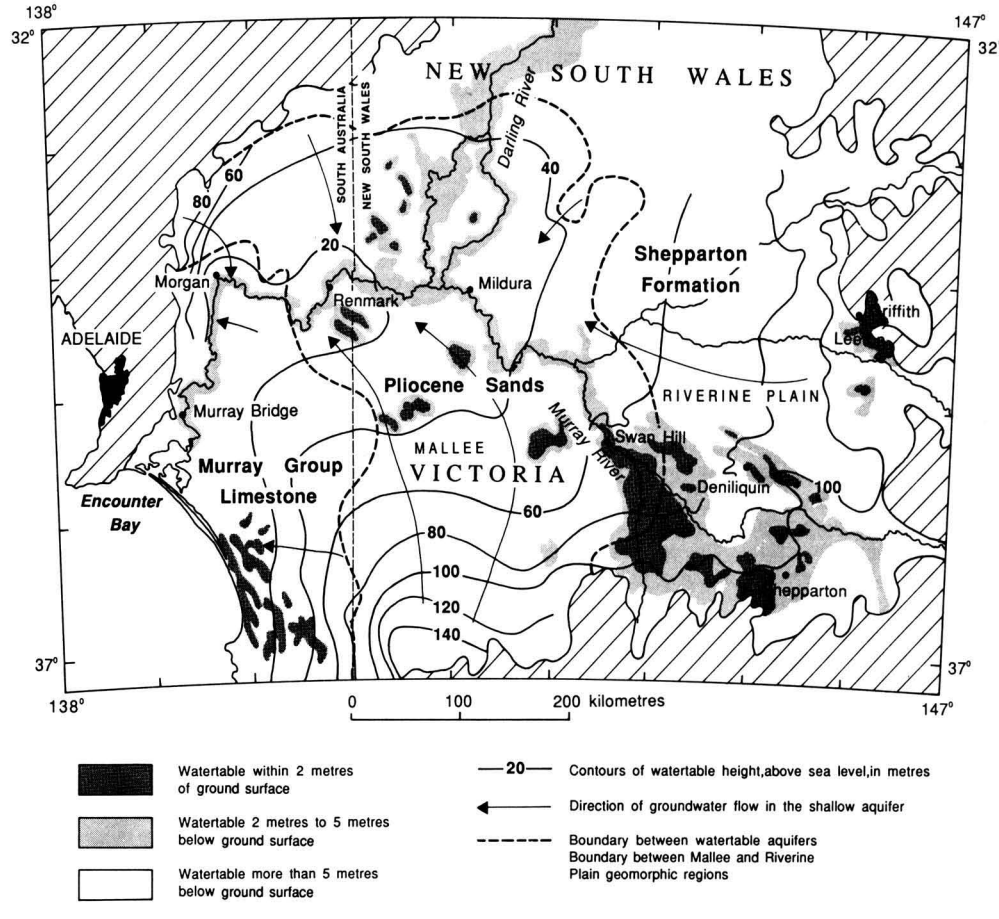

Fig. 1. Piezometric map and depth to watertable in Murray Basin (modified from Evans 1988).

wetyears. Similar problems exist in irrigated and dryland areas of New South Wales and South Australia.

Traditionally, the governments have acted to reduce river and land salinity problems principally through engineering solutions. These solutions include interception of saline groundwater and the diversion of irrigation returns, both with disposal to evaporation basins. Other engineering schemes consist of pumping groundwater in order to lower groundwater tables. The operation of salinity mitigation schemes in 1986 - 87 prevented the discharge of 173 Gg of salt to the river (River Murray Commission 1988) and in 1987/88 this figure rose to 291 Gg. Because of the cost-effectiveness of these interception schemes, additional similar schemes will be in operation in the future. Recently, there has been crucial acknowledgement that the availability of irrigation water is a strong contributor to the salinity problems of the basin. Increasing attention is being given to strategies encouraging more efficient use of water. For example, there is ongoing investigation of irrigation methods which yield lower accessions to

the watertable and the introduction of transferable water entitlements is imminent.

Examples of the use of quantitative methods in the southeast of Australia

Several mathematical models have been developed to quantify the different aspects of salinisation in specific areas of the basin. A brief description of some of the models developed is now given.

Groundwater modelling examples. Ghassemi et al. (1987 and 1989) have simulated the Mildura aquifer located on the southern bank of the River Murray. The objective of their study was to quantify the salt load from the aquifer to the river, evaluate the effectiveness of the groundwater interception scheme, and provide options to improve its effectiveness.

As shown in Fig. 2, the interception scheme consists of 17 pump sites or well fields. The groundwater generally flows from the south toward the river and groundwater salinity ranges from 1.2 to 84 g L^{-1} TDS. Saline effluents from the scheme are disposed first to Lake Ranfurly, then to the evaporation basins, 13 km from Mildura.

The flow of water in the aquifer was simulated with transient and steady-state models using a finite-difference approximation of the two-dimensional partial differential equation for horizontal groundwater-flow in a confined aquifer subject to recharge and pumping (Bear 1972) on a 200-m grid.

$$\frac{\partial}{\partial x}\left[T\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T\frac{\partial h}{\partial y}\right] = S(x,y)\ \frac{\partial h}{\partial t} + Q(x,y,t) \quad (1)$$

Here the transmissivity T and storativity S represent physical aquifer properties in space, h is the hydraulic head, Q is the source/sink term, and (x,y) represent a Cartesian coordinate system. Note that the temporal derivative $\frac{\partial h}{\partial t}$ is zero in the steady-state case.

For both transient and steady-state models, saline water flow from the aquifer to the river was estimated by assuming constant salinity in the aquifer. Salt fluxes to the river were obtained by multiplying flow rates computed at nodes along the river by corresponding groundwater salinity values at those nodes. The transient model simulation computes the nodal discharge and salt flow at each time step, and their average values for the whole period of simulation.

The results of the mathematical simulation showed that without the operation of the pumping scheme, the salt load to the river would be 125 Mg d^{-1}, while the average salt load during the period of simulation from 1980 to 1983 was about 65 Mg d^{-1}.

Using the transient model simulations the salt load from the aquifer to the river under different operation strategies was estimated. By increasing the pumping rate from 64 to 107 L s^{-1} in existing pump sites, the

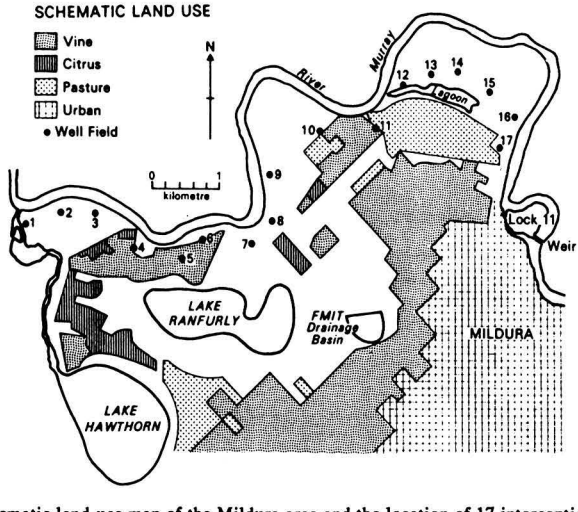

Fig. 2. Schematic land-use map of the Mildura area and the location of 17 interception well fields.

salt load would decrease to 36 Mg d^{-1}. Finally, by inclusion of three additional pump sites in the scheme (sites 18, 19, and 20) salt load would decrease to 24.4 Mg d^{-1} and the efficiency of the scheme in terms of salt interception would increase from the present 48 to 80%. Figure 3 shows the nodal salt load to the river under this management option.

As another example, Barnett (1989) has simulated the effect of the clearing of native vegetation on the rising water tables and river salinity in the Mallee region. Widespread clearing of native vegetation has dramatically increased recharge in the Mallee region by up to two orders of magnitude. The resultant rising water tables have caused land salinisation problems in low lying areas and in the long term will increase saline groundwater inflow to the River Murray with a consequent rise in river salinity.

A computer model of the Mallee region groundwater has been developed to assist in the determination of management strategies for the groundwater resources of the region. The model calculates groundwater flow rates and pressure distribution for the three major aquifer systems (Renmark Group, Murray Group Limestone and Pliocene Sands) on a 25 km grid (Fig. 4). Recharge to the model can be varied, depending on the distribution of Mallee vegetation. Groundwater outflow from the model is calculated and, knowing groundwater salinity next to the river (which is a discharge boundary), salt inflow to the river can be determined. Simulation runs have been made with various scenarios of vegetation cover, ranging from completely cleared to completed revegetated.

The model only calculates inflow from the groundwater system to the River Murray from south and east of the river. Upstream of Morgan, saline inflow is not expected to increase markedly from the north, because of the limited amount of clearing in the area, which receives marginal rainfall for cropping. Downstream of Morgan, a geological fault west of the river acts as a barrier to groundwater flow toward the river and would restrict any increase in saline inflow. Clearing is also restricted in this area, because the shallow stony soils are unsuitable for cropping (Barnett 1989).

Table 1 from Barnett (1989) shows the effect of modelling scenarios on the increased salt inflow on the River Murray salinity after 50 years of increased recharge.

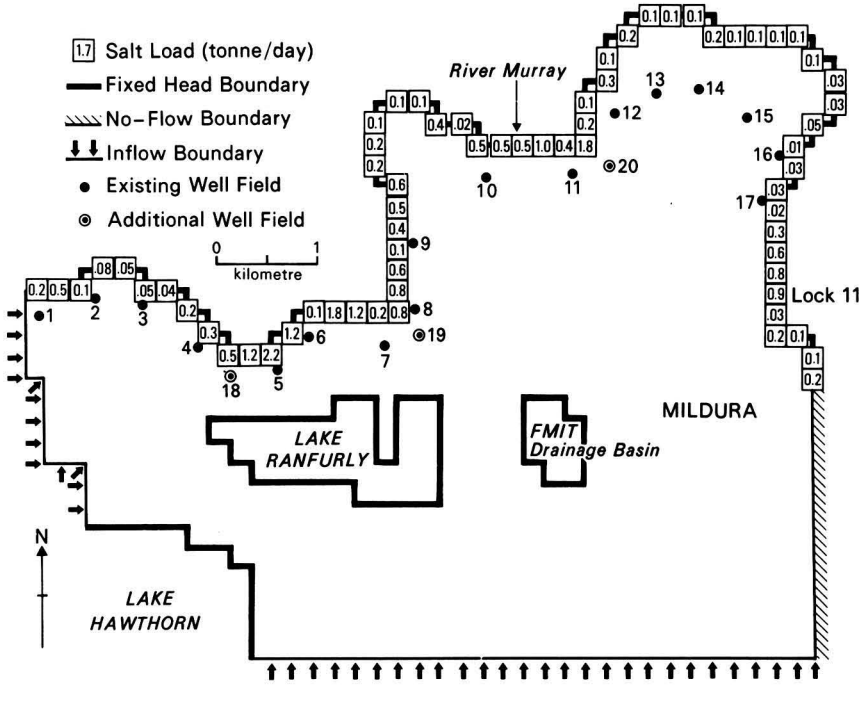

Fig. 3. Average nodal salt load from aquifer to the river with inclusion of three additional well fields (18, 19, and 20).

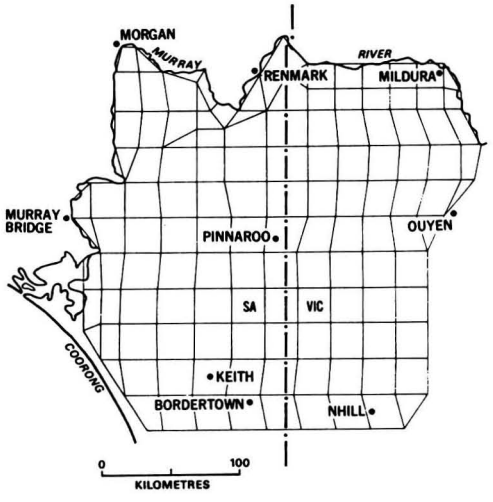

Fig. 4. Mesh of three-layer groundwater model (after Barnett 1989).

Scenario A uses the present vegetation distribution with 0.1 mm y^{-1} recharge and a conservative 5 mm y^{-1} recharge over all cleared areas. Under this scenario the salinity at Morgan will increase by 70 μS cm^{-1} due to an increase of 355 Mg d^{-1} of salt inflow to the river. Scenario B assumes the same conditions as Scenario A, but with a value of 10 mm y^{-1} recharge over cleared areas, which would increase the salinity at Morgan by 145 μS cm^{-1}. Scenario C assumes complete clearing of all vegetation and 5 mm y^{-1} recharge over the whole area. This would increase the salinity at Morgan by 72 μS cm^{-1} compared to 70 μS cm^{-1} under Scenario A. Scenario D maintains vegetation in the 40-km zone next to the river. This would reduce saline inflow very significantly and would increase the salinity at Morgan by only 16 μS cm^{-1}. Scenario D increases the salinity by 37 μS cm^{-1}. Finally, Scenario E, which is somewhat idealistic would increase the salinity by 35 μS cm^{-1}.

Stream modelling examples. Dietrich et al. (1989) and Jakeman et al. (1989) have developed a dynamic model for the transport of a conservative solute along

Table 1. Modelling scenarios and their effects on increased salt inflow on River Murray salinity after 50 years of increased recharge.

Scenario	Description	Increase in salt inflow to the river (Mg d^{-1})	Increase in river salinity at Morgan (μS cm^{-1})
A	Present vegetation pattern. 5 mm recharge over cleared areas.	355	70
B	Present vegetation pattern. 10 mm recharge over cleared areas.	722	145
C	All vegetation cleared. 5 mm recharge over whole area.	367	72
D	Present vegetation pattern. Assumes 40 km strip next to river has never been cleared. 10 mm recharge over cleared areas.	67	16
D_{25}	Assumes 25 years of higher recharge rates (10 mm y^{-1}), then revegetation of 40 km strip.	167	37
E	Whole area revegetated after 50 years of higher recharge rates (Victoria excluded).	197	35

Source: Barnett (1989)

a stream connected to an aquifer contaminated by the solute. It relates downstream concentration to upstream concentration, stream discharge, and piezometric levels in the aquifer. Also, submodels for solute travel time in the stream and aquifer inflow to the stream have been developed. They then applied the model to a reach of the River Murray.

Two objectives that the model is to achieve in the presence of scarce data are first to provide a daily estimate of stream salinity at a fixed downstream location during periods of low to medium flows in response to upstream flows and upstream salt concentration as well as to lateral inflows from salty aquifers, and second to quantify the salt load discharged from the aquifer into the stream in response to streamflow levels.

The first objective stems from the requirement to estimate downstream levels of salt concentration which if too high are damaging to irrigation activities. Such events usually occur during periods of low to medium flows since in such instances dilution is low and groundwater gradients toward the stream can be high. The second objective results from the need to assess management strategies aimed at reducing the influx of aquifer salinity into the stream.

One approach to achieve these objectives is to model the salt transport using the advection-diffusion equation (Thomann 1972)

$$\partial c/\partial t + u\ \partial c/\partial x = \partial/\partial x(D\ \partial c/\partial x) + r + r_{gw} \quad (2)$$

where c is the stream salinity, u is the averaged cross-sectional advective velocity, D is a diffusion coefficient, r_{gw} denotes the source of salt coming from the groundwater, and represents all sources or sinks of salt other than r_{gw}.

Solution of Eq. (2) requires estimates of the quantities, u, D, r and r_{gw}. It may be relatively easy to make measurements of D and r, and the advective velocity could be obtained independently from physical representations of streamflow such as the Saint Venant equations (Baltzer and Lai 1968). However, the salt inflow r_{gw} is likely to be very difficult to estimate and solution of the Saint Venant equations is not straightforward as they are nonlinear and of the hyperbolic type. In addition, observations contained measurement and sampling errors, and possible missing values, where the time series may be long but the spatial distribution is sparse. From this perspective alone, some element of aggregation and stochasticity is required in the model.

In view of these problems, Baltzer and Lai (1968) made some simplifying assumptions and transform Eq. (2) from its differential form to a more global representation that attempts to retain enough physically based structure to be sensitive to relevant variables required by the modelling objectives. In doing so, they focussed their attention on stream-aquifer systems where first, the solute concentration in the aquifer is high in comparison with that of the stream, and second advection dominates diffusion.

With advection dominating diffusion, Eq. (2) becomes

$$\partial c/\partial t + u\ \partial c/\partial x = r + r_{gw} \quad (3)$$

Using kinematic wave arguments, an estimate for u in Eq. (3) was obtained in the form of a travel time model that provides a daily estimate of the time taken by a water parcel to move from an upstream to a downstream location. Furthermore, a model for r_{wg} was obtained by convoluting r_{wg} with the stream stage height.

Having obtained these two submodels, Baltzer and Lai (1968) showed that Eq.(3) leads essentially to a dynamic single-input/single-output system representation that is linear in the parameters. It involves a rational transfer function between a function of aquifer inflow and stream discharge as input, and salinity accession as output. In this way, identification and estimation procedures for linear systems could be invoked. The resultant model is conceptually simple and can be implemented with modest computational requirements.

The developed models have been applied to a 207-km reach of the River Murray between Euston and Redcliffs. This stretch is characterized by a significant amount of salt intrusion from adjacent aquifers. The location of the study area and other geographical features associated with the River Murray and its tributaries are shown in Fig. 5.

For the study reach, the following hydrological data were available: stream discharge at Euston and Colignan, upper pool level at Mildura weir, and river salinity at Euston and Redcliffs. Stream stage height at Colignan and upper pool level at Mildura weir are instantaneous measurements collected daily. Salinity measurements are instantaneous (no continuous recordings were available) but not always available on a daily basis. Geologic evidence indicates that throughout the study area the shallow aquifer is hydraulically connected to the River Murray.

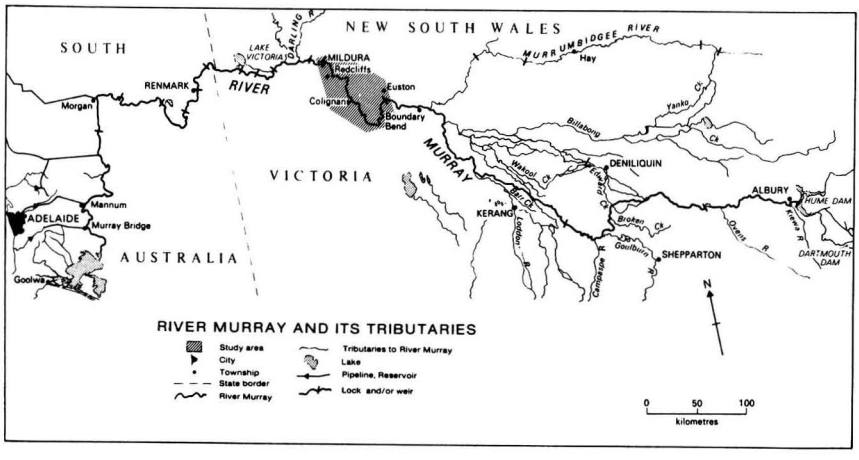

Fig. 5. Map of the River Murray and its tributaries showing the study area (shaded) between Euston and Redcliffs.

Figure 6 compares the historical and predicted salinity profile at Redcliffs. The predictions are regarded as quite accurate given the level of error in the data. They also estimated that the steady state load per unit stage height to be 292 Mg d^{-1}.

Salinity problems in the southwest of Western Australia

In the southwest of Western Australia (WA) the average annual rainfall reaches 1100-1300 mm in ranges parallel to the shore lines, but drops to less than 500 mm in the inland plateau. Major rivers flow west or southward and discharge to the Indian and Southern Oceans. In this part of the country, dryland salinity associated with non-irrigated land, commonly caused by the removal of native vegetation, has been a threat to the land and water resources of the state, causing major social, economical, and environmental problems.

Increased surface and stream salinity in WA occurs after the native vegetation is replaced by agricultural species and is almost invariably associated with a rise in watertable levels and an increase in the potentiometric heads of the aquifers. Rising watertables bring large quantities of previously stored salt to the soil surface and streams. This problem is particularly severe for areas with less than 900 mm of rainfall per year which are now predominantly under agricultural use. Following is a brief description of the salinity problems in southwest of WA summarised from Schofield et al. (1988 and 1989), Schofield and Ruprecht (1989), and the Steering Committee for Research on Land Use and Water Supply (1989).

Agricultural development in southwest Western Australia has led to extreme stream salinisation to the extent that 36% of the divertible surface water resources are no longer potable and a further 16% are of marginal quality. Additional considerable biological degradation of wetlands and rivers in low rainfall areas has occurred. Streams whose catchments lie wholly above the 1100-mm y^{-1} rainfall are essentially free of significant salinity risk. Streams with catchments which extend inland to areas receiving less than 1100 mm y^{-1} rainfall are at risk of salinisation. The risk increases the further inland a catchment extends. Stream salinities of fully forested catchments have been declining over the last two decades, probably in response to low rainfall conditions which have led to decreased groundwater levels and presumably less saline groundwater discharge to streams. In contrast, all rivers with partially cleared catchments in low rainfall areas have become increasingly saline. The rate of salinity increase is higher the lower the rainfall.

Salinity management of southwest catchments is based on salt hazard and degree of agricultural clearing. Forested catchments with significant salt hazard are managed with a policy of high protection of water quality. High salt storage catchments with some lower rainfall areas cleared, and with marginal but increasing salinity, have been the focus of considerable

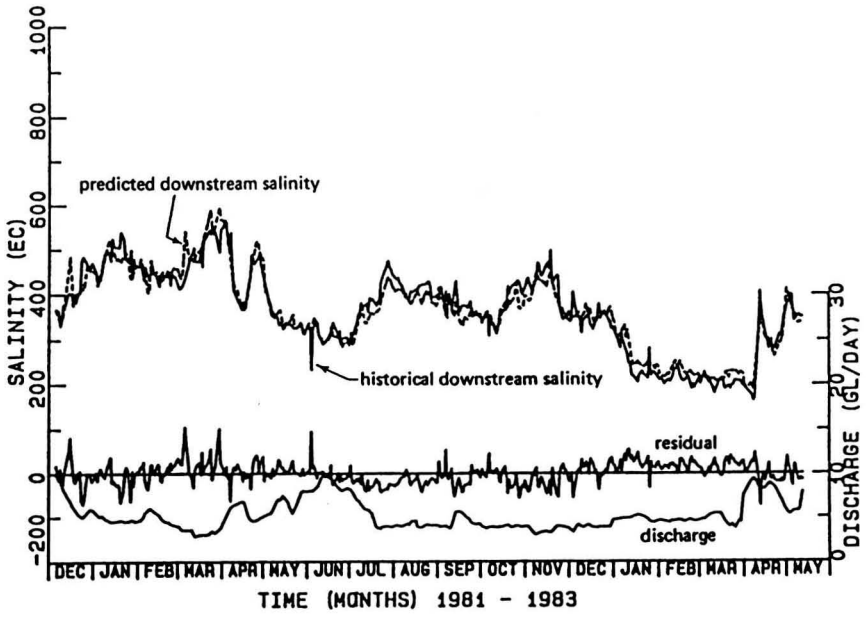

Fig. 6. Historical (continuous) versus predicted (dash) salinity profiles at Redcliffs.

attention over the last 30 years. Despite the legislative actions to control the release of Crown land and the controlled clearing of native forest of these catchments which are important water resources, stream salinities have continued to increase at an alarming rate due to earlier clearing. Further supplementary mangement was clearly required. The most promising approach is reforestation which was initiated in 1979. Reforestation is considered to be the most cost effective and environmentally acceptable method of reclaiming high salinity streams.

Examples of the use of quantitative methods in the southwest of Western Australia

In the southwestern part of Western Australia, like the Murray Basin, models have been developed to quantify the effects of salinity problems. The following is a brief description of some of the models developed.

Groundwater modelling example. Hookey (1987) has modelled the effects of land clearing on Wights and Lemon experimental catchments in the Collie River Basin (Fig. 7), to assess the response of the groundwater system to catchment clearing. Wights Catchment covers an area of 93.8 ha with a median annual rainfall of 1120 mm, while the Lemon Catchment has an area of 344 ha and a median annual rainfall of 820 mm. These catchments have been fully and 52% cleared, respectively, in 1976/77.

The groundwater model used was essentially that described by Prickett and Lonnquist (1971). The model employs a finite difference method for the solution of the classical partial differential equation of the two dimensional horizontal flow system (Bear 1972). The model parameters were calibrated comparing observed and predicted seepage areas and, when available, recorded groundwater levels.

The modelling exercise showed that the response in the high rainfall zone results in immediate groundwater discharge to stream systems. In the low rainfall zone a delay of some twelve years between the time of clearing and groundwater discharge is predicted (Table 2). The variation in response time directly influences changes in the salinity of streamflow as the rising groundwater intersects and flushes salts stored in the soil profile to the stream systems.

Stream modelling examples. According to Schofield et al (1988) a number of models have been developed for prediction of future stream salinity in the south west of Western Australia, which include:

1) Darling Range Catchment Model (DRCM). The DRCM has been developed by the Water Authority of Western Australia (Hopkins 1984 and Mauger 1986). The model simulates streamflow and stream salinity from data on rainfall, evaporation and physical characteristics of a catchment. The model has the ability

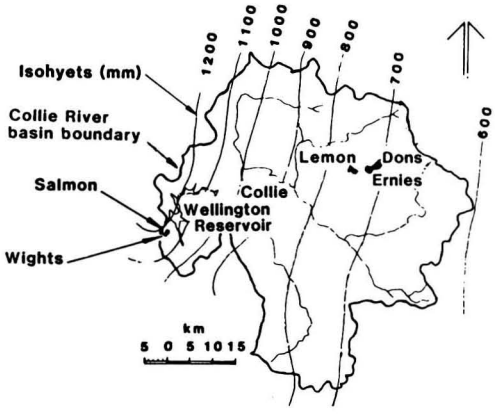

Fig. 7. Collie River Basin and locations of experimental catchments (Schofield 1988).

to take account of forest clearing, reforestation and seasonal leaf area changes.

The DRCM has been used to predict stream salinities of three potential water supply catchments; Jane, Susannah and Ellen which have been extensively cleared for agriculture. Following calibration, simulation for various clearing conditions were carried out over the period of climatic record 1911-83. The results are summarised in Table 3. The simulated change from fully-forested to totally-cleared conditions brought about substantial increases in streamflow on all catchments. The stream salinities of Jane and Susannah catchments increased approximately three times while there was only a marginal increase predicted for Ellen. The small change for Ellen arises because only 20% of the catchment contains significant salt stored in the soils.

2) Loh and Stokes Model. Loh and Stokes (1981) developed an empirical model to predict the future

Table 2. Simulation of groundwater response at Wights and Lemon catchments.

Time since clearing (year)	O/I	Area of seepage (ha)	Annual volume of seepage	
			(10^3 m^3)	(mm)
Wights catchment				
2	0.48	10.2	20. 9	22.6
4	0.64	13.9	59. 6	64.3
7	0.77	16.7	71. 8	77.4
10	0.86	19.7	79. 8	86.0
20	0.96	23.7	89. 5	96.4
Lemon catchment				
12	0.05	1.0	1. 5	0.4
14	0.34	5.0	10. 3	2.8
16	0.67	10.2	20. 2	5.6
18	0.88	13.0	26. 4	7.4
20	0.90	14.4	27. 0	7.5
25	0.92	18.6	27. 6	7.7
30	1.00	19.1	30. 0	8.4

O = volume of seepage; I = volume of recharge to cleared areas.
Source: Hookey (1987)

impacts of past agricultural development on annual salinity and flows into the Wellington Dam. The model has also been used to predict future salinities of some important marginal water resources.

Although the model is simple in concept, it does require a significant amount of information. This includes annual rainfall and annual cleared area, rainfall-runoff and salinity-flow relationships under forested conditions, rainfall-increased runoff relationship under cleared conditions, average overland/shallow subsurface salinity and average groundwater salinity, and groundwater discharge/recharge relationships as a function of time-since-clearing. In most cases generalised relationships were developed from data measured both within the catchment and from surrounding areas.

The observed and predicted salinities for Wellington Dam are shown in Fig. 8. The model gave good predictions after the mid-1960s but significant over-prediction prior to this time. A probable explanation of this over-prediction is the small groundwater discharge per unit area cleared resulting from the pre-1950 valley clearing compared to the relatively large groundwater discharge per unit area cleared resulting from the post-1950 upper-slope clearing.

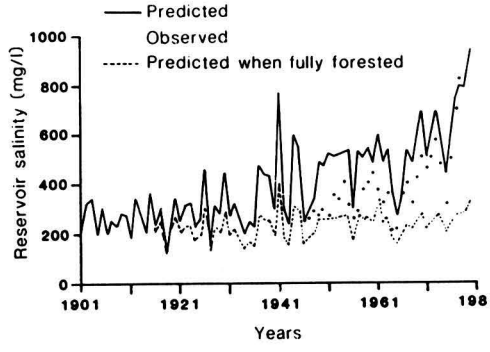

Fig. 8. Predicted and observed inflow salinites to Wellington Dam (Schofield et al. 1988).

3) Schofield-Peck Model. Schofield (1988) presented a catchment mass-balance solute model for predicting stream salinity increases following agricultural clearing. The model was applied regionally to the high, intermediate, and low rainfall zones of the south-west region. The predicted and observed stream salinity increases are shown in Table 4. The model under-predicted for the high and intermediate rainfall zones but over-predicted for the low rainfall zone. The over-prediction may be because the full effects of agricultural clearing on stream salinity are not yet manifest. However, the observed salinity increase in this rainfall zone is very sensitive to the catchments selected.

Table 3. Stream flow and salinity prediction for three water supply catchments (Jane, Susannah, and Ellen) using the Darling Range Catchment Model.

	Jane	Susannah	Ellen
Area (km^2)	74	27	540
Area cleared (%)	61	65	59
Mean annual rainfall range (mm)	1000-1050	950-1000	660-820
Stream monitoring period	1963-83	1981-83	1965-83
Predicted fully-forested salinity (mg L^{-1})	156	146	330
Predicted fully-cleared salinity (mg L^{-1})	433	444	380
Predicted salinity at current clearing level (mg L^{-1})	449	401	630
Predicted fully-forested flow (10^6 m^3)	7.9	3.1	20
Predicted fully-cleared flow (10^6 m^3)	27.2	8.1	130

Source: Schofield et al. (1988)

Table 4. Predicted and observed average stream salinity increases for different rainfall zones.

Rainfall Zone	Stream salinity (TDS) increases	
	Predicted ($mg\ L^{-1}$)	Observed ($mg\ L^{-1}$)
High rainfall zone (> 1100 mm y^{-1})	68	113
Intermediate rainfall zone (900-1100 mm y^{-1})	272	429
Low rainfall zone (< 900 mm y^{-1})	3416	2387

Source: Schofield et al. (1988)

CONCLUSIONS

Considering the limited freshwater and arable land resources of our planet, their salinisation due to irrigation and other human activities, such as land clearing, is a major problem bearing in mind the increasing world population. Salinisation causes production losses, damages to the environment and ecosystems, with their subsequent social and economical impacts. This suggests that land use changes and irrigation schemes should be designed and operated in a way to minimise the risk of salinisation.

The paper has demonstrated the role of surface and groundwater models as design, management, and predictive tools in salinity investigations. Groundwater models have the ability to simulate a wide range of problems such as estimation of salt load from aquifers to rivers and the effects of groundwater extraction, land clearing and reforestation. Surface water models can simulate the effect of solute transport in rivers, estimate downstream salinity on the basis of upstream dates and quantify saline accessions within a reach of river.

Finally, it should be noted that unsaturated flow and transport models are not used frequently because the processes are complex and not easily described in practice. Also, groundwater-solute transport models have not been used extensively because of data requirements, particularly the lack of hydrodispersive parameters and their spatial distribution.

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DECISION SUPPORT SYSTEMS FOR STORED WATER QUALITY: 1. THE ENVIRONMENTAL DECISION SUPPORT SYSTEM

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Environmental decision support systems (EDSS) contain three major components: a modelbase containing a number of numerical models, a database containing information from a large number of sites, and an interface to permit the user to access the models and data and to perform "scenario analysis" as an aid to decision making. Software decision support tools are currently promising to supply management support in a wide variety of industries. These are described here in the context of the management of stored water quality and the role of the database component of a typical EDSS is stressed. The use of this data set for model validation is discussed in Part 2 of this paper.

INTRODUCTION

Management of the engineering aspects of lake and reservoir water quality may be enhanced by the increasing availability of mathematical models and software tools.These can be used as part of the design procedure, for example, to assist in making decisions regarding the possible implementation of destratification devices and the location of inlets and outlets (e.g., Burns and Powling 1981; Smalls and Petrie 1983). In addition, day-to-day variations of the quality characteristics of the stored water may be predicted so that appropriate treatment can be assessed or so that in-lake management can be undertaken in order to minimize treatment costs.

Environmental decision support systems (EDSS) are beginning to be developed, which utilize concepts from the discipline of information systems (Guariso and Werthner 1989). These software systems are relatively new to water quality management. They require the synergism of numerical models (usually simulation models) with large databases, front-ended by a man-machine dialogue component. A frequent description of a DSS is an interactive computer system which assists decision makers to solve unstructured (or loosely structured) problems by utilizing both data and models (Ford 1985). In the "standard" DSS, there are three modules (Fig. 1): a database management system (DBMS), a modelbase management system (MBMS), and a dialogue generation and management software (DGMS) module (Sprague and Carlson 1982).

Water authorities have had little experience with these systems to date, although an increasing number are being installed. Decision support systems with user-friendly interfaces certainly provide problem-solving tools not previously available to the manager. However, in some currently available systems, the class of problems to which any specific DSS can be applied is relatively narrow. Although such information systems constrain the diverse and evolutionary nature of most environmental problems (Fedra 1985), this limitation is likely to disappear with the advent

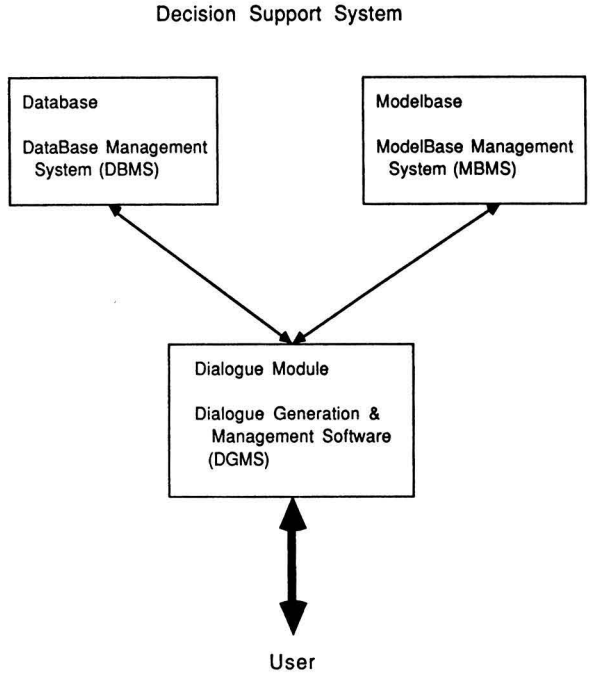

Fig. 1. Architecture of DSS according to Sprague and Carlson (1982) (after Guariso and Werthner 1989).

of more flexible and extendible software engineering methods.

In the section "Mathematical modelling for decision support" of this paper, we describe the components of such an EDSS in the context of mathematical modelling for decision support and consider in particular detail the database component. In Part 2 of the paper, an example application of one particular model is given.

MATHEMATICAL MODELLING FOR DECISION SUPPORT

Mathematical modelling is partly a science and partly an art. It encompasses the range of problem identification, through solution, to analysis and interpretation of the results, together with model verification/validation and sensitivity analysis. Problem identification, model building, and interpretation of results have been well discussed in the literature, both in a theoretical framework and through extensive examples and full case studies. Of equal (or even greater) importance, yet less intensively studied, are the areas of validation/verification and sensitivity analysis.

Modelling is the representation of the characteristics of a real system, often by mathematical functions realized on a computer, in a way which approximates reality (e.g., James and McDonald 1981; Neelamkavil 1987). This approximation is often because of constraints in the understanding of the physical interrelationships among constituent parts of the system (e.g., zooplankton predation rate). Alternatively, approximation may be necessary as a limitation in the way that the real, continuous, natural system can be represented on the computer.

Modelling studies may serve not only as an aid to understanding the nature and behaviour of lakes and reservoirs, but also as planning and management tools. As such, scientific detail may be sacrificed in the short term to gain the advantage of an engineering tool to solve real problems. A mathematical model can thus provide a useful tool to supplement insights gained from both field and laboratory observations.

Selection of the most appropriate model is determined by many factors. These include the evaluation

of the current state-of-the-art models (often within a predetermined computational budget) and an appreciation of the implicit temporal and spatial scales which any model builder will have necessarily encapsulated within the numerical algorithm. Such limitations to each model may not always be visible to the reservoir manager (as the model user).

Simulation models are those mathematical/computer representations of reality which mimic how the real world changes with time. In other words, they include a time-dependency. As such, simulation models may be the solution of partial differential equations (continuous simulation models) or be the solution of a set of discrete simultaneous equations whose behaviour is governed by some type of stochastic behaviour. (For a wider ranging discussion see Watson and Blackstone 1989.)

Computer simulation of aquatic ecosystems is becoming an increasingly important technique for the water engineer and water quality manager. In potentially water-stressed, semi-arid countries like Australia and southern Africa, small changes in urban drainage patterns, agricultural land use and even marginal changes in meteorological regimes, as a result of climatic change and climatic variability may be sufficient to change the ecological (and therefore trophic) status of the water. Such changes could potentially render the water less potable and of less use for irrigation. As well as enhancing understanding of the system dynamics, simulation also offers the possibility of forecasting such adverse changes and of providing management information which will permit strategic planning for the water resource.

Software simulation packages are sufficiently developed for them to be utilized in management decision making in an increasing number of environmental areas. It seems likely that the number of applications where decision support systems can assist will increase in environmental management fields. Once environmental managers become familiar with decision support systems, there is the opportunity for their decisions to become more effective. The large database, which is a vital component of a DSS, will give them access, and hence surrogate experience, to a much larger range of case studies than those within their direct experience. At the same time, problem identification is likely to become easier, and the basis of a decision more objective (Guariso and Werthner 1989).

Database

The data in the database relate to both lake characteristics and to the meteorological forcing variables responsible to a large degree for thermodynamic changes in the stored water. Temperature changes in the water then play a significant role in many of the chemical and biological processes determining water quality. Since the water bodies under investigation are located worldwide, it is essential that the database reflects this global distribution.

Data can be collected on a variety of time scales even for a single lake or reservoir sampling site. In a well-instrumented lake, data may be taken from a number of different sites, over a range of depths, and over a range of different timescales. However, such data collection exercises are expensive and operate only as intensive field campaigns. More commonly, a single site is used with data being collected weekly, over a range of depths (often every metre or so). It is therefore important to match the timescale of the data with the timescale of the model analysis. Data collected once a week are not useful if a daily simulation is to be undertaken; but are easily reconcilable with climatic types of simulation—as discussed here.

There are two aspects to the global database used in this study (global used here in the sense of worldwide, not in the sense of mathematically complete): (1) the meteorological data for forcing the model and (2) the lake thermal data for validation.

Meteorological data often need to be collected from several sources including a large number from the national meteorological service records. The data required include wind speed, solar radiation, relative humidity or vapour pressure, air temperature, precipitation, cloud amount and/or sunshine hours, and atmospheric pressure.

In this study, we are considering only the climatic response of the lake. There are several reasons for this. Firstly, for long-term management and/or design of new reservoirs, the concerns relate to, for example, bathymetry, the location of inlets and outlets, evaluation of the need for some type of destratification device, and their optimal location. Such a decision helps to determine the time and space scales of the data requirements. In general, meteorological records are archived on a timescale of a month, a timescale commensurate with the timescale of the hydroclimate simulations. In other words, there are frequently no data available from which to determine small timescale phenomena unless site-specific intensive field campaigns have been undertaken. Consequently, such time scales dictate that the simulated water quality regime is that of the hydroclimate such as the climatological response rather than the day-to-day meteorological response.

Within this climatological context, mean monthly values for each meteorological variable must be obtained for each lake under study. For many lakes, site-specific climatological data will not be available so that data sometimes from a site situated at a considerable distance from the lake have to be used. This is not unusual in lake and reservoir model validation studies. As noted above, data are frequently presented as monthly means in the source records. Each set of monthly means can then be averaged, for that month, over a number of years (usually five to ten) in order to force the model in its hydroclimatic mode. In this mode, the model is most easily run by fitting sinusoidal curves to each meteorological variable (except cloud cover). In the case of cloud cover, which tends to follow a seasonal cycle less well, mean monthly values are used as representative of the mid-month date with linear interpolation for the remaining days in each month. This would be inappropriate if day-to-day simulations were envisaged, since in process-based models such temporal variance could have significant impacts on the surface energy budget (McGuffie and Henderson-Sellers 1988). However, for climatological simulations aimed at providing essentially a first statistic (the mean), this interpolation is compatible with the other approximations (discussed above) used in hydroclimate modelling.

Additional data for each lake may have to be acquired from other sources. These data include location, cross-sectional area as a function of depth, and light extinction coefficient. Perhaps the most difficult data to obtain are values for the light extinction coefficient. In the absence of site and time specific data, it may be necessary to use lower grade observations (e.g., a single sample taken at a typical time, usually constrained by the time of regular sampling defined in the observational programme and thus often outside the control of the modeller). However, for relatively pristine lakes, it is reasonable to assume a value for clear water of $\eta = 0.1—0.2$ (in the absence of measurements). For many cases also, the time constant of the light extinction coefficient is long so that widely spaced (temporally) observations do not, in fact, introduce any unacceptable errors.

Published sources for lake temperature can be used for validation data although on occasions data are often made available to the modeller by personal contacts. Temperature data are generally made available as isopleth patterns. This is adequate for visual comparison, as discussed in Part 2 of this paper. However, in order to utilize more objective, quantitative statistical tests (Henderson-Sellers 1990), it is necessary to obtain gridded digital data for each site in the database utilized. Work in this area of objective statistical validation is ongoing.

The use of the database component of the EDSS will be expanded upon in Part 2 of this paper, where the data are used to assess simulation results obtained using one specific model which could be considered to have been selected from the modelbase. The interface between the database and the user is the database management system (DBMS). This is a standard software tool in information systems providing a transparent interface. The user, in running applications software, needs not be concerned with how data are stored in the database. The DBMS essentially provides the translation between the user's logical model of the data to the physical record and file structure of the data in the database itself.

Modelbase management system (MBMS)

The MBMS is fashioned on the DBMS, serving a similar purpose, and gives a DSS its special characteristic of an integrated (often synergistic) software system across these three different modules. The modelbase management system is thus able to cross-reference models within the modelbase, possibly creating new models by prototyping.

In the same way that a database is the repository of a range of readily accessible data, so the modelbase contains a suite of numerical models. These models can be driven with the widely ranging data from the database (Fedra 1985) so that simulation results are directly compatible and inter-comparable. In addition, the immediate availability of a large database transparently accessible to the user (here the simulation model) readily permits the implementation of a thorough validation exercise. The simulation results presented there (and elsewhere) are for a number of lakes worldwide, including Canada, U.S.A., and South Africa.

Dialogue generation and management software (DGMS)

The DGMS can help select models appropriate to a specific application by inspecting the features of models stored in the modelbase. These features would include model name, purpose, limitations, availability, hardware requirements, extent of validation, extent of available documentation, source, costs, etc. (Guariso and Werthner 1986). Such information could prove to be invaluable to the environmental manager who is attempting to evaluate available and applicable models either within or outside of the context of an environmental decision support system. In addition, the dialogue system (DGMS) must be flexible enough to

support a wide variety of user-preferred dialogue styles, contain several options in presentation format for the results, and perform error checking on all inputs.

Finally, the DGMS which provides the user interface is a crucial component of a decision support system, insofar as it ensures the decision support system will be an effective tool for the manager. Only with an appropriate and readily understandable interface (Fedra and Loucks 1985) will the decision-support tool be used by managers initially unfamiliar with the concepts of a software DSS. A good DGMS should offer the user a friendly dialogue style. For example, it should provide menus, forms to fill in, a command language, direct manipulation (mouse, touch screen, etc.), or natural language interface. In the future, voice can also be expected. Interface design is thus not simply a technical question but could involve, for example, psychologists, ergonomists, and cognitive scientists, as well as information systems professionals and computer scientists. Guariso and Werthner (1989) provide examples of user interfaces, and Simmonds and Reynolds (1989) discuss graphic art and typographic concepts.

CONCLUSIONS AND RECOMMENDATIONS

In the water industry, appropriate and useful software modelling tools include those for scientific evaluation (e.g., the degree of eutrophication expected in a reservoir), technical management (e.g., real-time control of a filter plant), and information systems similar to those used in most businesses today (e.g., payroll, maintenance scheduling, decision-support systems) (Henderson-Sellers and Gallagher 1990).

Water quality models for lakes, reservoirs, and rivers have, until recently, tended to remain in the domain of the model developer and to be applied in a consultancy framework. Only recently have some of these packages been released more widely. For example, the reservoir water quality models of the U.S. Army Corps of Engineers have been made available to the district offices of the Corps for some time. Some of the aquatic pesticide models are now readily available in the marketplace. Thermal stratification models and their counterparts of ecosystem/eutrophication models have been applied successfully in various parts of the world, but again usually as part of international collaborative research projects between the industrial water quality manager and the researcher. In some instances such as the Water Quality Modelling Research Center of the U.S. Environmental Protection Agency (Barnwell et al. 1987), a government agency provides model support for released versions of the code.

Selection of appropriate models for use in problem solving presents a difficulty to the water-quality manager who does not have detailed knowledge of the limits of applicability of various simulation models. An environmental decision support system (EDSS) offers the water quality manager encapsulated knowledge and software tools to assist in his decision making. In an EDSS, a large range of models are managed and utilized using data selected coherently from the database. Thus various simulation (and other management) models can be utilized in a totally compatible and synergistic mode so that the water quality manager gains "surrogate experience" to assist in decision making.

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DECISION SUPPORT SYSTEMS FOR STORED WATER QUALITY: 2. AN EXAMPLE APPLICATION

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The components of an environmental decision support system (EDSS) were outlined in Part 1 of this paper. Here, an example application is given using a range of data from the database in order to assess the utility of one specific model chosen from the modelbase: the one-dimensional thermal stratification model, EDD1. The model is applied to a range of lake types worldwide.

INTRODUCTION

In a previous paper (Henderson-Sellers 1991), the components of an environmental decision support system (EDSS) were described and emphasis was placed on the development of a useful database for model validation. In this paper, we consider one model from the modelbase and explore its application and validity in detail.

Although we restrict ourselves to the implementation of one physical model from the larger set which would normally form the modelbase of an EDSS, we have applied this model to a large number of lakes worldwide, in order to provide a diversity of test cases. The water bodies considered differ in (1) surface area (from several 100 km^2 to less than 0.5 km^2); (2) range of depths (static characteristics); (3)latitudes and altitudes (dynamically controlling by air temperature, radiation fields, extent of winter ice cover etc); and (4) water type (clear to turbid as influenced by both the aquatic biota and inorganic suspended sediments). The hypothesis tested in this paper is that, within certain constraints (as is the case for all models), the model can be applied generically across a large database.

As noted previously (Henderson-Sellers 1991), since we are restricting our consideration to the hydroclimatic response of the water body, the simulation can be considered to represent the mean response, of over 5-10 y, of the water body to climatological forcing; this forcing being derived from averaging meteorological data. The difficulty presented in the literature is essentially the short time series of observations available for many lakes, the result being that there is an insufficient number of years of observations to provide a true observed hydroclimate because often only "hydroweather" is represented by the observations. However, although much of the comparison made here with observations is with relatively short time series (often only a few years, or in some cases a single year) and is made subjectively, an overall subjective assessment of the model performance can still be undertaken. In the context of an overall appraisal of lake behaviour, on average, this is most appropriate for strategic planning and opera-

tion of a stored water supply. Sensitivity testing and Monte Carlo analysis may also be useful in delineating pseudo-confidence limits or ranges.

For the purposes of engineering design, especially with the common problem of retrofit destratification devices, several features of the particular stratification behaviour are likely to be of concern. These include the mean depth and duration of the stratified period. They also include the typical maximum summer temperatures (because of their important influence on the likelihood of occurrence of algal blooms), the typical summer hypolimnetic temperatures (with respect to oxygen saturation and temperature of compensation water discharged directly from the hypolimnion into fish-bearing rivers), and the frequency and duration of freezing. Of less concern might be the exact depth and rate of descent of the thermocline. In many cases, acceptable error bars might be $\pm 2^{\circ}C$ on temperatures and a few metres on thermocline depth in a deep lake. Depending upon locality and mode of operation of the water resource, it is unlikely that all these factors will be of equal importance in all cases. Consequently, there will still remain some subjective judgement necessary in managerial evaluation. The concept of the DSS is ideally suited to provide such assistance for managerial support.

MODEL VALIDATION, VERIFICATION, AND SENSITIVITY ANALYSIS

A numerical model may either be designed to apply to a single case study or designed to be more widely applicable. In the context of an EDSS suitable for a wide selection of water managers, the models in the modelbase must therefore be validated not only for the site for which they were developed (or sites nearby) but also for sites with very different characteristics. Such wide demographic testing means that managers are able to choose a model in which, although previously used and/or validated at a different site, they might have confidence that it is generically useful at the new and untested site.

In addition, model constraints which limit the range of applicability of an individual model must be clearly stated within the modelbase documentation. Existing models of thermal stratification in lakes have often been designed for a single application/case study and consequently frequently include tuning coefficients to permit simulation at only a single site. To implement such a model, it is first necessary to evaluate these tuning (or calibration) coefficients by trial and error on a single year's data (a learning set). When these have been selected, a second year's data are used to verify that the model is reasonably accurate and useful for this particular lake. Further simulations may then be made prognostically; although, whether such models can ever predict for conditions beyond their original tuning must remain severely in doubt (Henderson-Sellers and Reckhow 1989).

Although the terms validation and verification are often used interchangeably, these words actually describe two different aspects of model assessment: verification refers to the checking of the model's success in reproducing data for the system from which data were abstracted in order to develop the model initially; validation consists of the application of the verified model to a totally different data set, usually from a different site but still within the domain of the model.

As a consequence of the lack of a formal statistical methodology for model assessment (Beck and van Straten 1983), model acceptance tends to rely on extensive testing, in which simulations and observations are compared and evaluated for agreement. In such comparative assessments, one of the greatest problems is that of subjectivity. It would appear to be relatively easy to compare model results of a single dependent variable by use of, for example, a least-squares-fit technique. However, it is not always clear what measure of goodness-of-fit must be achieved before the model is deemed to be acceptable. Indeed, the widespread use of such qualitative terms as good, excellent, and acceptable abounds in the water quality modelling literature (Reckhow and Chapra 1983), although there is little relationship between the terms and quantitative measures of goodness-of-fit.

One further problem is that the modeler and the manager responsible for a particular water body may have very different objectives dependent upon, among other factors, the intended use of the water. Almost certainly, the evaluation of simulations presented in the literature has an implicit bias towards accepting poor simulation in parameters of less concern in specific application areas. Nevertheless, objective assessment criteria are currently being actively sought by several authors. In the absence of tried-and-tested objective measures, only a subjective assessment will be used here. Whilst acknowledging the concerns discussed above, this assessment can still give an overall feel for the model's performance, not in any one specific case, but over a widely differing range of lake types and locations.

Sensitivity analysis tests the degree to which the model responds to an imposed perturbation. If the

model exhibits a large response to a small perturbation, it is intolerant of small errors in the perturbing (usually the driving) variables. Consequently greater accuracy is required in parameter evaluation in order to prevent the model's usefulness from being severely degraded. This, therefore, suggests that an understanding of the variables and parameters to which the model is sensitive allows the field worker to concentrate on minimizing errors in data values collected for those variables, perhaps at the expense of larger errors in observations for the variables to which the model is least sensitive. Such a sensitivity analysis can be undertaken without resort to validation criteria and is a form of testing which should be carried out in parallel to verification and validation tests. The above discussion on sensitivity testing is not applicable to models which contain a strange attractor, i.e., those for which the theory of chaos can be applied. In that case, the sudden switch from one state to another, exemplified by an intransitive system, may be precisely the phenomenon being sought and analyzed. The model EDD1 utilized here has been shown to be of a transitive nature (Henderson-Sellers 1978) and therefore not likely to exhibit any characteristics of chaotic dynamics.

THERMAL STRATIFICATION MODELLING

The methodologies described here for testing mathematical models of natural systems are valid for any thermal stratification model. In this section, one such stratification model will be outlined; in subsequent sections, preliminary results from it will be analysed in terms of a large, geographically diverse database of lakes and reservoirs.

There are two main approaches to thermal stratification modelling in water bodies: mixed layer (ML) models and eddy diffusion models. The former are conceptually and mathematically simpler, but the simplifications used may tend to restrict their applicability for biological modelling since they do not permit easy representation of within-mixed layer processes. Nevertheless, the models have had wide and successful application in both oceanic and limnological situations (Henderson-Sellers and Davies 1989). On the other hand, the eddy diffusion approach has, until relatively recently, suffered from the lack of appropriate analytic descriptions of turbulent mixing. The capacity of this approach for finer resolution suggests that it may provide a more useful base for simulating aquatic biological processes; and in the context of coupled air-water models, it may be more compatible with the numerical schemes used in both dynamic ocean and dynamic/thermodynamic atmospheric models (Adamec et al. 1981).

Thus, ML models are advocated for situations when detail within the mixed layer is not required. For more detailed modelling or embedding in dynamical models, Eddy diffusion models appear to be more suitable. However, long-term future developments of stratification models may be able to benefit from a synergism of these two approaches (Denton and Wood 1981)—an approach which has yet to be fully explored.

The model selected for study here is the Eddy diffusion model EDD1 (Eddy Diffusion Dimension 1) (Henderson-Sellers 1988a). This is a one-dimensional prognostic thermal stratification model which describes the vertical temperature profile in a water body as a prelude to biological modelling. In many instances, profiles are indeed dominated by vertical processes. However, the code retains the capability to allow advective (horizontal) exchanges of heat and momentum through the water column (by including lateral boundary condition in the column model). This permits simulation of reservoirs used for storm water storage and for pumped storage as well as the more quiescent water supply reservoirs, without the need to implement full three-dimensional hydrodynamic/thermodynamic models. Nevertheless, the choice of an eddy diffusion model also permits the investigation of embedding within circulation models (Henderson-Sellers 1988b). The model EDD1 has no tuning coefficients; i.e., there are no arbitrary parameters for which values have to be selected based upon some optimization against an initial (learning) set of data. All parameter values can be determined from site measurements. The underlying equations are shown in Appendix I.

MODEL VALIDATION: BASIS FOR ASSESSMENT

The study presented here is an analysis of the hydroclimatic behaviour of the water body. Whilst the use of mean meteorological data to drive the model is readily identifiable as being appropriate in general, there is one parameter which deserves more detailed comment. It has been pointed out that the effect of the wind speed is non-linear. Fischer et al. (1979) point out that since the energy transferred to the water body depends upon the third power of the wind speed, then, the effect with respect to the transfer of wind energy of a daily mean wind speed of 5 m s^{-1} is 16 times less than if the lake were subject to a 20 m s^{-1} wind for only one quarter of the time. Whilst this calculation is undoubtedly correct, there are

two caveats which must be noted in the context of the hydroclimatic evaluation discussed here. Despite the power law behaviour of the wind, the actual energies involved are significantly smaller than the values for longwave and shortwave surface exchanges. Furthermore, of these only evaporation and sensible heat, which are themselves smaller than radiation exchanges, have a wind speed dependency. This suggests that the averaging effect noted above is essentially only second order and the overall energy budget change may well not be truly cubic. To illustrate this point, a numerical experiment has been performed; the results of which are shown in Fig. 1. For a typical deep, large surface area lake (DeGray Lake in Arkansas, see Table 1), the wind speed forcing was run in three, artificial modes: 1) a constant value of 5 m s^{-1}; 2) a mean value of 5 m s^{-1}, but with alternating days of 4 and 6 m s^{-1} (a typical value for day-to-day variability—assuming a basic timescale of 24 h.); and 3) a mean value of 5 m s^{-1}, but with the more extreme case of high day-to-day variability of alternating days of 0 and 10 m s^{-1}. Figure 1 shows that although there are differences in the details of these three simulations, the overall simulations, in the context of strategic management decision support, are comparable. This is also illustrated in the typical mid-summer profiles shown in Fig. 1(d) which shows vertical cross-sections for Julian date 180 from parts (a)-(c) superimposed.

In the context of decision support for managerial planning, then, this illustrative stratification model is to be judged over a broad range of validity criteria. Detailed agreement with temperatures is not anticipated, especially in cases where the data themselves are only for a small number of years and therefore still contain the year-to-year noise which the model does not attempt to reproduce. However, assessment is required for several parameters. These are the depth and duration of the stratification period, the accuracy of summer surface and hypolimnetic temperatures, and the duration of the ice-free period (for the Canadian lakes modelled here). These parameters indicate to the manager the necessity of destratification, or reaeration (using the version of such models containing a simulation of the annual oxygen profiles). They also indicate the need for determination of the appropriate level of abstraction (dependent on the use to which the water will be put); and of potential algal bloom episodes (an indication based here on the annual temperature range because future incorporation of an algal model will enhance this management mode). Simulated temperatures within the range of variability of the year-to-year changes seen in the observations can be considered to be acceptable and useful for management decision making. Only areas outside these year-to-year ranges require further attention.

If the models were to be used for more detailed assessment in a meteorological rather than a climatologi-

Table 1. Lakes cited in previous studies (Henderson-Sellers and Davies 1991) and in this current study. Some brief details of the contrasting characteristics of these lakes are also shown.

Lake name and location	Surface area (km^2)	depth (m)	Latitude	Winter ice
Windermere (North Basin): Cumbria, UK	8.05	64	54°20′N	NO
Nelson: Sudbury, Canada	3.09	51	46°44′N	Nov–Apr
DeGray: Arkansas, USA	68.80	57	34°25′N	NO
Clearwater: Sudbury, Canada	0.765	21	46°22′N	Nov/Dec–Apr
Buck: Muskoka region of Canada	0.403	30	45°05′N	Dec–Jan
Valencia:Venezuela	350	40	10°N	NO
Hartbeespoort Dam: nr Pretoria, RSA	20.3	31	25°46′S	NO
Buffelspoort Dam: nr Pretoria, RSA	1.4	23	25°48′S	NO
Solitaire: Muskoka region of Canada	1.24	31	45°37′N	Oct–Jan
Middle Lake: Sudbury, Canada	0.28	15	46°26′N	Nov–April
Greeson: Arkansas, USA	39.66	51	34°25′N	NO
Lindleyspoort Dam: nr Rustenburg, RSA	1.9	22	25°31′S	NO

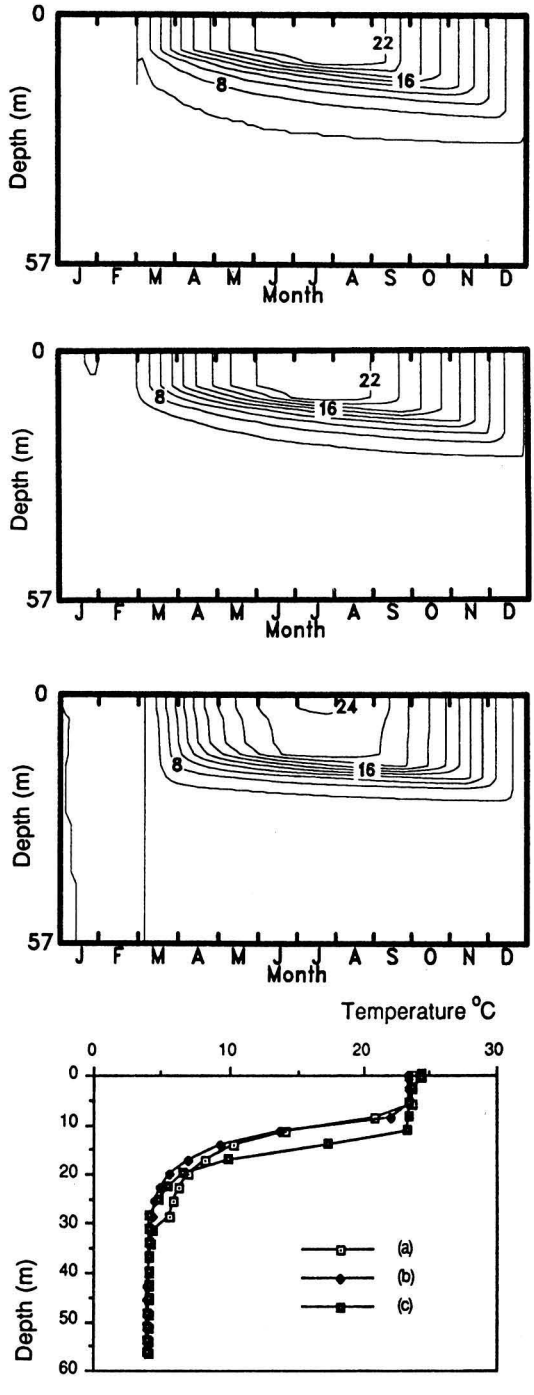


Fig. 1. Simulation of DeGray Lake, Arkansas with (a) constant wind speed of 5 m s^{-1}; (b) alternate days of 4 and 6 m s^{-1} wind speeds; (c) alternate days of 0 and 10 m s^{-1} wind speeds; and (d) comparative midsummer temperature profiles (Julian date 180). The three situations represent a range of cases when the mean wind speed is 5 m s^{-1} but with varying magnitudes of day-to-day variability.

cal context, then more detailed observational data would be required both for driving the model and for model validation. In this instance, a more detailed evaluation should take into account the small timescale phenomena discussed above (with respect to the wind speed factor) and different metrics would be required to assess the accuracy of the model.

CASE STUDIES

The model EDD1 has already been used successfully for a small number of lakes using local meteorological values to which a sine curve has been fitted to mean monthly values either published in this form or sometimes available as daily observations (sometimes as frequent as four times per day) and then averaged to a monthly timescale. Numerical details of the database of forcing variables used are to be found in Henderson-Sellers and Davies (1991).

To extend previous modelling studies, a further selection of over 30 lakes worldwide was simulated. From these, nine sites in the U.K., Canada, South Africa, and Venezuela were chosen to illustrate the wider applicability of this single, selected model, EDD1 (Henderson-Sellers and Davies 1991). These lakes are listed in Table 1. For example, Fig. 2 shows the simulation of a fully dimictic lake in Canada (45-46°N) which is of small surface area: Clearwater Lake, in the Sudbury region, with a surface area of 0.765 km^2. Only the unfrozen period of May to November is shown here, since there are no data available for ice thickness, only duration. There is

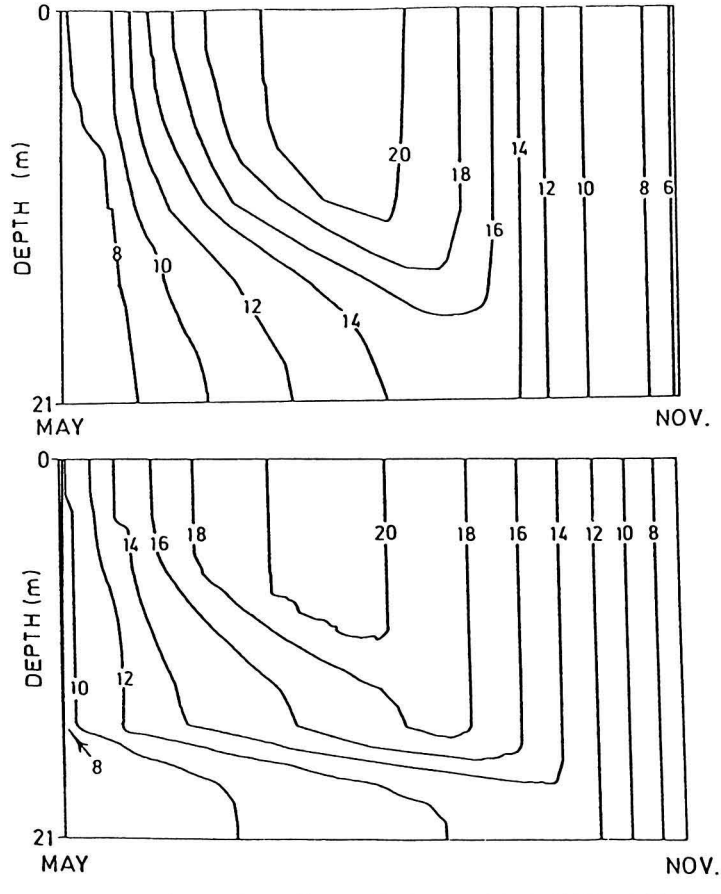


Fig. 2. (a) Observations averaged from five years' data (Sudbury Environmental Study 1982) and (b) simulated hydroclimate for Clearwater Lake, Ontario (Henderson-Sellers and Davies 1989) (Isopleths are in °C). (Reprinted with permission from: Tien, C.L.; Chawla, T.C., eds. Annual review of numerical heat transfer, Vol. 2. New York: Hemisphere Publishing Corporation; 1989.)

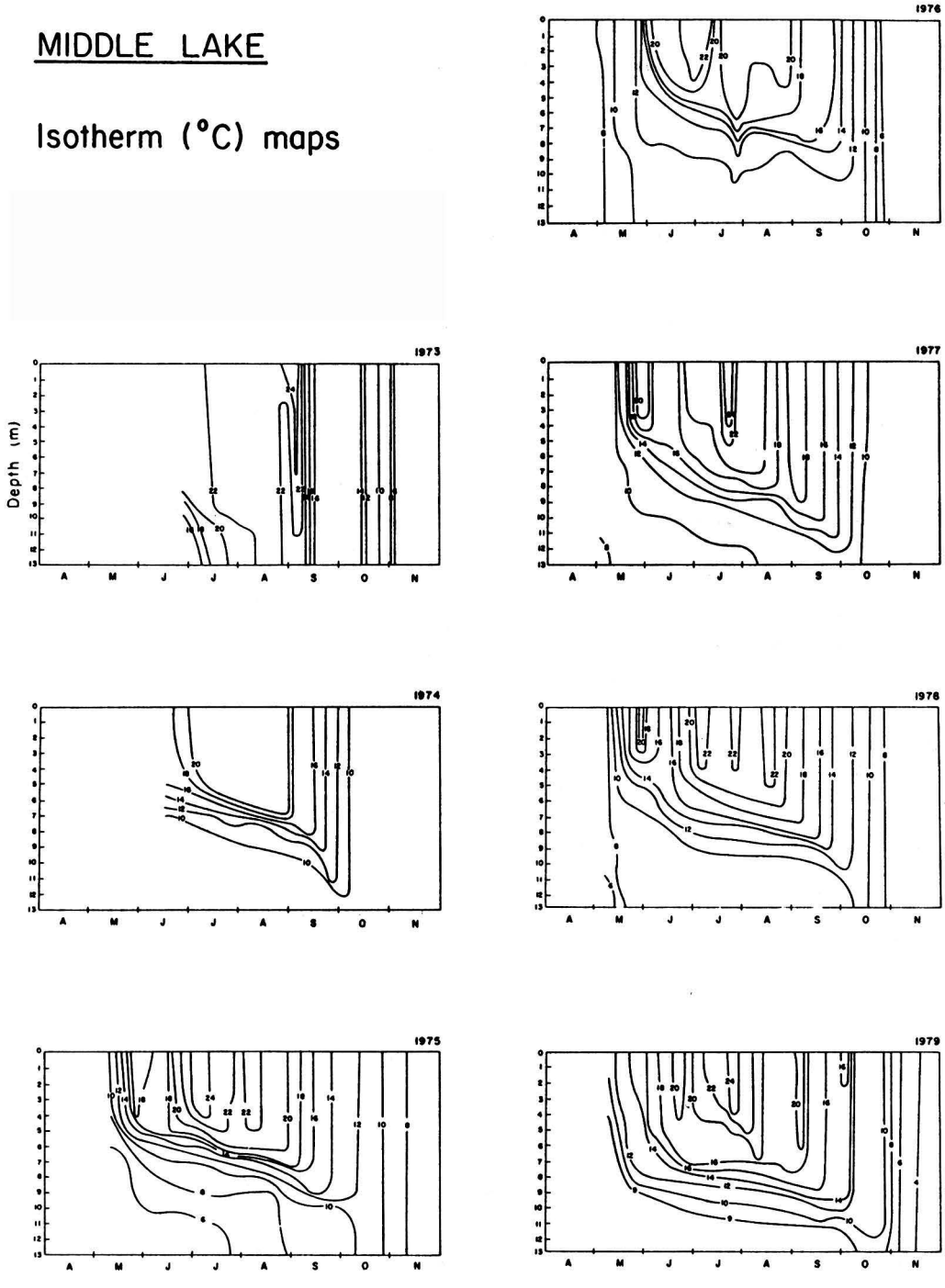


Fig. 3(a). Middle Lake: Observations from 1973-1979 (Sudbury Environmental Study 1982).

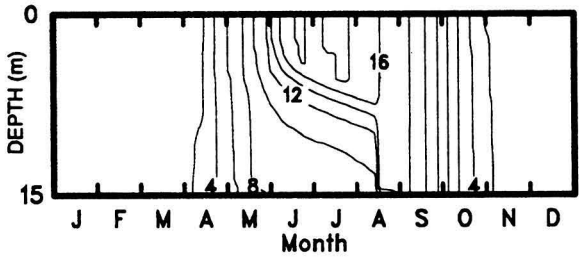


Fig. 3(b). Middle Lake: Simulated hydroclimate. (Isopleths are in °C).

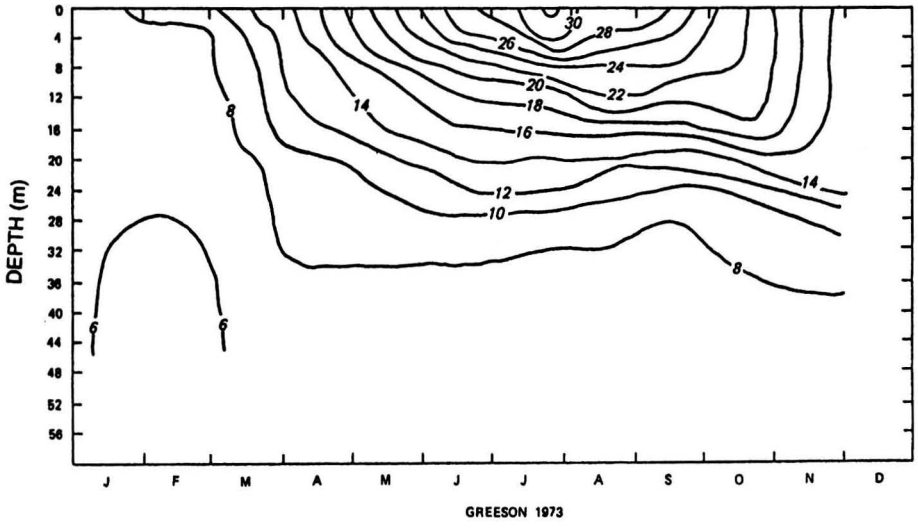
excellent agreement in Fig. 2 between a hydroclimatic simulation and data averaged over several years. All features of the stratification cycle are well modelled, although the hypolimnion warms slightly less than observed in summer. Such simulations illustrate the success not only of simulating lakes with winter ice cover (using a model based on that of Adams et al., 1960 and Ashton 1978) but also of small horizontal extent. In the model EDD1, the effect on mixing of the restricted wind fetch of small lakes is modelled using a decaying exponential modification to the wind speed.

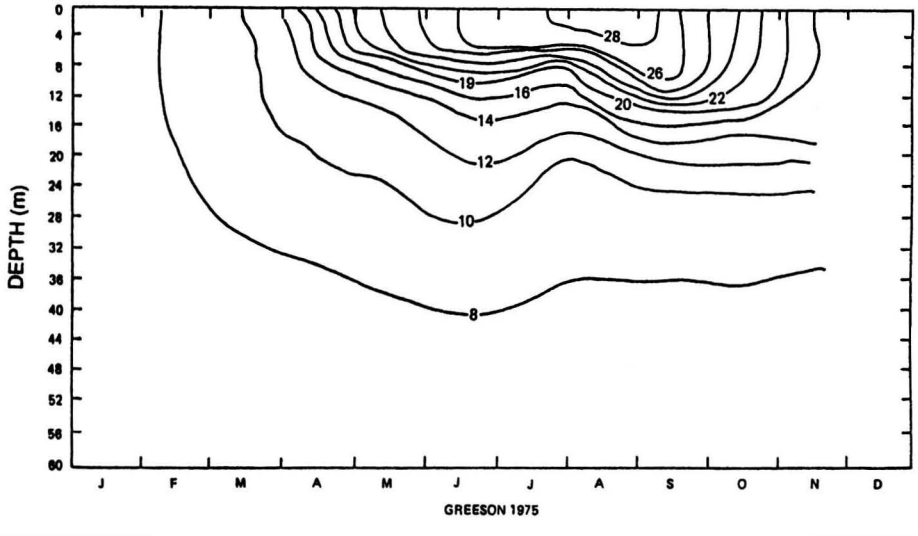
As a further, brief illustration, results from three other sites are shown. Figure 3 depicts seven years of data from the 15-m deep Middle Lake, in the Sudbury region of Canada, a second lake with winter icing. The surface area is 0.28 km^2, about three times smaller than Clearwater. Generally, Middle Lake's maximum surface temperatures are observed to be around 20-24°C and the normal stratification depth is about 8-10 m with summer hypolimnetic temperatures between 6 and 11° C. Although these data are not averaged, we can compare the observations with the hydroclimatically averaged simulation, based on this description. There is generally a reasonably good agreement with maximum calculated surface temperatures of 18°C (a little cool) and hypolimnetic temperatures of 9°C. The duration of ice-free conditions, from the end of April to November, is also well simulated. Note that observations are shown only for this period. Although the simulated values are for the full annual cycle, these are plotted with the same aspect ratio for the period in question in order to facilitate comparisons.

Figure 4 shows the results for Greeson Lake, situated in Arkansas. This lake has a considerably larger surface area of 39.66 km^2. Observations from 1973 and 1975 (Fig. 4), show that this lake stratifies loosely with summer temperatures ranging from about 7°C (bottom) to around 29°C (surface). The simulation is significantly cooler at the surface (by about 5 or 6° C) than the temperature observed in these two years. However, the overall stratification pattern is similar; the summer hypolimnion temperatures and overall winter temperatures being only slightly too cool. As noted above, many of the features of the stratification cycle which need to be simulated for use in management decision support in planning and operational management, (as opposed to rigorous objective agreement at all depths and all times of year) are clearly evident in the model results.

Figure 5 depicts a high altitude lake, Lindleyspoort Dam in the South African Transvaal. Data for both temperatures and the turbidity varied between 0.2 in winter to 0.8 in summer. Isotherms are shown from the summer 1975/76. They identify an isothermal winter period with temperatures dropping to about 12°C and with a relatively short stratified period with a loose stratification over the 5-10 m depth range and summer surface temperatures reaching about 22°C. The simulated winter temperatures are accurately simulated, although the summer surface temperatures appear a little too high. The overall stratification pattern is good with a simulated range of hypolimnetic temperatures (less so regarding the exact temporal progression).

An initial sensitivity study with this model (Henderson-Sellers 1988a) suggested that wind speed was the most important of the meteorological parameters, particularly at lower wind speeds. In addition, it was found necessary to include as accurate a specification of the water turbidity as possible, especially for oligotrophic to mesotrophic lakes. For changes in solar radiation, however, the lake recovered quickly—suggesting that the inclusion of a full surface energy budget permits the accurate simulation of the damping feedbacks present in the total lake system.





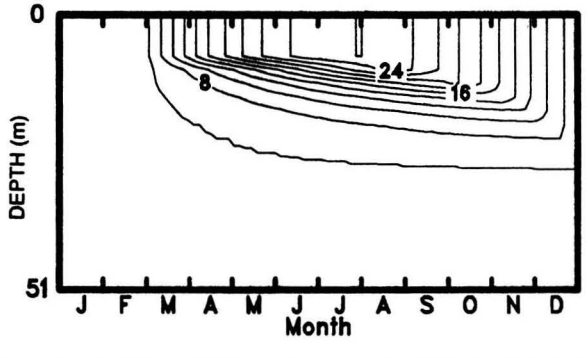


Fig. 4. (a) Observed hydroweather (for 1973 and 1975 after Johnson and Ford, 1981) and (b) simulated hydroclimate for Greeson Lake in Arkansas, USA. (Isopleths are in °C).

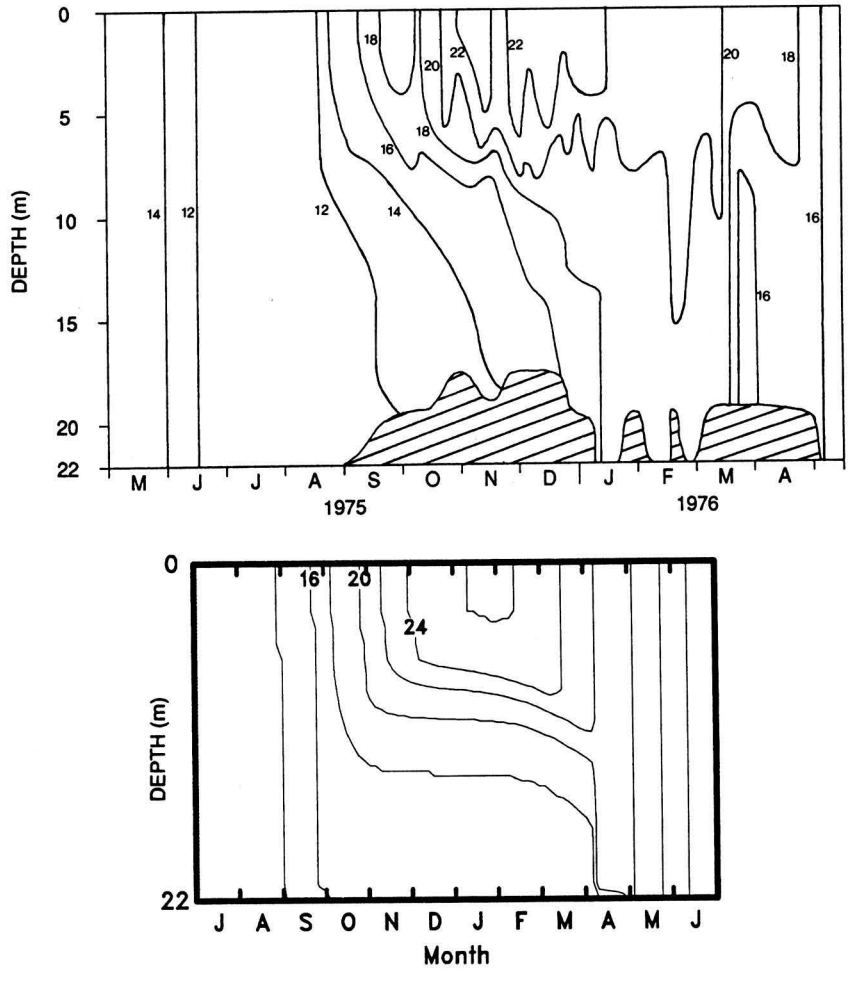


Fig. 5. (a) Observed hydroweather (for 1975/6) and (b) simulated hydroclimate for Lindleyspoort Dam in South Africa. (Isopleths are in °C).

The results of these extensive sensitivity tests are summarized in Table 2.

CONCLUSIONS

In the context of the modelbase component of an EDSS, the studies described here extend the validation of Henderson-Sellers and Davies (1991). Using a single systems model, constructed in such a way that site-dependent tuning is unnecessary, strategic planning and development of new water resources can rest more firmly on a scientific base. In a broader context, the availability of a selection of models within the DSS modelbase permits an even wider assessment of any specific management decision. The growing availability of environmental decision support tools provides the water quality manager with a more reliable basis for strategic and operational planning.

Acknowledgment — I wish to thank Danny Walmsley for supplying data from Lindleyspoort Dam; Peter Dillon, Norman Yan, and Barbara Locke for data for the Sudbury lakes. I also wish to thank Rebecca Davies for her work in compiling the meteorological database used in these simulations.

Table 2. The maximum impact on surface temperatures for various perturbation experiments. For each indicated variable and perturbation, the maximum value of ΔT (difference between perturbation and control experiment) is given (Henderson-Sellers 1988).

Variable (perturbation)	max ΔT (K)	Comments
Wind speed		
doubled	−3	Errors at low wind speed
halved	+5	more important
Aerodynamic drag coefficient		
(various formulations)		No significant effect
Air temperature		
increased by 3K	+2	Everywhere differences >1.5K
decreased by 3K	−2.5	Range of 0 to −2.5K
*Cloud cover**		
no cloud	+6	Large changes
total cloud	−6	everywhere
Atmospheric emissivity		
constant = 0.75	−2	
constant = 0.95	1.3–1.8 everywhere	
Extinction coefficient		
η = 0.3 within date range 160–290 plus		Max impact at thermocline
η = 0.5 within date range 180–250	~1	level of −5 to −7K
η = 0.8 date range 180–260	~1	Max impact at thermocline level of −5 to −7K
η = 0.4 for T > 288K plus		Max impact at thermocline
η = 0.8 for T > 293K	~1	level of −5 to −7K
η = 0.5 all year	−3 to +2	Max impact at thermocline level of −5 to −7K
η = 0.8 all year	−2 to +2	Max impact at thermocline level of −10K
Surface albedo		
0.06–0.08		No significant effect
±50%	<1	
Bathymetry		Significant differences
(realistic cf. straight-sided approximation)		especially at depth
Eddy diffusion coefficient		
multiplied by 10	−1	More significant for
divided by 10	+3	reduced eddy diffusion values

*Note perturbations applied to cloud cover are significantly likely to exceed natural variability or inherent observational inaccuracies and thus provide upper and lower bounds which are unlikely to be attained.

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APPENDIX

In the model EDD1, the one-dimensional heat transfer equation is written

$$A(z)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(A(z)\,[\alpha + K_H(z,t)]\,\frac{\partial T}{\partial z}\right) + \frac{\frac{\partial (Aq)}{\partial z}}{\rho c_p} \qquad (1)$$

In this equation, $A(z)$ is the horizontal cross-sectional area of the lake at a depth z below the surface, $T(z,t)$ is the temperature at depth z and time t, α and K_H are the coefficients of molecular and eddy diffusion of heat respectively, q represents the penetration of shortwave radiation, ρ is the water density and c_p its specific heat.

The functional form for the eddy diffusion coefficient is given by

$$K_H = K_{H_0} f(R_i) \qquad (2)$$

where the neutral value of the Eddy diffusion coefficient, K_{Ho}, is given by

$$\frac{k\, w_{*s}\, z}{P_0}\, \exp(-k^* z) \qquad (3)$$

for a given friction velocity, w_{*s} and neutral Prandtl number P_0 (and where k is the von Kármán constant). The parameter k^* is a non-linear function of wind speed, based on Smith (1979) and generalized as

$$k^* = 6.6(sin\theta)^{\frac{1}{2}}\, U^{-1.84} \qquad (4)$$

The functional form for the non-neutral dependency of the Eddy diffusion coefficient is given for stable conditions ($R_i > 0$) as

$$f(R_i) = (1 + 37R_i^2)^{-1} \qquad (5)$$

This formula permits more rapid damping of turbulence at high Richardson number than the classical form:

$$f(R_i) = (1 + a_3\, R_i)^{-(b_3+1)} \qquad (6)$$

and is strongly supported by the data of Ueda et al. (1981).

In the model EDD1, the surface boundary condition is given by the surface energy exchange which is calculated at each time step (the size of which is governed by the Courant-Friedrich-Lewy (CFL) numerical stability criterion). Convection is modelled simply in terms of an interactive energy balance (Ryan and Harleman 1971). Consequently, the metereological forcing variables, such as wind speed, air temperature, relative humidity, cloud cover, etc. play an important role. It is important, therefore, to assess how sensitive the model is to potential errors in these measured variable values (for instance, because there is no metereological observing site near the lake itself).

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BOOKS

Metal Complexes in Fossil Fuels Geochemistry, Characterization and Processing, by Royston H. Filby and Jan F. Branthaver. ASC Symposium Series 344, American Chemical Society, Washington, D.C., 1987. 436 pp., US$96.85 hardcover.

Knowledge of heavy metals content and their form in fossil fuel is of great importance for pollution control. The existence of porphyrins was found by Alfred Treibs in the 1930s.

Since the 1930s, much work has been published on the geochemistry of porphyrins and other metal complexes in geological materials. The emphasis of most of this work is on metalloporphyrins and chlorins because these compounds possess spectral characteristics that permit detection in small concentrations and chemical properties that sometimes allow substantial purification from background materials. Investigations of geoporphyrins have featured structure determinations, the results of which have shown that a great variety and number of compounds are derived apparently from a few biological precursors as a consequence of geochemical processes. The nature of these geochemical processes has been inferred from the observed transformations. These processes are of particular interest to those who search for fossil fuels, particularly petroleum.

While the geochemistry of metal complexes was being studied, it was found that metal complexes in fossil fuels cause serious problems in processing. Thus, while geochemists attempted to discover how metal complexes occur in fossil fuels, chemical engineers were trying to find ways to get them out or otherwise deal with their deleterious effects. Interaction between the two groups of researchers has been somewhat limited.

This 26-chapter book presents recent findings on the geochemistry, characterization, and processing of metal complexes, including metalloporphyrins, in fossil fuels. Geochemical studies include origins of sedimentary porphyrins, application of metal complexes in petroleum to exploration, and distribution of transition metals in North Alaskan oils. Characterization studies include techniques for isolation and characterization of chlorins and geoporphyrins, axial coordination in nickel and vanadium porphyrins, and interaction of Ni(II) complexes with asphaltenes. Processing studies include the reaction sequence of metalloporphyrins during heavy residuum upgrading, and modes of operation in hydrodemetallization.

The book seems to be of interest for geochemists and environmental chemists.

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Aerosols. Proceedings of the 3rd International Aerosol Conference, 24-27 September 1990, Kyoto, Japan. S. Masuda and K. Takahashi, eds. Pergamon Press, Oxford, U.K., 1990. 1348 pp. (ISBN 008 0375243) £164.50/$330.00 hardcover.

The two volumes contain the text of presentations at a conference. The book covers physical aspects of aerosols (nucleation, growth, generation, measurement, optical properties, and dynamics), engineering (filtration, separation, industrial processes, and applications), public health (indoor air, atmospheric aerosols, and radioactive aerosols), and health effects. As one expects from proceedings of symposia, the quality of the papers range from outstanding to average. This book is recommended as a reference for libraries.

Assessing Ecological Risks of Biotechnology. Lev R. Ginzburg, ed. Butterworth-Heinemann, Stoneham, MA, 1991. 379 pp. (ISBN 0-409-90199-7) hardcover.

Ecological risks are primary considerations for allowing or disallowing field releases of genetically engineered organisms. Regulatory agencies throughout the world are currently struggling with the problem of developing a sound scientific basis for regulating the explosive growth of biotechnology products. This book describes scientific foundation as well as the current situation within regulatory institutions. It presents a comprehensive analysis of ecological risk

assessment for biotechnology from the point of view of scientists doing research in this area, but also of regulators, philosophers, and research managers. Emphasis is placed on ecological risks associated with the release of genetically engineered organisms into the environment. This book is organized into four parts. The ecological experience gained from biological introductions is the subject of Part I. Part II explores the characteristics of microbial communities. Particular emphasis is given to the transport of microorganisms, since one of the ecological concerns about biotechnology is the spread of genetically engineered organisms to ecosystems other than the one into which they are released. Part III reviews mathematical models that can be used for ecological risk assessment at four different levels. At the lowest level, the effect of genetic engineering on fitness of individuals is explored. Other chapters use models at the genetic and population levels to predict the effect of introducing genetically engineered organisms into a biological system. Part IV covers the regulation of biotechnology, research trends, and social values. This is probably the only book on the market on quantitative ecological risk assessment. It is highly recommended to individuals as well as to libraries.

Controlling Chemical Hazards: Fundamentals of the Management of Toxic Chemicals. Raymond Cote and Peter G. Wells, eds. HarperCollins Academic, London, 1991. 310 pp. (IS 0-04-604002-1) £40.00/$75.00 hardcover.

Toxic chemicals pose environmental problems which require a multi-disciplinary effort to be resolved. Critical issues face those responsible for managing hazards and controlling problems associated with the manufacture, transport, storage, use, and disposal of chemicals. This text seeks to provide managers with guidance on the issues, management strategies, and tools from a 1990s perspective. It does this in two ways; first by looking at the disciplines involved—environmental chemistry, toxicology, engineering, economics, sociology, and political science—and second from the viewpoint of industry, government, academic, and non-government organizations. By covering such a judicious combination of topics, the book contributes to the rapidly advancing environmental protection and management fields and provides a timely overview of the essential disciplines and approaches for reducing chemical threats. University students in environmentally related programs such as environmental science, law, engineering, business, community, or public health and public administration will find this book to be useful. It will also be of interest to professionals in environmental and health agencies and all those involved in the chemical industry and in environmental organizations. It is recommended as a desk copy and as a reference for libraries.

Effluent Treatment and Waste Disposal. Proceedings of a symposium organized by Institution of Chemical Engineers. Hemisphere Publishing Corp., Bristol, PA. 402 pp. (ISBN 0 85295 251 1) $114.00 hardcover.

This conference, organized by the Yorkshire Branch of IChemE in association with the Institution's Environmental Protection Subject Group, addressed the areas of waste monitoring, developments in pollution control processes, and process economics and included as discussion of future trends in waste disposal. It all considered the impact of recent legislation upon the process industries. The Proceedings include 30 articles covering various aspects of waste treatment.

Deltamethrin. Environmental Health Criteria 97. World Health Organization Publications, Geneva, Switzerland, 1990. 133 pp. (ISBN 92 4 154297 7) Sw.fr. 16.-/$14.40 softcover.

This book evaluates the risks to human health and the environment posed by the use of deltamethrin, a synthetic pyrethroid insecticide mainly used against agricultural pests. Marketed since 1977, deltamethrin is most commonly used on cotton, on fruit and vegetable crops, and on cereals, corn, and soybean. Deltamethrin is also used for the post-harvest protection of stored cereals, grains, coffee beans, and dry beans. Major public health applications include use in the control of Chagas disease in South America and in malaria control in Central America and on the African continent. The book includes a brief description of the physical and chemical properties of this insecticide, a review of data indicating sources of environmental exposure and behaviour in soil, air, and water, including degree and speed of degradation. Dietary residues, particularly following post-harvest treatment, are identified as the most important source of exposure for the general population. Also included are the metabolic fate of deltamethrin in various organisms and its toxicity to different species. The final section evaluates effects on humans as observed following poisoning in cases of attempts suicide, occupational accidents, and both short- and

long-term occupational exposure. The book concludes that exposure of the general population to deltamethrin is very low and that, provided recommended rates of application are followed, use of this insecticide is unlikely to present a hazard to either occupationally-exposed workers or the environment. The book is recommended as a reference for libraries.

Cyhalothrin. Environmental Health Criteria 99. World Health Organization Publications, Geneva, Switzerland, 1990. 106 pp. (ISBN 92 4 154299 3) Sw.fr. 14.-/$12.60 softcover.

This book evaluates the risks to human health and the environment posed by the use of cyhalothrin, a synthetic pyrethroid insecticide having a high level of activity against a wide range of agricultural pests. Cyhalothrin is also used in public health and animal health, where it effectively controls a broad spectrum of insects, including cockroaches, flies, mosquitos, and ticks. The book finds no evidence of carcinogenicity, mutagenicity, or disturbed reproductive functions, and no evidence of adverse effects on any aspect of fetal development at any of the experimental doses used. Of particular interest are the effects on humans, notably the clinical significance of a subjective facial sensation reported in laboratory workers, workers in manufacturing plants, and field operators handling cyhalothrin. While noting the documented occurrence of this syndrome, the report concludes that it is a transient phenomenon, that symptoms are not associated with objective physical signs, and that recovery is complete. The report concludes that, when recommended safety precautions and rates of application are followed, cyhalothrin is highly unlikely to pose a risk to the health of the environment, the general public, or occupationally-exposed workers.

Tri-n-Butyl Phospate. Environmental Health Criteria 112. World Health Organization Publications, Geneva, Switzerland, 1991. 80 pp. (ISBN 92 4 157112 8) Sw.fr. 11.-/$9.90 softcover.

This book evaluates risks to human health and the environment posed by the production and use of tri-*n*-butyl phosphate. Tri-*n*-butyl phosphate is widely used worldwide as a solvent for cellulose esters, lacquers, and natural gums as a primary plasticizer in the manufacture of plastics and vinyl resins, in the formulation of fire-resistant aircraft hydraulic fluids, and as an antifoaming agent, mainly in paper manufacturing plants. In view of several weaknesses in available experimental data, the report was unable to reach firm conclusions concerning the risks posed by tri-*n*-butyl phosphate as a potential carcinogen, neurotoxic agent or dermal sensitizer, though a neurotoxic effect comparable to organo-phosphate-induced delayed neuropathy was judged unlikely. The evaluation of data on risks to humans is largely confined to reports of headache, nausea, and irritation of the skin, eye, and mucous membrane observed in workers. The report concludes that the production and use of tri-*n*-butyl phosphate pose a low risk for the environment and for the general population, and that the likelihood of long-term effects in occupationally exposed workers is small. The book is recommended as a reference for libraries.

Tributyltin Compounds. Environmental Health Criteria 116. World Health Organization Publications, Geneva, Switzerland, 1990. 273 pp. (ISBN 92 4 157116 0) Sw.fr. 29.-/$26.10 softcover.

This book evaluates risks to human health and the environment posed by the use of tributyltin compounds as molluscicides, antifoulants on boats, ships, quays, buoys, and equipment in the fishing industry, as wood preservatives, and as slimicides on masonry. Tributyltin compounds are also used as biocides for cooling systems, power station cooling towers, pulp and paper mills, textile mills, and breweries. These compounds pose a particular threat to the marine environment in view of their documented high toxicity to aquatic organisms, including commercially important shellfish. The book concludes that tributyltin compounds are a severe irritant to human skin and an extreme irritant to the eye, and that inhalation of aerosols can have especially hazardous effects on the respiratory tract. Despite the large body of experimental studies documenting toxicity, the book was unable to quantify the risk to humans posed by the consumption of contaminated fish and shellfish. This book is recommended as a reference in libraries.

Methyl Isobutyl Ketone. Environmental Health Criteria 117. World Health Organization Publications, Geneva, Switzerland, 1990. 79 pp. (ISBN 92 4 157117 9) Sw.fr. 11.-/$9.90 softcover.

This book evaluates risks to human health and the environment posed by the widespread production and use of methyl isobutyl ketone as a solvent, with major

applications in the production of lacquers and paint solvents, including car and industrial spray paints. Methyl isobutyl ketone also occurs naturally in food, is a permitted flavouring agent, and is used in food contact packaging materials. The book concludes that exposure to methyl isobutyl ketone can cause eye and respiratory irritation as well as symptoms of headache, nausea, and vertigo. It finds no evidence that exposure to this chemical causes permanent damage to the nervous system of workers or that its presence in the environment and in food poses any threat to the general population.

Forest Industry Wastewaters. Proceedings of the Third International Association on Water Pollution Research and Control (IAWPRC) Symposium on Forest Industry Wastewaters, held in Tampere, Finland, 5-8 June 1990. Pergamon Press, Oxford, U.K. 447 pp. (ISBN 008 0411509) £85.00/$162.00 softcover.

The progress of the pulp and paper industry worldwide to minimise its environmental impact is summarised in these proceedings, 46 selected papers, and posters from a symposium, which attracted experts from those countries with a significant presence in this industry. Particular attention was paid to slowly biodegradable compounds and nutrients. Amongst the latest innovations in control measures described here, are techniques for dealing with organochlorine compounds in effluents, particularly those from bleaching. There are also reports on the activated sludge treatments now being applied to achieve acceptable levels of nutrients. The environmental effects of mill effluents are described, as are the regulatory and policy frameworks in the USA, Scandinavia, continental Europe, and Australasia. The theoretical and case studies in these proceedings constitute a review of water pollution control in the pulp and paper industry. As such, this volume will be of interest to those who are concerned with ensuring that exploitation of forest resources does not harm the water environment. It is recommended as a reference for libraries.

Incinerating Municipal and Industrial Waste. Richard W. Bryers, ed. Hemisphere Publishing Corporation, Bristol, PA, 1991. 411 pp. (ISBN 1-56032-145-8) hardcover.

The American Society of Mechanical Engineers in conjunction with the International Engineering Foundation and the National Association of Corrosion Engineers, organized a symposium in October 1989. This book is the compilation of papers presented at that symposium. The objective of the conference was to bring together plant operators, equipment designers, and researchers to discuss, through formal and informal interactions, the cause and cure for high-temperature corrosion and deposits due to impurities in flue gas from the combustion of industrial and municipal refuse. It was the desire of the conference organizers to identify those constituents in refuse responsible for fireside problems, the mechanisms by which these impurities deposit and cause corrosion on heat transfer surfaces, economically viable solutions, and the areas in which further research may produce the most promising results. This book is recommended as a reference for libraries.

Spatial Data Analysis in the Social and Environmental Sciences. Robert Haining. Cambridge University Press, Cambridge, U.K. 1990. 409 pp. (ISBN 0 521 38416 8) £45.00/$65.00 hardcover.

A spatial data set is a data set in which each observation is referenced to a site or area. Within both the social and environmental sciences, much of the data collected is within a spatial context and requires statistical analysis for interpretation. The purpose of this book, therefore, is to describe to students and research workers in the social and environmental sciences, current methods available for the analyses of spatial data. Methods described include data description, map interpolation, exploratory, and explanatory analyses. The book also examines how spatial referencing raises a distinctive set of issues for the data analyst and recognises the need to test underlying statistical assumptions. Further, methods for detecting problems, assessing their seriousness, and taking appropriate action are discussed. This is an important text for any academic discipline that requires a broad overview of current theoretical and applied work available for the analysis of spatial data sets. It will be of particular use to research workers and final year undergraduates in the fields of geography, environmental sciences, and social sciences. It is recommended as a desk copy and a library reference.

Transfer of Radionuclides in Natural and Semi-Natural Environments. G. Desmet, P. Nassimbeni, and M. Belli, eds. Elsevier Applied Science Publishers Ltd.,

Essex, England, 1990. 693 pp. (ISBN 1-85166-539-0) £95.00 hardcover.

During the passage of the Chernobyl cloud over Western Europe, a number of semi-natural environments were affected. The contamination of these areas provoked some commotion in the world of radioecology and radioprotection. It was therefore considered useful to set up a meeting where, opposed to any non-scientific considerations, experts could give their opinions and discuss the contentious issues freely. A great number of scientists responded to this initiative, proving the importance of the subject. They were confronted with a new situation that had not been given much attention in the past by officials in charge of environmental monitoring. Environmental transfer of radionuclides was studied principally under agricultural conditions, and models were based on these results. It became clear that mere measurements of environmental contamination levels do not allow reliable predictions of the behaviour of radionuclides to be made, nor of the outcome of countermeasures. The organisers of this meeting tried to cover the area by scheduling a program comparing the different key topics which were revealed in the post-Chernobyl phase. This book contains the papers presented at the meeting. It is recommended as a library reference.

VDI Codes and Standards,Verein Deutscher Ingenieure. VDI-Kommission Reinhaltung der Luft, Düsseldorf, Germany.

The Association of German Engineers (Verein Deutscher Ingenieure) publishes consensus standards on topics of technological interest. The following standards have been published recently and are available from VDI-Kommission Reinhaltung der Luft (VDI-RdL) D-4000 Düsseldorf 1: VDI 2268 Part 4: Determination of Arsenic, Antimony and Selenium in Dust Emissions by Graphite-Furnace Atomic Absorption Spectrometry (May 1990); VDI-2453 Part 1: Determination of Nitrogen Dioxide Concentration. Photometric Manual Standard Method (Saltzman) (October 1990); VDI 2456 Part 10: Analytical Determination of the Sum of Nitrogen Monoxide and Nitrogen Dioxide. Dimethylphenol Method. (Nov 1990); VDI 3863 Part 2: Determination of Acrylonitrile Gas Chromatographic Method. Sampling by Absorption in Low Temperature Solvents (Feb 1990); VDI 3469 Part 8: Emission Control. Fibrous Dusts. Flat Gaskets (Mar 1991); and VDI 3792 Part 5: Standardization of Sampling of Leaves and Needles from Trees at their Natural Site (June 1991).

Improving Safety in the Chemical Laboratory, 2nd Edition. Jay Young, ed.. John Wiley & Sons, Inc. New York, NY, 1991. 406 pp. (ISBN 0-471-53036-0) $75.00 hardcover.

This book offers detailed procedures—from precautionary labeling to simulated drills, safety inspections, and the preparation of a chemical hygiene plan—for the development of a safety-enhanced workplace. Reflecting, in part, the upgraded procedures now mandated by the OSHA Laboratory Standard in the USA, as well as the WHMIS regulations in Canada and the COSHH regulations in the United Kingdom, this edition offers guidance on hazard control. The book is an accident prevention handbook for the professional in the lab that shows how to detect and eliminate the causes of dangerous mishaps—and virtually hazard-proof any lab environment. This book is highly recommended for individuals and as a reference in libraries.

Greenwar Environment and Conflict. Olivia Bennett, ed. The Panos Institute, London, U.K.; 1991. 156 pp. £7.95 softcover.

Preventing Pollution Through Technical Assistance. Mark H. Dorfman and John G. Riggio. Inform, Inc. New York, NY; 1990. 63 pp., $17.50 softcover.

Recycling: Energy from Community Waste: A Guide to Sources. Lesley Grayson, ed. The British Library, London, U.K.; 1991. 143 pp., £25.00 softcover.

Taking Stock: Animal Farming and the Environment. Alan B. Durning and Holly B. Brough. Worldwatch Paper 103. Worldwatch Institute, Washington, D.C.; 1991. 62 pp., $5.00 softcover.

Women's Reproductive Health. Jodi L. Jacobson. Worldwatch Paper 102. Worldwatch Institute, Washington, D.C.; 1991. 70 pp., $5.00 softcover.

Whose Trees: A People's View of Forestry Aid. Mohamed Ahmed Hisham, Jan Sharma, Anthony Ngaiza, and Nicholas Atampugre. The Panos Institute, London, U.K.; 1991. 138 pp., £7.95 softcover.

U.S. Investment Trends: Impact on Productivity, Competitiveness, and Growth. American Council for Capital Formation Center for Policy Research, Washington, D.C.; 1991. 69 pp., $15.00 softcover.

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NEW PATENTS

This Section contains abstracts and, where appropriate, illustrations of recently issued United States patents and published patent applications filed from over 30 countries under the Patent Cooperation Treaty. This information was obtained from recent additions to the Pergamon PATSEARCH® online database in accordance with interest profiles developed by the Editors. Further information about Pergamon PATSEARCH® can be obtained from Pergamon Orbit InfoLine Inc., 8000 Westpark Drive, McLean, Virginia 22102, U.S.A.

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4953478

ODOR CONTROL FOR A SLUDGE TREATMENT PROCESS

John Glorioso assigned to Enviro-Gro Technologies

A system is described for producing small uniform pellets of predetermined size which are substantially free of fines from mechanically dewatered sewage sludgeand a means for controlling odor from the production of said pellets. The system includes a process and apparatus for mixing the dewatered sludge with previously dried recycled particles of said sludge. Drying the mixture in a thermal drier, separating a substantial portion of the dried solids from the drier off-gas. Clarifying said separated solids to separate the pellets of predetermined size, oversized pellets, and undersized pellets and particles, mechanically crushing the oversized pellets and admixing the crushed oversized pellets with the undersized pellets and particles and recycling said mixture for mixture with incoming dewatered sludge to the drier. The off-gas from the mechanical separation process is then passed through a condenser to remove some of the water therein, and is routed to an afterburner wherein it is burned. The off-gas from the afterburner then passes through a heat exchanger with fresh air to heat the fresh air which is then routed to the drier as combustion gas.

4953479

METHACOAL INTEGRATED COMBINED CYCLE POWER PLANTS

Leonard J Keller, Austin N Stanton

Methacoal Integrated Combined Cycle Power Plants comprise a thermal separation plant for producing condensate liquid fuel and particulate carbonaceous fuel from Methacoal fuels, coal-methanol suspensoids or slurries; gas turbine generator plants for burning the liquid fuel to produce electric power; steam turbine generator plants for producing electric power; a boiler plant for producing steam for steam turbines; a small firebox for burning reative particulate carbonaceous fuel, with minimum retention time for high temperature combustion gases and minimum oxygen required for combustion, thus minimizing emissions of nitrogen oxides and hazardous ultra-fine particulates; and means for controlling ash fusion and slagging problems. The two generating plants are respectively sized to provide the capacity required, and to consume the two fuels in the proportions produced from the Methacoal fuels, during normal operations, allowing fuel inventory control. Gas turbine exhaust gases provide most combustion air for burning particulate fuel. Other uses of gas turbine exhaust heat facilitate control and achieving the high overall efficiencies. Capacity is about one-fourth gas turbine generated power to three-fourths steam turbine generated power for these new plants. Conventional combined cycle power plants have about two-thirds gas turbine generated power and only one-third steam turbine generated power. The invention facilitates low-cost retrofitting of steam power plants. New power plants will be much less costly than other coal or lignite power plants available, including fluid bed combustion plants and integrated gasification combined cycle plants.

4953976

GAS SPECIES MONITOR SYSTEM

Steve Adler-Golden, Neil Goldstein, Fritz Bien assigned to Spectral Sciences Inc

A gas species monitor system includes a sample volume for receiving a gas to be monitored; an external, independent laser source; means for directing the laser radiation to the volume; a multipass optical cell, responsive to the means for directing, for multiplying the laser radiation intensity in the sample volume; means for continuously flowing the gas to be monitored through the sample volume; a narrow bandpass filter; means for collecting more than a steradian of Raman scattered radiation from the sample in the volume and directing the collected radiation in parallel through the narrow bandpass filter; and means responsive to the parallel radiation from the filter for detecting the Raman scattered radiation representative of the concentration of the species in the gas sample being monitored.

4955391

FLUID MONITORING APPARATUS

Robert L Parker, Charles G Reed assigned to Invenomed Inc

A fluid monitoring apparatus has a canister into which fluid is introduced via an entry port at the top of the canister, a conventional volume measuring assembly within the canister and a flow control assembly that receives the fluid from the entry port and discharges the fluid at a controlled rate into the volume measuring assembly. The canister has a tubular body portion made of transparent plastic on which volume indicia are inscribed and is closed at its ends by a cover plate in which the entry port is formed and a floor plate in which a discharge port is formed. A pump connected to the discharge port is operable for removing fluid from the canister and is flushed with antiseptic solution via a second pump. The flow control assembly has a partition that extends across the interior of the canister and has an upwardly extending flange to form a fluid catchment and an integral funnel that discharges into the volume measuring assembly. A filter is provided across the canister or funnel. A suction port is formed in the cover plate and separated from the entry port by a partition that extends across a perforated cup that is secured to the cover plate about both ports and encircled by a tubular splash shield. Probes, including a pH probe in the cover plate, extend into the canister and an injection port is formed in lower portions of the canister.

4956092

METHOD FOR CONCENTRATING/ DEHYDRATING OF SEWAGE SLUDGE

Holger Blum, D 2000 Hamburg 13, Federal Republic Of Germany

In the method for concentrating/dehydrating sewage sludge including activated sludge with the aid of organic polyelectrolytes and/or inorganic flocculators the activated sludge portion is produced in an aerated biologic clearing step in presence of-based on the amount of liquid flowing into the clearing step-5 to 0.01 parts by weight per million parts by weight of at least one compound selected from the group consisting of folic acid, dihydrofolic acid and at least an ammonium alkali metal salt, alkaline earth metal salt and alkanolammonium salt thereof.

4956152

EMISSION CONTROL UNIT

James R Keough, Arthur E Miller, Charles Schrader assigned to Electro Statics Inc

An emission control unit is mounted in the exhaust line of a fossil fuel internal combustion engine and includes a tubular housing in which a lime sleeve is received. The sleeve has an axial opening through which a corona wire extends. Exhaust gasses pass through the sleeve along the wire. Placing a charge on the wire drives pollutants in the exhaust laterally outwardly into the sleeve at a direction which is 90 degrees to the direction of exhaust travel. The sleeve chemically interacts with the pollutants and neutralizes them with little hazard to the environment.

4956557

DOSIMETER FOR IONIZING RADIATION

Hugo Vlasbloem, Maasland, Netherlands assigned to B V Optische Industrie de Oude

There is disclosed a dosimeter to be used in connection with slit radiography and comprised of a gas filled chamber with one side wall provided with a plurality of X-ray transparent strip-like electrodes extending substantially transversely

to a longitudinal direction of the oblong-shaped casing and another side wall provided with wire electrodes extending parallel to such longitudinal direction of the oblong-shaped casing wherein each of the strip-like electrodes generates a signal representative of intensity of ionizing radiation and wherein the strip-like electrodes are divided into a number of groups, signals from the strip-like electrodes belonging to each group are combined to provide a control signal for a respective attenuation element.

4957049

ORGANIC WASTE FUEL COMBUSTION SYSTEM INTEGRATED WITH A GAS TURBINE COMBINED CYCLE

Charle Strohmeyer assigned to Electrodyne Research Corp

The invention comprising an organic waste fuel combustion and tempering gas flow control system integrated with a gas turbine combined cycle steam generating plant. The gas turbine exhaust, wherein the oxygen content is partially consumed is used to dry and support combustion of an organic fuel high in moisture content after said fuel has been dewatered and pelletized. A portion of the gas turbine exhaust gas stream dries the pelletized waste fuel while a parallel portion of the gas turbine hot gas stream is used to support combustion and furnish oxygen in the ignition zone of the pelletized waste combustor. The drying stream also tempers secondary combustion gas temperature. The two gas streams are combined downstream of the combustion zone. The regenerated combined stream is then utilized in a steam generating section to generate steam. The gas turbine exhaust flow provides the mass flow and heat required for drying and combusting the pelletized waste fuel and the heat input from the pellet firing system regenerates the gas turbine exhaust gas stream. The pellet combustion process is maintained at temperature levels which avoid formation of deleterious products of combustion during the incineration process.

4958075

GAS ANALYZER

Leslie E Mace, Daniel W Knodle, Lawrence L Labuda, Philip F Nuzzo assigned to NTC Technology Inc

Sampling attachments or systems for infrared gas analyzers of the non-dispersive type. Major components of the system include a sampling device or cuvette, a vacuum pump for effecting a flow of the gases to be analyzed through the cuvette, a microprocessor based pump control, and a switch which is closed and allows the pump to be turned on only if an appropriate sampling cuvette is connected up to the pump. The sampling attachments are designed for medical applications-to provide readings of tidal carbon dioxide, for example. They have a minimally invasive nasal cannula for collecting the gases which are to be subjected to analysis; viz., those exhaled by a patient. These gases are conducted to the cuvette through a line which is gastight but allows moisture to escape, thereby keeping moisture mixed with the gases being analyzed from corrupting the readings outputted by the gas analyzer. The attachment can be easily and quickly disassembled and the components disposed of or sterilized and recycled if they become contaminated. Provision is made for collecting the gases after they have been discharged from the cuvette so that they will not be discharged into and perhaps contaminate the ambient surroundings.

4958529

INTERFACE FOR COUPLING LIQUID CHROMATOGRAPHY TO SOLID OR GAS PHASE DETECTORS

Marvin Vestal assigned to Vestec Corporation

An improved interface is provided for receiving effluent from a chromatographic device and outputting sample particles of interest to a detector for analysis. The interface includes a gas diffusion cell having a membrane therein separating the cell into an aerosol flow chamber and a sweep gas flow chamber. The effluent is sprayed as an aerosol into the aerosol flow chamber, and vaporized solvent diffuses through the gas membrane into the sweep gas flow chamber while particles of interest are output to the detector. Sweep gas is passed through the sweep gas flow chamber for removing the solvent vapor, and the flow rate of sweep gas is controlled to achieve little or no net flow of gas across the membrane. Efficient solvent removal may be achieved at room temperature for certain LC flow rates, and high detector resolution is possible by maintaining laminar flow of the carrier gas through the aerosol flow chamber.

4959010

AUTOMATICALLY REGULATED COMBUSTION PROCESS

Heinz Burtscher, Andreas Schmidt-Ott, Hans-Christoph Siegmann, Zurich, Switzerland assigned to Matter & Siegmann AG

In a combustion process a fuel is mixed with an oxygen-containing gas in an adjustable ratio. This fuel-gas-mixture is burned and thereby an exhaust gas is produced. At least a part of the exhaust gas is collected and exposed to an ultra violet radiation source, thereby generating positive and negative charge carriers in the exhaust gas by means of a photoelectric charge separation process. The kind or amount of the positive and/or negative charge carriers is detected to produce a measurement value which reflects the amount and/or the charge of the carriers. Therefrom a control signal is derived and the mixture-ratio of the oxygen-containing gas and the fuel, the so-called lambda-factor, is adjusted in response to said control signal in order to improve the efficiency of the combustion and to reduce the emission of toxic substances.

4959084

COMBINED AIR AND WATER POLLUTION CONTROL SYSTEM

Billy Wolverton, Lamont Jarrell assigned to The United States of America as represented by the Administrator of the National Aeronautics and Space Administration

A bioaquatic air pollution control system for controlling both water and atmospheric pollution. The pollution control system includes an exhaust for directing polluted gases out of a furnace and a fluid circulating system which circulates fluid, such as wastewater, from a source, past the furnace where the fluid flow entrains the pollutants from the furnace. The combined fluid and pollutants are then directed through a rock/plant/microbial filtering system. A suction pump pumps the treated wastewater from the filter system past the exhaust to again entrain more pollutants from the furnace where they are combined with the fluid (wastewater) and directed to the filter system.

4959569

STATOR COIL WATER SYSTEM EARLY ALERT HYDROGEN LEAKAGE MONITOR

Owen R Snuttjer, Michael Rasinski assigned to Westinghouse Electric Corp

An apparatus for monitoring hydrogen leakage from a generator frame into the stator coil water cooling system. The monitor is designed to alert the operator should leakage exceed a rate of twenty cubic feet per day (20 cfd). A pressure relief valve set at four (4) psig and orifice are provided, along with a second relief valve having a higher setpoint than the first, such that pressure will increase in the holding tank if leakage exceeds 20 cfd setpoint of the orifice. A high pressure alarm, set at a level higher than the first relief valve but less than that of the second, will then sound to alert the operator to protect the system from an overly large or gross failure of the system. By continusouly monitoring a relatively small steady state leakage rate, the operator can be aware of a minor problem which can be corrected at a scheduled maintenance outage, before a gross failure of the system, requiring a costly shutdown of the turbine-generator, would otherwise occur.

4960041

REGULATION OF ATMOSPHERIC CONDITIONS WITHIN A CONFINED SPACE

Thomas E Kiser assigned to Professional Supply Inc

An improved system for maintaining atmospheric conditions within prescribed parameters throughout the interior of a building. The building interior is essentially an enclosed system and sufficient outside air is admitted through air handling units to continuously maintain the interior of the building under a slight positive pressure throughout. Controllable vents are provided at strategic locations around the perimeter of the building, and sensing units are located throughout the building to continuously monitor atmospheric conditions such as temperature, humidity, and the level of particulates and pollutants. The sensing units or monitoring stations are periodically polled by a central computer, with signals from each station providing an indication of atmospheric conditions at that station. The signals representing existing atmospheric conditions are compared with stored data indicative of prescribed parameters for desired atmospheric conditions at the stations. Signals are generated in repsonse to noted deviations from the prescribed parameters, and the signals are utilized to regulate the controllable vents and air handling units so as to modify the incoming air or cause air to be discharged through appropriate vents in the area of the monitoring station until atmospheric conditions again fall within the prescribed parameters. Air is thus delivered from the air handling units to specified areas in a controlled manner without the use of ductwork.

4960496

ATMOSPHERIC HCI MONITOR

Steven H Hoke assigned to The United States of America as represented by the Secretary of the Army

A device for performing rapid determinations on a real-time basis of about three to five seconds of the concentration of HCl in the atmosphere includes an air inlet conduit for sampling the HCl laden air, a pump for introducing trapping solution into the air inlet conduit, a spiral impinger for mixing and combining the air and trapping solution, a separator for separating a portion of the trapping solution and entrained air from the remaining trapping solution, and electrode flow cell for receiving the remaining trapping solution and for determining the chloride ion concentration in the trapping solution. The electrode flow cell includes a measuring electrode having a silver wire having a silver chloride coating inserted in the flow path of the trapping solution. A selector valve is inserted between the separator and the flow cell for alternatively feeding either the separated trapping solution to the flow cell or a standardizing solution to the flow cell.

4960565

ACID MONITORING KIT

William S Shurben, Kanata, Canada assigned to Ecostix Environmental Inc

An acid monitoring kit is provided which is especially useful for monitoring acid rain. The kit includes a base plate having three discrete areas.

One area is provided with a plurality of discrete separable bibulous pH indicator strips, each strip being impregnated with a selected acid-base indicator which is visually recognizable as at least one unique color in each such bibulous pH indicator strip when the bibulous strip is dry, and as a different color upon being wetted with water, the different color being dependent on the pH of the water. A second discrete area is provided with a plurality of color comparison reference standards in a plurality of zones, each zone being of a unique color which corresponds to the color of the water-wetted bibulous pH indictor strip, whereby comparison of the unique color of the pH indicator strip with the unique color of the reference standard provides an indication of the pH of the water. A third discrete area is also labelled to provide the requisite information for the use of such acid monitoring kit to correlate the unique color developed in the bibulous pH indicator strip to a unique color of the reference standard to provide an indication of the pH of the water.

4961462

CONTROL APPARATUS FOR AUTOMOBILE AIR-CONDITIONERS

Katsumi Iida, Akihik Takano, Konan, Japan assigned to Diesel Kiki Co Ltd

An apparatus for controlling an automobile air-conditioner wherein the direction of solar radiation is determined based on a signal which is obtained by retarding the leading edge of a solar radiation signal and the position of an air-distributing door is controlled according to the thus obtained signal. A signal whose leading and trailing edges are progressively increasing and decreasing, respectively, is used for the calculation of a signal corresponding to the thermal load in the vehicle passenger compartment. The operation of various components of the air-conditioner including a blower is controlled by the result of calculation of the thermal load signal.

4961854

ACTIVATED SLUDGE WASTEWATER TREATMENT PROCESS

John W Wittmann, Donald J Thiel, George W Smith assigned to Envirex Inc

Wastewater and recycled activated sludge are homogeneously mixed in a first aeration zone by injecting an oxygen-containing gas such as air into the lower portion of the zone under conditions which produce a complete mix reaction and sufficient oxygen is supplied to meet the biological oxygen demands of the mixed liquor. The gas is introduced, preferably by a plurality of fine bubble membrane diffusers, in the form of fine bubbles having a diameter less than about 4 mm. The bubbles provide both the mixing to keep solids in suspension and the oxygen required to maintain the overall dissolved oxygen content in the first aeration zone as close to 0 as possible. The mixed liquor is sequentially contacted with an oxygen-containing gas in second and third aeration zones under conditions which produce a complete mix reaction, preferably by fine bubble membrane diffusers, clarified and a portion of the settled sludge is recycled to the first aeration zone.

4962368

RELIABILITY AND WORKABILITY TEST APPARATUS FOR AN ENVIRONMENTAL MONITORING SYSTEM

John J Dobrzanski, Jeffrey J McCabe, Robert Right assigned to General Signal Corporation

An environmental monitoring system in which a controller is arranged to test the workability and reliability of a plurality of detector units on a cyclic basis. Each unit has an analog sensor and an analog to digital converter for converting the analog sensor voltage to a digital value in a range of 0 to N. Each unit responds to a test instruction to cause the sensor analog output to assume an alarm value. The sensor output is limited to a maximum value that under a no drift condition of the analog to digital converter, its corresponding digital signal value will be intermediate a tolerance range of values, the upper limit of such range being less than N. The controller includes a test routine program for bothissuing the test instruction and for determining if the digital signal test value is within the tolerance range and issuing a trouble output indicative of the test value being outside the range. The controller also includes a polling program which directs the polling of the detector units such that a test instruction is sent sequentially to the detector units on successive loop polls, where a loop poll is one poll of all the units coupled to the line.

4963167

AIR DELIVERY MONITORING SYSTEMS

Peter S Young

An air delievery monitoring system covers an aperture of an air duct with an insert having a bore. A filter element in communication with the inside of that air duct through that bore is made accessible from outside of that duct. Air escapes from the duct through the bore in the insert to the filter element which traps contaminants in such air for subsequent laboratory analysis. The filter element is preferably encapsulated in an apertured filter element housing which is mounted in the insert in communication with its bore. After removal of that housing from the insert, the contaminated filter element can be transported or sent to the laboratory for the performance of several analyses thereon.

4963259

SLUDGE DEWATERING FILTER PRESS

Lyle B Barcomb, Lawrence El-Hindi assigned to Filter Tech Inc

A mechanical sludge dewatering system including a plurality of first rollers, one or more second rollers and a liquid-permeable, endless belt passing between the first and second rollers from an inlet to an outlet end. At least some of the rollers of the first set are tapered from their ends to a smaller diameter at the center, the amount of taper decreasing from the roller at the inlet end to that at the outlet end, the opposing one or more second rollers being of constant diameter. The sludge carried on the belt passes through the cavities defined by the tapered first rollers and the cylindrical second roller(s), which decrease in cross section from the inlet to the outlet end, thereby squeezing water from the sludge. The first rollers each have grooves around their periphery adjacent each end, and the belt carries a protruding strip along each side, the belt being laterally constrained by the strips riding in the grooves. In a first embodiment, the second roller comprises a single drum; in a second embodiment a second, endless, liquid-impermeable belt is superposed with the liquid-permeable belt; in a third embodiment the single drum is replaced by a plurality of cylindrical rollers arranged in opposed relation with corresponding ones of the first rollers.

4963273

MODIFIED NON-POLLUTING LIQUID PHASE SHALE SWELLING INHIBITION DRILLING FLUID AND METHOD OF USING SAME

Alphonse Perricone, Dennis Clapper, Dorothy P Enright assigned to Baker Hughes Incorporated

The present invention provides a modified liquid phase drilling fluid having desirable properties of shale swelling inhibition, lubrication, and high temperature performance. The fluid does not rely on the incorporation of inorganic salts or high molecular weight water soluble polymers for control of shale swelling or shale disintegration and exhibits performance characteristics, approaching those of oil base drilling fluids, without the objectionable properties of hydrocarbon oils or its potential hazardous impact on the environment. The fluid is comprised of the following: (1) a liquid phase containing; (a) a water phase comprising fresh water, seawater, brine, simulated brine, or mixtures thereof; and (b) a water-soluble component selected from the class consisting of polyhydric alcohols, glycol, glycol ethers, polypropylene glycols, polyethylene glycols, ethylene oxide-propylene oxide copolymers (EO-PO), alcohol-initiated EO-PO copolymers and/or mixtures thereof, the ratio of said water-soluble component in the total liquid phase being from about 5% to about 50% by volume; (2) a viscosifier for suspension of solids in said liquid phase; and (3) a filtration control agent. The fluid with the water soluble component will exhibit a lubricity coefficient lower than that for substantially the same fluid without the water soluble component as determined by the American Petroleum Institute's Procedure for Determination of Lubricity Coefficient (Tentative) (1980), and the linear swelling on a reconstituted gumbo shale inserted for about 60 minutes of said drilling fluid being from lower than that for substantially the same fluid without the water soluble component, as measured by the Swelling Test , Rigsite Shale Evaluation Techniques for Control of Shale-related Wellbore Instability Problems , SPE/IADC Paper No. 16054, pages 52-53, (1987).

4964732

METHOD FOR CONTINUOUSLY PRODUCING A FLOWABLE MIXTURE

Angelo Cadeo, Ruedi Zellweger, 4852 Rothrist, Switzerland assigned to Miteco AG; Cadeo Angelo

The mass flow of the individual goods fed from a respective storage tank by a conveying apparatus is measured by a flowmeter. The mass flow is controlled via a controller. As long as the actual value of the flow masses of each separate component does not correspond to their respective rated value, all mass flows are returned via a switch-over valve and a return line back to the respective storage tank. When all actual values correspond to their rated values, the switch-over valves will switch such that the individual components are guided through the feed line to the mixing apparatus. The mixture produced in this mixing apparatus is once more analyzed by further detecting devices. If the analyzed actual values again do not correspond to the rated analyzed values, an immediate switching of the switch-over valves to the return bypass operation is again initiated. It is therefore no longer necessary to lead a mixture in the form of waste away during the time span, during which the individual control circuits begin to stabilize, because at such duration the product will not yet correspond to its rated values. The individual components are rather fed back again to their respective storage tanks during such time span, such that no loss of production is suffered and a high quality of the final product is attained.

4965121

SOLAR CONTROL LAYERED COATING FOR GLASS WINDOWS

Paul I Young, Jesse D Wolfe assigned to The BOC Group Inc

A five-layer coating, commonly called a stack , for glass windows in order to control the proportion of solar radiation permitted to pass through the window, the remainder being reflected by the coating, while maintaining a desired visible light characteristic transmission. Particularly, the technique is applied to vehicle glass windows, such as truck and automobile windshields, where the amount of solar radiation allowed to pass into the vehicle through the window is minimized within the constraints of maintaining visible light transmission above a certain legal level. The characteristics of the coating are also selected for visible light reflected from the window to the outside to be a substantially neutral color, highly desirable for the overall appearance of trucks and automobiles.

4965962

HYDROPONIC CULTURE SYSTEM

Shizuka Akagi, Chiba, Japan assigned to Q P Corporation

A hydroponic culture system comprising an angle panel having a plurality of holes for sup-

porting plants with roots projecting through the holes, and a hydroponic solution feeding means comprising a hydroponic solution spraying means for supplying a hydroponic solution onto the roots of the plants and a hydroponic solution pumping means for supplying the hydroponic solution to the hydroponic solution spraying means, in which the hydroponic solution spraying mechanism is movable along the longitudinal direction of the angle panel, or the angle panel is disposed in a plant cultivation structure which is supplied with carbon dioxide through a duct for controlling the environment within the structure, or a plurality of angle panels are disposed in a plurality of rows and top edges of the adjacent angle panel rows are connected with canopies to form substantially triangular-sectioned spaces between the adjacent angle panel rows for enhanced lighting efficiency, thereby cultivating the plants systematically and almost uniformly with improved cultivation efficiency and economy.

4966096

WATER PURIFICATION SYSTEM AND APPARATUS

Walter H Adey assigned to Ecological Systems Technology L P

The present invention provides a water purification system that creates an integrated, small-scale marine or fresh water ecosystem that is particularly useful as a home, school, office, or laboratory aquarium. In operation, water from the aquarium tank is routed to an algal turf scrubber screen or equivalent algal-growing surface placed in a moveable, substantially flat, horizontally positioned, tray-shaped receptacle. An algal turf, comprising preferably a dense colony of microalgae, resides on the screen. As the receptacle fills with water, the center of gravity of the receptacle moves across the axis of the pivots upon which the receptacle is mounted. At this time, the substantially filled receptacle rotates on its pivots and the desired surge effect across the scrubber by the exiting water is achieved. The surge, light energy provided by lights above the receptacle, and algal photosynthesis promote metabolic cellular-ambient water exchange to remove carbon dioxide, dissolved nutrients and organic compounds, and other pollutants. Oxygen is also released into the water. The substantially emptied receptacle returns to its horizontal position and the purified and oxygenated water is then returned to the tank. In addition, other appropriate components of the ecosystems may be included, such as tide creators, high intensity, broad spectrum artificial lights over the tank, salinity controllers, pH controllers, sediment removers, temperature controllers, automatic feeders, timers and the like.

4966155

APPARATUS FOR MONITORING PHYSIOLOGICAL PARAMETERS

John Jackson, Lesmahagow, United Kingdom assigned to The University of Strathclyde

An apparatus is disclosed for monitoring physiological parameters comprising a harness adapted to be worn by a human being and electrical circuitry connected to the harness for calculating physiological parameters in accordance with predetermined algorithms. The harness includes a band which extends around a trunk portion of the human being. The band comprises an inelastic portion and an elastic portion. The elastic portion incorporates an electro-conductive elastomeric means which has a resistance value which changes as a function of elongation of the elastic portion. The electrical circuitry connected to the elastomeric element calculates and displays various physiological parameters.

4966705

WASTE WATER TREATMENT PLANT AND PROCESS

Donald F Jamieson, Paul Cardinal, Clontarf, CA, Australia assigned to Austgen Biojet Holdings Pty Ltd

A waste water treatment plant of simple design and high efficiency which is particularly adapted for use in small communities is described. The plant comprises a reaction tank and an aeration tank, inlet means to admit raw waste water continuously into the reaction tank, a first airlift pump or a penstock to transfer waste water intermittently from the reaction tank to the aeration tank to displace treated waste water therefrom through an outlet, aerators to aerate the aeration tank when the first airlift pump or penstock is inoperative, a second pump for transferring sludge and waste water from the aeration tank to the reaction tank after the first airlift pump has ceased operation and before the aerator is actuated, and control means to stop the aeration in sufficient time before actuation of

the first airlift pump or penstock to allow substantial settling of the sludge in the aeration tank.

4966706

PROCESS FOR TREATMENT OF CLARIFICATION SLUDGE

Carl H Gregor, Gr Federal Republic Of Germana assigned to Peroxid-Chemie GmbH

The present invention is in a process for the treatment of clarification sludge, wherein a sludge is treated with a per acid containing up to 3 carbon atoms and subsequently allowed to digest in a septic plant.

4967238

CLEANING PERFORMANCE MONITOR

Jan Bares, Richard H Tuhro assigned to Xerox Corporation

An arrangement for detecting toner or debris deposits on an imaging surface is arranged downstream from the cleaning station. The imaging surface is illuminated with a light source, a light intensity detecting sensor arrangement is provided to view the illuminated surface and produce a signal representative of detected light intensity, and a response signal is produced indicative of the condition of the surface.

4967553

SYSTEM FOR MONITORING A HYDRAULIC ACCUMULATOR

Jean-Claude S Barthomeuf, Anse, France assigned to Eimco-Secoma Societe Anonyme

A high-pressure source of hydraulic fluid and a sump are connected to a cyclically operating user of hydraulic fluid having a hydraulic accumulator by a high-pressure feed line having one end connected to the source and an opposite end connected to the accumulator and user. A pressure-limiting valve has an input side connected to the high-pressure line between the ends thereof and an opposite output side connected to the sump. This valve opens only when pressure in the line exceeds a preset maximum to allow flow between its sides. A detector is connected to the output side of the valve for measuring the peak pressure thereof over several operating cycles of the user and a controller is connected to the detector for operating when the peak pressure detected over several operating cycles exceeds a predetermined threshold.

4967664

METHOD AND APPARATUS FOR AUTOMATICALLY CLEANING LIQUID SUPPLY ROLLERS OF OFFSET PRESS

Takashi Iijima, Yokosuka, Japan assigned to Kabushiki Kaisha Tokyo Kikai Seisakusho

Method and apparatus capable of automatically cleaning a dampening water supply passage to a plate cylinder in an offset press, as well as an ink supply passage to the late cylinder. The apparatus comprises an operation instruction means producing operation signals in a sequence to driving portions of various means which include ink supply-stopping means, means for supplying a cleaning solvent, cleaning waste recovering means, means for bringing ink supply rollers out of contact with the plate cylinder, means for bringing dampening water supply rollers out of contact with the plate cylinder, and main control means, a start instruction means that starts the operation instruction means, and a manual instruction means. This manual instruction means permits the operator to select either cleaning of only the ink supply passage or cleaning of all the ink supply passage and the dampening water supply passage.

4968407

SLUDGE DEWATERING AND DESTRUCTION WITHIN A DELAYED COKING PROCESS

Michael McGrath, Rino Godino assigned to Foster Wheeler USA Corporation

Wet refinery sludges are disposed of by feeding them into a delayed coking process. The sludge is fed to the blowdown drum of the delayed coking process and mixed with oil condensed from the coke drum overhead, and the resulting sludge-oil mixture is fed to the coke drum where it is converted into coke. In order to remove the water from the sludge, a portion of the sludge-oil mix-

ture is heated and recirculated to the blowdown drum where it provides the heat for drying and heating the sludge. The recirculating sludge-oil mixture is heated by a low level heat source, such as one of the fluid streams taken off from the fractionator.

4968437

FLUID PURIFICATION SYSTEM

John R Noll, Stephen V Montvila assigned to Electrolux Water Systems Inc

A fluid purification system includes an elongated ultraviolet radiation emitting tube and independent fluid flow-controlling conduits. Each conduit is transparent to allow ultraviolet light emitted by the tube to enter the conduit, and defines a continuous, and is helically wound closely about the tube to insure that fluid flow through the conduits is exposed to the ultraviolet light. The system includes a filter having inlet and outlet ports. An end of each conduit is connected to one of the inlet and outlet ports of the filter. The system thus exposes the fluid to ultraviolet radiation both before and after the fluid is filtered.

4968941

APPARATUS FOR MONITORING THE STATE OF CHARGE OF A BATTERY

Wesley A Rogers

An apparatus for monitoring the state of charge of a battery having a shunt resistor connected in series with a battery and an integrating circuit connected across the terminals of the shunt resistor is provided. The integrating circuit includes a Memoriode having a large capacitance and the capability to store charge for long periods of time, so that the integration can be performed along the same curve even if power to the integrating circuit is interrupted.

4969130

SYSTEM FOR MONITORING THE CHANGES IN FLUID CONTENT OF A PETROLEUM RESERVOIR

Cameron B Wason, Geoffrey A King, Edward L Shuck, E Alle Breitenbach, Robert C McFarlane assigned to Scientific Software Intercomp Inc; Halliburton Geophysical Services Inc

A system of monitoring the fluid contents of a petroleum reservoir, wherein a reservoir model is employed to predict the fluid flow in the reservoir, includes a check on the reservoir model by comparison of synthetic seismograms with the observed seismic data. If the synthetic output predicted by the model agrees with the observed seismic data, then it is assumed that the reservoir is being properly worked. If not then the reservoir model, in particular its reservoir description, is updated until it predicts the observed seismic response. The seismic survey may be periodically repeated during the productive life of the reservoir and the technique used to update the reservoir model so as to ensure that the revised reservoir description predicts the observed changes in the seismic data and hence reflects the current status of fluid saturations. Implementation of this invention results in more efficient reservoir management.

4970391

RADIATION DETECTOR WITH AN IONIZABLE GAS ATOP AN INTEGRATED CIRCUIT

Arthur E Uber assigned to Medrad Inc

The radiation detector includes tissue equivalent bubbles of plastic defining volumes of gas to be ionized by radiation. One or more integrated circuit (ICs) are disposed below the volumes of gas and a collecting electrode on the IC is in direct contact with the gas. Circuitry for generating an electric field within the volume of gas moves the ions therein to the collecting electrode. The collecting electrode is part of an amplifying circuit disposed within the IC. The output from the amplifier is representative of the collected ions and therefore representative of the radiation. The signal from the amplifier is sent to an interface which conditions, buffers and stores the signal. The radiation dose and dose rate are computed in the interface. A communications section transfers that data from the radiation detector. A separate calibration and display unit calibrates the interface by controlling the conditioning of the signal. An area monitor and air monitor are further enhancements of the radiation detector. The radiation detector includes several circuitry arrangements for minimizing inaccuracies due to leakage currents to the collecting electrode from the amplifying circuit. Such circuitry arrangements include duplicate

discharge and amplifying circuits not connected to a functioning collecting electrode; subtracting circuitry for subtracting a signal valued proportional to the leakage current; and a current source inducing current opposite in polarity to the leakage current.

4970803

METHOD FOR DRYING SLUDGE

Karl Keller, Gutenzell, Federal Republic Of Germany assigned to Sulzer-Escher Wyss GmbH

A sand layer is fluidized by a gas stream or current in a fluidized bed dryer and indirectly heated by immersed stationary heat-exchanger tubes. The sludge to be dried is continuously fed under pressure in a pumpable conditon from above onto the fluidized sand layer. The sludge is coagulated in the fluidized sand layer to form sludge lumps. Here, the sludge lumps are successively dried from the surface down to the core thereof, and the already dried layers of the sludge lumps are successively abraded by the fluidized sand, whereby the sludge lumps are entirely comminuted and the dry matter thereof is pulverized to form dust. This product dust is continuously discharged together with the exhaust-gas stream from the fluidized bed dryer and continuously separated as a product from the exhaust-gas stream. The gas stream or current freed from dust is partially recycled in a closed circuit back to the fluidized bed dryer for fluidization of the sand layer.

4970988

METHOD AND APPARATUS FOR MONITORING ANIMAL MIGRATION

Paul G Heisey assigned to RMC Environmental Services Inc

Method and apparatus for monitoring migration of tagged fish which also facilitates their retrieval, including a selectively activated floatation device and securing member and a method for employing them.

4971691

QUICK CHANGE SLUDGE PROCESSOR

Donald Meylor, Patrick Finn

A sludge processor is provided which enables rapid disassembly and reassembly for changing between a sludge thickener configuration and a press configuration, and for enabling rapid disassembly for cleaning in the press configuration. The processor includes a frame with opposite sides and roller-holding bearing devices at the opposite sides for holding rollers about which a belt extends past a sludge dewatering region. The bearing devices can be arranged in a first configuration (FIG. 2) wherein the belt (12A) extends in an even path, and a second configuration (FIG. 1) wherein the belt extends in a tightly convoluted path so it and material thereon is squeezed between adjacent rollers. The bearing devices (50, FIG. 4) are releasably mounted to the frame sides to enable rapid conversion, and to enable rapid removal of the rollers for cleaning the processor when used in the second configuration. Each side of the frame includes a plate with a hole (60) having a narrow inner part (64) and a wider outer part (62). Each bearing device includes a block (52) with grooves (72, 74), the block fitting into the outer hole part and then sliding into the inner hole part, with the opposite walls of the inner hole part sliding into the grooves of the block. A clamp (82) can be attached to each block to press against the extreme outer side of the hole to hold the bearing device in position.

4972178

FIRE MONITORING SYSTEM

Takash Suzuki, Tokyo, Japan assigned to Nittan Company Limited

In a fire monitoring system for monitoring the occurrence of a fire in which a space to be monitored is imaginarily subdivided into plural subspaces so that plural channels passing through the subspaces are set so as to intersect to each other in a lattice form. The propagation speed of ultrasonic waves propagating through each of the channels is measured, on the basis of which the propagation speed of the ultrasonic waves in each of the subspaces is calculated in the same manner as the solution for each element of a matrix is obtained, and then the temperature in each of the subspaces is obtained. By providing

the system with a humidity sensor, the temperature for a dry condition is obtained.

4972837

CONTRAST AGENTS FOR NUCLEAR MAGNETIC RESONANCE IMAGING

Barry L Engelstad, Robert Brasch, Robert S Hattner, Georg Wesbey, John Huberty assigned to Regents of the University of California

A method is provided for obtaining in vivo differentiation of tissues in an animal by nuclear magnetic resonance imaging comprising the steps of introducing into the animal a complex comprising a paramagnetic metal ion and a chelator.

4973194

METHOD FOR BURIAL AND ISOLATION OF WASTE SLUDGE

Melvin N A Peterson assigned to The United States of America as represented by the Secretary of Commerce

A method of disposal of waste solid material in an underwater geologic formation on the continental margins comprises the steps of: drilling a large diameter hole into the geologic formation to a depth of several hundred feet in a single stroke operation; depositing a slug of a paste of waste material into the bottom of the hole thereby burying the slug; and permitting the geologic formation adjacent to the hole above the buried slug to fill the hole above the slug, thereby sealing the buried slug in the geologic formation. A continuous slug of waste material can be used, or the waste material can be formed into discrete charges of material.

4973511

COMPOSITE SOLAR/SAFETY FILM AND LAMINATED WINDOW ASSEMBLY MADE THEREFROM

Peter Farmer, Stanley S Ho, Raymond Riek, Floyd E Woodard assigned to Monsanto Company

A laminated window construction includes a solar control film formed by a flexible plastic substrate such as a PET sheet having on one surface a multilayer solar coating. This multilayer solor coating includes at least one thin layer of metal and at least one adjacent adherent layer of a dielectric material. An energy absorbing safety film of the type normally used in shatterproof glass laminates (e.g., plasticized PVB) is bonded to at least one side, and preferably both sides, of the solar control film to form a composite solar/safety film. This composite solar/safety film is specially designed to contribute, after incorporation into a glass laminate, no more than about two percent of visible reflection (based on total incident visible radiation) which has the effect of substantially masking the visible effects of wrinkles in the solar control film substrate (i.e., the wrinkles are made less visible). This low level of visible reflection contribution is achieved by careful control of the optical properties of the solar control film, the safety film or both. Outer layer transparent glass panes are laminated to one or both sides of the composite solar/safety film to provide a safety window which in one preferred embodiment is a windshield having at least seventy percent normal visible light transmissibility, and a total reflection of visible light of generally less than ten percent.

4974335

METHOD AND APPARATUS FOR DRYING SEWAGE SLUDGE

Dietmar Bege, Siegfried Meininger, Erlangen, Federal Republic Of Germany assigned to Siemens Aktiengesellschaft

A method and apparatus for drying sewage sludge includes diverting steam escaping during the drying of the sewage sludge and feeding the steam to a compressor. Thermal energy of the compressed and therefore heated steam is supplied to the sewage sludge to be dried through a heat exchanger system. Condensate is drawn off from the heat exchanger system and collected. Thermal energy of the condensate is supplied to the sewage sludge prior to the drying for reinforcing a preliminary degassing.

4974816

METHOD AND APPARATUS FOR BIOLOGICAL PROCESSING OF METAL-CONTAINING ORES

Robert C Emmett, Lawrence T O'Connor assigned to Envirotech Corporation

A method and attendant apparatus for use in bioleach processing of metal-bearing solids is disclosed. The method includes the placement into a tank of metal-bearing solids, a predetermined quantity of water, oxygen, carbon dioxide, nutrients and a species of microorganisms capable of oxidizing some portion of the metal-bearing solids and obtaining energy for growth from that oxidation. The slurry formed by this placement is continuously filtered to remove process delimiting metabolic end products products by the oxidation reaction. The ratios of the various slurry components are monitored and controlled to effectuate an optimized environment for oxidation to occur. The attendant apparatus includes a means of introducing oxygen into the bottom of the reactor vessel in the form of small widely dispersed bubbles.

4975194

PROCESS FOR THE DISINFECTION OF SEWAGE SLUDGE

Leonhard Fuchs, Martin Fuchs, Mayen 1, Federal Republic Of Germany

The process for the disinfection of sewage sludge prior to introducing same into an anaerobic sewage sludge processing step involving the recovery of methane gas by heating the sewage sludge in a preceding disinfection step at from 50 degrees C. to 70 degrees C., and preferably at from 55 degrees C. to 65 degrees C., for a period of from 1 to 72 hours, and preferably of from 12 to 36 hours, while throughly mixing the sewage sludge with an oxygen-containing gas is carried out by using, as the oxygen-containing gas, a mixture comprising from 10 to 70% by volume of fresh air and 30 to 90% by volume of vent gas from the disinfection step, the oxygen contents of the gas mixture being maintained within the range of from 5 to 15% by volume, and preferably of from 7 to 12% by volume.

4975377

CELL GROWTH CHAMBERS AND METHOD OF USE THEREOF

Marc E Key

Growth chambers for anchorage-independent cell growth therein are formed of a gel matrix having a surface disallowing anchorage-dependent cell growth over the full interior thereof. In a preferred form the chambers have a generally cylidnrical wall and an integral convex bottom wall forming an annular volume at the foot of the cylindrical wall which is substantially lower than the central portion to concentrate such anchorage-indpendent cells. The gel matrix is sufficiently permeable to permit passage of cell-growth nutrients and waste product solutes through said wall when the chambers are filled below the open end and submerged in a growth medium. Preferably the gel matrix is formed of 1% to 5% cross-linked polyacrylamide and from 99% to 95% water. In a preferred method of using the growth chambers, undifferentiated tumor cells and normal cells, including fibroblasts, are cultured together. Anchorage-independent tumor cells proliferate while anchorage-dependent cells are unable to grow without attachment. The method is useful for evaluating in vitro therapeutic agents to control tumor growth, normal cell growth or microspheres and generation of immunoglobulins from lymphocyte cells.

4975585

RADIATION DOSE MONITOR

Katsuji Asai, Amagasaki, Japan assigned to Mitsubishi Denki Kabushiki Kaisha

A radiation dose monitor includes a power supply electrode disposed on one side of an ionization chamber containing a gas which is ionized by a radiation beam, and a first pair of coplanar collector electrodes disposed on the other side of the ionization chamber from the power supply electrode, being separated from each other by a first band-shaped gap. A second pair of coplanar collector electrodes are disposed adjacent to the first pair of collector electrodes on the same side of the power supply electrode as the first pair of coplanar collector electrodes, and separated from each other by a second band-shaped gap which extends in a direction at an angle with respect to the first band-shaped gap. The second pair of coplanar collector electrodes receive an ionization current from the ionization chamber and through the first band-shaped gap.

4976209

FURNACES FOR INCINERATING WASTE MATERIAL

Peter R Piggin, Gaulby, United Kingdom assigned to Erithglen Limited

A vertical chamber for waste disposal and heating purposes has an upright combustion chamber with an inlet for waste material, a grating at a lower chamber end and an adjustable burner controlled by a temperature sensor so that the burner operation can be adapted to allow for the calorific value or requirement of the material to be incinerated. A trap door is situated at the lower end for ash removal and is arranged by air passages to permit air to pass upward past the door for combustion and to open periodically for removing ash. The grating may be water cooled and step down towards the trap door to permit ash to be blown off onto the door before the door is opened.

4976853

CONTROL VALVE MEANS FOR USE IN A FILTRATION APPARATUS FOR TREATING WASTE PRODUCT

Chung Y Lee, Dongjak Ku, Seoul, Republic Of Korea

An improved control valve for use in a filtration apparatus for treating waste product which comprises a tapered rotary cylinder, a rotary filtration cylinder disposed around the tapered rotary cylinder, a fixed steam injection pipe disposed above the rotary filtration cylinder, and a plurality of control valve members whereby the waste product which is conveyed inside the rotary filtration cylinder and is heated, and which collects in the holes of the rotary filtration cylinder is cleaned away by the spraying of the surface of the rotary filtration cylinder with hot steam through nozzles of a fixed injection pipe under the control of the pressure in a treatment zone between the tapered rotary cylinder and the rotary filtration cylinder.

4976863

WASTEWATER TREATMENT PROCESS

Donald M Stearns assigned to PEC Research Inc

A process for treating wastewater containing insoluble solid waste material and soluble solid waste material including the following series of steps: (1) controlling the oxygen content of the wastewater to a level at which growth of anaerobic bacteria is substantially eliminated, (2) separating the insoluble solid waste material from the wastewater, (3) treating the soluble solid material in the wastewater with a predetermined amount of aerobic bacteria, and (4) reducing the amount of aerobic bacteria in the wastewater. The insoluble solid waste material separated from the wastewater can be burned to produce electrical energy. Apparatus for carrying out the process are also disclosed.

4976876

POINT-OF-USE MEMBRANE FILTRATION SYSTEM

Charles Diman, David Marcus, Philip Mitchell, Baruch Sachs assigned to The Kendall Company

A point-of-use membrane filtration system and method for water or other liquids including an automatic control system for purge, rinse-up, sanitization, or combinations thereof. The system may be used for microfiltration, ultrafiltration or hyperfiltration (reverse osmosis) depending on the membrane pore size of the filtration cartridge employed in the system. A reject valve at the bottom of the filter cartridge is automatically opened when filtered product is drawn, thus to direct some water and any waste to drain. The control system is programmed to accomplish purge, rinse-up and sanitization procedures at predetermined intervals with predetermined combinations of procedures.

4977094

PROCESS FOR MONITORING THE QUALITY OF WATER

Arthur Goldstein, Edgardo J Parsi assigned to Ionics Incorporated

A process is disclosed for monitoring the quality of water, said process comprising a first heated zone, means for introducing at least a portion of said water into said first heated zone, means for gently evaporating at least part of the water in the first heated zone and passing the vapor into and through a second heated zone, means for maintaining the temperature of said second heated zone in the range of from about 450

degrees to about 1000 degrees C., means for collecting and condensing vapor from said second heated zone to condensed liquid water and means for measuring the electrical impedance of at least a portion of said condensed liquid water.

4977393

METHOD AND APPARATUS FOR MONITORING THE CONDITION OF CHARGE OF A BATTERY CONNECTED TO AN APPLIANCE AND INCLUDING COUNTERS COUNTED WITH RESPECT TO THE TIME AND DRAIN OF THE BATTERY

Werne Arnold, Peter Grundl, Nuremberg, Federal Republic Of Germany assigned to Diehl GmbH & Co

A method and apparatus for monitoring the state or condition of charge of a battery which supplies a plurality of electrical consumption devices in an electronic circuit. A consumption device is operatively connected to a series of counters so that the count condition charges in response to a pulsing rhythmic cycle by one of a plurality of numerical values toward a final count condition, in which the numerical values are specific in relation to the power consumptions of a plurality of electrical consumption devices, and that a signal is generated upon the reaching of a final count condition.

4978374

LIQUID HYDROCARBON DELIVERY MEANS INCLUDING MEANS FOR MONITORING GAS CONTENT

Sylvain Janssen, Jacques Fournier, Neuilly, France assigned to Schlumberger Industries

When a hydrocarbon liquid is pumped (11) for retail delivery, it is degassed by means of a vortex device (13). A control valve (21) shuts off delivery if the gas content in the degassed liquid being delivered via a main duct (16) is too high. Unlike prior systems which sense gas content only in the liquid being delivered, the present invention senses the greater gas content in the recycled gas-enriched fraction from the vortex separator device (13). This is done by means of a venturi system (19) controlling a servo-valve (25) which in turn controls the control valve (21). By using a magnified image of the gas content, the system is made more sensitive and more reliable.

4978506

CORROSION PRODUCT MONITORING METHOD AND SYSTEM

Andrew S Calderwood assigned to Westinghouse Electric Corp

A corrosion product monitoring system and method are described using a recirculation loop including a sample line, a particulate collection vessel, a recirculating pump, a microporous membrane cross-flow filter, and valves to control the flow rate and pressure of a fluid sample taken from the secondary fluid system of a nuclear power plant. The liquid sample is processed at a constant flow rate and temperature. When a relatively short time has elapsed in a trial sample run to stabilize conditions in the sample line, an actual sample run is started by feeding sample into the loop. Non-soluble, particulate concentration increases in the filter and particulate collection vessel as the run progresses. The permeate of soluble contaminants is passed through an ion exchange column to concentrate soluble ions in the sample. The filter is backwashed on a timed cycle by filtered water pressurized by a pump, or gas pressure, by realigning the system valves. A total sample volume is determined by measuring the amount of filtered, deionized water discharged during the actual sample run, based on total weight, total flow or time at a constant discharge rate. A concentration factor can be determined from the total sample volume divided by the initial system volume. A sampleof the non-soluble particulates can also be drawn from the particulate collection vessel for analysis. The related method includes the steps of: taking a sample from a fluid system; introducing the sample to a recirculation loop having an initial system volume; separating non-soluble particulates from soluble contaminants; suspending the solid particulates; collecting the solid particulates in a particulate collection vessel; and determining a corrosion concentration factor from the total sample volume divided by the initial system volume.

4979122

APPARATUS AND METHOD FOR MONITORING POWER

Richard K Davis, Keith W Curtin assigned to GE Fanuc Automation North America Inc

A power monitor, for determining real and imaginary power associated with one or more line signals, samples a plurality of line cycles during an observation window to generate a plurality of voltage-current sample sets for each line cycle. The sampling of the sample sets is timed such that the voltage-current sample sets are taken at different relative time positions. The power monitor stores incoming voltage-current sample data in one memory area and concurrently analyzes sample data already stored in another memory area. Deletion of sample data is not permitted until transient analysis of such data is complete. In another embodiment, the power monitor includes a working data memory area coupled to the sampling circuitry such that the sample sets occurring during each observation window are stored in the working data memory area in interleaved fashion to simulate a single cycle of data. This power monitor further includes a transient data area, coupled to the sampling circuitry, for storing the sample sets occurring during an observation window in a non-interleaved or sequential fashion. Power analysis is conducted on the sample sets in the working data memory area unless a power transient is sensed. Upon sensing a transient, data from the transient data area is provided for analysis.

4979679

U.V. RESISTANT ZINC COATED PVC OR RELATED PLASTIC PIPE

Ernest W Downs

A conduit and an integrated system for utilizing same, such as a foam control spray system for a sewage treatment facility, where said conduit is exposed to a hostile environment, such as solar ultraviolet (U.V.) radiation. The conduit and transmission components of such system comprise tubular members consisting of a solar U.V. degradable plastic, such as polyvinylchloride (PVC), having a preferred outer layer of metallic zinc diffusion bonded thereto, such as by spray arc metallizing the zinc onto the plastic surface, whereby the zinc prevents deterioration or breakdown of the plastic from solar U.V. radiation.

4980030

METHOD FOR TREATING WASTE PAINT SLUDGE

Jeffrey C Johnson, Andrew Slater assigned to Haden Schweitzer

A method and apparatus are disclosed for the treatment of paint sludge and for reducing volatile organic compound emissions from a paint spraybooth operation, thereby obtaining a recyclable material for use in new coating products. In such an operation, uncured paint resins mixed with volatile organic compounds are sprayed onto an article to be painted and at least a portion of the overspray is mixed with water to form a waste stream containing water, uncured paint resin, volatile organic compounds and inorganic substances. The method includes the steps of: removing a portion of the water and liquid volatile organic compounds from the waste stream; heating the resultant sludge to volatilize the residual water and liquid volatile organic compounds and to cure the uncured paint resin; collecting the residual solids stream, and removing all of the volatilized organic compounds from the resultant stream, thereby generating a volatile organic compound-free gas effluent. The amount of volatized organic compounds removed is at least about 5% of the volatile organic compounds input to the paint spraybooth operation. The apparatus includes a waste paint stream dewatering device and an enclosed rotary screw heat exchanger maintained in an inert environment; the apparatus also provides a system for adding a scouring aggregate to the sludge before heating and for removing the aggregate after heating. Finally, the apparatus includes a separator for removing entrained solids from the resulting gas stream, and provides a system for processing the gas stream to remove all volatile organic compounds.

4980040

PHOTOPROMOTED METHOD FOR DECOMPOSING OXIDES OF NITROGEN INTO ENVIRONMENTALLY COMPATIBLE PRODUCTS

Norman N Lichtin, Kallambella M Vijayakumar, Junchang Dong assigned to Trustees of Boston University

A method is provided for the photopromoted

solid-catalyzed decomposition of oxides of nitrogen such as nitric oxide which are major pollutants of air and the environment at large. By this method, oxides of nitrogen are decomposed into molecular nitrogen and molecular oxygen by reactive passage over a solid metal oxide catalyst at an elevated temperature under irradiation at wavelengths absorbable by the catalyst. In this manner, the major oxides of nitrogen pollutants originating in the exhaust gases produced by automobile engines, jet engines used in the propulsion of aircraft, gas-turbine power generators, and the combustion of fossil fuels generally are controlled and eliminated.

4980118

NUCLEAR POWER GENERATING STATION EQUIPMENT QUALIFICATION METHOD AND APPARATUS

Arnold H Fero, Lawrence M Potochnik, Ronald W Riling, Kenneth F Semethy assigned to Westinghouse Electric Corp

Apparatus for monitoring an object piece of qualified equipment in a nuclear power plant includes first passive means for memicking the effect of radiation received by the object piece, second means for mimicking hte effect of a thermal history of the object piece, and means for mounting the first and second mimic means in close proximity to the object piece in the nuclear power plant. In order to generate and maintain evidence to assure that qualified equipment used in such stations will operate on demand, the first and second mimic means, mounted in close proximity to the object piece, are exposed to the environment of a normally operating power plant and periodically analyzed to determine whether the qualified life of the object piece may be extended.

4980130

SYSTEM FOR PREPARATION OF SAMPLES FOR ANALYSIS

Andre Metzger, Peter Grimm, Andre J Nohl, Vance J Nau, Le Verger, France assigned to Ciba-Geigy Corporation

There is disclosed herein an automated sample preparation system for chemical assay of samples of materials. The sample preparation system includes a sample preparation chamber which includes a removable cup for taking to the location of solid or very viscous samples. The cup may be attached in sealing relationship to a cap through which extends various utilities such as a mixer/grinder to grind solid samples and mix non-homogeneous samples, a fill pipe to pump in liquid samples, an effluent pipe in the sump of the cup to allow pump of samples and solvents and a nozzle to allow liquids to be sprayed against the walls. A sample metering valve associated with the sample preparation chamber allows a known volume of sample to be isolated so that solvent may be pumped in to dilute the sample to a user defined concentration. A reversible pump is coupled by a pair of manifolds which are themselves coupled by solenoid operated valves to various sources of solvents, pressurized gas, vacuum, water, the sample preparation chamber and the assay system. A control system coordinates the operation of all remotely controllable units in the system to allow the user to customize various preparation processes.

4980132

APPARATUS FOR INFECTIOUS RADIOACTIVE WASTE

Margaret C Stinson, Mitchell S Galanek assigned to Massachusetts Institute of Technology

An apparatus is disclosed for housing radioactively and biologically contaminated waste materials during treatment thereof to inactivate the biological contaminants and render the wastes more suitable for disposal in a solid landfill. The apparatus is nonporous and thermally resistant. Additionally, the apparatus features at least one opening within which is disposed a filter for entrapping any radioactive compounds contained in gases exiting the apparatus during the treatment. The apparatus is used in conjunction with an autoclaving procedure which inactivates the biological contaminants while preventing volatile radioactive compounds from escaping into the environment.

4980137

PROCESS FOR NOX AND CO CONTROL

Sidney Nelson, Brian Nelson assigned to Sanitech Inc

An improved process is described for reducing the levels of nitrogen oxides and carbon monoxide present in flue gases. The process consists of preparing a bed of expanded vermiculite, expanded perlite, or borosilicate glass wool and passing a flue gas containing nitrogen oxides and carbon monoxide through the bed, whereas the vermiculite, perlite, or glass wool making up the bed material serves as a catalyst for the reduction of the nitrogen oxides to gaseous nitrogen and oxygen and the reduction of carbon monoxide to carbon and oxygen, the carbon being deposited on the bed particles. After the deposition of carbon, the bed material is then exposed to an oxidizing gas stream, during which time the deposited carbon is converted to carbon dioxide and the bed material is conditioned to accept flue gas again.

4980325

METHOD OF CONTROLLING MOISTURE IN COMBUSTION SECTION OF MOVING BED REGENERATION PROCESS

Paul A Sechrist assigned to UOP

A method for continuously or semi-continuously regenerating reforming catalyst by the recirculation of a gas stream advantageously controls the water content by using an oxygen-deficient makeup gas stream to supply the oxygen for combustion of coke. The volume of makeup gas entering the process is increased by reducing its oxygen concentration so that additional waste gases from the combustion of coke on the catalyst can be vented. The venting of additional gas from the circulating gas stream lowers the overall water concentration during the combustion of coke. The oxygen-deficient makeup gas stream can be supplied by oxygen and nitrogen separation from air. Where the production of the oxygen-deficient makeup gas stream also produces an oxygen-enriched stream, the oxygen-enriched stream is advantageously added to a catalyst reconditioning step for an increased dispersion of metals in the catalyst.

4980538

HEATING AND TEMPERATURE-CONTROL DEVICE FOR BIOLOGICAL SAMPLE CONTAINERS

Claudio Calzi, Paolo Bonfiglo, Milan, Italy assigned to Instrumentation Laboratory S p A

A heating and temperature-control device for biological sample containers includes an assembly of lamps emitting infrared radiation within a wavelength of 1-5.5 micrometers and heating said containers by irradiation, and a sensor for infrared radiation of wavelength 7-14 micrometers which picks up the emission from the containers which derives from their heating. The signal obtained from said sensor is used to control the lamp emission in such a manner as to obtain the required container temperature and then keep it constant.

4981411

SELF-LOADING TRANSPORT BODY FOR RECYCLABLE WASTE

Larry W Ramsey assigned to Rogers Manufacturing Co Inc

A tiltable truck body is specially adapted for loading, transport, and unloading of recyclable waste materials. Plural interior waste compartments are separated by independently controlled inner doors. Side mounted buckets mounted on roller tracks and connected to a hydraulic drive assembly by hinged lift arms permit separable curbside loading and dumping of waste material in confined areas.

4981600

METHOD AND MEANS FOR TREATING SLUDGE

Hugh J Tobler, Larry G Lepper assigned to Cemen-Tech Inc

The method and apparatus of the present invention comprise an elongated auger housing having a rotatable auger therein. Augers are provided for delivering sludge and an additive such as cement kiln dust to the intake end of the mixer housing. An auger within the mixer housing conveys the material to the discharge end of the housing, and at the same time mixes the materials together.

4982231

WASTE TONER RECOVERY DEVICE FOR USE IN ELECTROSTATIC COPYING MACHINES

Yasuyuki Matsuuchi, Osaka, Japan assigned to Minolta Camera Kabushiki Kaisha

A waste toner recovery device for use in electrostatic copying machines has a sensor and control unit which provide an advance warning when the volume of waste toner in a waste toner recovery bottle reaches a specific warning-start quantity. The control unit allows a desired value corresponding to the warning-start quantity to be selected in the copying machine.

4982605

AIR FLOW MONITOR AND TEMPERATURE COMPENSATING CIRCUIT THEREFOR

James W Oram, Price R Hodson, Paul Haake assigned to Alnor Instrument Company

A temperature compensated air flow monitor which measures true flow velocity or volume flow. The air flow monitor can be mounted in or coupled to a fume hood and includes a fluid flow tube having a pair of thermistors mounted therein. A first cold thermistor is utilized to provide temperature compensation to the second hot thermistor which provides the fluid flow velocity measurement. The pair of thermistors can be mounted to or in a probe for a portable air flow monitor application. The measured flow velocity or volume flow can be utilized in a display for the operator and also can activate one or more alarms when the flow velocity varies from a desired range.

4982788

APPARATUS AND METHOD FOR REMOVING VOLATILE CONTAMINANTS FROM THE GROUND

Lawrence A Donnelly

Hazardous volatile contaminants are removed from the ground by circulating air between two substantially parallel wells and by removing the vapors of the organic compound from the circulated air using at least one of a condenser and a demister. To enhance efficiency the air is recirculated in a closed loop. The heat output of the condensation process is used to heat the recirculated air. Pipes having openings along only a limited portion of their lengths are placed in the wells and the depth of the openings adjusted to treat one level at a time, thereby preventing shunting of air through more porous soil layers. Flow rates can be equalized by using circumferentially placed induction wells surrounding an extraction well (or the reverse) and by controlling air flow through individual sections of a given level.

4983118

LOW NOX REGENERATIVE BURNER

James E Hovis, Harry P Finke assigned to Bloom Engineering Company Inc

A regenerative burner having heat storage units with combustion effluent/combustion air ducts therethrough, fuel intake means and a burner body, wherein the burner is designed to suppress NOx formation and to control flame shape and characteristic in the regenerative system during combustion. The regenerative burner may include a burner baffle, or may include a plurality of gas jets entrained in generally converging fashion for control of the flame characteristics and shape dispositive of NOx formation. The burner may provide for staged combustion, either by means of sequential fuel injection or sequential provision of combustion air, or the burner may depress NOx formation by vitiation of combustion air with products of combustion. The present regenerative burners suppress NOx formation yet preserve the remaining characteristic features of regenerative systems.

4983296

PARTIAL OXIDATION OF SEWAGE SLUDGE

Matthew A McMahon, Robert M Suggitt, Ronald J McKeon, Alber Brent assigned to Texaco Inc

Municipal sanitary sewage sludge is disposed of by an improved partial oxidation process without polluting the environment. Aqueous slurries of sewage sludge are upgraded by hydrothermal treatment, preferably while being sheared, concentrated, and then mixed with a supplemental fuel, preferably coal. A pumpable aqueous slurry of sewage sludge-coal and/or petroleum coke is thereby produced having a greater total solids and heat content (HHV) as well as containing an increased amount of sewage sludge for reacting with free-oxygen containing gas in a free-flow partial oxidation gas generator. Hot quench water or steam produced by cooling the hot raw effluent stream of syn-

thesis gas, reducing gas or fuel gas from the gasifier may provide heat for the hydrothermal step.

4983298

PROCESS FOR THE DISINFECTION AND AEROBIC STABILIZATION OF SEWAGE SLUDGE

Leonhard Fuchs, Martin Fuchs, D 5440 Mayen 1, Federal Republic Of Germany

A process for the disinfection and aerobic stabilization of concentrated sewage sludge in several steps, using one or more heat-insulated containers, preferably with stirring, with the addition of an oxygen-containing gas, described wherein (a) the sludge coming in, having been concentrated to at least 2% of dry matter, is caused to reach the thermophilic temperature range of >50 degrees C., with pre-heating if required, and then solely by an aerobic degradation without supplying external heat within from 2 to 4 days, (b) the sludge is disinfected by further aerobic degradation without supplying external heat at about 50 degrees C. to 55 degrees C. for at least 20 hours or at >55 degrees C. for at least 10 hours, and (c) the sludge is stabilized to become mesophilic by way of actively cooling it down to about 25 degrees C. to 45 degrees C. and a further aerobic degradation within about 2 to 8 days, and preferably within from 3 to 5 days.

ENVIRONMENT INTERNATIONAL

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Report: NIH (Nationa Institutes of Health). Report of the National Institutes of Health ad hoc working group to develop radioepidemiological tables. NIH 85-2748. Washington, D.C : U.S. Department of Health and Human Services; 1985.

Book: Henderson, P.m Inorganic geochemistry. New York, NY: Pergamon Press; 1982.

Regulation: USEPA (U.S. Environmental Protection Agency). National primary drinking water regulations: fluoride. 40 CFR Parts 141, 142 and 143. Fed. Reg. 50:47142-48933; 1985.

Proceedings: Swedjemark, G.A.; M.jönes, L. Exposure of the Swedish population to radon daughters. Berglund, B.; Lindvall, T.; Sundell, J., eds. Proc. 3rd international conference on indoor air quality and climate. Vol. 2. Stockholm: Swedish Council for Building Research; 1984:37-43.

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