Edward A. McBean

RISK ASSESSMENT

Procedures and Protocols

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Dedicated to Matthew, Derek, and Melissa as they are the future.

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Preface

The intent in this book is to carefully describe the methodologies, typical mathematical notation, and assumptions typically used in risk assessment calculations. Subsequently, the book's chapters describe various statistical analysis procedures that are used for estimating the parameters used in risk assessment methodologies. Numerous examples and descriptions of the bases of the methodologies are provided.

Unlike much of the professional literature in statistics, this text makes concerted efforts to describe statistical techniques in terms comprehensible to the nonstatistician. This is accomplished by downplaying mathematical notation, comprehensively explaining the development of equations, and emphasizing example applications. Thus, as example problems of interpretations of environmental monitoring results are described, the text demonstrates through use of simple examples, how the procedures are utilized. References are provided, with particular emphasis on works describing applications reported in the technical literature. Problems included at the end of the chapters stress fundamentals and increase the usefulness of this book as a classroom text, intended for senior undergraduate and graduate students in environmental engineering and environmental sciences.

The collection and laboratory analyses of samples needed to characterize environmental quality are expensive. Further, as society expresses increasing concern for environmental protection and as instrumentation technology evolves to allow detection of contaminants at ever-lower concentrations, expenditures for monitoring environmental quality will continue to increase with time. As a direct consequence of the substantial costs of environmental monitoring, it is essential to use available environmental quality data as effectively as possible. Effective utilization involves answering questions such as, "Is the environmental quality acceptable?," "Is the environmental quality improving or deteriorating?," and "Is the risk acceptable and/or need to be managed?" Responding to these types of questions requires interpretation of data, and this stage of assessment is beset with difficulties. Some difficulties with interpreting environmental-monitoring results include:

i) Since environmental data are frequently expensive to accumulate, the data sets being interpreted are typically modest in size.
ii) The data may involve a vector of chemical and biological constituent measurements because consideration must typically be given to a range of constituents. Correlation between the constituents may help the infilling of missing data or the identification of outlier data.
iii) Early detection of any deterioration in environmental quality is highly desirable because early detection may provide the opportunity for controlling the problem, at a lower cost, before the problem magnifies. Any procedure for identifying early warning signals must not, however, falsely identify a problem of apparent environmental deterioration when one

does not actually exist, a so-called false positive, nor should it fail to identify a problem when one does exist, a so-called false negative.

iv) The vagaries of nature typically introduce significant noise, and sources of variability such as seasonal effects, make the identification of trends more difficult.

v) The derivation of quantitative risk assessments is, in many ways, data dependent. However, a key question is whether the information returned by risk estimates warrant additional data collection efforts?

The net result of difficulties such as the five examples mentioned above is that making sense of the data relevant to risk assessment methodologies necessarily involves statistical interpretation. Statistical interpretation procedures must be sensitive to small changes in environmental quality and yet recognize the potentially substantial costs of any additional data collection requirement.

The need for the statistical interpretation of data is widespread. The range of concerns for each environmental media – air quality, surface water quality, groundwater quality, and soil contamination – is similar in many respects. And yet, there is no single statistical analysis procedure universally applicable to the variety of problems associated with environmental quality data. Instead, the practitioner needs to have an array of statistical procedures available. A multitude of statistical analysis tests are available, but each of the tests possesses assumptions that may, or may not, be appropriate for specific circumstances and hence, having a number of techniques is frequently required. Computer programs now becoming widely available facilitate the use of various procedures (e.g. ProUCL, EPA, 2013). The difficulty remains for the student and practitioner to learn which conditions dictate a particular procedure and which conditions render it highly inappropriate.

Following the introduction (Chapter 1), the book is organized into three parts as follows:

Part I – Chapters 2 through 4 develop the fundamental calculation procedures and methodologies for risk characterization.

Part II – Chapters 5 through 7 describe the characteristics of common distributions as utilized to describe data.

Part III – Chapters 8 through 12 describe the bases used in hypothesis testing to determine when there are differences in environmental quality at various locations. Problems of censored data are considered as they influence the utilization of alternative tests. Chapter 12 focuses on nonparametric procedures, an alternative to the parametric procedures utilized in previous chapters.

Author of the Book

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Acknowledgments

The work reported in this book is the assembly of work completed by many. A much earlier version of this book was published under the title of Statistical Procedures for Analyses of Environmental Monitoring Data and Risk Assessment by Prentice-Hall in 1998, but this book is no longer in print. The copyright for this early book was requested, and received, from the publisher. Extensive rewriting and examples have been introduced into this book. Most importantly, the emphasis of this current book is on risk assessment and the information provided on statistical data in support of risk assessment methodologies.

In addition to the literature, the experience and efforts of many individuals has been important in developing this book, and for this assistance I am truly grateful. In particular, the talent and expertise of Frank Rovers, a co-author of the previous book, is gratefully acknowledged. Frank has been an inspiration as well as a colleague and friend throughout my professional career.

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In an undertaking of the magnitude of this text, it is not possible to avoid errors, and for this I apologize; but this book is supplied in good faith. While I have taken reasonable care to avoid errors, I accept no liability for any damage, consequential or otherwise, that may be caused by the use of this book. Any suggestions for corrections, criticisms, or suggestions for improvements will be greatly appreciated and I will work towards improvements in any future versions of this book. As well, many of the coefficients continue to be updated, and hence, the reader must refer to the Internet and other sources of the information for these updates; the emphasis in this book must necessarily be on the methodological processes and explanations thereof. I would also welcome any additional information and data that would make future editions of the book more complete.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/McBean/RiskAssessProcedure_1e

Scan this QR code to visit the companion website

The BCS is a compilation of answers to various questions in the book itself. The intent in providing these is to expand the opportunity for the students to “learn through using the information provided in the book.” Many of the questions are from old examination questions generated over the years while using the book in “draft” form.

1

Background to Risk Assessment and Management

1.1 The Case for Risk Assessment, Leading to Risk Management

Many different definitions of risk exist, using such terms as hazard, danger, and exposure. Therefore, to put oneself "at risk" means to participate voluntarily, or involuntarily, in an activity or event that could lead to injury, damage, or loss. Hence, "risk" refers to the possibility of experiencing harm from a hazard, and thus risk assessment involves evaluating the likelihood or frequency of experiencing a risk.

Since risks are about events that cause problems, risk identification typically starts with attention to the source of the problem or risk. According to US EPA, a risk assessment involves the evaluation of scientific information, including such dimensions as a dose–response relationship, and the extent of human exposure to a chemical. "Someone or something that creates or suggests a hazard" would be an example.

There is a distinction between hazard and risk; we need to understand this so that attention of resources can be directed to actions based primarily on the level of risk rather than just the existence of a hazard.

It is also important to be mindful of the distinction between risk and uncertainty. Risk can be characterized by consequences or impacts multiplied by probability. On the other hand, uncertainty is a term that applies to, for example, the predictions of possible events (e.g. the chemical concentration to which someone is exposed). Perhaps some of the events are only partially observable. Uncertainty might exist due to limited knowledge – perhaps we just do not know enough about how to describe a circumstance or a future outcome. The result is that both risk and uncertainty are highly relevant to the subject of risk assessment; both dimensions must be incorporated. Given this differentiation between "risk" and "uncertainty," the first set of chapters in this book will focus on "risk" where some possible outcomes are undesired or may result in a significant loss. Alternatively, attention to uncertainty is discussed primarily in Chapters 4 through 12.

Another important element of risk assessment is that society is moving toward more involvement in many decisions (e.g. where is a landfill to be sited?). This involves working toward rejecting having risks imposed on the public, and hence, an appreciation of the attitudes of the public is essential. There is an association of risk with chance or probability. One of the important dimensions of this is that it requires the quantification of the probability. It also means that the procedures by which risk assessment are developed must be logical and transparent to allow open dialogue with the public about how the risks are calculated.

As apparent from the above, there is a multistage process in which the elements of risk are calculated: first, the dimensions of risk are assessed, which is then followed by a decision whether risk management is required (is the risk sufficiently severe that efforts to control or

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Table 1.1 Steps related to risk management.

1) Establish the context of the risk – Criteria appropriate to judge the risks need to be carefully laid out. This will include consultations and communications with the needs of pertinent stakeholders to be initiated early in the process
2) Identify the risks – The hazards (what can go wrong) and the causes of such hazards need to be carefully delineated
3) Analyze the risks – The likelihood (probability) and severity (magnitude) of any and all consequences need to be characterized
4) Evaluate the risks – The risk estimates need to be considered in relation to the criteria set out in the beginning of the procedure
5) Treat risks – Practical options feasible to manage the high priority risks and monitor the low priority risks need to be determined
6) Monitor and review – Because circumstances may change, the basis must be monitored and periodically reviewed
7) Periodically communicate and consult – Extensive experience has consistently demonstrated that leaving communication and consultation steps to the end of the risk management process will usually create stakeholder outrage and avoidable conflicts

manage the risk are required?). This is accomplished by the first step in this process being to identify the risks, followed by the determination whether management of the risks is necessary and feasible. This will include consideration of the probability of recurrence (Table 1.1).

The development of risk assessment and management processing is definitely "a work in progress" as the profession continues to learn about the issues. There is substantial uncertainty that still remains. Regardless, it is important to understand the underlying principles; the assembly of data will continue to evolve. An example of a challenge is an individual who decides to undertake a potentially dangerous activity such as skydiving. The scientific approach to risk analysis does not necessarily allow the person to decide on how to deal or manage this type of risk although there may be strong evidence that certain activities are dangerous. Instead, most of the attention herein will be on risk in its most fundamental form. The approach in this book will involve the following: (i) identify a hazard, (ii) analyze the risk associated with that hazard, and (iii) determine if the elimination, or control, of the risk is warranted.

Risk enters the purview of the public in a wide spectrum of dimensions. Examples of risks that we may encounter on a daily basis are indicated in Table 1.2. Each day we weigh risks of different types of activities. We weigh the risk of injury when driving a car or riding a bicycle. We assess the number of people engaged in the activities and our perceived rate of injury and we decide whether or not to participate.

In words, innumerable aspects of everyday society involve a risk. It should be apparent that we cannot make all of the risks become zero but we can, and often do, avoid some risks. Different approaches are needed for different circumstances and different degrees of data availability. One of our concerns will be in establishing how to assemble and interpret data as a basis from which risk assessment can be developed. The strategies must consider both humans and the environment. In this context, the book develops the concepts and then builds the concepts and techniques into a strategy to undertake risk assessments.

This book primarily focuses on environmental risk. As will be shown, risks are pervasive. We can use parallels to other risks we face in society to develop reasonable trade-offs to allow decisions on risk management.

Ultimately, what is needed is to describe exposure assessments to human health and the environment, but the complications of risk assessment will be apparent when confronted with the spectrum of dimensions such as the degrees to which a chemical bioaccumulates and

Table 1.2 Examples of risks encountered on a daily basis.

Examples of risks	Basis for risk
Turning on the light	Possible electrocution
Soap in the shower	There may be a chemical that fluoresces in the soap and/or the potential for increased slippage as a result of the soap
Falling on stairs	Concern with falling
Coffee/tea as a result of the caffeine	Due to elevation of blood pressure
Sweetener in coffee/tea	Sugar/fat/heart disease exacerbated
Peanut butter	The aflatoxin (a mold) and liver cancer where, particularly in the developing world, the storage of peanuts is an issue
Riding a bicycle to work	Increased potential for involvement in an accident
Drinking of water	As a result of the disinfection byproducts arising from chlorination of water
Brick and cinder blocks	Radon and hence cancer potential
X-rays for disease identification	May cause cancer
Air travel	Through a combination of the radiation hazard as well as the potential for a plane crash

biomagnifies, the importance of ecological modeling, and dose–response methodologies. The preceding should be sufficient to demonstrate that the field of risk assessment and management is very data intensive and requires careful appreciation of data variability.

The emphasis herein will be on risk assessment. Risk management procedures go far beyond risk assessment and must deal with multifaceted aspects of a problem and must be responsive to the severity of conditions as well as to how much money is available and the degree to which management is feasible.

1.2 The Need for Risk Quantification

Key words in the preceding definition of risk in Section 1.1 are "voluntary" and "involuntary." Voluntary risks are hazards associated with activities that we undertake voluntarily such as walking down the stairs, riding a motorcycle, smoking cigarettes, or skydiving. Involuntary risks are negative impacts that may occur without a person's prior consent or knowledge. Involuntary risks include, as examples, lightning strikes, tornadoes, floods, and exposure to environmental contaminants.

Risks may also be characterized as "statistically verifiable" or "statistically nonverifiable." As the first name implies, statistically verifiable risks are risks for voluntary or involuntary activities that have been determined from direct observation (e.g. statistics related to motor vehicle accidents). These types of risks can be compared to one another since data exists. Statistically nonverifiable risks are risks from involuntary activities that are based on very limited datasets and mathematical equations. For example, we know that the risk of a nuclear energy generation incident killing a person is low but because there are very few events that have occurred, it is difficult to establish probabilities. Hence, while aspects of statistically verifiable and nonverifiable risks are similar, they are also very different. This means that although we must consider both, we cannot necessarily compare them.

Another complication is that the magnitudes of risks associated with different activities and phenomena vary widely. For example, one's chances of being struck by lightning are low compared with fire-related deaths. Both of these are largely involuntary risks, as they represent risks over which we have limited control.

On the other hand, voluntary risks are associated with activities that are largely controllable. There are risks associated with living in our society and individuals are (or should be) constantly evaluating various actions with varying degrees of focus and caution. Essentially, these types of assessments are often just part of one's experience. People consider risks as they relate to voluntary activities, and generally, people try to stay out of harm's way. For example, you could travel to work by bicycle, but there is a risk of being struck by a vehicle while en route. This risk could be avoided by taking a bus to work, but there are other risks associated with bus travel. As well, if we were to drive a vehicle to work, we could take risk precautions by reducing speed and/or wearing a seat belt.

One of the most challenging stumbling blocks regarding risk is that the vast majority of people do not understand and quantify the risks they face on a day-to-day basis. Most people behave as if life is largely free of risk (or, at a minimum, the thrill of participation makes the risk acceptable). Undertaking activities that are considered to be "risky" is frequently taken as irrational and should be avoided. Risks imposed on us by others are generally considered to be unacceptable. There are dangers associated with travel; people are aware of the potential for airplane accidents, as an example. However, there are dangers associated with staying home – 25% of all fatal accidents occur in people's homes. Everything we do involves risks. It enters all aspects of our daily lives, contributing to the way we live. Generally, people do not use formal procedures to estimate risks but instead rely on personal attitudes and experiences, media reporting, and input from friends and colleagues.

The logical procedure for minimizing risks is to quantify all risks and then choose those that are smaller in preference to those that are larger. However, this does not translate to mean that we should not try to minimize our risk exposures, but it is important to recognize that attempts to minimize anything is best accomplished using a quantitative procedure. We cannot minimize our risks by simply avoiding those we are aware of, because those we are aware of are likely those publicized by the media. Many more risks may exist as unknowns.

The result is that decision-making processes regarding risk are highly complex, with multiple features that influence the degree of hazard and danger. These features should also serve to affect the actions we take to minimize risks. The means that will be developed in this book to approach risk assessment, and therefore influence how we assess risks, will be primarily quantitative.

The intent in this book is to provide the framework for the process of quantifying specific types of risks and to allow assessment of the trade-offs. In most respects, the emphasis herein is related to environmental risks although not exclusively. To compare risks, we must be capable of calculating or quantifying the risks.

Risks will usually be expressed as a probability of effects associated with a particular activity (e.g. drinking water with low levels of arsenic). In this book, we will be evaluating the probabilities of various types of events or exposure scenarios. Scientific notation will be used to present quantitative methodologies and information. Hence, there is a component of risk management that involves data compilation and evaluation, and, in many respects, this is a question of uncertainty, a concept that was discussed in Section 1.1. As well, there will be the development of exposure assessments, toxicity assessments, and, ultimately, a risk characterization.

A comment made by many is that the world seems like a hazardous place. However, as Wilson (1979) indicated, if we look back at the world of a century ago, we realize that life expectancies have increased substantially from 50 to 70 years. Therefore, the sum of all risks must be less than it was historically. However, now we are more aware of risks due to increased societal focus on such dimensions as media, publicity, and education.

1.3 Environmental Risk

Concern with the quality of the environment is pervasive. Members of the public, politicians, the media, lawyers, scientists, engineers, and so on are all watchful of current environmental quality levels and the perceived trends in these levels. Much of the concern with environmental quality is real and appropriate, arising from a legacy of inadequate environmental protection, but some is only perception. As a result, attention to and concern about environmental quality is a growing phenomenon, one that must be addressed by professionals throughout the environmental industry (in the broadest context, to food, to water, to the air we breathe, etc., so not just a question for environmental engineers).

During the past several decades, the public has been increasingly demanding that the risks associated with the exposure to environmental contaminants be reduced. The demands have been directed in part toward government agencies responsible for soil, water, and air quality for the protection of human health and ecosystems. The result has been the need for dramatic increases in the requirements for professionals to analyze and interpret environmental quality data. Suggestions on tools and approaches that can be utilized to assess risk management are described in the chapters that follow.

Directions and opportunities will be used to demonstrate, by example, how to access various types of data that are available and valuable (e.g. sources of epidemiology and toxicology). The emphasis here is on using the data – scientists and engineers are not always involved in the collection of the data.

1.4 A Measure of Quantifying Risk: Loss of Life Expectancy

There are many ways of expressing or quantifying risks. One of these is loss of life expectancy (LLE). LLE is the average time period by which a person's life is shortened by the risk under consideration. Thus, LLE is the product of the probability that a risk will cause death and the consequences in terms of lost life expectancy if it does cause death.

The LLE is a highly useful concept but there are limitations as to how to interpret it. As way of explanation, if we assume the life expectancy of a man is 80 years, and he is currently 50 years old, and if that person takes a risk that has a 1% chance of being immediately fatal, this risk causes an LLE of $0.01 \times (80 - 50)$, or 0.3 years. It is important to understand that this does not mean that the man will die 0.3 years sooner as a result of accepting the risk but if 100 people of this man's age took this risk, $(0.01) \times 100 = 1$ person might die immediately, having his life shortened by 30 years, while the other 99 would not have their lives shortened as a result of that risk. The result is that the average lost lifetime for the 100 people would be 0.3 years. This is the LLE associated with that particular risk.

While it is important to consider this concept, the real world is much more complicated. Society is made up of many people of many ages, and the effects must be summed over a lifetime, making the calculations much more complex than the simple LLE example described above. The intent in this book is to provide guidance on how the various methodologies may be developed and to demonstrate how the calculations may be done. In the initial chapters, the equations that can be used to make the calculations for risk will be developed. The second part of the book involves the development of statistical data tools to allow the calculations to be completed. Risk assessment generally focuses on extremes, and available data are typically rather minimal. For reasons that will be explained later, the increased risk of death is typically on a scale such that the risk of one-in-a-million is considered acceptable and hence rare. Risk assessment is a step in the risk management process. It is generally more appropriate to characterize risks by providing an upper limit on a risk reflecting uncertainty and then assessing which risks are acceptable.

The assessment of procedures for managing risk in some management responses will be obvious. For example, if the concentration of a chemical in drinking water causes an unacceptable health risk, then either water treatment must occur or an alternative water source must be identified. Hence, ways of managing risk are, in many ways, a natural outgrowth of risk assessment. It is important to understand the underlying principles because they are not subject to change and apply in a broad sense to risk assessment. Some are quantitative and some remain qualitative.

Statistical interpretation of environmental quality data has a major role to play in such areas as qualifying effects, assessing consequences, measuring risks, and interpreting evidence. The intent is that this book will assist the student and the practitioner in all of these areas.

The book was prepared for use for instruction to senior undergrad and grad students in technical disciplines. Guidance is provided to the technical literature for those wishing a greater understanding of the technical details, but the mathematical basis and structure of the arguments are hopefully at the level of detail that can be followed from the material presented herein.

1.5 Reliance on Environmental Data

1.5.1 Characteristics of Data

The basis of environmental risk is upon environmental data. Data interpretation is necessary to allow the development of risk assessment. For environmental risk, the need is to assess the potential severity and the probability of occurrence, hence fundamental in terms of understanding environmental data. Risk assessment must be based on defensible data and interpretation of that data.

Collection of samples from the field, the need for laboratory analyses of these samples, and the time requirements for interpreting the resulting information can represent enormous expenditures for government agencies, corporations, and citizens. Consequently, when assessing the resulting data, diligence must be utilized to ensure the interpretation of the data is comprehensive and defensible.

There are many reasons for the increased focus on environmental quality. These reasons include the increases in human population and urban densification that have resulted in more locally concentrated pollutant releases and deteriorated environmental quality. The reasons also include the result of enhanced laboratory technologies (e.g. LC-MS-MS), which can now detect concentrations of substances such as pharmaceuticals, at levels that previously were not quantifiable. With the intensive monitoring efforts now being carried out, instances of deteriorated environmental quality are now identified, which previously might have remained undetected.

The focus on environmental quality has resulted in greatly enhanced needs to understand the evolution of environmental quality conditions. Part of the understanding of the evolution is gained from the enhanced statistical interpretation capabilities now available to interpret environmental quality data. However, by no means is statistical interpretation by itself sufficient. Other needs may include mathematical modeling of air quality and surface and subsurface water and soil quality. Thus, in addressing the statistical analyses of environmental quality data, the statistical analyses described in this book must be tempered with many other considerations. The use of statistics is only one of the tools we employ when interpreting environmental quality data. Statistical analyses are not an interpretation of the facts, but, when properly used, these analyses make the facts easier to see and allow other evidence to enter into judgments about environmental phenomena (Unwin et al., 1985). This is relevant because we rely on environmental data that is notoriously challenging, for reasons that will be discussed in many of the following chapters.

As will be apparent, an extensive theoretical basis exists for statistical methodologies. However, much of the statistics literature is premised on the availability of very lengthy data records, a circumstance that seldom exists for environmental phenomena. In interpreting the data, we must therefore understand the limitations and assumptions of the statistical procedures and how these affect data interpretation. In addition to brief datasets, the difficulties of dealing with environmental data may include the presence of numerous parameters, high degrees of variability in some constituents, and "censored" data where censored indicates that the magnitude of a constituent is known only as being less than some specified magnitude. As well, analyses must reflect the frequent occurrence of incompatible data due to different sampling methods, different laboratory analytical methods, and/or different times or spatial intensities of monitoring. Frequently, some of the information available is anecdotal. For example, some data are the result of nonstatistical sampling, grab samples, and vagueness in terms of where, how, and when the samples were collected.

Conceptually, environmental processes are characterized as complex, multifaceted, chaotic, and dynamic. The result is that we are limited in our ability to use many of the procedures described by statisticians in the available literature (or, at a minimum, we have to be inventive in the application of these procedures). One of the reasons for preparation of this book is to respond to some of these concerns. This is accomplished using examples and discussion of the advantages and disadvantages of the various statistical analysis procedures and how statistics can be utilized to assist in these endeavors. Clear, complete, statistically accurate, and understandable information is essential in making informed decisions. Broadly, statistics attempts to characterize order in "disorder," such as the quantification of equation error or measurement error. One must always temper statistics with a clear understanding of the problem, so that spurious information is not introduced, nor valid information omitted. Statistical analyses of data are not an interpretation of the facts; statistical analyses are just another way of making the facts easier to see and therefore interpret (McBean and Rovers, 1990).

1.5.2 Indications of the Sources of Variability in Environmental Data

The nature of the variability of environmental quality data greatly influences statistical analyses of the data. The specifics of statistical analyses will depend upon the way the phenomena of interest is defined and sampled. In general, the ability of a sample of environmental quality data to characterize the population from which it is drawn is related to such aspects as (i) the size of the sample, (ii) the degree to which it was selected at random, (iii) the degree of independence between the observations comprising the sample, and (iv) how the data can be employed.

If extensive monitoring requirements are specified in governmental legislation, this will translate into sizable expenditures in terms of time and dollars to collect the data. Nevertheless, samples of environmental quality are just that, namely, subsets of the populations that are of interest. The result is that in many assessments of environmental phenomena, estimates of groundwater quality, for example, must be developed from only very brief data records, brief being with respect to both temporal and spatial dimensions. The result is that there may be substantial quantities of data, but there is only a finite amount that is usable for specific applications.

These features stress the difficulty with statistical interpretation of environmental data in relation to risk assessments. There is a need for the analysis procedure to be sensitive to small changes (e.g. early detection of contamination is desirable), and yet a point of diminishing marginal returns also occurs. There may be more data collected than is necessary to make a decision, and thus, some of the money spent in data collection may be unnecessary.

The result is that on many occasions we must be inventive in terms of how statistical analyses for risk assessment should proceed. Many standard statistical analysis techniques that are valid for long records have little utility in situations possessing only a brief record or, at a minimum, the techniques must be modified to correct for biases created because of the brevity of the record. A further complicating factor is that many of the data records are highly variable or "noisy" due to, for example, seasonal phenomena. An additional consideration arising in part with increasing instrument technology is that we can measure features that previously were reported only as censored (less than) data. Further, a number of chemicals have maximum concentration levels (MCLs) to which humans and the environment can be exposed to while not incurring injury, which are very close to the technological instrumentation capability in being detected. The result is that problems associated with statistical analyses of censored datasets are increasing.

For the variety of reasons indicated above, there is not a single approach to statistical analysis. Instead, what is frequently needed is a series of approaches, each of which possess useful attributes that may be appropriate, in addressing a particular question. Statistical interpretation of environmental quality data therefore has a major role to play in such areas as qualifying effects, assessing consequences, measuring risks, and interpreting the ramifications.

1.5.3 Independence of Successive Data Values

Time-series analyses are pertinent to the problem of estimating trends and cycles (e.g. seasonal variations). For example, consider the situation where there is a tendency for a groundwater monitoring well that is yielding high chloride concentrations today to also yield similar values tomorrow and for nearby monitoring wells to also yield sampling aliquots with elevated chloride concentrations. Hence, these types of sampling results are not necessarily independent from each other. Similarly, replicate sampling (e.g. the splitting of field or laboratory samples into several samples) does not create independent samples. As a result, there are differing degrees of independence of monitoring results, and these aspects must be assessed during the statistical analyses of the resulting data.

Many statistical analysis procedures assume independence of data. Dependent samples exhibit less variability, and statistics determined from dependent data will therefore have underestimated sample variances. Dependence can severely influence the results of testing any hypothesis. See Example 1.1 for an indication of hypothesis testing.

Concerns with hypothesis testing include those dealing with the independence/dependence of successive samples. One approach to minimize dependence in samples is to allow sufficient time between sampling times to allow the "real-time memory" of the system to be exceeded. For example, the statistical analysis of annual peak flows (the highest flow in an individual year) involves statistical analysis of independent events since the peak flow in 1 year is unlikely to be related to the peak flow in a later year.

For some situations we can avoid the problem of dependent data. We might "deseasonalize" the data by removing the periodic characteristic(s) associated with the seasons. However, the ability to remove seasonality in environmental quality data records may be constrained by the brief length of environmental data available, which limits our ability to isolate the seasonal variability from the other sources of variability, which are present in the dataset.

Example 1.1 Example of Statistical Hypothesis Testing
Consider the question of whether a landfill is leaking leachate, which will contaminate the underlying groundwater, as depicted in Figure 1.1.

One way to consider this question is to monitor the groundwater quality both upgradient (Point A) and downgradient (Point B) from the landfill. We might then compare the quality at A and B to determine if there is a difference. Thus, a hypothesis might be the following:

Hypothesis – There is no statistically significant difference between the quality of the groundwater at the two locations.

Outcome 1: If we accept the hypothesis, then we conclude that there is insufficient information to indicate the landfill is leaking.
Outcome 2: If we reject the hypothesis, evidence exists to indicate that the landfill is leaking.

The question of hypothesis testing in environmental phenomena is a recurring one. The details of hypothesis testing will be a recurring question throughout this book, and the quantitative aspects of hypothesis testing will be left to later chapters.

1.5.4 Uncertainties and Errors in Environmental Quality Data

There are different levels of "observational" data. For example, "proxy" data are observations of one variable that have a high probability of being indicative of levels of another variable. Such data are indirect "observations." Another example is remotely sensed data by which many "indices" are derived from satellite data including temperature and vegetation. Image classification techniques may allow patterns in "data" to be recognized as signatures of certain environmental features.

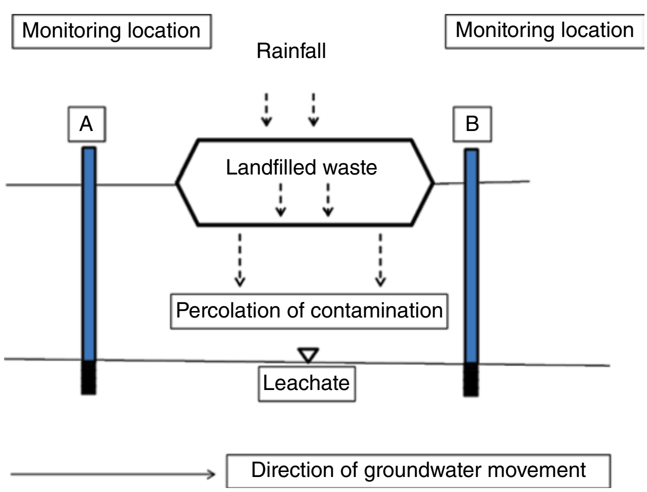

Figure 1.1 Schematic depiction of monitoring in the vicinity of a landfill.

In the strictest sense, there are very few types of data that are direct "observations" of a variable. Data on animal (or human) demography are collected by observing various signs, such as spores, tracks, nests, houses, income tax reports, and so on. Even something as obviously "observable" as the digital elevation is subject to interpretation, according to the methods used to produce the measurements. The validity of these "data" depends on such features as one's confidence in a particular measurement method and the reliability of calibration techniques of the instruments, all of which must then be considered when interpreting the data.

Quantifying observations involves the employment of sensory techniques, indirect measurements of related variables, and various levels of processing. It can then be argued that data are observed only in the context of the experimental design in which they are produced. It becomes a matter of interpretation as to what degree of processing is appropriate to produce a quantified observation that will then be called "data."

Errors in sampling procedures, inadequate sample storage and preservation techniques, and laboratory analytical errors are examples of errors in environmental datasets. As a demonstration of the multifaceted initiation points for such errors to exist in a dataset, further examples of the sources of error in the collection and analysis of groundwater quality data are listed in Table 1.3 and for air quality listed in Table 1.4.

There is always a degree of uncertainty associated with each discrete measurement of environmental quality. In interpreting data, each discrete measurement is really a range of statistically probable values instead of a single value. There are two subdivisions of reproducibility criteria, namely, replication and repeatability. Replication is when two or more results are obtained by the same operator in a given laboratory using the same apparatus of successive determinations on identical test material, within a short period of time. Often this is done

Table 1.3 Examples of sources of error in the sampling and analysis of groundwater quality data.

Sampling of a nonhomogeneous region in which wells and springs intersect more than one chemical type in water
Piezometers and wells that are inadequately flushed out prior to sampling of groundwater may result in a subsequent sample of the groundwater not being representative of conditions in the adjacent soil environment
Monitoring wells that are subject to temporal variations in water levels resulting in variations in chemical concentrations may exhibit significant sampling error
Cross contamination of a sample may occur at the time of sampling as a result of an unclean container into which the sample is placed
An error in the laboratory protocol of the experiment during the laboratory samples
Improper preservation techniques. For example, groundwater samples are often particularly susceptible to changes in pressure and improper sample storage. Improper preservation techniques can result in a chemical alteration of the sample as it adjusts to new equilibrium conditions. For example, the pH levels in groundwater samples have been noted as increasing up to 1.0 pH units due to CO_2 escape to the atmosphere during storage

Table 1.4 Examples of possible sources of error in the collection of air quality data.

Instrumentation error may arise due to poor calibration or "drift" of the calibration of the instrument with time
Channel error incurred during transmission from the monitoring locations to a central data processing unit
Fluctuations in meteorological conditions or quantities being released by the emission source, resulting in nonrepresentative air quality conditions

during quality assurance and quality control testing of a laboratory to assure that the lab results are trustworthy. Alternatively, repeatability is a quantitative expression of the random error associated in the long run with a single operator in a given laboratory obtaining successive results with the same apparatus under constant operating conditions on identical test material. Obviously, the requirements for quality assurance and quality control can be substantial.

Many of the statistical analyses described in this book are concerned with sampling errors and the estimation of population characteristics from samples of data. The fact that sampling errors are inherent in random data does not mean, however, that statistical manipulations and sophistication can in any way overcome faulty data. The quality of any statistical analysis is no better than the quality of the data utilized. Furthermore, statistical considerations should not be used to replace judgment and careful thought in analyzing data. Statistics must be regarded as a tool or an aid to understanding, but never as a replacement for careful thought.

1.6 Some Summary Indications of Approaches for Statistical Analyses

The concern with the statistical interpretation of data is widespread. However, the variability encountered in one circumstance is quite possibly very different from that encountered in another circumstance. There is no convenient "recipe" that can be utilized to stipulate an approach that can be universally applied. Instead, statistical analyses of environmental data have become the science of collecting, analyzing, and interpreting data with the findings at each decision point assisting in identifying the next stage of analysis. Statistics is concerned with the scientific methods used in collecting, organizing, analyzing, summarizing, and presenting data as well as with drawing valid conclusions and making reasonable decisions. Statistical analyses do not consist of a standard set of rules. Instead, analyses involve successive tests and refinements, with each test gaining an improvement in understanding of the data (and its information content). The findings of the tests may well be that additional statistical analyses are needed.

Since there is no convenient recipe, the practitioner needs to have available at his or her disposal a set of approaches, with each approach having utility in application to a class of problems. In selecting the procedure for use in a particular application, there are no absolute rules, only guidelines. To a large extent, the selection of the best procedure involves careful scrutiny of the characteristics of the problem at hand and the assumptions implicit in the particular statistical interpretation.

An analyst must still understand the basics in terms of both how to characterize a problem and the method by which the results may be interpreted. With the automated calculation procedures available in today's software, it is all too easy to employ a computer package without understanding the basis for the statistical procedures. The intent in this book is to explain the features of the various techniques in terms understandable to the nonstatistician and to provide some order to the available procedures by presenting the advantages and disadvantages of the limitations of the procedures. The discussion included in this book describes some of the sources of error and how these error sources should be reflected in the statistical analyses and in their interpretation. Proper application of statistical methods by someone who understands the utility and limitations of these methods can be most helpful in revealing the information that the data hold.

The emphasis in the chapters dealing with the statistical analyses of data is on examples to develop the equations and relationships to demonstrate how the various procedures may be used. References are provided for those wishing to pursue specific features in greater depth. Much of the theoretical background is omitted, with the focus being on the engineering applications to environmental quality data.

The various statistical methods are tools for data analysis that, like any tools, have proper and improper applications. The person using a statistical method is responsible to see that it is applied properly since the value of the results obtained depends on it. Even in the best circumstances, however, statistical data analysis can provide only evidence, never proof. Inferential statistics are aimed at distinguishing between random noise in the data and the real effects that are of interest. Only through careful consideration and interpretation of all the evidence can one hope to even begin finding answers to questions about causes for, and effects on, environmental quality.

1.7 Overview of Book Content

Morrison and Henkel indicated that "Alas statistical interference is not scientific inference. To have the latter we will have much more than the facade that claims of (statistical) significance provide. There are, of course, no computational formulas for scientific inference: the questions are much more difficult and the answers much less definite than those of statistical inference."

In this context the contents of the book are organized in the following manner:

1) Part II consists of Chapters 2 and 3. Chapter 2 describes ways of calculating risks, while Chapter 3 deals with public perceptions of risks and some of the more advanced challenges in risk assessment. Public perceptions of risks are a very important area of concern as many of the issues of environmental risk are directly related to the public's willingness to accept risk.
2) Part III of the book deals with the statistical analyses of data. For questions focused on risk perception, we have minimal data unlike, for example, situations of rolling of a dice. Chapter 4 focuses strictly on the fundamentals of statistical characterization of data since that is the underpinning of much of environmental risk assessment. Chapters 5 through 7 examine the attributes of commonly used probability distributions, as appropriate to environmental quality data. Chapter 8 uses these distributions to develop alternative types of control charts and to identify data outliers. Chapter 9 examines the capabilities of correlation and regression to better summarize data behavior. Chapters 10 through 12 examine different procedures for hypothesis testing. Chapter 10 considers relatively standard tests, whereas Chapter 11 examines procedures for multiple comparisons and Chapters 12 describe procedures appropriate when the data include numerous censored (less than) data.

1.8 References

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Unwin, J., Miner, R.A., Srevers, G., and McBean, E. (1985). Groundwater Quality Data Analysis. *National Council for Air and Stream Improvement Technical Bulletin, No. 462.*

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1.9 Problems

1.1 The probability of an earthquake of Richter scale 8 (i.e. a very severe earthquake) is estimated as 10^{-12} occurring some time over the next 70 years at location A. The probability of a similar earthquake is 10^{-9} at location B and 10^{-5} at location C.

i) Would you consider the likelihood at location C as being de minimis risk?
ii) How much greater is the risk for C than for A?

1.2 Explain what the term means when you indicate "a 1 in 25-year storm" in your approach to managing the risk of flooding.