Environmental Geology
GEOL 2390

Course Manual

2008 Printing

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The University of Manitoba, Distance and Online Education

Acknowledgments

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Bill Last was born in Illinois and immigrated to Canada shortly after receiving his B.Sc. degree in Geology from the University of Wisconsin in 1971. After four years as a petroleum exploration geologist with Shell Canada Ltd., he moved to Winnipeg where he completed his Ph.D. at The University of Manitoba. He worked as a research officer in the Tar Sands/Heavy Oil Division of the Alberta Geological Survey until 1980 when he joined the faculty at The University of Manitoba in the Department of Geological Sciences.

Professor Last's main research interests lie in the fields of sedimentology, environmental geology, and global change. With over 150 publications to his credit, he has maintained a long research involvement in environmental geoscience in North and South America, Australia, and Asia. His research efforts are currently directed mainly at geolimnology and paleolimnology in western and northern Canada, northern United States, South America, and Australia. He is editor-in-chief of the *Journal of Paleolimnology*, associate editor of *Sedimentary Geology, International Journal of Salt Lake Research, International Journal of Lakes and Rivers*, and *Environmental Reviews,* and past associate editor of the *Bulletin of Canadian Petroleum Geology* and *the Prairie Forum*. He has written or edited six books on paleolimnology and geolimnology, and is the Series Co-Editor of the book series *Developments in Paleoenvironmental Research*. He teaches undergraduate courses in environmental geology, Earth system science, petroleum geology, sedimentology, energy resources, and basin analysis. His graduate course offerings include advanced clastic sedimentology, petroleum geology and geochemistry, and evaporite sedimentology and geochemistry.

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Introduction to the Course

Course description

The University of Manitoba *Undergraduate Calendar* describes GEOL 2390 as follows:

> Examination of geological processes and material as they interact with human activities, environmental planning, and management. Also available by correspondence. Prerequisite: university geology or GEOG 1290 or GEOG 1291 (or 053.129) (C) (or GEOG 1200 or GEOG 1201 (or 053.120) (C)), or consent of instructor.

Geology is the science of the Earth. Environmental geology is that subject area that relates the science of geology to human activities. This is obviously a very broad subject, much too broad to adequately cover in detail in just a single, one-term (thirteen weeks) course. The major emphasis of our studies during this term will be on the impact that humans and society have on the natural geoenvironmental systems and how the science of geology can help mitigate problems associated with society's activities. We will strive to understand the importance of geological sciences in environmental affairs and to show the close relationship between it and everyday human activities. A second important area of environmental geological investigation, namely the geoscience of natural hazards, will only be *reviewed* and rather briefly discussed here. A more complete handling of the geoscience of natural hazards is done in the course Environmental Earth Sciences GEOL 1360, which you may have already taken.

Course goals

Why do we study environmental geology? It is clear that the environment and environmental problems have become matters of intense concern on local, national, and international levels. With this increasing awareness, the need for rational, informed decision making by the public and by policy makers is imperative. Environmental Geology GEOL 2390 has three main goals:

- to present and discuss the role that natural geologic processes play in creating conditions that are detrimental to human activities;
- to assess how human activity can negatively affect the natural geoenvironmental setting on local, regional, and global scales; and
- to examine how the impact of these natural and human-induced processes—human suffering, property damage, and economic disruption—can be mitigated by proper consideration of geologic factors in planning.

As you systematically progress through the course material, you will:

- define the relationship between environmental geology and other branches of physical, chemical, biological, and social science;

- demonstrate how nearly all of our major environmental concerns and hazards are rooted in basic geological processes;
- describe how environmental geology is a collage of many different geological subdisciplines, from hydrology to geochemistry, from economic geology to geomorphology;
- outline how our perception of geologic hazards, environmental and resource conservation, and human interaction with geological processes has evolved over time and is different in various other cultures;
- describe human's role in aggravating normally nonhazardous geologic processes to the point that a threshold is exceeded, resulting in rapid and often catastrophic changes; and
- show how the organization, control, and coordination of new industrial and urban development can be integrated with a basic knowledge of geological processes to protect environmental, cultural, and aesthetic characteristics of the land.

Course materials

The following required materials are available for purchase from the University of Manitoba Book Store. Please order your materials immediately, if you have not already done so. See your *Distance and Online Education Student Handbook* for instructions on how to order your materials.

Required text

Pipkin, B. W., D. D. Trent, Hazlett, R. and Bierman, P. *Geology and the Environment.* (5th ed.). Belmont, CA: Brooks/Cole—Thompson Learning, 2008.

The *Distance and Online Education Student Handbook*

The *Distance and Online Education Student Handbook* is located online in each course site and on the Distance and Online Education website. You can bookmark the site for easy access at your convenience. If you need to order a printed copy, please consult your *Distance and Online Education Guide* staff directory for the general inquiries contact information.

Accessing both the *Handbook* and the *DE Guide* throughout the year provides you with detailed information regarding the management/administrative aspects of this distance education course. The *Handbook* tells you how to access the following:

- Your instructor;
- Writing your final exam at a location other than the University of Manitoba campus;
- Distance and Online Education Student Services;
- Using technology (online access, communication tools);
- The University of Manitoba Libraries;

- Information on ordering your course materials through the University of Manitoba Book Store; and
- Information on accessing your grades and submitting assignments online.

Going online

Interacting with other students

Take advantage of communication tools in the course website. The tools include e-mail, discussion, and chat. Post your questions or comments in the discussion area. Activities such as these provide other students with an opportunity to interact with you. Consider creating online study groups.

Interacting with your instructor

Questions? Concerns? Discussion? Your instructor is prepared to assist you. Do not hesitate to address any concerns regarding the course and assignments directly with your instructor. Check your instructor's contact information to determine how best to communicate—not all instructors communicate online.

Using the libraries

Additional readings enrich your learning experience and your understanding of your course topics. Textbooks and course materials often contain suggested reading lists, and you can search any library, using online library search tools, to find these and other related materials.

Course content

Environmental geology is a very broad branch of *applied* geology that focuses on the entire spectrum of possible interactions between people and the Earth's environment. Obviously no single course can fully cover the wide range of topics germane to environmental geology as modern professional geoscientists view it. The topics you will cover in this course represent an overview of only a few *selected* concepts, processes, problems, and solutions of critical importance to a practising environmental geologist today. The selection and coverage of these topics are based not only on the traditional view of environmental geology as a "corrective" science (the treating of environmental problems after they occur), but also on its role as a "preventative" science (anticipating the problems induced by human interaction with the geologic environment). An important objective of geoenvironmental work and study should be to determine which types of construction and resource extraction methods minimize damages to the land-water ecosystem. This objective must be linked to attempts to understand and find solutions to the environmental problems that exist, whether natural or the result of human activity.

Just a word of advice concerning the use of the course materials: these course notes are intended to **supplement** your textbook reading. I strongly suggest that you spend as much time (and probably even more) reading and understanding the textbook assignments as you do on these course notes. There are many aspects of the course that are not covered in detail in these notes but are discussed at length in the textbook.

I will assume you have already successfully completed one of the introductory first-year courses in geological sciences (e.g., Physical and Historical Geology, Earth and Planetary Science, Environmental Earth Sciences, Dynamic Earth, etc.) or a course in Physical Geography. If you are attempting to take this course concurrently with one of the first-year introductory courses, consult with me to get a supplementary reading list. You will frequently be using the concepts, information, and techniques learned in the introductory course(s) to better grasp the fundamentals of environmental geology. Finally, some comments directed specifically to those who have already taken Environmental Earth Sciences GEOL 1360: you will undoubtedly recognize several areas of overlap between the two courses, notably in the discussion of endogenic and exogenic hazards. This is necessary and unavoidable because not everyone taking GEOL 2390 will have had the benefit of the introduction to environmental Earth sciences via GEOL 1360. Nonetheless, this overlap is good in the sense it will at least help to refresh your memory about the key environmental concepts that were introduced in that first-year course.

The course GEOL 2390 is broadly organized in such a way as to present first the developmental history of environmental geology as a modern science, then the Earth processes that influence human settlements (hazards), and finally with the near-surface and surficial processes that must be understood by planners and policy makers to undertake proper environmental management. Within this broad framework, specific attention will be given to the following topics (in order of coverage):

Module 1 What is Environmental Geology?

Basic concepts and historic development: The general concept, evolution, and perception of environmental geology in science and society.

Module 2 Geologic Hazards

Endogenic hazards: Earthquake and volcanic hazards: mechanisms, potential dangers and sources of damage, prediction, and mitigation.

Exogenic hazards: Flood, mass movement, and subsidence hazards: types, magnitude and frequency analysis, identification, prediction, and mitigation.

Module 3 Geoscience in Coastal Environmental

Geology of the coastal zone: Types of coastlines, water and sediment dynamics, coastal erosion and problem mitigation.

Tsunami and storm surges: Occurrence, prediction of tsunami; geological impact of large storms.

Module 4 Pollution Geology

Geology of pollution: Introduction to geological and geochemical aspects of common pollution problems; water and soil contamination, liquid waste and disposal systems; solid wastes and landfill geology.

Hazardous wastes: types of hazardous wastes and the geology of their disposal problems; mining and pollution, acid drainage and acid precipitation, radioactive waste disposal.

Module 5 Water Resources and Environmental Geology

Water geoscience: water as a substance, the hydrologic cycle, groundwater geology and hydrology, water supply and use, wetlands systems,

Geology of water resources: water resources control by dams, geology of dam sites and dam impacts.

Module 6 Drought, Desertification, Salinisation, and Problem Soils

Drought: Types of drought; role of human actions versus large-scale atmospheric controls.

Desertification and salinisation: Introduction and differences; sources of problems; the salinisation process and sources of salts; management schemes; expansive soils and related problems.

Evaluation and grading

You should acquaint yourself with the University's policy on plagiarism, cheating, and examination impersonation as detailed in the General Academic Regulations and Policy section of the *University of Manitoba Undergraduate Calendar*. Note: These policies are also located in your *Distance and Online Education Student Handbook* or you may refer to Student Affairs at http://www.umanitoba.ca/student.

General guidelines

To meet the course requirements you must complete the following:

- Four assignments of varying weights to be submitted throughout the term. These are worth **40%** of your final grade. Please contact your instructor well in advance if you cannot meet the due dates that are posted below. Marks will be deducted for late assignments unless you have prior permission.
- A final examination that will cover the entire year's work. The final exam will be schedule by the University as indicated in the *Distance and Online Education Program Guide*. The final exam is worth **60%** of your final grade.

Distribution of marks

Assignment	Percentage
1	5
2	8
3	15
4	12
Final examination	60
Total	100

Please note: All final grades are subject to departmental review.

Assignments

You will be asked to use the knowledge you have assimilated in the course to examine, evaluate, and solve a variety of practical environmental geology problems. There will be four assignments that will help you to bridge the gap between the theoretical aspects of the science and the practical application of these concepts. Most of the questions posed in the assignments are straightforward short-answer type of queries requiring that your recall some key points or information from your textbook or course manual. Some, however, require more extended thought and/or actual manipulation of data to arrive at a suitable response. It is very important that you think about and work through these “practical” problems as completely as possible. Environmental geology is very much a practical, applied, and pragmatic science whose goal is to generate viable and reasonable solutions to perceived or anticipated problems. Your ability to *apply* what you have learned is the single most critical factor in successful completion of this course. Although the problems you will be solving are based on real-world data and situations, in order to complete the tasks asked for in a reasonable amount of time, simplifying conditions and constraints are often built into the exercises.

My philosophy about assignments/exercises (and even examinations) is that they should be learning experiences. If you submit an answer that is subsequently marked incorrect or there are points taken off, please do take the time and make the effort to sort out what went wrong. However, please accept that in no cases will I simply give you the 'correct' answer. But I will try to point you in the right direction and will work with you in order to get a more acceptable approach to the particular problem.

Finally, you should be aware that the four exercises/assignments are not intended to cover all aspects of the course. In particular, the final three units of the course (Units 10, 11, and 12) are not covered in any of the assignments.

In total, the problem sets and exercises you are assigned during the term are worth **40%** of your final mark. Assignment title sheets are located at the back of the course manual. Please note that marks will be deducted for late assignments (unless you have prior permission from the instructor); see below.

Assignment due dates

Assignment	Sept.–Dec.	Jan.–Apr.	May–Aug.
1	October 10	February 8	June 10
2	October 24	February 26	June 24
3	November 7	March 8	July 7
4	November 21	March 22	July 21

If you need to write the final exam at a location other than the University of Manitoba main campus, you must complete an application. Please consult your *Distance and Online Education Student Handbook* for directions.

Note: If the assignment due date falls on a Saturday, Sunday, or statutory holiday, it will be due on the next working day. If the assignment due date falls during the Mid-term Break in February, it will be due on the Monday following the Mid-term Break. If you are unable to submit an assignment on time, contact your instructor well in advance of the due date. Marks will be deducted for late assignments (unless you have prior permission): 35% penalty for up to one week and additional 25% for each week (or fraction) thereafter.

Final examination

This examination will be designed to test not only your grasp of the theoretical concepts of environmental geology, but also the more practical critical evaluation and problem-solving abilities you have acquired. Questions for the final examination are taken from both the course manual (notes) and from the textbook reading assignments. The format of the final examination will be a combination multiple choice and long answer/essay type. For the essay part, you will be given a choice of questions (i.e., respond to 3 of 4 or 4 of 6, etc.)

Grading scale

Letter grade	Percentage range	Description
A+	90 – 100	Exceptional
A	80 – 89	Excellent
B+	75 – 79	Very good
B	70 – 74	Good
C+	65 – 69	Satisfactory
C	60 – 64	Adequate
D	50 – 59	Marginal
F	49 and below	Failure

A word of caution about the assignments and the final examination

Some students find that they do very well on the assignments, but they do not do nearly as well on the final examination. While your grades on the assignments will give you some idea of how well you are mastering the material, they may not indicate how well you will do on the examination because the examination is written under very different circumstances. Because the assignments are open book, they do not require the amount of memorization that a closed-book examination requires nor are they limited to a specific time period. Some students have told us that, based on the high marks they received on the assignments, they were overconfident and underestimated the time and effort needed to prepare for the final examination.

Please keep all this in mind as you prepare for the examination. If your course has a sample exam or practice questions, use them to practice for the examination by setting a time limit and not having any books available. Pay careful attention to the description of the type of questions that will be on your final examination. Preparing for multiple choice questions involves a different type of studying than preparing for essay questions. Don't underestimate the stress involved in writing a time-limited examination.

Your Course at a Glance

Week 1: Introduction to the Course and Unit 1	Week 2: Unit 2	Week 3: Unit 3
Topic What is environmental geology: Basic concepts and historical development? **Activities** • If you live outside Winnipeg and your course has a final examination, please submit the "Application Form for Examination at a Location Other than the University of Manitoba Campus" immediately. Refer to the *Distance and Online Education Student Handbook* for more information. • Check to be sure that you have all the course materials. • Complete the activities for unit 1.	**Topic** Geologic hazards: Introduction to geologic hazards **Activity** • Complete the activities for unit 2. • Review the requirements for all assignments and the final examination.	**Topic** Geologic hazards: Endogenic geologic hazards **Activities** • Complete the activities for unit 3. • Begin work on assignment 1.
Week 4: Unit 4	**Week 5: Unit 5**	**Week 6: Unit 6**
Topic Geologic Hazards: Exogenic hazards **Activities** • Complete the activities for unit 4. • Continue working on Assignment 1; this assignment is due no later than Feb. 8. • Review the materials for units 1–4 to consolidate your understanding.	**Topic** Coastal environmental geology: Coastal problems **Activity** • Complete the activities for unit 5. • Begin work on assignment 2. **Assignment 1 due no later than Feb 8**	**Topic** Coastal environmental geology: Tsunami and storm surges **Activities** • Complete the activities for unit 6. • Continue working on Assignment 2; this assignment is due no later than Feb 26 • Check the U of M website for the date and time of your exam.

Week 7: Unit 7 **Topic** Pollution geoscience: Geology of pollution **Activities** • Complete the activities for unit 7. • Begin work on assignment 3. **Assignment 2 due no later than Feb 26**	**Week 8: Unit 8** **Topic** Pollution geoscience: Hazardous wastes **Activities** • Complete the activities for unit 8. • Continue working on Assignment 3; this assignment is due no later than March 8.	**Week 9: Unit 9** **Topic** Water resources and environmental geology: Water geoscience **Activities** • Complete the activities for unit 9. • Review the materials for units 5–8 to consolidate your understanding. **Assignment 3 due no later than March 8**
Week 10: Unit 10 **Topic** Water resources and environmental geology: Geology of water resources modifications **Activities** • Complete the activities for unit 10. • Begin work on Assignment 4; this assignment is due no later than March 22	**Week 11: Unit 11** **Topic** Drought, desertification and salinisation: Drought **Activities** • Complete the activities for unit 11. • Begin reviewing material for the final examination. **Assignment 4 due no later than March 22**	**Week 12: Unit 12** **Topic** Drought, desertification and salinisation: Desertification, salinisation, & problem soils **Activities** • Begin the activities for unit 12. • Continue reviewing material for the final examination.
Week 13: Unit 12 **Topic** Drought, desertification and salinisation: Desertification, salinisation, & problem soils continued **Activities** • Complete the activities for unit 12. • Prepare for the final examination.	**Complete and submit the online course evaluation form.**	

Module 1
What is Environmental Geology?

Notes

Unit 1
Basic Concepts and Historical Development

Topics

Introduction, definitions and scope of environmental geology

The role of Earth science in environmental science

Historical development of environmental geology

Modern environmental geology

Sources of environmental problems

Introduction

We begin by describing the basic concepts and fundamentals of environmental geology and looking at key historical developments of the science. We will trace the evolution of environmental geology as a branch of the Earth sciences and examine how this evolution has been affected by cultural preferences and scientific discovery.

Learning objectives

In order to profit from your exposure to environmental geology in this course, you must first be aware of how this branch of Earth science is viewed by geoscientists today, how it came to be a separate subdiscipline of the Earth sciences, and how it is related to other branches of geology as well as to other sciences. You should also be aware, if you are not already, of the parallel historical developments and evolution of the conservation movement in Western society and the role this movement played in the formulation of environmental geology as we now practise it.

By the end of this section you should be able to:

- identify why environmental geology is more pertinent now than it was 10, 50, or 100 years ago;
- define "environmental geology";
- relate environmental geology to ecological and environmental ethics;
- name the factors of "Western civilization" that are most responsible for environmental degradation;
- discuss the problem with the term "environmental geology" and explain why it is essential to maintain the use of this terminology;
- differentiate between corrective geology and preventative geology;

- specify the role that religion has played in causing and perpetuating environmental disruption;
- cite examples of early efforts to use environmental geology, particularly with regard to “Old World” urban and landscape problems;
- summarize the more noteworthy accomplishments of environmental geologists of the late nineteenth and early twentieth century;
- describe the role(s) of environmental geology in military activities;
- examine the ways in which environmental geology has changed since World War II;
- critically evaluate why society has been slow to accept geological conservation;
- list the basic underlying, unchanging, unifying concepts that control nearly all aspects of environmental geology;
- relate the concepts of feedback and threshold to environmental geology;
- assess how rates and changes in rates of geological processes are viewed in environmental geology; and
- identify the two most pressing problems or sources of problems in environmental management and discuss these problems in light of environmental geology.

Before you begin this unit

1. If you live outside Winnipeg and your course has a final examination, please submit the “Application Form for Examination at a Location Other than the University of Manitoba Campus” immediately. Consult the *Distance and Online Education Student Handbook* for information.
2. Check to see that you have all your course materials.
3. Skim the course manual and the textbook to get an idea of what the course is about.
4. Review the requirements for the assignments and the final examination.

Learning activities

1. Read the study notes and answer the review questions.
2. Read pages xii–xvi, 1–69 in your textbook and answer the study questions at the end of each chapter. Note: much of chapters 2 and 3 should be **a review** of material you learned in your first-year geoscience course.

Study notes

Introduction, definitions, and scope of environmental geology

Environmental geology is composed of a very diverse collection of subjects, including engineering geology, economic geology, sedimentary geology, process geology, geochemistry, and geophysics. Although I have taught introductory courses in environmental geology for nearly a quarter of a century, I have constantly advised the curriculum developers that the topic of environmental geology is best taught only as a senior undergraduate or graduate-level course! Why? Because few persons ever become knowledgeable enough in all aspects of environmental geology until the latter part of their university experience. The tremendous breadth of knowledge required by a practising environmental geologist is a function of the wide range of geological factors that can interact with human activities and the great many ways in which people can adversely affect the geological environment.

In many respects environmental geology is a branch of ecology dealing with relationships between humans and their geological habitat. A basic law of ecology (stated very simply) is: everything is related to everything else. Geology—the study of the Earth and Earth materials/processes—has significant and direct applications to the atmosphere, hydrosphere, and biosphere, as well as the very obvious links to the lithosphere. The lithosphere is the ultimate source of nearly all of our minerals, fuels, industrial products, and building/construction materials required by today's society. The weathered lithosphere, or soil, is essential for life. The atmosphere controls to a major degree what raw materials people require, what can be derived from the weathered lithosphere, and ultimately what type of weathering the lithosphere is undergoing. The hydrosphere is likewise fundamental to all life, and it provides very important roles in waste disposal, cooling, and recycling of elements.

The broad arena of environmental science can be very simply defined as the study of natural processes and their interaction with each other and with humans. In this course we are concerned with the geologic aspects of the environment: their effects on people, and people's effects on the environment.

Much has been written about the precise meaning of the term environmental geology. No other branch of the Earth sciences has received such a detailed discussion and scrutiny about its name. Environmental geology is not a new field of investigation. In the 1850s von Cotta wrote a textbook titled *The Geology of the Present*, which included virtually all aspects of modern environmental geology. In Europe, anthropogenic sedimentation (or increased sedimentation due to the onset of human activities) was recognized as a major problem over a thousand years ago. In 1826 von Grouner wrote a major treatise on the use of geology in military science—a theme that dominated environmental geology for over a century!

However, large-scale public awareness of this branch of geology *per se* did not come about until the latter part of the 1960s. The 1970s have often been called "the environmental decade," and there was very rapid advance and dramatically increased awareness of the role of geology in environmental issues during this time. In contrast, the various energy and mineral resource crises that presented themselves during the 1980s and 1990s have caused people to hail the last two decades of the twentieth century as "the resource decades". Clearly, environment, energy, and minerals are all intricately interwoven; this complex and still incompletely understood relationship is a fundamental theme in this course.

There are other environmental geology themes that we will examine. For example, we need to realize that environmental concerns act as a two-way street: human activities greatly alter the land-water ecosystem, and natural processes, in turn, can produce significant losses for human society. The delicate balance between society and the geoenvironment must be constantly at the forefront of our discussion of environmental geology in this course.

The post-1990s era has witnessed a renewed public and government awakening and a new perception of environmental matters, which have been manifested in many ways. Numerous environmental laws have been enacted to safeguard people and their investments from pollution and other forms of air, water, and land degradation. The past decade has also been a period of massive environmental changes produced by the combination of urbanization, population growth, and new technology and fuels.

Two major points need emphasizing here. The first point is that environmental geology is a field that has grown out of a *social* need to broaden the application of Earth sciences. Particular emphasis is today being placed on problems associated with industrialized society's use of the Earth and its resources. The basic tenet is that society can better manage the Earth's natural resources if society (or at least its decision makers) knows something about the Earth. The second point is that with more pressure on the Earth to supply energy, materials, food, recreation, etc., the more complexity is built into the system. The more complex the system is, the more vulnerable it is to disruption. As this vulnerability increases, the margin for error decreases, and the probability of disaster (natural and human-induced) increases. These two basic themes will arise many times during this course.

What's in a name?

Much controversy over use of the term "environmental geology" arises from the obvious semantical defect: if geology is the study of the Earth and changes on or in it, whether from natural causes or human activities, then the term "environmental geology" represents "terminological inexactitude"; the two terms, when used together, are redundant. It can be argued nearly *all* of geology is environmental geology! However, some fields of geology relate to humans more than others. Economic and petroleum geology, for example, are directly and intimately concerned with obtaining the Earth's natural resources in order to sustain the endeavors of society. Engineering geology is involved with the evaluation of Earth materials and their stability in construction efforts by human.

In similar ways, many other subdisciplines of geology have important environmental roles to play. The geophysicist can provide valuable information about earthquakes; the volcanologist can assist in giving important information about volcanic hazards; the geochemist can give significant data on pollution and waste products; the geohydrologist can offer insight in water resource analysis and management, as well as flood mitigation. Thus, environmental geology is a collage of many geological subdisciplines. Furthermore, it considers humans as a force that changes nature. Finally, it must be emphasized that almost all of environmental geology is the *practical application* of the geological sciences in the service of society. This cannot be overemphasized, environmental geology is fundamentally straightforward geology that is keyed to solution of practical and critical problems facing society.

Thus, a definition of *environmental geology* is the application of Earth sciences to the benefit of humans and the biosphere; it is the integrated application of many branches of Earth science. Importantly, in this course we will often be taking a pragmatic viewpoint of environmental geology. Much of environmental geology today is aimed at attempting to replace "corrective" geology with "preventative" geology. Corrective geology implies treating the environmental problem or consequence of the hazard *after* the human activity has interfaced with it; preventative geology is the anticipation of the problem and the application of social, scientific, and technological means to avoid major negative consequences. Geology is excellent for this purpose because it is a "retrodictive" science, unlike engineering, biology, chemistry, etc. On the one hand it is basically an historical science, but on the other it is largely predictive.

Scope of modern environmental geology

The scope of environmental geology is so broad that it encompasses not only the subdisciplines of geology but also areas that are of interest to other physical, biological, and social sciences. Environmental geology is a true multidiscipline with significant interdisciplinary character.

The subject matter of environmental geology includes all human-related aspects of Earth materials, Earth processes, landforms, and rate and time considerations. It comprises a wide spectrum of such topics as the location and mining of natural resources, the evaluation of physical and chemical changes in the land-water ecosystem when human action rearranges Earth materials or interferes with natural processes, the assessment of either endogenic or exogenic Earth forces and hazards that affect human health and safety, and the determination of energy systems for use and storage and elimination of waste products. Implicit in these topics is the inclusion of such aspects as conservation, reclamation, and planning.

Thus, environmental geologists very often become involved in policy matters. They become part of the decision-making process whenever it involves planning and management of features relative to the surface of the Earth or extractable Earth materials. For example, many flood-control projects are designed for the "100-year flood" event. The data on flood magnitude and frequency that the environmental geologist supplies in such projects are crucial to the design of the structure or to factors such as zoning and urban development.

The role of Earth science in environmental science and environmental problem solving

“Environment,” “ecology,” “ecosystems,” “pollution,” “global change,” “greenhouse warming” are words that are in the headlines and television news broadcasts almost daily. The environment and problems with the environment have been important rallying cries in recent years. Some critics have tried to pass off our current preoccupation with environmental concerns as sensationalism, extremism, bandwagon trends, or doomsday predictions. Most scientists, however, in government, academia, and industry, recognize the basic legitimacy of much of the environmental rhetoric. Unfortunately, all too often the fundamental role that the geosciences play in the planning and execution of society’s stewardship of the Earth is lost, or at best set aside in favor of more “obvious” or more immediate pursuits.

As environmental geologists, we must face up to two distinct and often significant gaps in knowledge: “theirs” and ours. The “they” are those people who deal with the Earth as planners, developers, administrators, policy–makers–people who are not geoscientists but who need geologic information to perform their jobs. Their knowledge gap can be filled much more easily than ours. We must simply establish and maintain communication.

Much has been said about this communication problem, and it has not been completely solved. Nonetheless, we know what the problem is and, in general, progress toward solving it is encouraging. For example, only few years ago it was unheard of to have a geologist involved in planning an urban landfill. This important task was almost exclusively the domain of the municipal planner, engineer, and public health officer. Now, certainly at the federal and provincial levels, and even in many local government circles, it is recognized that geologic appraisal and advice is absolutely essential in the siting of sanitary landfills.

The other and more serious knowledge gap is ours. This knowledge gap is, in part, a “map gap” and, in part, a “rate gap.” In fact, there is still much that we do no know about the processes operating at or near the surface of the Earth. Indeed, in many places in both developed, highly industrialized nations and in the Third World, rapidly developing countries, we do not have a model (i.e., geologic map or understanding of the geology) of the Earth's surface and near surface at a scale and with accuracy sufficient for even the most basic land use planning, nor do we have adequate information on rates at which many geologic processes work. For example, it is somewhat surprising that in most drainage basins of the world we do not know *how much* sediment is being removed from the area, or *where* is it going, or *how fast* it is getting there, or what *effect* this dissolved and particulate material is having on lakes, reservoirs, rivers, estuaries, and coastlines. Quantitative answers to questions about what processes are now operating clearly must come before we can quantitatively predict what the consequences of society’s impact is on the environment.

The term “environment” is usually used to describe the entire composition of our human surroundings and all our works. It also includes those conditions and materials that influence the character of the natural setting, such as the weather, water, soils, rocks, flora, and fauna. “Ecology” is the science that deals with analysis and interpretation of life forms and their relation to the environment. The emphasis in ecology is usually placed on the organic, whereas in environmental geology we will most often be discussing reactions and phenomena that are either inorganic or a combination of inorganic and organic. The interactions of the biotic community with its physical environment constitute an ecosystem. Humankind, as an organism, cannot be divorced from these relationships because we play an integral part in creating changes in both the organic and inorganic components that constitute the system.

Although there are many different types of ecosystems, they have common elements. Ecosystems involve the transfer of matter and energy into new forms that represent stability for the system. A fluvial drainage basin, for example, constitutes one variety of a land-water ecosystem in which the stream characteristics and its channel are adapted to the physical variables inherent in the basin (i.e., soil, bedrock, topography, precipitation, etc.). When we alter these components, physical changes will occur in the geohydrologic character of the stream, which then affect the channel morphology, capacity, and competence.

The human environment consists essentially of the Earth's natural resources and the cultural (human) modifications of them. Natural resources, then, are those materials, organisms, localities, and Earth processes that are useful or of value to society. It follows from this that nearly everything on Earth qualifies as a resource: air, water, soil, minerals and rocks, organisms, all forms of energy, etc.

Historical development of environmental geology

Although it was not until the 1960s that the term “environmental geology” appeared in print, humans have been using geology in the development of society for much longer. Much of human history is interwoven with the geoenvironmental setting. What we (as humans) were able cultivate depended on soil and climate conditions, which, in turn, were basic functions of the geological setting. What we constructed our dwellings and other buildings from was controlled by the availability of natural geologic materials. Items that were not locally abundant but yet deemed necessary for the development of the society were traded, bartered, or purchased by revenue obtained from local materials.

During much of early human social development, man was a nomad, moving with the food supply and only staying in one place sufficiently long enough to irreversibly damage the environment’s ability supply food and habitat. The first major environmental impact by humans came with the discovery of creation and control of fire. This was not only the start of human-induced pollution but also signaled large increases in erosion rates. Prehistoric (and historic!) practices such as slash-and-burn led to significant increases in rates of erosion and correspondingly high sedimentation rates in lakes, rivers, and coastal areas.

Another major impact by early humans occurred when the nomadic life was changed to more agrarian activities. This Agricultural Revolution was synchronous with the domestication of animals for food. Clearly this new approach to organized society required a more sedentary life style and the concentration of both human and animal populations in relatively small geographic areas. Humans developed tools to artificially disturb the soil, which brought about even more extensive acceleration in soil erosion. There are many instances in which convenience and/or comfort for human settlement superseded the possible dangers that existed within the geoenvironment. For example, we settled in the shadow of volcanoes because the soil was rich, or on floodplains because of the combination of fertile soil, level ground, and easy access to water and waste disposal.

With the increased emphasis on concentrated populations, the need expanded for more complex tools and equipment for the construction of dwellings and other necessities. As early as 8,000 years B.P. copper was extensively used; bronze (copper and tin) came into use about 5,000 years ago, and iron about 1,500 years after that. The first major cities, with populations exceeding 20,000, had developed by 5500 yr B.P.

Although the rise and fall of any particular urban center or concentrated civilization generally has several interrelated causes, geoenvironmental factors have contributed to the decline of several. For example, many experts cite the loss in soil fertility due to salinisation, one of the topics we will explore later in the course, as the main cause for the demise of several Middle East empires. The well-known Mayan Empire of the Americas likely failed because the slash-and-burn agricultural techniques caused excess erosion and siltation of lakes and water sources. It is now well known that drought, and the resulting changes in the Nile's flow regime, was the principal cause of famine, and other significant civilization disruptions and declines about 4,000 years ago in Egypt.

Another example of social upheaval that is frequently cited is the decline of the Roman Empire. Although this case is much more complicated than that of ancient Egypt or the Americas, the fall of Rome is clearly related to at least several major geoenvironmental factors. The climate in much of Europe and western Asia was gradually becoming drier. This caused lower populations of game animals, which ultimately led to large-scale migration and population pressure by the so-called barbarian hordes. Furthermore, much of the Roman military (and, hence, the expansion of the Roman Empire) was financed by mines in Spain. However, by about 100 A.D. mineral production had peaked and for the next 200 years continuously declined. Because metals (silver in particular) were the foundation of the Roman monetary system, this resulted in the gradual increase of a less efficient “barter economy.” Finally, one of the initial reasons for early colonization of the southern Italy region by the Greeks was the high fertility of the soils and the development of wheat-based agriculture. However, by 200 B.C. grain production in most of the region had become unprofitable due to decreasing soil quality, erosion, and loss of productivity. With dwindling grain supplies, Rome was forced to rely on the much more expensive imports of wheat from their distant colonies, which, in turn, led to spiralling costs for basic foodstuffs and other commodities. This combined loss in land productivity and high costs of food resulted in a greatly weakened socio-political structure of the society.

Conservation philosophy

Many other examples will be mentioned later in these course notes and in your textbook. It is apparent that throughout history society has been remarkably slow to develop conservation methods for the environment. This reluctance is generally viewed to be the result of philosophical deterrents rather than knowledge or practical limitations. For example, society has often viewed "man" as the superior being, implying that the rest of nature is simply on Earth for our benefit and use. Thus, instead of adopting a position of stewardship, society has often adopted the role of as master.

We have often liked to think of the environment as self-healing. This certainly was the attitude of many early cultures that saw constant seasonal renewal and regeneration and extrapolated these observations to be true of all nature. Thus, even though humans might change or destroy certain environmental components, this loss was viewed as being temporary only; nature would have a rebirth and renewal, given sufficient time. Closely associated with this philosophical stance is the belief that nature is cyclic. The observation that all things progress through a series of stages that humans are powerless to change leads to the logical conclusion that humans need not attempt to carefully manage their resources. This view of inevitability of natural trends greatly hastened the depletion of many of the ancient world's environments.

Finally, a philosophical stance that is still very much evident today is the "now generation" approach to life. People want all the benefits at the present time and certainly during their own lifetime. Thus, we find that Earth materials, fuels, and minerals have been (and still are) extravagantly used and abused because little thought is given to future generations. Also closely associated with this view is that the Earth's resources are plentiful (inexhaustible) and even if somehow a particular resource were to become scarce, there are always new frontiers and sources. Probably no better example of this philosophy can be found than is commonly cited with respect to energy resources.

Modern environmental geology

The mission of environmental geology, then, is to develop information about the Earth, Earth processes, and human interactions with the Earth for public purposes. This must be done in a systematic manner, focussing on the problem(s) or perceived problem(s). Most importantly, the results of environmental geology must be useable to the educated layperson. In summary, essentially environmental geology is "normal" Earth science activity that is directed and has a major emphasis on practical applications and on communication with the public.

Much of the practice of environmental geology stems from several fundamental concepts. Most of these are applicable to all subdisciplines of environmental science, but several (e.g., uniformitarianism, feedback, and threshold) have special and direct implications for environmental geology.

- We are dealing in nearly all cases with a closed system. For example, a common misconception is that flushing pollutants into the aqueous environment somehow gets rid of them. This is the "out of sight, out of mind" and "the solution to pollution is dilution" philosophy. However, pollutants only appear to go away. In actuality, they simply relocate from one place to another or from the land to the lake, river, or ocean. They may even become absorbed and hidden, or chemically altered. But they still are in our environment. Geologists understand the fallacy of such thinking today; for the most part, Earth experiences neither gains nor loses of significant material to space; material is merely transferred and later recycled. In short, if you dump something toxic, sooner or later it affects you or others.
- The Earth is presently our only habitat and resources are finite and limited.
- Uniformitarianism does apply, but uniformitarianism says nothing about rates. The geological processes may be the same throughout the 5–billion-year history of our planet, but the rates at which given processes occur can and do vary dramatically.
- There always have been natural hazards. There is nothing to be done to stop most of them. Thus, many times simple avoidance is the only way to mitigate the hazard threat.
- Proper planning must consider both economics and aesthetics.
- In environmental geology we must try to consider the cumulative effects of an action. In some cases, the solution to a geologic environmental problem in one area results in development of the same problem, or a different one, in another area. This is referred to as a displaced problem. For example, taller smokestacks in the Midwest United States and east-central Canada industrial areas have greatly reduced local industrial atmospheric pollution. However, industrial gases, which are now injected into high-altitude winds, are carried much farther eastward and have increased acid rain in northeastern United States and Canada. Along shorelines, migrating sand replenishes eroding beaches. Where erosion has been severe, structures, called groins, are often built perpendicular to the coast in order to trap migrating sand and build up the beach. Groins are locally successful for their intended purpose, but they often create a displaced problem by causing or increasing erosion on the other side of the groin complex.
- Few geologic environmental problems are ever truly solved, but some can be or have been reduced in severity. To reduce severity and to prevent displaced problems, it is essential to understand the dynamic and interrelated nature of Earth processes. Unless we do, the solution to a

problem in one area may lead to the development of another problem in an adjacent area.

- The geologic environment and the underlying geologic factors in environmental planning are the *most basic* and *fundamental* components to consider.
- Complexity is the norm in natural processes and systems. The implication of this is that many factors influence an action. This is in direct conflict with the simplicity of the law of parsimony, which contends that the “correct” answer lies with the least complex alternative.
- Every action will have a feedback on some other component of the environmental system. The classic example of this is groundwater use by a municipality. Overpumping of the groundwater results when withdrawal rates are greater than recharge rates. This leads to a lowered water table, which leads to collapse and subsidence of the surface of the land. The lowered water table also feeds back to the economics of the use of groundwater: drilling costs are higher because deeper drilling is required to reach the groundwater. In addition, in much of western Canada the deeper water is of poorer quality (higher salinity), which leads to salinisation of the soils when used in agriculture. Salinisation leads to loss of fertility, which causes a decrease in the carrying capacity of the land. Complex feedback loops like this exist in virtually every other type of environmental geology problem or hazard.
- Threshold concept: a great many geologic systems have a critical point. If stress is applied which exceeds this critical point, the system changes rapidly, often with extreme negative results. This threshold concept is not unusual and is found in many other natural science systems: in physics an example is critical mass; in engineering an example is bearing load; in geography and agriculture an example is the carrying capacity of the land; in rock mechanics and mining an example is yield strength of the material; in hydrodynamics examples are Froude numbers and Reynolds numbers.
- Recurrence intervals are an important but often misunderstood component of environmental geology. Even some of our worst geohazards, such as a major river flood or an earthquake, begin to fade from people’s memories after 5 to 10 years. After just one generation (~25–30 years), recollections of the event become mostly anecdotal. This inevitably leads to the attitude “it hasn't happened in years, so why worry.” Because geologists have a special perception of time (geological time) we are in a particularly unique position to evaluate the fallacy of this kind of approach. Because we are trained to consider the long-term history of an area, we fully understand that if a destructive geologic event has occurred here before, it undoubtedly will occur again.
- Environmental decisions involve and produce conflicts. These conflicts tie in closely with society’s basic ethics of resource management. There are essentially three “end-member” viewpoints of resource management. Often

political parties, governments, administrations, and company managers are categorized as one or other of these types:

Utilitarian ethic (good environmental management means mastery over nature).

Conservation ethic (good environmental management means maximizing the use of the resources through time).

Preservation ethic (basically that the only environmental management that is necessary is preservation: we should not make any basic changes or alterations in natural areas).

In North America, the conflict between preservationists and conservationists was very noticeable in the nineteenth century with the long-standing disagreements between J. Muir (preservationist) and G. Pinchot (conservationist). Similar arguments are raging even today as exemplified by conflicts over water use in Alberta, dam construction in Saskatchewan, or oil and gas drilling in national parks and wild areas of Alaska.

Sources of environmental problems

Obviously, today there are many factors that can be cited in causing or contributing to environmental problems. Ultimately, the two most important causes of problems are population and urbanization.

Population density of the Earth overall is about 30 persons per km^2, but the actually spatial distribution is very poor. Densities range from less than 2 persons per km^2 to greater than 5,000 persons per km^2. The present rate of growth of population is about 1.7% per year. Although short-term prediction is very imprecise, it is abundantly clear that we are dealing with exponential growth. Thus, in virtually all aspects of environmental geology an understanding of the arithmetic of exponential growth is essential. Certainly this is the single most important concept in areas such as oil and gas resource management and base metal exploration and development.

A growth rate of 1.7% per year means that growth is occurring at a constant or fixed percentage per unit time. Thus, the time required for the quantity to double in size (i.e., increase by 100%) is fixed. This is referred to as the doubling time or T_2. In very broad general terms, the doubling time can be approximated by $T_2 = 70/p$; where p is the percentage increase per year. For example, in the case of population, $T_2 = 70/1.7$ or approximately 41 years. This means that about every 40 years the population of the Earth doubles. It is interesting to calculate the doubling times of the use/consumption of geologic resources such as oil, gas, coal, metals, etc. For example, our record of long-term use of fossil fuels indicates an average increase in consumption of 7% per year. The repercussions of exponential growth are truly impressive. Some generalizations of the arithmetic of exponential growth are:

- Exponential growth is characterized by a doubling of the quantity in a fixed period of time.
- Just a few doublings can generate huge quantities.

- The size (quantity) of material after each doubling is always greater than (or possibly equal to) the sum or total quantity of the material before the doubling took place. Using our example of consumption of oil and gas, with a growth rate 7% per year, $T_{2\text{ is}}$ ten years. Thus, the total amount of oil and gas that will be needed between 2,000 and 2010 is greater than the total amount of oil and gas consumed from 1850 to 2,000!

The implications of exponential growth to world population growth in a finite environment are obvious. The favourite story that is often cited in introductory geology and ecology courses is that of the bacteria in a bottle. Assume that bacteria grow by simple division: one bacterium becomes two; two become four; four become eight, etc. Also assume that the bacteria are growing at a rate of 1.16% per second (i.e., T_2 = 60 seconds). You place one bacterium into a bottle at 11 am and notice the bottle is completely full at 12 noon. If you were to map this growth you would notice the following: at 11:54 the bottle was 1/64 full; at 11:55 it was 1/32 full; at 11:56 it was 1/16 full; at 11:57 it was 1/8 full; at 11:58 it was 1/4 full; and finally at 11:59 it was 1/2 full. At 2 minutes before noon (11:58) you realize what is going to happen and you make a frantic effort to find more room (more bottles; or more “resource’). At 11:59 you rejoice in finding 3 new empty bottles; a total of four times the space (resource) that you started with. How long will this resource bonanza satisfy your growing population? Just 2 more minutes! At 11:59 the first bottle is 1/2 full; at 12:00 noon the first bottle is full; at 12:01 both the first bottle and second bottle are full; at 12:02 all four bottles are full! It is most instructive to think about how close to noon we are with respect to natural resources.

In any type of discussion of growth in a finite environment (whether it is population growth, energy consumption growth, growth in the use of zinc, etc.) it is essential to realize the options that are available (presuming, of course, that the resource is finite). In population dynamics, there are two basic options:

- Population crash.
- Gradual approach to zero population growth.

Obviously, the first is not preferred by most of society. It would result in starvation, famine, and chaos until a new population level is attained. Some population dynamics studies suggest that this could occur by 2030. The second is a preferable scenario assuming that:

- We have not already exceeded the threshold level with respect to essential resources.
- Humanity can or will slow its growth voluntarily.
- There are sufficient resources left to maintain the stabilized level of population (estimated to be 8–16 billion).

We will postpone a detailed discussion of the second most important factor/cause of environmental problems—urbanization—until later in the course. Suffice it to mention here that urban populations are growing at a much faster rate than the overall growth. The problems associated with urbanization include encroachment into areas that are less desirable (geologically), and the concentration of human activity in relatively small areas can initiate and accelerate many normally nonhazardous geologic processes.

Key concepts and terms to remember (see also concepts lists in the assigned reading)

closed system	law of parsimony
complexity	map gap
conservation ethic	military geology
corrective geology	population growth
cumulative effects	population crash
doubling time	preservation ethic
ecology	preventative geology
ecosystem	rate gap
environment	recurrence interval
environmental ethics	residence time
environmental unity	self-healing
environmental geology	terminological inexactitude
exponential growth	threshold
feedback	uniformitarianism
geology	utilitarian ethic
knowledge gap	zero population growth

Review questions

(Also examine the review questions in your textbook.)

1. Give two reasons why the term “environmental geology” should be *kept* (i.e., not abandoned as suggested by some Earth scientists)
2. Briefly explain the concept of threshold with regard to environmental geology. Give an example.
3. Explain the concept of doubling time.
4. Explain the meaning of the statement by Thomas Malthus that “the power of the population is infinitely greater than the power in the Earth to produce subsistence for man.”
5. Give two examples of “feedback” in environmental geology.
6. Society has been slow to accept geological conservation. List three possible reasons for this slow acceptance.
7. Describe an example (past or present) of environmental geology being used in military activities.
8. Why is geology a retrodictive science?
9. Define “uniformitarianism” and discuss it in the context of environmental geology.

Note: Sample answers are given in the Answers Appendix.

Notes

Module 2
Geologic Hazards

Notes

Unit 2
Introduction to Geologic Hazards

Topics

Introduction to geologic hazards

Classification of hazards

Overview of geologic hazard mitigation

Introduction

Geologic hazards have affected the lives of many North Americans. This section will set the stage for our brief overview discussion of natural hazards by describing the range of natural hazards and identifying some of the broad actions that environmental geologists can suggest to planners and decision makers in an effort to mitigate the effects of these hazards. Remember, a more complete handling of the topic of geohazards is done the course Environmental Earth Sciences.

Learning objectives

A significant part of the effort of many environmental geologists today can be broadly classified as "hazard" geology—the investigation of processes that have potential for harmful impacts on people. The single most important point to realize in hazard geology is that the geologic process in itself is usually not a geologic hazard. Indeed, many times the processes are greatly beneficial to human activity, such as is the case with volcanoes and floods. It is only when the process (or some result of the process) poses a threat to society that we can speak of it as a geologic hazard.

There are many kinds of hazards, both natural and induced by humans. The objective of this section is to provide an overview of the range of processes that can be identified as natural hazards and to summarize the spectrum of mitigation techniques that can be recommended by the environmental geologist.

By the end of this section you should be able to:

- summarize the major genetic groupings of hazards;
- differentiate natural and technological hazards and give examples of each;
- discuss hazard prediction;
- explain how society perceives hazard severity; and
- summarize the main avenues or techniques that geologists can use to mitigate losses from geologic hazards.

Learning activities

1. Begin reading chapters 4 and 5 (pages 70–147) in your textbook and answer the study questions after each of these chapters. You should plan to complete this reading by the end of unit 3.
2. Read the study notes and answer the review questions.
3. Begin working on Assignment 1. This assignment should be submitted to the Student Services Office no later than the deadline date indicated in the Assignment due dates.

Study notes

Introduction to geologic hazards

Although other courses offered in the Geological Sciences Department provide a more complete treatment of geologic hazards, it is absolutely essential that anyone taking GEOL 2390 be aware of the importance of this topic, if for no other reason than purely economics. Geologic hazards very often lead to significant economic losses as well as loss of life and property. Furthermore, many geologic hazards can influence very large regions of the globe. It is also entirely appropriate to devote a small part of our discussion to hazards simply because they constitute the most dramatic evidence of nature's dominance over human activities.

A geologic hazard is most simply defined as a geologic condition, process, or event that poses a threat to the safety or welfare of people or the activities and economy of a group of people. Many factors enter into such a definition. Some Earth scientists consider a key feature of a hazard to be its short duration (e.g., it is an "event") as opposed to damage caused by longer-term processes. Thus, the distinguishing mark of a hazard compared with other geologic processes that may negatively impinge on society is its short duration. For example, erosion, sedimentation, expansive soils, and salinisation all produce enormous monetary losses on a global basis, but these losses occur over time periods measured in years to decades or centuries.

Many engineers and geologists also refer to hazards in the terms we discussed in the previous section: it is a geologic process that can produce significant loss of life or property when the *critical threshold* is exceeded. Whichever definition we ultimately adopt, it is very important to realize that the process, in itself, is usually not hazardous. Natural geologic events or processes quite often have very positive effects. For example, river flooding is a natural sedimentological/hydrological response of nearly all fluvial systems. The floodplain of a river is appropriately named: it is the flat land adjacent to a river that is periodically inundated by high water levels (i.e., a plain where floods occur). Riverine flooding only becomes a geologic hazard when people attempt to live on the floodplain. Such is the case in nearly every geologic hazard known: it is only when the process interacts in a negative way with people that the term geologic hazard applies. Strictly speaking, there is no hazard unless humans, their possessions, or their activities are involved. Thus, as we learned in module 1, environmental geology is very much a “social science.”

Also, we must not forget that humans have always been capable of producing hazards, or at least making the potential for hazards to occur much more likely, simply by occupying and modifying the land. It is true that if all potentially dangerous areas were considered, there would be few places for settlement. Thus, the location of our cities and development areas is very much a gamble; society has learned to assign risks, make priorities, and then take its chances.

Nearly all Earth areas are subject at some time to either short- or long-term geologic disturbance. In some cases hazards may be prevented or mitigated, and the potential damage substantially reduced. In many cases, however, the hazard may be so great that no amount of construction or modification can prevent loss. Thus, the only course of action is avoidance or abandonment of the area.

Classification of hazards

There are many ways of classifying and subdividing geologic hazards. One way of thinking about hazards is to examine the origin of the process: if the hazard arises from deep seated, internal Earth processes, the term *endogenic* hazard applies. This category includes ground shaking, surface faulting, and other earthquake-induced ground failures, volcanoes, some types of landslides and subsidence, and in many cases, tsunami or “tidal” waves. In contrast, exogenic hazards originate from or develop in association with processes that occur at or near the surface of the Earth. Examples of these hazards are river and coastal flooding, some types of landslides, compaction and karst-related subsidence, and non-earthquake-related ground failures.

Another way of looking at hazards is to assign the event or problem to either natural causes (e.g., volcanoes, most earthquakes) or to the direct outgrowth of some human activity or action (e.g., flooding due to failure of a dam, land subsidence due to mining). Thus, the terms “natural hazard” and “technological hazard” (or sometimes “man-induced hazard”) can be often found in popular literature, such as magazine articles and newspaper reports. Because a geologic process in itself is not usually hazardous, this subdivision into natural versus technological hazards is somewhat ambiguous and arbitrary; practising Earth scientists rarely use the terms.

There is also a popular theme among the news media that we are experiencing, or at least on the threshold of, an age of hazards and disasters. Part of this perception no doubt is directly related to the ease of worldwide communications: for example, many of us subscribe to Internet services that give notice of earthquakes anywhere in the world in near-real time. With just a few clicks of the mouse we can easily acquire satellite imagery of potential flood events, etc. Thus, this perception of an age of increasing environmental disasters and geohazards is not strictly correct. On the other hand, whereas geohazards have always been with us, there are some factors that indeed have been working to increase the incidence and scale of hazards. These include:

- Increased populations and population concentrations.

- Increased technological development and dependence.
- Over intensive agriculture.
- Increased industrialization.
- Increased use of fossil fuels.
- Poor technological practices in construction, water management and waste disposal.
- Excessive emphasis on commercial development.
- Increased scientific "tinkering" with nature without proper anticipation or concern for possible long-term effects.

Which hazard is the worst?

Society's perception of the impact of geologic hazards also leads to yet another way of classifying the event. As discussed in your textbook, which hazard is the "worst" depends on the criteria of evaluation: worst in suddenness or lack of warning? Worst in size of area affected? Worst in dollar value of losses? Worst in terms of lives lost? For example, certainly many people would rank earthquake hazards high on their list of worst events due to the limited success of prediction and the often large areas affected. Others argue that volcanoes are the most frightening and awesome. Without question, landslides have become more severe and much more frequent with our help. However, it is surprising to find that the world's worst hazard, in terms of monetary losses, is simple river and coastline flooding. Equally surprising is the fact that in North America losses of between \$4 x 10^9 and \$12 x 10^9 per year are sustained from expansive soils and freeze-thaw phenomena, amounts greater than the total losses by all other geologic hazards!

Overview of geologic hazard mitigation

We want to study geologic hazards in order to understand more completely the physical processes that cause them. Understanding these processes is the most important step in devising methodologies for reducing losses. In North America, the average annual losses have been increasing steadily over the past half-century. As we discussed previously, this is largely due to increasing population and the fact the population centers are being expanded into hazard-prone areas such as floodplains, high seismic risk areas, near potentially active volcanoes, exposed coastal locations, and landslide-prone areas. Obviously, this growth and replacement of land use causes more greater-valued property and construction to be exposed to geologic hazards every year. Thus, the first line of hazard mitigation is that urban planning and decision-making with respect to hazards from processes such as earthquakes, floods, ground failures, and volcanic eruptions should take place at all levels of government. At each level, Earth science information is essential. Unfortunately, even with the best geological data and information, the choices are often difficult to make for several reasons. First, future geologic hazards are exceedingly difficult to predict in terms of place, time, and magnitude. Secondly, decision makers sometimes wrongly conclude that actions to reduce losses, based on geoscience information, are incompatible with other more important or more immediate social or economic demands, such as housing or industrial development.

The variety of actions for reducing losses from geologic hazards includes:

- **Avoidance.** Avoid the hazard by selecting other appropriate areas in which to live and build where the probability of occurrence of the hazard is lowest.
- **Land-use zoning.** Reduce losses to certain types of structures that may be particularly susceptible to a particular hazard either by reducing their density or by prohibiting them within parts of the area. Examples include denial of a permit to locate a nuclear reactor in an area with a known geologic fault or prohibition of housing development on the floodplain of a river.
- **Engineering design.** Allow all types of structures within a potentially hazardous area, but require site-specific engineering design and construction to increase the capability of the site or the structure to withstand the hazard. Building codes frequently specify the type of materials and the construction techniques. Such codes have been effective in minimizing damage to structures during earthquakes in California. Sometimes whole communities are protected by engineering structures. For instance, New Orleans is built along the Mississippi River, and much of the city is nearly 2 m below sea level. Floodwalls, pumping stations, and floodgates protect virtually all of New Orleans.
- **Distribution of losses.** Use insurance and other financial methods to distribute the potential losses in a potentially hazardous area.
- **Warning and Evacuation.** Some communities rely on combinations of warning systems and evacuation to mitigate losses due to hazards. For example, Hawaii uses sirens to warn coastal inhabitants of approaching seismic sea waves (tsunami).

By implementing one or more of these mitigation actions, society can greatly increase safety and ultimately reduce monetary loss by geohazards. However, any geologic hazard, either current or potential, still requires awareness by the society and population of the area. Furthermore, in some situations the people (or their government) decide not to take strong action against a potential hazard. This lack of action is sometimes due to limited funds or that the perceived cost/benefit ratios are such that society can adequately bear the costs and disruptions caused by a hazard.

Key concepts and terms to remember

avoidance
critical threshold
distribution of losses
endogenic hazard
engineering design
exogenic hazard
geologic hazard
Hazard
hazard mitigation
hazard warning
natural hazard
risk
technological hazard

Review questions

(Also examine the review questions in your textbook.)

1. What are the two basic subdivisions of geologic hazards most commonly used by environmental geologists? Give examples of each.
2. In your opinion, which is the worst geologic hazard and briefly summarize why?
3. Give at least two reasons why the popular press is often implying that society is on the verge of a new era of frequent and common geologic hazards.

Note: Sample answers are given in the Answers Appendix.

Unit 3
Endogenic Geologic Hazards

Topics

Earthquakes hazards

Volcanic activity

Introduction

From earliest history, humans have searched for an explanation of the terrifying natural phenomena called earthquakes and volcanic eruptions. These premier natural hazards, although quite rare relative to many other geohazards such as floods and landslides, have commanded the attention of some of the most influential minds of all cultures. Over two thousand years ago, Aristotle clearly identified the aspect of frequency, which is so important in earthquake hazard studies today, and believed that small to moderate earthquakes were caused by wind escaping from caves within the bowels of the Earth, whereas the more severe shocks were the result of gales that found their way into great subterranean caverns.

Globally, there are over a million earthquakes each year, and there are about 1500 active volcanoes today. Of all natural hazards, earthquakes and volcanoes release the most energy in the shortest time. The famous Northridge, California, earthquake in 1994, the most costly endogenic hazard event ever to impact North Americans, lasted a scant 10–15 seconds. The single eruption event of Tambora in Indonesia in April, 1815, put enough ash and other "contaminants" into the atmosphere to significantly affect global climate and cause widespread famine in Europe and North America for several years after. Geoscientists now realize that the distribution of earthquakes and volcanoes is not random across the Earth's surface, but their occurrence and frequency are directly related to crustal plate boundaries. The causes and mechanisms for earthquakes and volcanoes—subjects about which you already have considerable knowledge from your first-year course in Earth science, are extremely relevant to our understanding of their impact as hazards. As environmental geologists, we must also delve into the recent advances that have been made in the areas of monitoring these crustal activities—monitoring selected precursor phenomena provides a very promising avenue for predicting major destructive events. While both long and short-term forecasting of earthquake and volcano occurrences are essential, mitigation efforts also involve various geoengineering and structural considerations.

Learning objectives

After our brief introduction to geohazards and a short summary of mitigation possibilities available to environmental geologists in unit 2, this section will launch into a closer look at two very important endogenic hazards: (1) earthquakes and related problems associated with ground shaking, surface faulting, and substrate failure, and (2) volcanic eruptions. Although this is not a course in geohazards and, indeed, many of you may already have been exposed to the geology of natural hazards in GEOL 1360, nonetheless, units 3 and 4 provide succinct overviews of this topic, which is important to every environmental geologist.

By the end of this section you should be able to:

- distinguish the various types of seismic waves, their velocities, and wave forms;
- describe the impacts of the various seismic waves on structures at the surface of the earth;
- outline the difference between earthquake magnitude and earthquake intensity and discuss how each are evaluated;
- classify the types of faulting associated with earthquakes;
- explain man's role in initiating earthquakes;
- relate hazards due to ground shaking, faulting, and failure to substrate type;
- describe ground failure and the types of hazard it produces;
- summarize the global distribution of the main types of endogenic hazards;
- compare and contrast the various types of volcanic eruptions;
- illustrate how earthquake and volcanic hazards can be mitigated;
- describe the physical and chemical processes involved in volcanic eruptions; and
- list the major types of hazards associated with volcanoes and discuss their short-term versus long-term impacts.

Learning activities

1. Finish reading chapters 4 and 5 (pages 70–147) in your textbook and answer the study questions after each of these chapters. Read the study notes and answer the review questions.
2. Continue working on Assignment 1; this assignment should be submitted to the Student Services Office by the due date noted in the Assignment due dates.

Study notes

Earthquake hazards

Earthquakes are short-lived events that generally occur without warning. They are capable of causing more damage and loss of life in a short period of time than any other geohazards. Within two minutes an earthquake can level a significant part or all of a major city through shaking, faulting, and ground failure.

The specific hazards associated with earthquakes include (1) ground shaking, (2) surface faulting, (3) earthquake-induced ground failures, and (4) tsunami. We will not specifically discuss tsunami in this section but will cover this topic later in the course manual. However, it is a good idea to study the section on these waves in your textbook, as well as later in the Coastal Environmental Geology Module.

Impact

Although earthquakes characteristically cause much *less* economic loss annually in North America than exogenic hazards like floods or expansive soils, they are largely unpredictable. This unpredictability, combined with the capacity for immense damage and their suddenness, set earthquakes apart from the other geohazards. Furthermore, in the case of a tsunami that may be generated by an earthquake, impact can be both local and along very far distant coastal communities. Depending on its location and magnitude, an earthquake can damage buildings and structures valued collectively in many billions of dollars, can cause loss of life and injury to tens of thousands, and can dramatically disrupt social and economic functions of urban areas—all within a minute or two.

Countless human settlements throughout history on a global basis have faced the hazards and losses from the several million earthquakes that happen annually. As discussed in your textbook and as you remember from your first-year course in geology, the greatest threat to human activity is from moderate earthquakes because these happen more frequently than large ones. For example, in California one moderate earthquake (magnitude 6–7) takes place on the average of about once every 3 years, but a large one (magnitude 8 or above) happens only about once every 100–150 years.

Within North America earthquakes happen most frequently in Alaska and the west coast areas of the continent and least frequently in the eastern seaboard area and in the center of the continent.

Review of characterization of earthquakes

The characteristics and causes of earthquakes should already be familiar from your first-year geoscience course. Following is a brief review, but you should also study the appropriate sections of your textbook.

An earthquake is the sudden release of energy stored in a volume of rock. The rock contains energy because it has been elastically strained. This energy is transmitted from the earthquake source in the form of waves passing through the Earth's crust. These waves reach the Earth's surface, causing the bedrock or surface sediments to vibrate. Structures situated on the bedrock or surface sediments are also set in motion by these waves. We use instruments called seismographs to record the ground vibrations produced by the passing of these waves.

The seismograms recorded by the seismograph are used by geologists to better understand the nature, source, and magnitude of the Earth movement that caused the quake. One of the major features studied is ground motion caused by the P and S waves. The first impulse to show on the seismogram is caused by the arrival of a wave that has travelled through solid rock deep beneath the surface. This wave is called the P (for primary) wave. It is a compressional wave with movement very similar to that of a sound wave. The velocity of P waves is about 5.5 km per second (15,000 miles per hour) in near-surface rocks. The second "blip" on a typical seismogram, usually arriving only a few seconds after the P wave, records the arrival of the shear wave or secondary wave (S wave). It is characterized by a transverse motion and normally travels through surface rocks.

The difference between the time of arrival of the P wave and the time of arrival of the S wave is a function of: (1) the difference in velocities of the two waves (which is known) and (2) the distance of the seismograph from the earthquake source (which is usually unknown). Thus, it makes sense that the farther away the earthquake is from the seismograph, the greater the time is between the arrivals of the relatively fast P wave and the slower S wave. We can use this difference to calculate the distance from the earthquake source to the seismograph.

This will give us the distance to the earthquake from our station, but not the direction. To get the direction we need to compare the records from three or more seismograph stations. Combining the distance and direction, we are then able to determine the epicenter, which is the point on the surface of the Earth directly above the source of the earthquake. The source itself, in the subsurface, is called the focus.

Seismograms also show that other movements occur after the arrival of the S and P waves. These are related to arrival of waves that have travelled along the *surface* of the Earth (versus the P and S waves, which follow paths *within* the Earth). These surface waves are called Love and Rayleigh waves.

The amplitude of the motion of the Earth that is represented on the seismogram is directly related to the amount of energy released at the source and to the distance between the source and seismograph. Measurement of this amplitude provides the basis for characterizing the earthquake in terms magnitude. It is important to remember that the magnitude is related to the energy released by an earthquake at its source, not at the location of the seismograph. Several different measures of magnitude are commonly used, but the most widely cited is the Richter magnitude, although as discussed in your textbook, geoscientists often prefer to use the more quantitative moment magnitude for describing earthquakes.

Cause of earthquakes

An earthquake is just as the name implies: the sudden motion or trembling of the Earth caused by an abrupt release of slowly accumulating strain. Of the millions of earthquakes that happen throughout the world each year, most are minor tremors that are perceptible only to very sensitive instruments. Few are large enough to be felt and even fewer significant enough to cause damage or loss of life.

Perhaps the greatest contribution that the study of geology has made to human thought has been the concept of plate tectonics. Like most important ideas in science, plate tectonics is successful because it not only answered many existing questions about Earth, but also worked well as a predictive tool. The theory of plate tectonics can explain many of our earthquakes. As you recall from your first-year course in geoscience, the "solid" Earth is broken into several major plates. These 100 km thick rigid plates or segments of the Earth's crust and upper mantle move slowly and continuously over the interior of the Earth, meeting in some areas and separating in others. Velocities of the plates range from less than a centimeter per year to as much as 10–15 cm per year. Although these velocities are slow by human standards, they are very rapid by geologic reckoning. For example, a motion just 1 cm per year adds up to nearly 50 km in only a million years.

As these plates move, strain accumulates. Eventually, faults along or near plate boundaries slip abruptly and an earthquake occurs. A fault actually represents the surface of a distinct rupture plane. The three basic types of faults are:

1. Strike-slip faults: Displacement of one rock mass past the other is principally in the horizontal direction, parallel with the strike of the fault.
2. Reverse faults: Displacement of one rock mass past the other is principally in the dip direction. The block above the fault moves upwards over the underlying block.
3. Normal faults: Displacement is again principally in the dip direction but this time the block above the fault moves downward relative to the underlying block.

Ground shaking

Ground shaking is a term used to describe the vibration of the ground during an earthquake. Shaking is the result of seismic waves reaching the surface. In general, the severity of shaking increases as the earthquake magnitude increases and decreases with distance from the source. As we learned above, P waves propagate through the Earth with the greatest velocity and are the first waves to cause vibration and shaking. S waves arrive second but actually cause more damage to a structure because they vibrate from side to side (rather than the vertical motion of P waves).

Surface faulting

Surface faulting is the differential movement of the two sides of a fracture at the Earth's surface. As summarized above, strike-slip, normal, and reverse faults are the most common, but combinations of the strike-slip with the other two are also common. Although faulting can result from landslides and other shallow Earth surface processes, most often significant differential movements are caused by deep-seated forces.

Death and injuries caused directly by surface faulting are very unlikely, but casualties can occur indirectly through fault damage to structures. Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, the damage to structures located in the fault zone can be very high, especially where the land is intensively used for building, roads, pipelines, etc. The most common structures that are damaged by surface faulting include dwellings and commercial buildings, railroads, highways, tunnels, bridges, canals, and drains, and water, gas, and sewer lines.

The displacements, lengths, and widths of surface fault ruptures show great variability. In North America, fault displacements and differential movements have ranged from less than a centimetre to as much as 10 m. As expected, the severity of damage increases as the size of the displacement increases. The lengths of the surface fault ruptures have ranged from about a kilometre to more than 400 km. Most displacement is confined to a narrow zone usually less than a few hundred meters wide.

Almost all historic surface faulting in North America has taken place on faults that are young (i.e., there has been movement in relatively recent geologic time). Therefore, prediction is based on identification of these young faults. Such faults can be easily identified by the topography: the faulting has created scarps (small steps or cliffs), troughs, or ridges, or by the presence of diverted streams.

Avoidance and engineering design are the main actions that can be suggested to reduce losses from surface faulting. However, avoidance requires accurate location of the fault and an equally precise assessment of its history of activity during the past.

Ground failures

Throughout the world, ground failures induced by earthquakes have caused many thousands of casualties and billions of dollars in property damage. For example, during the 1964 Prince William Sound, Alaska, earthquake, ground failures caused about 60% of the estimated $500 million total damage. In this earthquake, five landslides caused about $50 million damage in the city of Anchorage alone; lateral spread failures damaged highways and severely disrupted use of railways and bridges. Flow failures in three Alaskan ports carried away docks, warehouses, and adjacent transportation facilities.

One of the most problematic conditions associated with ground failure is that of liquefaction. Liquefaction is actually not a type of ground failure; rather, it is a physical process that takes place during earthquake-induced ground shaking that may lead to ground failure. As a consequence of liquefaction, some types of unconsolidated sediments and surface deposits temporarily lose their strength and behave as viscous fluids rather than as solids.

Liquefaction takes place when the seismic waves pass through a water-saturated granular soil or sediment layer, distorting its granular structure and causing some of the pore spaces to collapse. Disruptions to the unconsolidated sediments generated by these collapses cause transfer of the surface load from grain-to-grain contacts in the sediment to the pore water. This transfer of load increases pressure in the pore water. When the pore water pressure rises to about the pressure caused by the weight of the column of sediment, the sediment layer behaves like a fluid rather than a solid for a short period. The main types of ground failure caused by liquefaction are lateral spreads, flow failures, and loss of bearing strength.

Liquefaction is restricted to certain geologic settings and environments. It occurs mainly in areas of recently deposited sands and silts and where ground water is within a few meters of the surface. Generally, the younger and looser the sediment and the higher the water table, the more susceptible an area is to liquefaction.

Volcanic activity

Volcanoes and related features were present on Earth long before any life had evolved. Volcanic hazards—events and conditions that result from volcanic eruptions that adversely affect humans—include airfall debris (tephra), hot avalanches (pyroclastic flows), mudflows, and lava flows. Except for airfalls of fine-grained tephra (ashfalls), volcanic hazards are generally quite restricted and only affect regions immediately around active volcanoes.

Volcanic eruptions, like earthquakes, can occur suddenly with little or no warning. In addition, volcanic eruptions can induce other hazards, such as earthquakes, floods, and landslides. Eruptions take place infrequently, and, relative to other hazards, such as earthquakes, floods, and ground failures, they cause low annual losses. Nevertheless, an eruption can have a significant short-term economic impact. For example, the total cost of the Mount St. Helens eruptions, from March through August 1980, exceeded $3 billion.

The term "volcano" is derived from the Latin name Vulcan, the Roman god of fire. Volcanoes, like earthquakes, are geohazards that originate from endogenic forces within the Earth. While earthquakes result from the movement of *solid* rock, volcanism is the movement of *liquid* rock (magma). As with many geological processes that adversely affect humans, several paradoxes are evident when we examine the impacts of volcanoes on humans. Although volcanoes erupt with sudden fury and can destroy nearby property and life, their long-term impact is overall beneficial. For example, soils that develop on volcanic materials are among the richest in the world. Volcanoes are often important sources of water, minerals, and geothermal energy. Volcanic edifices provide some of the most aesthetically pleasing scenery of all terrains. Nonetheless, the impact of volcanic eruptions cannot be overstated. Major eruptions inject huge amounts of aerosols into the atmosphere that can cause abnormal and costly weather conditions.

Overview of occurrence and distribution

Volcanoes are hills or mountains constructed by expulsion of magma and other materials from the Earth's subsurface. They can be composed of lava (extruded molten rock) or tephra (pyroclastic material blown into the air by explosive eruptions). There are just under 1,000 major active volcanoes in the world today, with over 75% of them located in the "ring of fire" or Circum-Pacific belt surrounding the Pacific Ocean.

Most volcanoes, like earthquakes, are located near the boundaries of lithospheric plates. Where *divergence* of plates is occurring along mid-ocean ridges, basaltic extrusions dominate. Where *convergence* of plates is occurring (subduction zones), intermediate to felsic extrusives dominate. This basic difference in magma type reflects the acidic nature of the weathered and eroded sedimentary rock materials that are being remobilized in the subduction trenches and the continental crust, which is commonly near subduction zones. Linear volcanic mountain ranges tend to develop landward of the trenches, either as island arcs (e.g., Japan, the Aleutians) or, if on the continent, as ranges a short distance inland (e.g., the Cascades of North America, the Andes of South America).

Volcanic activity is common wherever the Earth has been fractured by significant tectonic movement. On continents, many volcanoes occur along rift zones where the crust is under tension. In North America, examples include the Rio Grande valley in New Mexico, the Snake River Plain in Idaho, and parts of the Basin and Range province in the southwestern United States. Globally, perhaps the best-known and most pronounced rift zone is the famous African Rift valley.

Isolated areas of volcanism, such as the Hawaiian Islands and the Yellowstone region of western United States, are surface expressions of deep-seated plumes of hot**,** low-density, mantle material. Where the plume reaches the surface, a localized hot spot develops. The movement of lithospheric plates over plumes can often be charted by a line of extinct volcanoes that increase in age as they move away from the active hot spot. This is the case with the chain of volcanic islands in the central Pacific Hawaii area.

Classification

A number of schemes have been used by geologists to classify volcanoes. They have generally been classified on the basis of: (a) their period of activity, (b) type of activity, (c) typography: type of landforms created, and (d) the volcano's explosive tendency.

Period of activity

This is the simplest classification system. The volcano is active if it has erupted during historic times; otherwise it is inactive, dormant, or extinct. Unfortunately, many supposedly extinct volcanoes have abruptly returned to life, yielding catastrophic results for people living in false security nearby. Volcanoes can remain dormant for thousands of years before another eruptive phase commences. For example, in 78 A.D. Mt. Vesuvius, an attractive, smooth-sided conical mountain overlooking Italy's Bay of Naples that was believed to be extinct, began a series of eruptions that have continued at unpredictable intervals to this day. Three nearby cities (Herculaneum, Pompeii, and Stabiae) were immediately engulfed by up to 15 m of volcanic rubble together with poisonous fumes that killed more than 2,000 people.

Type of activity

This classification is based largely on the severity of eruptions and degree of explosivity. The names used are derived from various active volcanoes.

- Pelean: extreme explosiveness.
- Vesuvian: intermediate explosiveness.
- Strombolian: eruption of incandescent fragments accompanied by white gas clouds.
- Hawaiian: essentially lava outpourings from craters, with minimal particulate ejections or explosiveness.
- Icelandic: essentially lava outpouring from fissures rather than a central vent.

Topography

Topographically, we can easily separate volcanoes into three basic categories. *Cinder cones* are simple steep-sided piles of pyroclastic materials that collect around a central vent. An inverted cone-shaped crater often overlies the vent at the top of the cinder cone. Cinder cones can form very rapidly. For example, the cone of Paricutin, which erupted from a Mexican cornfield in 1945, attained a height of 300 m within a month. Thousands of cinder cones, most well under a few hundred meters high, dot volcanic landscapes around the world.

Shield volcanoes have broad dome-shaped features with gently sloping sides. They are composed almost entirely of basaltic lava flows and frequently have a large caldera (a wide, flat-floored crater) at the summit. Shield volcanoes `can attain massive size. The largest single mountain on Earth is the Mauna Loa volcano in the Hawaiian Island chain. The dimensions of this shield volcano are approximately 100 km long, 50 km wide, and 9 km high, with a total volume of some 67,000 km^3. The magmas from which the basalts of shield volcanoes are derived tend to be very fluid. They flow easily, release gases readily, and generally produce gentle eruptions of lava, often through long fissures along their flanks.

Finally, *stratocones*, or often called composite volcanoes or stratovolcanoes, are typically symmetrical and steep-sided. They are composed of alternating layers of intermediate lavas, such as andesite and pyroclastics, and can attain heights of several thousand meters. These mountains are among the world's most spectacular scenic attractions. Unfortunately, they are also the Earth's most dangerous and unpredictable features. The intermediate to felsic magmas feeding stratocones are highly viscous. Thus, they tend to retain gases, solidify rapidly, and block vents, thereby causing pressures to build up within the volcano. This results in sudden explosive eruptions in which the volcano can literally "blow its top off," as was the case in 1883 with the violent eruption of Krakatoa. Many of the volcanoes of the Cascade Range in the Pacific Northwest, including Mts. Hood, Shasta, Ranier, and St. Helens, are of this type.

Explosivity

Volcanic eruptions can also be classified as nonexplosive or explosive. Nonexplosive eruptions are generally caused by a basalt-rich magma, whereas explosive eruptions are derived from a silica-rich magma. The explosive eruptions produce large amounts of fragmental debris (airfall ash and pyroclastic flows).

Lava flows

There are many variations on the above types of volcanoes, and not all volcanoes fit readily into any of the classification systems we used above. In addition to volcanoes there are a great many other types of volcanic features. These are discussed at length in your textbook and should already be familiar from your first-year course. One very important feature is the lava flow. The largest of all volcanic landforms are the basalt plateaus, such as the Deccan

Plateau in India and the Columbia Plateau in northwestern United States. These have formed as highly fluid flood basalts were extruded from large fissures in the crust. They cover many thousand of square kilometres. The flood basalts of the Columbia Plateau cover an area of over 500,000 km^2, reach a maximum thickness of over 3 km, and contain over 400,000 km^3 of basalt.

Individual lava flows vary greatly in their characteristics. The more viscous lavas produce thick flows with rough, jagged surfaces. In the most viscous type, large blocks of angular lava are often pushed along from behind by the advancing lava stream. These are referred to as block flows. Broken fragments of rock are carried along on top of an advancing flow by moderately viscous lavas producing aa flows. Low viscosity mafic lavas produce a much smoother, undulating surface with the lava forming a ropy, pahoehoe surface.

Frequency and prediction

Similar to earthquake frequency, an inverse relationship exists between the size of eruptions and how often they occur. Small eruptions occur much more frequently than large ones. As illustrated and discussed in your textbook, the volumes and frequencies of past eruptions provide the major basis for defining the various geohazard zones.

Because each volcano or volcanic area has its own unique record of eruptive activity, it is difficult to generalize about frequency of volcanic activity on a global basis. A given volcano may have remained relatively constant for thousands of years or it may have gradually or suddenly undergone dramatic changes. The record of activity in prehistoric and historic time is the key for defining the hazard potential. This record provides us with an idea of what kinds of eruptions have occurred, what areas have been affected, and how often they have taken place. For example, on the basis of a large amount of geological investigation, environmental geologists have suggested that a small volume eruption may be expected at some place in the Cascade Range of northwestern United States once every 100 years. One consisting of a large volume has a predicted frequency of about once every 1,000 to 5,000 years. An eruption of very large volume will occur once every 10,000 years. During the past several million years, western North America has experience a few very large volume eruptive events. These eruptions were in and near Wyoming (Yellowstone), at Long Valley, California, and in the Jemez Mountains of New Mexico. These eruptions deposited ash over very large regions of the western and central United States and Canada.

Scientific instruments can be used to forecast the possible locations and times of future eruptions. A seismometer is one of the most effective instruments used to monitor a volcano. It is used to detect earthquakes that typically increase in size and number just before a volcanic eruption. In Hawaii the number of shallow earthquakes usually increases greatly a few days to several hours prior to an eruption. Ground deformation (doming) also commonly precedes volcanic eruptions and can be used to forecast the locations of possible eruptions. Other phenomena that can be reliably monitored include changes in composition of volcanic gases and changes in electrical and magnetic fields.

Hazard mitigation

Losses from a volcanic eruption can be reduced in several ways:

- Knowledge of the past eruptive activity of a volcano can be used to define the potential kinds, scales, locations, extents, effects, and severity of future eruptions and to define hazard zones.
- Monitoring systems can be established to forecast an impending eruption and to provide warning.
- It is essential that a well-conceived disaster preparedness and emergency evacuation plan be in place.
- Finally, various protective measures, land-use planning, and insurance can help reduce the economic impact.

Key concepts and terms to remember

active volcano	intensity
ash	liquefaction
andesitic magma	magma
basaltic magma	magma dome
caldera	magnitude
cinder cone	modified Mercalli scale
composite volcano	plate tectonics
convergent plate boundary	P wave
creep	Richter scale
divergent plate boundary	seismic wave
dormant volcano	seismograph
earthquake	subduction zone
epicenter	surface wave
extinct volcano	S wave
fault	tsunami
focus	shield volcano
frequency	stratovolcano
hot spot	tephra

Review questions

Do the review questions for chapters 4 and 5 in your text.

Unit 4
Exogenic Geologic Hazards

Topics

Floods and flood hazards

Landslides

Subsidence

Introduction

Historically, exogenic hazards, as a group, have been the most destructive natural geologic hazards in North America. Much is known about the causes of many exogenic hazards, and, in most cases, hazard controls, predictability and mitigation are readily feasible. Despite this knowledge, however, risk due to such things as flood hazard and landslides has actually increased dramatically on a global scale in the past half century. For example, during the decade between 1970 and 1980, flooding killed an average of 50,000 people per year. The average was more than twice this number during the past decade.

The study of flooding and flood analysis is not a new subject. For many years, however, this study has been fragmented and treated in many different ways by different groups of physical and social scientists. Our approach in this section will be to bring together these often quite different views and perceptions of floods so that application of the scientific concepts and data can be done in a uniform and holistic manner.

Learning objectives

Exogenic hazards are the most widely distributed and by far the most destructive geologic hazards facing society. For example, each year for the past decade damage due to floods in North America alone cost more than $\$1 \times 10^9$. Some of these exogenic hazards are the result of spectacular or unusual events such as dam failures, hurricanes, or unusual weather patterns. Most, however, are the result of normal and predictable natural functioning of streams, slopes, and surface sediments.

By the end of this section you should be able to:

- outline the various physical components of a river system;
- assess the impact of floods on society over the past century;
- define a flood from an geoengineering perspective and discuss how this use of the term might be different than society's general perception of a flood;
- identify the various causes of floods;
- describe, in general terms, how human activities can increase flood hazard;

- summarize the role of urbanization in flooding;
- review the pros and cons of channelization with respect to flood hazards;
- discuss how various geologic aspects of the drainage basin affect flood magnitude and intensity;
- define mass movement and related terminology;
- categorize landslides and mass movement with respect to the speed of movement, the amount and type of material involved, and the nature of the movement of the material;
- discriminate the various physical and chemical factors that can increase the landslide hazard in an area;
- explain specifically how each of the factors of water, topography, climate, and time affect mass movements;
- describe, with the use of appropriate examples, how human activities can influence the magnitude and frequency of landslides;
- summarize and evaluate the various landslide prevention and correction techniques; and
- list the most common causes of land subsidence.

Learning activities

1. Read chapter 9 (pages 246–275) and chapter 7 (pages 178–212) in your textbook and answer the study questions at the end of each of these chapters.
2. Read the study notes and answer the review questions.
3. Finish Assignment 1 and submit it to the Student Services Office no later than the due date indicated in the Assignment due dates.

Study notes

Floods

Floods have been and continue to be one of the most destructive natural hazards facing residents of North America and many other areas of the world. Because of the dual problems of increased population and increased urbanization, the probability exists that a greater flood hazard will exist in many areas than has been experienced in the past.

What is a flood?

The definition of a flood is intuitively easy: a flood is simply any abnormally high streamflow or level of water that overtops (or threatens to overtop) the natural or artificial embankments. Flooding is a natural characteristic of most rivers and many coastline areas of the world. Floodplains are normally dry areas adjacent to rivers that periodically act as natural reservoirs and temporary channels for floodwaters. Very simply, if more runoff is generated than the banks of the channel system can accommodate, the water will overtop the banks and spread over the floodplain. This is a natural process of riverine geohydrology and, as such, would normally imply that the potential for significant losses would be small because it is such an obvious and predictable hazard. However, as we discussed earlier, floodplains are very attractive places for human settlement because they are flat, close to adequate water source, and near a convenient waste disposal mechanism.

Impact

This point is very important to remember: even though floods are natural and regular recurring events in most fluvial systems, they become a hazard when humans compete for the use of floodplains. The natural function of a floodplain is to carry away excess water in time of flood. Society's failure to recognize this most basic function has led to rapid, unregulated, and haphazard development on many floodplains. As a consequence, we have seen a significant increase in flood hazards, despite the fact that many millions of dollars are spent each year on hazard mitigation. This increased loss is *not* due to greater floods but to increased encroachment of humans on flood-prone land. Floodplain occupancy and use are often based on the obvious economic advantages of level ground, fertile soils, ease of access, and available water supplies but with little consideration of flood risk. Historically, many people in flood-risk areas are simply uninformed about the risks that they face. The average annual flood loss in North America has increased by an amazing 300% in the past 50 years and by about 1.4 x in just the past decade.

The nature of flood damage varies widely depending on the terrain and degree of settlement of the area. Some damage begins as soon as the stream overtops its normal banks and water begins to occupy the floodplain. A further rise in stage may cause flooding of ground floors of residences and other buildings. Eventually, as the velocity of the water in the floodplain increases, houses may be swept off foundations, and other movable property may be carried away by the current. Large floods in rural areas generally destroy crops and livestock, and frequently make the land unfit for use because of erosion of soils and deposition of sand and mud.

Review of flood terminology

You should already be familiar with the details of the hydrologic cycle, with the partitioning of rainfall and snowmelt between surface runoff and groundwater, and with the basic concepts of measurement and reporting of discharge. This information on stream discharge is the fundamental raw material with which environmental geologists and water-resource managers work.

River stage is measured at gauging stations. *Stage* is simply the geohydrologist's term for the height of the water surface of the stream or lake or other body of water above a reference surface. The reference surface, or datum plane, is a locally defined elevation to which local water levels may be referred. Use of a local datum plane makes it possible to express water level position in terms of a relatively small number versus the much larger numbers that would be needed if the water level was expressed in terms of actual elevation above sea level. For example, along a lakeshore, the reference plane might be the mean lake level or the mean low-water level for that lake.

One stage of particular interest is the stage at which the river channel is just filled with water. This stage is the flood stage or *bankfull stage*. The morphology of most river channels is controlled by the water flowing in the channel when the flow fills or nearly fills it. The value of stream discharge at this bankfull stage is called the bankfull discharge. Any increase in discharge over this value will result in spilling water over the channel top onto the land adjacent to the channel. Once the water begins to spill over the banks of the channel, it spreads out over the adjacent land.

Environmental geologists concerned with land use in river valleys have an interest in knowing how often they can expect to have discharges of various levels or stages. These estimates are derived from statistical analysis of the historical bankfull discharge data. Obviously, the longer time period an individual gauging stations has been in operation, the better the predictive quality of the dataset.

An annual discharge record from a gauging station on a river that has had little human modification will usually show a number of small peaks at values less than bankfull, and it may show one or more peaks at values equal to, or greater than, bankfull discharge. However, there will be only one maximum discharge in any one-year period. The environmental geologist uses a compilation of these annual maxima (annual maximum series) in computing flood frequencies. Over a long period of time (decades or more), the values for annual maxima may show a great range. In general, the longer the record, the greater the range that will be observed. Obviously, events at either end of the range (very small and very large) are rare; the most frequent event on the annual maximum series is the value that represents the probable maximum discharge in any single year. Thus, it follows that there is a smaller chance (lower probability) that the discharge will be higher and similarly a smaller chance that the discharge will be lower.

Recurrence interval and flood probabilities

To obtain actual estimates of probability, it is necessary to do some simple arithmetic on the values in the annual maximum series. First, the maxima are ranked, designating the largest as $m = 1$, the next largest as $m = 2$, and so on to the smallest for which $m = n$, where n is the number of years of record. The values of m and n are then substituted in the following equation to obtain values for a quantity called the recurrence interval (R).

$$R = (n + 1)/m$$

The recurrence interval is the average time interval between the occurrences of two hydrologic events of a given (or greater) magnitude. Importantly, it is not the actual recorded time between two such events. We are also interested in expressing this information in terms of probability. For example, it is desirable to know how probable it is that a certain discharge value will be equaled or exceeded at least once in any single year. This probability is obtained by taking the reciprocal of R (i.e., 1/R) or by using the following form of the above equation: P = m/(n + 1), where P is the probability (or sometimes called the annual exceedance probability). Be sure to read carefully the sections in chapter 9 of your textbook and to work through and understand the practice examples.

We noted above that bankfull discharge is an important reference point in the discussion of flooding. Bankfull discharge typically has a recurrence interval between 1 and 3 years for typical rivers in north temperate humid settings. In other words, most rivers reach a stage at least as high as bankfull once every 2 years. It is also very important to note that human activities will change a river such that recurrence intervals and exceedance probabilities computed from the historic record are no longer valid. Dams, levees, and other structures affect discharge, and the analysis of hydrographic records must take these effects into account. In addition, these changes can affect the relationship between stage and discharge. For example, if the channel cross section is decreased by partial filling, then the river stage will be higher for any specific discharge than in the natural state.

Landslide hazards

Ground failures involving landslides and subsidence are a major threat each year to millions of people in North America. Landslides, a general term covering a wide variety of mass-movement landforms and processes involving the downslope transport of soil, sediment, and rock material under gravitational influence, are a significant hazard in virtually every province in Canada. Although individual landslides generally are not as spectacular or as costly as other geohazards, they are more widespread and, collectively, they cause major economic loss and casualties. In addition, landslides commonly take place in conjunction with other hazards such as earthquakes, floods, and volcanoes.

Because damage from landslides varies from minor to dramatic over both short and long periods of time, an estimate of their cost is very difficult to make. Direct costs relate to losses incurred in actual damages to installations or property. Indirect costs include loss of tax revenues on properties devalued as a result of landslides, reduced real estate values in areas threatened by landslides, loss of productivity of agricultural or forest lands affected by landslides, and loss of industrial productivity because of interruption of transportation systems by landslides. Indirect costs of landslides are usually substantially greater than direct costs. Landslides in both Canada and United States have generally not resulted in major loss of life because most catastrophic slope failures have taken place in nonpopulated areas.

Classifications

As reviewed in your textbook, landslides can be classified in many ways, with each nomenclature system having some usefulness to environmental geologists. Two criteria (type of *movement* and type of *material*) are typically used. Types of movement include falls, topples, slides, spreads, flows, and combinations of two or more of these basic types. Types of material include two main groups: bedrock and unconsolidated soils and sediments.

The environmental geologist must consider two important aspects of landsliding: *incidence* and *susceptibility*. Incidence of landsliding refers to areas where landslides have occurred in the past. Areas of high incidence are defined as having more than 15% of the slopes exhibit some evidence of past failure. Areas of moderate incidence have about 1–15% failed slopes. In contrast, susceptibility to landsliding refers to the strength of the Earth materials in the area. High susceptibility areas are underlain by weak or fractured materials. In North America, areas of high susceptibility include the Appalachian region, Alaska, the Rocky Mountains, and the coastal ranges along the Pacific Ocean.

Causes

All landslides involve the failure of Earth materials under shear stress. The initiation of the process can, therefore, be thought of in terms of the factors that contribute to increased shear stress and the factors that contribute to low or reduced shear strength. Although a single action, such as addition of water to a slope, may contribute to both an increase in stress and a decrease in strength, it is helpful to separate the various physical results of such an action.

The principal factors contributing to increased shear stress are:

- Removal of lateral support by natural erosion and various construction activities such as road cuts, quarries, pits, and canals.
- Loading by such natural or human means as weight of rain and snow, accumulation of loose rock fragments or accumulated volcanic material, stockpiles of ore or rock, waste piles, and weight of buildings and other structures.
- Vibrations from earthquakes, blasting, machinery, and traffic.

The main factors contributing to low or reduced shear strength include:

- The initial state or characteristics of the material including its composition, texture, structure, and slope geometry.
- Changes due to weathering and other physicochemical reactions.
- Changes in water content and pore pressure and in structure of the material.

Hazard mitigation

An urban area faced with a landslide is mainly interested in preventing the harmful effects of the slide. Usually, the physical cause of the slide cannot be removed, so it may be more economical to reduce losses either by continuously or intermittently modifying the conditions without actually removing the physical cause. However, the many examples shown in your textbook illustrate that the most damaging landslides are closely related to the activities of human and that substantial loss reduction can be achieved by regulating land use before human activities take place. Effective regulation involving measures such as land use controls and drainage or runoff controls requires close cooperation among geologists and engineers, in which the research must first be done to identify the problem, followed by synthesis of information and communication with planners.

Subsidence as a geologic hazard

Subsidence, the lowering or collapse of the land surface either locally or over broad regional areas, has taken place throughout most of North America and is very common in other parts of the world. Although subsidence is usually not spectacular or catastrophic, in fact it causes billions of dollars in damages annually in North America. Loss of life due to subsidence is rare; however, a catastrophic mine collapse in South Africa that caused numerous deaths serves as a reminder of the potential danger.

Causes

Subsidence can be caused by a large number of natural and human activities. Natural processes causing subsidence include the dissolution of limestone and other soluble materials, earthquakes, and volcanic activity. Large areas of North America are underlain by limestone and other soluble bedrock materials. As groundwater percolates through this soluble material, minerals dissolve, forming cavities or in some cases large caverns. Land overlying these caverns can collapse suddenly, forming deep sinkholes. Other times, the land surface can settle slowly and irregularly. The landscape created by such subsidence is called karst terrane. This type of subsidence usually causes extensive damage to structures located directly over the pits and sinkholes; sometimes it has even caused deaths. Although the formation of sinkholes is a natural phenomenon, the process can be accelerated by rapid groundwater withdrawal and disposal of waste water. The major locations of karst terrane and caverns in North America are in parts of many of the southeastern and midwestern States and both eastern and western Canada.

Earthquake-related subsidence is also a common hazard in earthquake prone regions such as western North America. This type of subsidence results from vertical movement on faults and may affect broad areas. This process took place in 1964 in southern Alaska in conjunction with the Prince William Sound, Alaska, earthquake. More than 150,000 km^2 were tilted downward more than a meter and subsequently flooded. As we discussed previously, subsidence can also result from intense ground shaking associated with earthquakes and by collapse above shallow tunnels formed by the flow of lava. Collapses over much broader areas can also occur as magma chambers are emptied by volcanic eruptions.

The withdrawal of subsurface fluids, oil, gas, and water, has increased dramatically in the past 75 years. Because subsurface fluids fill intergranular spaces and help support sediment grains, removal of the fluids results in a loss of grain support, reduction of intergranular void spaces, and compaction of sediment. Indeed, land surface subsidence is very common wherever widespread subsurface fluid extraction has taken place. Probably the most dramatic examples of subsidence caused by withdrawal of oil, gas, and water are along the Gulf Coast of Texas, in Arizona, and in California. For example, the harbour at Long Beach, California, has subsided as much as 7 m because of withdrawal of gas and oil. The Houston-Galveston area of Texas has experienced as much as 2 m of subsidence locally. In this case and for other coastal regions, the subsided areas are now more susceptible to flooding and hazards by marine processes associated with storm surges and hurricanes.

Underground mining, especially shallow coal mining, is another cause of subsidence. The rocks above mine workings may not have adequate support and can collapse from their own weight, either during mining or long after mining is completed. Subsidence in areas of underground mining has caused hazardous conditions in the old coal mining areas of Pennsylvania and other Appalachian states, and in western United States.

Hydrocompaction, or the settling of sediments after water is added, is another significant cause of subsidence, especially in western Canada and United States. Hydrocompaction takes place when normally dry surface or shallow subsurface deposits are wetted. This may happen when land is irrigated for crop production. Wetting causes a reduction in the cohesion between sediment grains, allowing the granular material to shift and change the natural packing of the deposit.

Hazard mitigation

Identification and mapping of areas susceptible to subsidence is the key to devising loss-reduction strategies. However, because subsidence can be caused by a great many combinations of natural and human-induced conditions or processes, potential hazardous areas are often difficult to identify. Often it is necessary to conduct a site-by-site evaluation of an area. In the case of karst subsidence and places where accurate historical records of mining activity are not available, it is necessary to undertake geophysical exploration and drilling programs to insure that a site has a low subsidence hazard potential.

Restriction of activities in areas identified as being potentially susceptible to subsidence is the best overall strategy. For example, to prevent compaction, the water resources of an urban area may have to be supplied from surface sources rather than from groundwater. Non-intensive land uses, such as parks or golf courses, can be planned for areas where subsidence is anticipated.

Geoengineering methods can sometimes be used to help stabilize the land in subsidence-prone areas where development has already taken place or cannot be avoided. For example, subsidence caused by the withdrawal of underground oil, gas, or water can be dealt with by several methods. In the Los Angeles-Long Beach, California, area, where oil and gas have been withdrawn from beneath the harbour district for over 50 years, subsidence was reversed by the injection of water into sediments to replace the oil being withdrawn. In areas such as the San Joaquin and Santa Clara Valleys in California, subsidence was either reduced or stopped when additional imported water was returned to subsurface sediments to replace the ground water that was withdrawn. Subsidence associated with coal mining can be prevented by taking actions during or immediately following the mining operation. If mining is carried out in such a way that enough coal is left to support the roof of mine workings, the chance of later subsidence is reduced. Also, the voids remaining when coal is removed can be filled with compacted mine waste. This action will significantly reduce surface subsidence but may introduce the risk of contaminating groundwater.

Key concepts and terms to remember

bankfull stage
collapse
flood stage
discharge
driving forces
hydrocompaction
incidence
karst
landslide
probability
recurrence interval
sinkhole
stage
shear strength
shear stress
stress
susceptibility

Review questions

1. Discuss the parameters that can be used in the classification of landslides.
2. Give two examples of how flooding benefits society.
3. What two factors influence slope stability?
4. Describe several ways in which hillside development may aggravate landslide hazards.
5. How would you identify a landslide area on a topographic map?
6. List several ways in which urbanization increases flood hazard risk.
7. What is the relationship between recurrence interval and probability in flood analysis?

Notes

Assignment 1

1. (15) Most ground subsidence occurs in areas underlain by clastic sediments deposited within the past few tens of millions of years. Explain why this is so.
2. (5) China has achieved what appears to be an impressive success in cutting the country's birth rate by more than 30%. Even with this decrease, however, China's average annual growth rate during 1990–1995 was 1.42%. How long will it take for China's population to double?
3. (10) What are the most critical natural resources that determine the carrying capacity of the Earth?
4. (10) Why is subsidence often associated with oil fields? Explain how this hazard can be mitigated.
5. (5) What kinds of crushed metamorphic rocks would be best for a highway road bed and explain why.
6. (5) You have just landed a job with CPR and you are given the task of acquiring new ballast for the railway roadbeds. On a field trip to a railroad track, you determined that most of the ballast is made of angular gravel that has been crushed. However, alluvial gravels are much less expensive. Why do you think it is essential to have manually crushed gravel for rail bed ballast?
7. (5) What is the difference between relative geologic time and absolute time? How are the two determined?
8. (10) Summarize the various types of plate boundaries and the ***environmental geologic processes*** associated with each of them.
9. (15) Compare and contrast the types of volcanoes; contrast sizes, shapes, and rock/magma types; and explain the differences in their eruptive styles.
10. (20) You are an environmental geologist working for an international engineering corporation in charge of investigating possible sites for constructing a billion dollar oil refinery in a remote, unpopulated coastal area in the Middle East. The main concern is earthquakes and possible ground rupturing by motion along faults. The Islamic poems originating in the region include laments about death by earthquake; thus, earthquakes must have occurred in the area and thorough geological investigation seems warranted. What specific features are you going to look for in your investigation?

Notes

Module 3
Coastal Environmental Geology

Notes

Unit 5
Coastal Problems

Topics

Introduction to the coastal zone

Types of coastlines

Coastal erosion

Prediction

Introduction

Module 3 deals with the processes and geoenvironmental problems occurring along shorelines. The processes controlling shoreline deposition and erosion have considerable impact on human activities in all parts of the world. Likewise, man's preferential occupation of coastal areas, both lakeshores and ocean coastlines, has led to major disruptions of some of these natural processes and to severe land-water ecosystem degradation.

Learning objectives

Even if you rarely visit the Maritimes or the west coast of Canada, a simple glance at a map of North America, or even of Manitoba, illustrates that marine and lacustrine coastlines vary greatly in their morphology. This is because the kinds and intensities of geologic processes that occur along them also vary dramatically. One of the main objectives of this section is to gain an appreciation of the spectrum of morphologies and to understand most common of these processes so that we, as environmental geologists, can apply the knowledge of the processes to land use studies and management schemes in coastal environments.

By the end of this section you should be able to:

- describe wave motion;
- identify why coastal areas are unique with respect to geoenvironmental problems;
- use the basic parameters of wave mechanics and fluid flow to calculate the erosion and transportation of granular material in the nearshore zone;
- identify the main problems associated with human occupation of barrier islands;
- sketch a profile through a typical nearshore-coastline environment showing the various morphological and sedimentological features;
- differentiate the processes and motion of deep water versus shallow water waves;

- calculate the velocity of a wave;
- discuss the relationships between wave height, form, motion, and beach morphology;
- summarize the main kinds of shore defences and outline their impacts;
- describe when (what depth conditions) a wave will break;
- show how longshore drift occurs;
- construct a coastline profile for each of the various tidal regimes; and
- illustrate how breakwaters and groins influence the movement of sediment in the nearshore zone.

Learning activities

1. Begin reading chapter 10 (pp. 276–310) in your textbook. You should plan to complete this reading by the end of unit 6.
2. Read the study notes and answer the review questions.
3. Begin working on Assignment 2; this assignment should be submitted to the Student Services Office no later than the due date indicated in the Assignment due dates.

Study notes

Introduction to the coastal zone

More than half the people in North America live close to the coast and many more make regular pilgrimages to coastal areas in search of recreation. Consequently, homes, apartments, hotels, and motels now crowd many shoreline and nearshore settings; in many areas these facilities are competing with other more traditional human uses of coastal land, such as public recreation areas, power generation stations, refineries, and ports. This competition makes coastal land extremely valuable and also especially vulnerable to stress. Historically, most of this land has been allocated by allowing simple supply and demand to determine the usage. While this market-driven allocation of land-use generally works well for land away from the coast, it is clear that coastal areas pose special usage problems. The special features of coastal land that give rise to some of these problems are:

- The boundaries between coastal land, wetlands, and the ocean or lake water shift constantly, making the coast a difficult zone to legally and scientifically define and manage.
- Coastal wetlands and nearshore lake and ocean waters are biologically very productive and usually ecologically and economically important.
- Wetlands and nearshore waters are easily modified by human activities along the coast and by disposal of wastes.

- Coastal land and water are both highly valued for their recreational potential.
- Major petroleum and other resources are found along many coasts.

Consequently, it can be argued that simple "highest price" market allocation cannot be used to adequately manage development in a lake or ocean coastal zone. Occasionally environmentally knowledgeable groups and environmental geoscientists have successfully put their views before the public and the policymakers, and, in so doing, have stimulated analysis and change. Unfortunately, for the vast majority of coastline mileage in North America, environmental geologists are usually put into the position of being asked to cure a problem after considerable damage has already been done by unregulated or poorly conceived development. The major issues we will explore in this module include: shoreline type and processes, and shoreline erosion.

Types of coastlines

Your textbook and online web materials provide an excellent framework and review of nomenclature that are widely used in discussing the coastal zone. The coastal zone extends from the edge of the continental shelf inland across the coastal plain. Two classes of coast are generally recognized: (1) coasts with barrier islands, and (2) coasts with sea (or lake) cliffs, although more complex subdivisions can be easily constructed. For example, coasts fringed by coral reefs and coastlines that are dominated by estuaries and flooded river valleys are also important types.

Cliff coasts

Worldwide, the most common type of coast is the cliff-dominated coast, comprising about 80% of all marine coastlines. The continental shelf along this kind of coast is narrow. Terraces are prominent along cliff coastlines, with each terrace representing a wave-cut bench. Most importantly, these cliffed coasts usually do not have barrier islands and wetlands.

There are three main types of cliffs:

1. Active cliffs are those that are being actively eroded by wave action. Debris that falls to the base of the active sea cliff is rapidly removed by wave action.
2. Inactive cliffs are characterized by the accumulation of talus or debris at the base of the cliff.
3. Former cliffs are hidden beneath accumulated debris.

It is important that we understand the mechanisms and rates of retreat of sea cliffs in order to manage the land and determine the best land-use policy. Often people who consider coastal cliff terrain for residential development believe that the terrain is more stable than it really is. This misconception is primarily due to the fact that cliffs tend to erode and retreat in bursts of activity separated by long periods with no retreat.

Barrier island coasts

Barrier islands border approximately 4,000 km of the coasts of North America. These islands and *barrier island complexes* (BIC) separate the open ocean from shallow lagoons that lie between the islands and the mainland. The islands are normally dominated by sand-sized material and have been built up over the past 10,000–15,000 years, although a large proportion of them have been constructed in just the last several millennia.

We can characterize the islands in terms of their morphology. The morphology of a barrier island depends on the conditions under which it formed and evolved. For example, along coasts where the tidal range is small (1–2 m), barrier islands tend to be tens of kilometres long, are cut by only a few tidal inlets, and are overlain by many fan-shaped deposits of sand called *washover fans*. Along coasts where the tidal range is greater (2–4 m), the islands tend to be much shorter (usually less than ~20 km long), and typically are cut by closely spaced tidal inlets. Washover fans are rare.

The nomenclature that is used in discussing the nearshore and shore zones of barrier islands is relatively simple: the *nearshore zone* ranges from mean low water outwards to deeper water in which the waves do not interact with the sediment. Waves or swells entering the nearshore zone begin to interact with the bottom in the *breaker zone*, culminating with the wave breaking against the foreshore. The breaking waves interact with bottom sediments in the nearshore zone, and longshore currents are often generated that move sediment parallel with the coast. *Offshore bars* can exist in the nearshore zone as a result of temporary sediment transport and deposition. The *beach zone* is the region between low-water level and the upper limit of the area affected by wave action. This beach zone consists of a *foreshore* region affected by the swash and backwash of water driven up on it by incoming waves and a *backshore* region, distinguished by the presence of nearly horizontal sand platforms called *berms*. Typically, the highest berm is a feature shaped during the winter or whenever storm activity typically drives water high onshore. The lower berm is usually formed during the summer. Further inland are *dune ridges*, which are shaped by wind (aoelian) processes carrying sand onshore from the exposed beach zone. Even further inland are *salt marsh* or mangrove zones (if marine) along the boundary between the barrier island and the lagoon.

Coastal erosion

As we mentioned above, the coastal zone is the site of many conflicts. These arise because of the large number of possible uses that are focused on a very narrow strip of land and water. Some of the many problems include coastal erosion and the control of erosion, the siting of homes, power plants, waste disposal facilities and industry, and the management of saltwater and freshwater wetlands.

The many environmental geologists and other scientists maintain that coastal erosion is one of the most severe environmental problems facing United States and Canada today. Over 25% of the total coastline of the east and west coasts of

USA and Canada is undergoing significant erosion, in some cases the erosion is critical enough to necessitate relocation and other very expensive mitigation techniques.

Several important concepts have emerged during the past decade of research on this problem. These include:

1. Human are directly responsible for much of the erosion "problem" by constructing buildings near the shoreline. Essentially there is no erosion problem where there are no buildings or settlement. Or another way of saying this: there is no shoreline erosion problem until someone builds something on the beach to measure it by.
2. Fixed shoreline structures, such as breakwaters, groins, seawalls, etc., *can* be successful in prolonging the life of structures built on the beach. However, the mitigation structures almost always accelerate the natural rate of beach erosion elsewhere along the coast.
3. Most shoreline stabilization projects protect property, not beaches. In most cases, the protected property belongs to just a few individuals, a very small number relative to the number of people who actually use the beaches. The interests of beach property owners should not be confused with the overall interest and use of the coastal area by society.
4. If left alone, beaches will always be present, even if they are constantly moving.
5. The cost of saving beach property by stabilization is extraordinarily high. Often it is greater than the value of the property to be saved, especially if long-range maintenance costs are considered.
6. Long-term shoreline stabilization (i.e., time measured in decades) usually results in severe degradation or a total loss of the open beach environment. Basically, in order to save the beach, you must ultimately destroy it.
7. Shoreline stabilization is generally irreversible. Once a beach has been artificially stabilized, it will always remain in a stabilized state, with increasing costs to the taxpayer. In short, once you start stabilization, you cannot stop.
8. Construction on the beach reduces flexibility and, in itself, causes erosion.

Factors controlling coastal erosion

The morphology and distribution of beaches, cliffs, and other shoreline features are developed through processes that strive to reach *equilibrium*. In other words, once a coastline has been established, if the environmental conditions are not changed, then the equilibrium forms (i.e., shoreline morphology) will not change significantly with time. However, when conditions are changed in any way, the form, location, and type of coastal features will change also. For example, the elevated water levels and large waves accompanying the passage of a hurricane clearly impose abrupt changes on the form of many coastal features. Environmental geologists who deal with such changes or who must make decisions concerning the use of coastal land need to know what effects can be expected for given specific changes in the physical and biological environment. The major variables in this system are: (1) mean water level, (2) wave "climate," (3) current patterns, (4) sediment supply, and (5) properties of the coastal materials.

Water levels

The specific location of the shoreline at any moment is determined by the water level elevation at that moment. It follows therefore, that the *average* location of the shoreline during any time interval is determined by the average water level during that time interval. This is an obvious but important point. For example, the water level elevation on Lake Winnipeg displays an annual cycle of variation controlled by seasonal fluctuations in precipitation, evaporation, and ice formation, *and* by long-term fluctuations related to century or millennia-based climatic variations over the entire drainage system of this large lake. When water levels on the lake were near record lows a few years ago, the shoreline moved relatively far out from its long-term average position. Subsequently, when water levels were close to record highs, the shoreline moved landward. During periods of high water, beaches, berms, and bluffs (including cottages, piers, and other man-made structures) that had been safe from wave attack were suddenly confronted by breaking waves that caused erosion.

In ocean coastlines the location and morphology of many features are controlled by the elevation of the mean water level along those coasts. This mean water level lies between the average high and average low water levels (MHW and MLW), with tides and the tidal regime being an important factor. The elevation of these levels changes over time, as does the elevation of the land surface due to long-term subsidence or uplift. These changes in the relative positions of the mean water level and the land surface elevation determine the position of the shoreline and the precise "point of attack" of waves on the land. This can easily be seen by geologically examining virtually any BIC in the world. These barrier systems, in general, can be seen to have migrated over the past 8–10,000 years; this migration is controlled mainly by rising sea level associated with melting of continental ice sheets. In addition, in many parts of North America, superposed on this is the isostatic rebound of the crust due to removal of the large weight of continental ice.

Tide-gauge records in many coastline areas of the world also show that the sea level is still rising; indeed, global sea level has risen about 10–12 cm in the past century. These recent increases are likely related to the warming of the oceans. As cold ocean water is warmed under the influence of increasing global average temperature, the *volume* of ocean water is increased. Furthermore, if the rate of melting of glacier ice in the Arctic, the Antarctic, and Greenland also increases due to global warming, then an influx of water from the melting glaciers would further increase the volume of ocean water, contributing even more to a rise in sea level.

Waves

The main agent responsible for movement of material along a beach, and ultimately for erosion of beaches, is wave energy. Waves are generated by wind as it moves across open water. The movement of waves shoreward provides a means for transferring energy from the wave (or more precisely the wave form) to the water itself. Once in the shore zone, the energy in the water can be expended in doing the work of breaking. The types of waves and the distribution of wave types of a specific coastal area are referred to as *wave climate*.

Your textbook and online supplementary material summarize the main features and types of waves and provide exceptional graphics that show the major types of movement. The periodic rise and fall of any part of the wave is done by the orbital (or circular) motion of water particles. This orbital motion, as measured by the diameter of the small circles, is greatest at the surface and decreases downwards, becoming negligible at a depth equal to about one half the wavelength. At this point there is little movement of the water particles and, of course from an environmental geology perspective, little energy available for erosion or transportation of bottom sediment. When wave steepness reaches values of about 0.14 to 0.10, the wave becomes unstable and breaks.

There are two types of waves generated by the movement of wind over water. Waves generated by storm activity on the open ocean are called a *sea*. These waves are generally steep and they display a variety of periods and wavelengths. These storm generated waves form in an area of the ocean called the *fetch*. The waves that make up a sea are usually reorganized in the open ocean into a set of waves that are much more regular and much less steep. These more regular waves are called a *swell*. Swells can travel very long distances (hundreds to thousands of kilometres) across the open ocean before impinging on coastlines.

In *deep water* (defined as water depth > half the wavelength), the waves move landward at a velocity (*celerity*). The celerity is equal to the *wavelength* divided by *period*. In deep water, the waves do not interact with the bottom sediments, and, thus, they are not slowed by the frictional or drag effects of the bottom. However, as the waves approach shore, the orbital movement is affected by the bottom. As water depth approaches a value of one-half wavelength, the wave begins to interact with the bottom, and this interaction leads to slowing of the incoming wave and erosion, resuspension, and transport of bottom sediments. This interaction between the wave and the bottom also leads to an increase in wave height. As the waves steepen, they begin to break. Breaking occurs as the waves enter a depth zone in which the water depth is about 1.3 times the wave height.

The zone in which waves break is called the *surf zone*. Within this zone, part of the energy carried by the waves is expended in moving sediment on the bottom. The ultimate fate of this eroded material depends on the nature of the incoming waves and on the current patterns. Normally, the net movement of bottom sediment is shoreward. However, steeper storm waves, such as those experienced during the winter storms on many lake and ocean coasts can result in substantial seaward transport of sediment.

Currents

As a wave approaches the shore and is influenced by the gradually shallowing conditions, the velocity is slowed. Furthermore, if the wave is not hitting the coast or shallowing water in a perpendicular direction, then the wave trace will be bent due to the relative slowing of one part of the wave versus the other. This bending is referred to as *wave refraction*.

The process of wave refraction concentrates wave energy on specific parts of a coastline. In effect, the energy that was uniformly distributed along a unit length of wave becomes concentrated on a segment of shoreline that is much less than that unit length. Such a segment may then be prone to wave-generated erosion.

As a result of wave refraction, incoming waves tend to become aligned parallel with the shape of the shoreline. However, often the orientation is not perfectly parallel with the shoreline and a net movement of water parallel to the shoreline is created. This net movement results in the formation of a *longshore current*. This current can also erode bottom material and move it along the shoreline in the downcurrent direction. Finally, these longshore currents may also be punctuated by *rip currents,* which move sediment (and water) away from the shore.

Thus, it is apparent that the length and location of the section of the shoreline that is affected by wave-induced erosion is determined by the following factors:

1. The height of the incoming waves.
2. Their steepness.
3. The angle at which the waves approach the coast.
4. The water level at the time of wave approach.

During storms, when waves are high and steep, sediment will be eroded from the backshore that was built up during periods dominated by normal swell. If the water level is sufficiently high, then the waves will break directly against bluffs, dunes, or structures, causing substantial erosion.

In unregulated coastlines, this process is cyclic and the storm-induced changes are simply transitory and of short-term duration. The nonstorm profile is usually quickly restored. However, if the profile is not restored, either due to an interruption in the source of the sediment or artificial barriers to the normal flow of sediment, then the shore zone must evolve to a new state.

Sediment supply

Every beach has a *sediment budget*: sediment is fed to the beach and is lost from the beach. The nature of this simple economy is easily appreciated when one looks at nearly any natural coastline. For example, along the California coast, where most of the beaches are fed by sediment-laden rivers, a fraction of the sediment passes through the beach and ultimately to deep water. This loss is usually made up for by steady additions from the rivers. These segments of a coast that are in equilibrium and include a supply, a beach, and a point at which sediment moves to deep water are *called littoral cells*. Clearly, interrupting the sediment flow in the littoral cell by, for example, creating dams on the rivers, will adversely affect the sediment budget.

Prediction

One of the ongoing problems in observing and predicting changes in coastal morphology is that of scale. Often the equilibrium process is not rapid; changes might occur on time scales ranging from a few hours to several centuries or millennia. Unfortunately, the degree of public and governmental concern with coastal changes is directly related to the time scale: the shorter the time scale, the greater the concern. Yet long-term coastal changes are exceedingly important. Some indication of long-term changes can be done studying aerial photographs that provide a limited time series over a period of perhaps decades in many places in North America (but much less in most developing countries).

Barrier islands undergo constant change even under natural equilibrium conditions. These changes are much more evident on the sections of the systems near tidal inlets. Environmental geologists have measured the rate of migration of barrier islands in different settings in many areas of the world. In large areas of eastern North America, recession rates (i.e., landward migration) averages as much as 1.5 m/yr. Comparison with prehistorical rates (as determined by geological investigations) indicate that recession rates have increased by about 30–40% due to human actions. Thus, long-term forecasts can be made by extrapolating these historic trends under both natural and human-modified condition.

Combining these historical trend estimates with detailed dynamic predictions based on our understanding of the responses of coastal processes and on the expected changes in controlling factors, such as sea level or lake level, results in a valuable method for coastal-zone geoengineering and management. It is important to realize that coastal modification is typically employed wherever coastal erosion is perceived as a threat. Unfortunately the aim of most engineering efforts is to provide a solution to a *local* problem only, often without any understanding of how the modification will affect the large-scale picture of sediment erosion and transport.

Many of the problems facing environmental geologists working on coastal problems today involve sediment supply. Sediment supply to a beach can be readily interrupted by damming rivers or placing structures along the shore. In the case of river damming, the cutoff of sediment supply leads to a decrease in beach size. Therefore, if the beach is to be maintained, it must be artificially supplied with sediment. The magnitude of the original sediment input must be determined in order to estimate the scale at which the beach must be artificially fed. Finding a source of sediment and creating an artificial feeding system are obviously very costly problems that can be difficult to solve.

Key concepts and terms to remember

barrier island
beach
beach face
berm
breaker zone
groin
lagoon
littoral cell
longshore current
orbital path
regression
surf zone
swash zone
wave climate
wave energy
wave frequency
wave number
wave refraction
wave steepness

Review questions

Begin working on the study questions for chapter 10 in your text. These should be completed by the end of Unit 6.

Unit 6
Tsunami & Storm Surges

Topics

Introduction to tsunami and surges

Tsunami occurrence, mechanism, and mitigation

Hurricanes, cyclones, and storm surges

Introduction

Tsunami, or seismic sea waves, are particularly hazardous around the Pacific Ocean basin. Tropical cyclones (Pacific) and hurricanes (Atlantic) often impact severely on highly populated coastal areas. During these storms flooding caused by surges can cause waters to rise to far in excess of normal high tides.

Learning objectives

The objective of this unit is to discuss the propagation, potential damage, and mitigation techniques for these significant coastal problems. By the end of this section you should be able to:

- summarize the major problems associated with recognition and identification of tsunami;
- characterize the "wave components" of a tsunami;
- outline how tsunami and surges are generated and differentiate the different mechanisms involved in each;
- compare and contrast the coastal areas of the world that are most influenced by tsunami and surges;
- calculate the theoretical surge height due to atmospheric pressure changes; and
- illustrate how the morphology of a coast plays a role in determining the impact and size of a storm surge.

Learning activities

1. Check the University of Manitoba website for the date and time of your final examination.
2. Finish reading chapter 10 in your textbook and answer the study questions.
3. Read the study notes and answer the review questions.
4. Finish Assignment 2 and submit it to the Student Services Office no later than the date indicated the Assignment due dates.

Study notes

Introduction to tsunami and surges

The most destructive waves on Earth are not wind-driven waves but rather waves generated by displacement of the bedrock on the ocean floor. Tsunami (the word is both singular and plural) are water waves caused by subaqueous earthquakes, volcanic eruptions, or landslides. Tsunami are often called tidal waves, but this term is a misnomer. Unlike regular ocean tides, tsunami are not caused by the tidal action of the Moon and Sun.

One of the most problematic things about tsunami is that they are literally unrecognizable in the open ocean because their wave height is usually only a few tens of cm—much less than wind-generated seas or swells. It is their wavelength, usually more than 100 km, which gives these waves their remarkable speed, energy, and destructive power. The great distance between wave crests of most tsunami prevents them from dissipating energy as a breaking wave or surf. Instead, tsunami result in rapid water levels to rises (and falls) along coastlines. When one of these waves impinges on the shallow water areas along a coastline, sea level (nearshore) rapidly retreats far below the mean low water level and then the rebounds at a very high velocity to, in some cases, many meters above high water level. The impact on a populated coastline is usually disastrous. For example, when a tsunami hit a coastal district of northern Japan in1896, sea level fell and then rose to nearly 25 m above high tide in a few minutes. The earthquake responsible for the wave had occurred less than an hour earlier at a point some 700 km away.

Hurricanes and cyclones clearly are major atmospheric disturbances capable of causing significant damage and disruptions to coastal settlements. A major component of these storms (in addition to the strong winds and heavy rainfall) is the storm surge. Storm surge, sometimes driven well ahead of the advancing storm, can significantly damage or entirely destroy structures along the shoreline such as beachfront retaining walls, jetties, and buildings.

Tsunami occurrence, mechanism, and mitigation

Historically, no destructive tsunami have occurred along the east coasts of North America or South America. This is a consequence of the generally low levels of seismic activity in the Atlantic region and the lack of vertical fault displacements. The only tsunami known to have been recorded on the Atlantic Coast of North America was generated by an earthquake off the Newfoundland in the early part of the twentieth century; it caused a tsunami with maximum height of 0.3 m.

Tsunami most commonly occur in the Pacific Ocean because the majority of the world's earthquakes take place along that circum-Pacific belt. Most vulnerable are Japan, Hawaii, Alaska, Indonesia, and the Pacific coast of South America. A tsunami can strike any coastline in the Pacific region. Tsunami generated by earthquakes in South America and the Aleutians characteristically pose a greater hazard to the west coast of the United States and Canada than do locally generated tsunami.

The Hawaiian Islands have experienced many destructive tsunami because of their location in the central Pacific Ocean; indeed, about 90% of all recorded tsunami since the early nineteenth century have been recorded in the Hawaiian Islands. Most of these have originated from earthquakes occurring Aleutian regions of the northwestern Pacific.

There is still considerable uncertainty about exactly how a tsunami forms, although it is clear they are most often initiated by submarine earthquakes or other related phenomena that cause a sudden vertical offset in the sea floor. This abrupt rise or lowering of the floor of the ocean displaces a large volume of water, producing a depression in the level of the sea surface. As shown on your CD, water rushes in to fill the depression and then spreads out at right angles to the axis of the offset. An oscillatory wave motion is created and waves of large wavelength move away from the point of disturbance.

The wave period of a tsunami varies from 20 minutes to several hours and its wavelength can be hundreds of kilometers. Both length and speed depend on water depth. For example, the average depth of the Pacific Ocean is 5 km, so the typical speed of a tsunami in the open ocean is about 700 km/hr. With an average wave period of 40 minutes, the length of the wave will be 480 km. However, as it approaches the shoreline, its speed, like that of all waves, decreases and its wavelength is compressed. The enormous amount of energy that had been stored in the very long wavelength is thus transferred to wave height. In some cases funnel-shaped inlets and estuaries in the coastline allow the tsunami to be even more amplified, resulting in a high-speed wall of water weighing millions of tons that crashes inland with immense power.

Hazard mitigation

Tsunami have produced great destruction and loss of life in Hawaii, southeast Asia, and along the west coast of the United States. Indeed, in the past 60 years, more people have been killed as a result of tsunami than as a direct result of earthquake ground shaking. Destruction to structures and other facilities is a consequence of the time between successive tsunami crests, the wave heights at the shoreline and inland locations, and the wave and current velocities. The effects of tsunami include structural failure, scouring, significant shoreline and inland erosion, and flooding.

Because tsunami cannot be prevented, a warning system is the primary way to reduce losses. The Tsunami Warning System of the Pacific was established in response to the Aleutian tsunami of 1946 that caused great damage and loss of life in the Hawaiian Islands. The first major test of this warning system occurred in 1952 with the Kamchatka earthquake. Advance warnings were provided to communities in the path of this tsunami; the result was a reduction of damage and no casualties. Similarly, in 1957 loss of life was averted when a major tsunami crossed the Pacific from an Aleutian earthquake.

Hurricanes, cyclones, and storm surge

Tropical cyclones and their Atlantic-Caribbean cousins, hurricanes, can cause significant property damage and loss of life in coastal areas through many different impacts. Flooding can be caused by exceptionally heavy rainfalls associated with these storms. A typical cyclone can dump 100 mm per day of rain in a widespread area. Although the impact of rain-induced flooding varies as a function of the local topography, duration of storm and other weather and climate related aspects, it is not uncommon for a single storm to yield rates of over 3 m of rain in just a few days.

Geological significance

About 100 cyclones and hurricanes develop every year. Thus, in only a 1,000 years—a very short period in terms of geological time—about 100,000 major storm events can be expected to occur worldwide. Obviously, these seemingly rare or isolated events take on major geological significance when it is considered that they frequently impact on coastlines that are inhabited and can intrude well into continental interiors. This fact can seriously affect the environmental interpretation that geologists might derive from the rock record. For instance, cyclones can easily carry and deposit wind-blown marine fauna and flora far inland, thus contaminating nonmarine sediments with a false marine signature. Cyclones not only transport salt water inland but also agitate marine bottom sediments that are far below normal wavebase. Similarly, flooding and flood deposits associated with surges and setup could be misinterpreted as a marine transgression in the geologic record when, in fact, they simply represent single storm depositional events. Most marine geologists now contend that the stratigraphic record on much of the continental shelf has been affected by significant sediment movement associated with major storms.

Another aspect that must be considered by geologists attempting to interpret paleoenvironments is that hurricane-generated swell can travel thousands of kilometers away from the actual storm site. For example, waves more than 4 m in height frequently impinge on the southeast coast of Australia from storms over 1,000 km north in the tropics. These waves are capable of eroding sediment in the shelf area at water depths of as much as 100 m.

Impact

The impact of cyclones and hurricanes is usually assessed mainly in terms of deaths and direct damage due to wind or water. Globally, the number of deaths have decreased during the past century mainly because of the adoption of a total evacuation policy by many developed countries and the instigation of early warning systems. Costs, however, have increased dramatically due to the ever-escalating human settlement and development in coastal areas.

The impact of these storms goes beyond just loss of life and structural damage. Geoscientists now realize that cyclone-induced flooding causes increased soil salinity, which has long-term economic consequences on the agricultural productivity of a region. Contamination of water supplies and simple destruction of crops caused by the addition of up to several meters of water on an agricultural field also frequently leads to disease and famine. Indeed, some of the large death tolls associated with hurricanes in the nineteenth and early twentieth century were due to large-scale starvation after the event.

Cause of surge

In any major storm such as a hurricane, storm surge plays a major role in damage. Storm surge was the main cause of death in 1,900 when 6,000 residents of Galveston, Texas, died because of marine inundation. Storm surge is generated by a number of factors, including: wind set-up, lower atmospheric pressures that decrease the atmospheric weight on the water, the direction and speed of movement of the low-pressure system, the shallowness of the continental shelf, bay or estuary, and the shape of the coastline.

Set-up

The main reason for storm surge is simply the piling up of water by the strong winds. This is referred to as *set-up*. The amount of water involved in the set-up obviously depends mainly on the speed of the wind, and its duration and direction relative to the movement of the storm and its center. In general, for a hurricane with 200 km/hr winds, one would expect a wind set-up of greater than 2 m in the vicinity of the story.

Atmospheric unloading

In addition, the actual level of the sea (above some datum) depends to a great extent on the weight of air positioned above it. If all air were removed from an area, then sea-level would rise dramatically. Typically, atmospheric pressure in large cyclones can be reduced by 10–13%. It is possible to calculate the theoretical surge height due to the lowered pressure (i.e., atmospheric unloading) according to:

$$H_{max} = 0.0433\ (1023 - P)$$

where h_{max} is the height of the storm surge due to atmospheric effects, and P is the pressure at the center of the hurricane in hPa (hectopascals). From this equation, it can be seen that the lowest pressure ever recorded for a cyclone (~870 hPa) would produce a surge height (due to atmospheric pressure unloading) of 6.6 m.

Wind direction

If a storm moves in the direction of its wind, it will tend to drive a wall of water ahead of it. This wall behaves as a wave and travels with the same speed as that of the storm. The height of the wave is related to the size of the storm. Along the east coast of North America this wave can have a height of several meters. As the wave approaches land and moves through shallower water, its speed decreases and, in order to conserve the energy flux through a decreasing water depth, wave height must increase. Thus a shallow body of water can generate very large surges.

Coastal morphology

Finally, the morphology of the coastline helps account for the extraordinary size of some storm surges. An excellent example is the Bay of Bengal, where storm surges have drowned so many people. The basin is funnel-shaped, such that any surge moving "up the funnel" will be laterally compressed. In addition, the shape of the basin can lead to resonance or an enhancement effect.

Key concepts and terms to remember

atmospheric unloading	tidal wave
cyclone	tsunami
energy dissipation	Tsunami Warning System
hurricane	wave crest
sea	wave height
set-up	wavelength
surge	wave period

Review questions (for both Units 5 and 6)

Finish the practise tests for chapter 10 that are located in the EarthScienceNow materials at http://earthscience.brookscole.com/pipkingeo4e

1. What is the difference between a wave of oscillation versus a wave of translation?
2. Why are long wavelength waves considered to be most powerful? Consider wave base in answering this question.
3. What causes wave refraction?
4. What is an estuary?
5. What is the northeast quadrant of a hurricane, in the northern hemisphere, and why is it considered the most dangerous area of the storm?
6. What is the leading cause of death and destruction in hurricanes and why?
7. How are hurricanes classified?
8. Are all of the effects of El Niño bad? Explain your answer.
9. There were 61 deaths from the tsunami that hit Hilo, Hawaii in 1960. Why were there so many deaths considering that a tsunamis warning had been issued and coastal warning sirens had been sounded?
10. What is the most common solution applied to the problem of infilling of protected anchorages by sand carried by longshore currents?

Assignment 2

1. (10) Rainfall is higher along the recently uplifted shores of the Baltic Sea than it is along the Italian coast. Why, then, are sand dunes so much more abundant on the North German and Polish coasts than near Naples?
2. (5) Why does stream velocity generally *increase* downstream even though there is a *decrease* in stream gradient downstream?
3. (10) The headwaters of a river are at an elevation of 3,000 m and the river flows 300 km to the sea. What is the river's average gradient, ***expressed as a decimal*** (be careful with your units)?
4. (15) How does urbanization of a region affect the hydrograph of a drainage basin (be sure to address changes in such factors as peak discharge, height of maximum flood, lag time, and frequency of flooding)?
5. (15) Nearly 100 "undernourished" beaches (i.e., beaches undergoing rapid erosion) along the East Coast of United States have been artificially replenished by pumping sand to the shores. Discuss the overall relative success or failure of these replenishment efforts and provide insight into the reasons for success or failure.
6. (5) If you are in the open ocean in a ship, how can you recognize a tsunami that passes under your ship?
7. (10) Coastal flooding has been identified as the "greatest natural hazard threat to human." Explain why this statement would/could be made. What causes such flooding? What area(s) of the world (specific countries) have been the most severely affected by coastal flooding?
8. (10) What are factors that determine the length, period, and height of ocean waves?
9. (5) Compare and contrast the similarities and differences between hydrocompaction and liquefaction.
10. (15) You are considering buying a hillside lot overlooking the beautiful Bow River in Calgary on which to build your retirement mansion. Now that your are (almost) an experienced environmental geologists, what evidence are you going to for in order to determine if the hillside has (or had) a mass wasting "problem."

Notes

Module 4
Pollution Geoscience

Notes

Unit 7
Geology of Pollution

Topics

Types of contamination

Liquid wastes and water pollution

Solid wastes

Introduction

This module has to do with the geoscience of pollution and waste disposal. The two topics are closely related. As many pollution problems are solved, waste disposal problems are increased. Some aspects of environmental deterioration are natural and occur with or without human activities or interference. For example, the single largest source of atmospheric pollution on a global scale is volcanic activity. Similarly, the average Winnipeg resident is exposed to about 100 times more radiation hazard due to naturally occurring radon in their basements than to all other radiation sources and far above the levels found in uranium mines. Unfortunately, much of today's pollution is simply and directly the result of careless waste disposal or even a complete lack of disposal efforts. The old adage "out of sight, out of mind" unfortunately rarely applies to disposal systems. The environmental geologist's knowledge of natural process-response systems and the geological settings in which they operate is essential for rational planning of waste disposal and land/resource use.

Learning objectives

The environmental effects of industrial and social activities are enormous and far-reaching. Our overall goals in this section are first to simply review the major types and causes of pollution, and to decipher the main impacts of pollution on the natural processes and responses of the near surface geologic environment. Armed with this information, we can then develop concepts and approaches to better deal with the proper disposal of wastes and pollutants.

By the end of this section you should be able to:

- outline the role that geology and Earth scientists can play in pollution studies and waste disposal;
- categorize the major types of contamination with respect to sources and effects of the pollutants;
- explain the different types of industrial, municipal, and agricultural water pollution;
- describe the relationship between the breakdown of organic matter, BOD, and eutrophication of water bodies;

- differentiate point source pollution from nonpoint source contamination;
- evaluate water pollution in terms of its net effect on human activities;
- describe thermal pollution;
- explain the origin of sediment pollution;
- outline the principal types of solid waste that require disposal;
- summarize the major methods of solid waste disposal;
- distinguish dumps from sanitary landfills;
- critically evaluate ocean dumping;
- compare the trench method and the area method of landfill disposal;
- discuss the formation, composition, and movement of leachate; and
- quantitatively assess the effectiveness of a landfill;

Learning activities

1. Begin reading chapter 13 (pages 370–411), chapter 14 (pages 412–446) and chapter 15 (pages 447–473) in your textbook and answer the study questions at the end of each of these chapters. You should plan to complete this reading by the end of unit 8.
2. Read the study notes and answer the review questions.
3. Begin working on Assignment 3. This assignment is due no later than the due date indicated in the Assignment due dates.

Study notes

Introduction

> [The property] ... has been filled, in whole or in part, with waste products resulting from the manufacture of chemicals... and [the Board of Education of Niagara Falls] assumes all risk and liability incident to the use thereof.
> (Niagara Falls Gazette, 9 August 1978)

This clause was part of an indenture provided by the Hooker Corporation for the sale of the Love Canal property to the Board of Education of Niagara Falls, New York, in 1953. Incredibly, despite this explicit warning, the Board of Education proceeded with land development, including the building of a school, houses, and apartments, without conducting any scientific examination or evaluation of the hazard potential. The Love Canal disaster (see unit 8) has not only highlighted modern man's ability to foul his living environment, but has become a classic example of poor decision making by uninformed politicians, public servants, and industry personnel.

Man's pollution and environmental contamination of his own habitat is nothing new. The agricultural revolution, the industrial revolution, and the urban revolution all were earmarked by significant advances in man's ability to degrade his own environmental setting. However, the scale, magnitude, and type of degradation today are different than in the past. In addition, society's position with respect to the physical environment has also changed: today it is no longer possible to simply move on to other areas or to rebuild our cities and dwellings on top of the rubbish of earlier groups. The disposal of waste material is a monumental problem in nearly every urban area in North America. Environmental contamination and degradation has become, in this last decade of the century, a major preoccupation of scientists and politicians.

The topic of pollution is very broad involving aspects and concepts from fields as diverse as ecology, biology, medicine, toxicology, and epidemiology. Our concern here is with the role that geology plays in the realm of pollution, particularly water and soil contamination. Studies involving pollutants and waste product management are probably the most controversial and volatile area of activity for an environmental geologist.

While it is absolutely essential that environmental geologists become involved with decisions concerning waste management, quite often this is an area that is not viewed as a fundamental geological problem. However, the environmental geologist's knowledge of Earth materials and structures, and the characteristics and dynamics of both surface waters and groundwater is a prerequisite for any environmental decision and management. For example, the location of disposal sites for solid waste has for too long been left to politicians, economists, and other persons poorly qualified to critically evaluate the site and its long-term suitability for landfill; this has often lead to significant negative consequences for the local community and society in general. It is (or should be) entirely within the realm of a geoscientist, working in conjunction with the appropriate social scientists, to identify, test, evaluate, and recommend solid waste disposal sites for urban areas. Many other examples could be cited: disposal of liquid wastes, incarceration of more toxic components of industry and manufacturing, even problems associated with acid rain. Although all of the various pollution and contamination problems facing society today cut across many scientific and economic subdisciplines, the Earth science components are the most vital aspects to help assure the successful location and operation of disposal systems that have a high degree of integrity and provide maximum safety and well-being for society.

The last half-century has seen an interesting shift in attitudes. The early environmental/conservation movement was concerned mainly with preservation of natural resources. Nevertheless, beginning in the 1960s more emphasis was placed on fixing problems associated with improper or questionable use of the resources, particularly with respect to pollution of water, air, and soils, and disposal of waste material. Many factors have contributed to this shift in emphasis: the huge number of inhabitants in the world's cities, the inventiveness of humans in creating new products and chemicals, and the deliberate act of using the least expensive production methods regardless of environmental impact are just a few of the major factors.

Types of contamination

Water and soil contaminants originate from a wide variety of sources. It is important to realize that many things identified as “contaminants” or “pollutants” are such only because of the quantity in which they exist in the soils or water, or because these substances have a significantly negative impact on man. A *contaminant* is defined, therefore, as a substance that may cause harm or may adversely affect the functioning and character of the ecosystem. In addition, to be a contaminant the concentration of the substance must be above that of background levels, since presumably the ecosystem has adapted to the substance at the background concentration. In terms of human activities, the most readily apparent adverse consequences are health effects that manifest themselves immediately upon exposure. These usually include nausea, dizziness, and eye, lung, or skin irritation. Much more common and much more problematic, however, are the chronic health problems that develop and affect the population over substantial periods of time. These include a diverse array of diseases and malfunctioning such as liver, kidney, lung, and central nervous system diseases, many types of cancer, and genetic damage.

Water and soil pollution generally take place gradually. Thus it is possible to monitor the processes of pollution and describe reasonably accurately the stage of contamination of an area. The speed with which a contaminant progresses through a medium depends on the nature of the source of the pollution, the characteristics of the medium, and the geochemical and biochemical characteristics of the contaminant as it moves through the medium. One of the major complicating factors in pollution geology is the fact that different contaminants behave differently after entering a particular medium. This behaviour depends ultimately on three basic factors:

1. The geochemical stability of the compound.
2. The interaction of the compound with the medium.
3. The interaction of the compound with other introduced compounds and contaminants in the medium.

Many contaminants are *geochemically unstable*. In other words, they break down spontaneously in a relatively short period of time. One of the best examples of this is the radioactive contaminant tritium (^3H) that is created by nuclear explosions and commercial nuclear reactors, the topic of unit 8. This radioactive element can create a potential source of harm if released with the reactor’s cooling water or directly into the atmosphere. However, the half-life of tritium, or the length of time it takes for one-half of the initial mass of the isotope to decay, is just over 12 years. Thus, unless new sources are constantly available, the concentration of ^3H will decay rapidly within a few decades. In contrast, the half-life of many other inorganic and organic contaminants is much longer.

The major groups of pollutants are: oxygen-demanding wastes, disease-causing agents, inorganic chemicals, minerals, and sediment, organic chemicals, plant nutrients, radioactive substances, and heat. Table 7.1 summarizes the major sources and effects of these pollutants.

Pathogenic microorganisms have their origin mainly from human and animal wastes. They include bacteria and viruses that cause diseases. The organic chemicals and compounds category includes thousands of synthetic chemicals used in industrial processes, pesticides, food additives, and various drugs. Some of the most problematic contaminants in this category include:

- Low molecular weight chlorinated hydrocarbons, such as trichlorethylene, carbon tetrachloride, tetrachlorethylene, and vinyl chloride.
- Pesticides, such as toxaphene, endrin, methoxychlor, lindane, and DDT.
- Polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs), and dioxin.

Many of these latter compounds present severe pollutant problems in urban areas because they have all been shown to cause cancer in laboratory animals and are suspected to be the source of miscarriages, birth defects, and other adverse reproductive effects in humans.

Radioactive nuclides are harmful because they can emit ionizing radiation upon decay, which causes atoms and molecules to be electrically charged. The harmful effects of this radiation arise because the radiation damages the deoxyribonucleic acid located within the genes that control the normal functioning of living cells.

Table 7.1 Sources and Effects of Pollutants

Pollutant	Common Sources	Effects
Oxygen-demanding wastes.	Human sewage; animal wastes; decaying plant life; industrial wastes from oil refineries; paper mills; food processing.	Depletion of dissolved oxygen in water: fish kills; odours; poisonous gases.
Disease-causing agents.	Domestic sewage; animal wastes.	Waterborne diseases such as typhoid, hepatitis, cholera, dysentery; infected livestock.
Inorganic chemicals, minerals, and sediment.	Mining; industrial wastes; irrigation; oil well drilling; natural runoff; de-icing of roads; forestry; runoff from urban areas; burning fossil fuels; pesticides; smelting; fungicides.	Outright kills organisms; increases the solubility of some harmful minerals; makes water unfit for domestic use.
Plant nutrients.	Agricultural runoff; domestic sewage; industrial wastes; inadequate water treatment; food-processing industries.	Algal blooms and excessive aquatic plant growth; kill fish; eutrophication; odours.
Organic chemicals.	Machine and automobile wastes; pipeline leaks and breaks; offshore oil well blowouts; natural seepage; shipping accidents; agriculture; forestry; most plastics manufacturing; paper industry.	Toxic; eutrophication aesthetic damage; odor; cancer; birth and genetic defects; bioaccumulation in food chain.
Radioactive substances.	Natural sources; uranium mining and processing; nuclear power generation; nuclear weapons testing.	Cancer; genetic defects.
Heat.	Cooling water from industrial and electric power plants.	Decreases solubility of oxygen in water; fish kills; disruption of ecosystem.

In terms of quantity and magnitude of impact, the *inorganic substances* are the largest source of pollution throughout most of the world. Sediment contamination, in the form of accelerated land erosion and sedimentation, is the single largest source of water pollution in North America. Studies have shown that natural rates of erosion can be increased by up to 10 times through agricultural development, 100 times by road construction and urbanization, and as much as 500 times by certain types of mining techniques. In the case of inorganic contamination, it is very important to properly establish the background levels that are present in the ecosystem before attempting to evaluate the degree to which the soil or water is contaminated. Inorganic compounds of various types, salts, and sediment are all normally present in the soil and water, and are essential components. However, in some cases elevated levels of the compounds are detrimental or even toxic.

Large quantities of *heated water* are recycled back into the hydrologic system by power and industrial plants. While most environmental specialists view heated water as a waste product, there are actually a number of benefits from heated water and some scientists and investigators speak in terms of thermal "enrichment" of water rather than thermal pollution. The main benefits include:

- lengthening the commercial fishing season and increasing the catch size in commercial fisheries;
- reduction of ice cover and a decrease in the likelihood of fish kills due to winter stagnation;
- enhancing the recreation potential of water bodies;
- use of the warm water in aquaculture industry such as the cultivation of catfish, shrimp, carp, and oysters; and
- use of the heated water in buildings, snow removal, and various other chemical and industrial purposes.

The undesirable effects from excess heat in the aquatic system include the following:

- death of organisms due to thermal shock associated with repeated alternating exposure to hot and cold water;
- increased sensitivity of organisms to disease and parasites;
- lowered dissolved oxygen levels in the water and a higher oxygen demand by most organisms ultimately leading to decreased productivity;
- reduction of species diversity;
- increased abundance of "undesirable" blue-green algae; and
- decreased viscosity and density of the water resulting in increased sedimentation.

In the case of power plants that often have their own water-cooling towers, the thermal "efficiency" can be quantitatively evaluated by:

$$TE = \frac{T_i - T_r}{T_i} \text{ x } 100$$

where TE is the thermal efficiency, T_i is the temperature of the water used in the power generation, and T_r is the temperature of the waste water emitted from the plant. Values of 30 to 40% are considered low enough to be environmentally harmless.

Contaminants can also be classified as *degradable* (either slowly or rapidly) or *nondegradable*. Rapidly degradable pollutants can be broken down within a few weeks to a few years by natural chemical weathering processes as long as the chemical system is not overloaded. Examples of rapidly degrading pollutants include domestic sewage, plant nutrients, and many types of organic compounds. Slowly degradable pollutants are those that remain in the sediment or water systems for longer periods of time but are still eventually broken down or reduced to harmless levels by natural processes. Examples include some radioisotopes and many organic and inorganic compounds such as DDT, PCBs, and phenols. Slowly degradable wastes offer a more difficult problem for disposal because:

- The site or technique of disposal must prevent or minimize the pollutant's entry into the environment but still allow geologic and normal physical/chemical weathering processes to interact with the material.
- The system of storage/disposal must be secure and immune from the changes in geologic processes for relatively long periods of time.

Finally, non-degradable pollutants are not efficiently broken down by natural processes. Many metals, salts, synthetic organic compounds (such as plastics), and sediment fall into this category; they must be controlled through removal and pre-treatment or recycling.

Liquid wastes and water pollution

As emphasized in the last section, water is a requirement for life. However, when this water is degraded, it is worse than having none. Historically, water has provided an excellent medium for waste disposal because it is cheap, convenient, and effective for dilution and removal of most liquid wastes. However, overloading the aqueous system has resulted directly in the spread of disease and death associated with use of the contaminated water.

Water has the limited ability to self purify in a variety of ways: by filtration through the groundwater system, by dilution, and by oxidation of the wastes. Most natural systems are easily overburdened. The amount or level of burden is usually determined by measuring the *biochemical oxygen demand* (BOD) or the amount of oxygen used by living microorganisms feeding on the organic pollutants. Normal Winnipeg city domestic sewage before treatment has a BOD of about 300 ppm, whereas after treatment it has less than 15 ppm. Unpolluted groundwater from beneath Winnipeg has a BOD of less than 3 ppm.

Sources of water pollution

Most water pollution is from *nonpoint sources*, or areas that are so indistinct or diffuse that they cannot be isolated on maps. Major nonpoint sources of pollution include:

- agricultural and urban grassed areas;
- irrigated agricultural lands; and

- large urban areas, and airborne contaminants.

The major problem with nonpoint sources of pollution is that they are almost impossible to control. In contrast, *point sources* of contaminants are easily identified and readily controlled. Common point sources include: septic tanks and cesspools, sewage treatment systems, feed lots, landfills and dumps, mines, power plants, smelters, and drilling operations.

Water pollution can have a number of harmful effects on individual organisms, populations, or entire ecosystems. These effects can be subdivided into:

- aesthetic and general nuisances such as odor, taste, unsightliness;
- property damage;
- plant and animal toxicity;
- damage to human health;
- damage to genetic and reproductive processes; and
- major ecosystem disruption.

Most areas of North America have experienced effects (i) and (ii). Many urbanized areas are now attempting to cope with (iii). Many developing nations are facing (iv) and (v). Finally, the threshold has only been reached locally in a few isolated areas of the world, but the frequency has been increasing significantly over the past two decades.

Rivers versus lakes

Terrestrial aqueous systems can be classified as *lotic* (flowing) or *lentic* (standing) systems. Because of these differences in water movement, rivers and lakes differ considerably in their water pollution problems. Because rivers flow, most can recover fairly fast from some forms of pollution, especially the introduction of oxygen-demanding wastes and heat. The river's volume and velocity control its ability to assimilate these wastes: in sluggish rivers, such as the Red River or the Assiniboine River, the ability to self purify can be readily overwhelmed.

In contrast to rivers, lakes have relatively little flow. While the *flushing time* of rivers is usually measured in terms of weeks, the renewal in lakes can take hundreds or even thousands of years. Many lakes in the north temperate climatic realm consist of three distinct zones:

- The nearshore littoral zone in which rooted aquatic plants are found.
- The limnetic or photic zone through which sunlight can penetrate.
- The profundal zone of deep water that is not penetrated by sunlight.

In addition, a lake's water column can be subdivided into three vertical zones:

- An upper, relatively warm layer of water termed the epilimnion.
- The thin zone of transition called the thermocline.
- The lower, cold, dense bottom water of the hypolimnion.

The separation of the lake into these layers is due mainly to temperature differences: the warm epilimnion being less dense than the cold hypolimnion; in some cases chemical stratification is also present. A lake characterized by chemical stratification is termed *meromictic*. During fall when the upper water mass cools, wind can easily mix the entire water column, resulting in lake turnover. The same thing happens during the spring when the ice melts and the temperature of the upper water rises sufficiently to be mixed with the lower water. This mixing of the lake's waters is very important because it reoxygenates the bottom water, thereby allowing fish and other organisms to live. A meromictic lake does not usually mix on an annual basis.

Obviously, lakes of the type described above are extremely susceptible to degradation by thermal processes. In addition, however, all lakes, whether they are deep enough to be thermally stratified or not, are very susceptible to a processes called eutrophication. *Eutrophication* is the acceleration of plant growth due to an increase in nutrient supply by the addition of nitrates and phosphates. Natural eutrophication occurs in lakes located in areas in which the bedrock supplies an abundance of nutrients. For example, Lake Manitoba, the third largest lake in the province, is naturally eutrophic because it receives inflow from rivers draining the nutrient-rich sedimentary bedrock of the northern Great Plains. However, cultural eutrophication is also common in many regions due to the addition of nutrients supplied by farming, sewage treatment plants, feedlots, detergents, and mining.

When a lake is overloaded with nutrients, plants, especially green and blue-green algae, undergo a population explosion or bloom. Algal blooms are generally regarded as negative features because they make the water taste and smell bad. Although the blooms contribute large amounts of oxygen to the water through photosynthesis, when the organisms making up the bloom die and fall to the bottom of the lake, they are decomposed by oxygen consuming bacteria. This process depletes the bottom water of dissolved oxygen, thereby leading to fish kills. In shallow lakes, the decomposition of the dead algae can use up all the oxygen in the surficial water, resulting in a complete "failure" of the lake's chemical system. As nutrients continue to flow in, anaerobic bacteria take over; at this stage the lake is generally considered to be dead.

Approximately 30% of North America's lakes are experiencing accelerated cultural eutrophication. One of the most famous is Lake Erie. During the 1960s and early 1970s it was close to being "dead"; however, a massive effort on the part of both United States and Canada to clean up the water in this large shallow Great Lakes basin has resulted in a slow but definite improvement in eutrophic conditions. In the late 1980s beaches that had been closed for nearly three decades were allowed to be opened. Sport fish such as lake trout, Coho salmon, and walleye have made a comeback. By 1991 it is estimated that nearly 100% of the industries on both sides of the lake will be complying with international regulations on liquid waste disposal. Also, over 90% of the municipalities within the immediate drainage basin of the Lake will be pre-treating their sewage.

Liquid waste disposal

There are many liquid waste disposal and purification schemes in use in North America today, ranging from simple dilution to complex chemical and biogeochemical treatments. One of the most common ways of eliminating particularly toxic and hazardous liquid wastes has been disposal in the deep subsurface. Subsurface disposal of liquid wastes is particularly attractive in highly urbanized areas in which the surface lakes and river may already be severely stressed. There are many problems inherent with this method of waste disposal. Rarely is an underground aquifer completely isolated from other aquifer systems. Thus, waste fluids that are pumped into the subsurface often find their way into aquifers that are used for water resources. Also, as discussed earlier and was graphically illustrated by the U.S. Army disposal of nerve gas chemicals outside of Denver, injection of fluids into the subsurface can very likely induce earthquakes.

The point that must be remembered in any type of subsurface disposal scheme is that the aquifers into which the waste fluids are being injected are not isolated and often do not react in a predictable manner. For example, in the early 1980s a chemical company wanted to use abandoned oil and gas wells in southwestern Manitoba to dispose of various types of acids. The subsurface reservoir into which they suggested injection was a Jurassic aged sandstone at a depth of about 1,200 m. Since the wells were not productive and were already drilled, not only would the company save a considerable amount of money, but by not having to drill new disposal wells, it was also considered an environmentally sound waste management scheme. However, upon further detailed study it was found that the reservoir consisted of mainly quartz with small amounts of feldspars, calcite, and chloritic clay cement. Disposal of the acid into this reservoir would have caused considerable problems because the acid would have reacted with the chlorite to form insoluble hydroxides, which would then plug any available porosity and permeability. The acid would also attack the calcite and feldspar cements and authigenic components, resulting in breakdown of the rock and eventual subsidence. In addition to these plugging and corrosion problems, many other negative aspects have been documented in subsurface disposal systems including: changes in the clay mineralogy of the reservoir, formation of toxic gases, and polymerization and/or oxidation of organic matter in the rock.

Many of North America’s larger towns and cities attempt to somewhat modify or purify municipal liquid wastes before disposal. Unfortunately, many of the treatment plants are old, out-dated, and badly under designed. Outside of North America and Europe however, pre-treatment of liquid wastes is rare.

Water treatment techniques most commonly used for urban municipal wastes consist of one or more of the following procedures:

- sedimentation, in which suspended silt, sand, and other particulate materials are allowed to settle out in a basin;
- filtration through screens to remove the coarsest debris or through a sand/silt bed to remove finer material;
- coagulation, which consists of adding aluminium or iron salts to the water to cause flocculation of the very fine-grained material and therefore more rapid sedimentation;

- aeration or the addition of oxygen to the water;
- water softening by passing the water through a material that will exchange or replace any water hardening elements (such as Ca^{2+} or Mg^{2+}) with Na^{+}; and
- disinfection of the water by addition of chemicals, such as Cl^{-}, which kill the pathogenic bacteria and other organisms.

These techniques are used individually or in combination to give three main groups of water treatment plants based on the level of purification attained. Primary treatment is the simple removal of particles in the water, usually by sedimentation or filtration. Secondary treatment involves chemical removal of very fine colloidal material and the oxidation or biological consumption of biodegradable matter. This is usually done by a combination of coagulation and then seeding the waste water with bacteria that will utilize and consume the dead organic material. Tertiary treatment is designed to remove many of the inorganic contaminants, such as trace metals or water hardening elements, and any persistent organic matter that remains after the secondary treatment.

Solid wastes

Magnitude of the problem

Normal human activities produce an amazing amount of debris. Unfortunately, the amount of trash is not only increasing because of the population increase, but also due to a dramatic increase in the amount generated per capita. In 1930 a typical North American city resident created about 1 kg of trash per day; by 1970 this was up to 2.2 kg/day; today it is about 5 kg/day. Thus, the exponential increase in population plus the astronomical amounts of solid refuse generated per person has severely stressed existing systems of disposal in many urban areas. In Winnipeg about 1,000 tonnes of trash are generated per day. The monetary expenditure for collection and processing of this waste material is nearly a third of the municipal budget. In North America, approximately $30 x 10^9 is spent each year on solid waste collection and disposal.

A study done in 1985 indicated that about half of all of North America's cities over 50,000 population would run out of disposal sites within five years! Many of the larger centres have run out of "convenient" sites long before this and have adopted interesting alternatives. As an example, for nearly five decades up until disastrous pollution of the shorelines in 1981, New York City used the Atlantic Ocean as a disposal site for its solid (and liquid) refuse: nearly 10 million tonnes of solid waste per year were dumped into the Atlantic offshore from New York. Although the ocean has a limited capacity to recycle much of this material, the system became so overloaded that garbage was routinely being washed ashore.

Given the tremendous diversity of material making up the typical trash of an urban center, it is indeed a difficult problem to properly dispose of the material in a completely nonpolluting manner. Most urban areas today use some kind of multilevel disposal system. For example, in Chicago "class 1" disposal has virtually no limitations on the type of material accepted. It is intended to be more or less permanently isolated from the hydrogeological environment. "Class 2" disposal is intended for decomposable organic wastes and other material that can be broken down under normal weathering and near-surface processes. This material is selectively isolated from the hydrogeologic environment for a period of years or until decomposition and chemical alteration has reduced the pollution potential. Finally, "class 3" disposal is intended for all inert, nonwater soluble, nondecomposable solids such as rock, concrete, brick, asphalt, and other construction solids.

Dumps versus landfills

Throughout history, open dumps have been the most common disposal method of solid wastes, and, unfortunately, still are today. About 80% of the cities in North America use dumps. They are the most economical means of disposal, provided that land is available. A dump *per se* requires little preparation or maintenance. However, the large numbers of dumps have become an environmental disaster. Surface water and groundwater contamination is normal. Disease can be easily spread because the breeding of pathogenic organisms is uninhibited and the site is usually overrun with flies, rodents, and scavengers.

A much more viable and effective method of disposal is by *sanitary landfill*. It is important to note that a sanitary landfill differs considerably from an open dump. Less than 5% of the cities in North America use sanitary landfills. The term "sanitary" is applied to this method because there is an attempt to contain all wastes and potential pollutants at the site. This is done by first of all choosing a site that has the following characteristics:

- A relatively deep and predictable water table.
- Little possibility of flooding.
- An adequate source of suitable cover material such as clay.

Sanitary landfills strive to use the smallest practical area, and to reduce the refuse to the smallest practical volume. The base of the site should be relatively impermeable so that downward leaching to the water table is not possible or is very slow. Often the base of the landfill is lined with plastic to assure that liquid draining through the waste (leachate) will not contact the regional or local groundwater.

Secondly, the waste is compacted and covered on a daily basis. This greatly decreases subsequent subsidence due to oxidation or decomposition and also prevents the trash from blowing around. Infiltration of rainwater is decreased. Finally, drainage systems are often installed to direct the leachate into a segregated basin or lagoon, which is periodically drained and treated.

Other disposal methods

Incineration is another common technique used for solid waste disposal. Unfortunately incineration is considerably more expensive than landfills, and merely reduces the volume of waste that has to be disposed. Beginning in the early 1970s high temperature incineration plants were developed that could reduce the total volume of typical urban trash by an average value of 97%. In addition, a by-product of this high temperature process is the generation of methane, which can be recycled as a fuel for the incinerator or diverted by pipeline to the city.

Other methods of solid waste disposal include the following:

Composting

Allowing biochemical degradation of the organic matter in the garbage to generate a humus-like end product, which is then either recycled or disposed of in a different manner. Composting is usually done only on a small scale because it is relatively expensive and requires segregation of organic from inorganic materials.

Grinding

Pulverizing garbage and mixing the material with water to form a slurry, which is then handled by the municipal water treatment system. Grinding has become quite popular both on an individual home scale and on a municipal scale. It greatly reduces the volume of solid matter that has to be handled and gets rid of the garbage immediately. However, the sewage sludge still has to be disposed of after grinding. The process, of course, greatly increases the load on municipal water treatment facilities.

Salvage, reclamation, and/or recycling

The reuse of solid waste is certainly not a new concept. It has been shown to be effective in substantially extending the life of some natural resources and can greatly reduce the volume of urban waste. Unfortunately, the reprocessing involved is still not economic for most material so there is little monetary incentive to recycle. Also, some of the processing plants are major contributors of water and air pollution themselves. By increasing the throughput of these plants, the level of pollution is often raised.

Ocean dumping

As was mentioned above, New York City has been dumping both solid and liquid wastes in the offshore area of the Atlantic for over 50 years. In fact, New York's dumping during the 1970s became the single largest source of any type of sediment entering the Atlantic Ocean! However, the large-scale disposal of waste oil and various toxic wastes, such as nerve gas liquids, pesticides, and trace metals, led to an international agreement to decrease ocean dumping in the mid-1970s.

Pollution problems of solid waste disposal

The overall pollution potential of any waste disposal scheme is determined by the following factors:

- The reactivity of the waste: This is basically a function of the amount of organic matter, soluble inorganic material, and easily oxidized substances.
- The physical stability of the refuse.

- The geologic and hydrologic parameters at the site, including porosity, permeability, topography, elevation of the groundwater table, and groundwater flow dynamics.
- The efficiency of an upper surface seal, which in turn is controlled by the physical character of the material used to cover the fill.
- The climate of the area: Chemical reactions occur slower at lower temperatures and leaching of the waste is slower in low rainfall climates.
- Degree of aesthetic deterioration.

Many old dumps, disposal sites, and even sanitary landfills can eventually turn into point sources of water pollution. Some of the more common problems giving rise to this type of hazard include:

- Depletion of dissolved oxygen and a complementary increase in CO_2 in the groundwater or surface water caused by oxygen-demanding organisms that are decomposing the waste.
- Bacterial contamination.
- Physical impairment of surface streams and lakes by sediment and debris.
- Increased salinity and increased nutrient content of the groundwater.

Gas generation is a particularly common problem in many older landfills and dumps. The main gases that can be formed from the buried material are methane and carbon dioxide. Carbon dioxide is heavier than air so it usually sinks in the landfill. If the CO_2 comes in contact with the groundwater it can dissolve in the water creating carbonic acid, which is a very effective leaching agent. Methane is, of course, very unstable and can cause explosions if allowed to build up in the landfill. Old dumps outside of Chicago have sufficient quantities of methane trapped within the fill such that the CH_4 is actually being commercially produced and used as an energy source in various industrial and domestic establishments.

Leachates from landfills and dumps are one of the most serious problems with waste disposal today. *Leachate* is defined simply as a very complex fluid composed of variable proportions of organic acids and gases, inorganic compounds, and toxic trace elements that originates by circulating water through a waste disposal site. Although generalizations are very difficult to make, most leachates are characterized by high total dissolved solids (TDS), and high levels of nitrates, chlorides, sulphates, many iron compounds, and toxic trace metals. Indeed, the main problem with leachates is that each one is unique, depending on the type of material making up the waste.

Landfill evaluation

The single most important factor for the environmental geologist to decipher in leachate-landfill management is the route of migration of the groundwater (and, hence, leachate) in the vicinity of the disposal site. If the landfill is ideally located and constructed, the leachate will be funnelled into a subsurface drainage collection system that will be directed toward a leachate pond.

However, this ideal situation is not always the case, and thus, each disposal site in which there is a leachate problem must be individually assessed. The general list of factors that need to be evaluated include:

- **Geologic factors:** The nature of the bedrock and surficial deposits, the type and thickness of the soils, the grain size, porosity, and permeability of the sediment, and the topographic setting.
- **Hydrologic factors:** Rainfall, temperature, elevation, and seasonal fluctuations of the water table, and the direction and rate of movement of the groundwater.
- **Type of waste and the nature of the decomposition products.**
- **Social factors:** The rate and direction of urban expansion.
- **Economics of the site and of the municipality.**

Key concepts and terms to remember

aerobic
anaerobic
BOD
CFC
compost
cultural eutrophication
epilimnion
eutrophication
flocculation
hypolimnion
incineration
intractable waste
leachate
lentic system
limnetic zone
littoral zone
lotic system
Love Canal
methane
multilevel disposal
nonpoint source
nutrients
pH
photo-decomposition
photic zone
point source
pollutant
primary wastewater treatment
profundal zone
residence time
sanitary landfill
secondary wastewater treatment
secure landfill
septic tank
tailings pond
tertiary wastewater treatment
thermal efficiency
thermal stratification
thermocline

Review questions

1. Describe the advantages of a sanitary landfill versus a dump.
2. Use of an in-sink garburator in the home is sometimes described as on-site garbage disposal. Is this accurate? Why or why not?
3. Both landfills and incinerators can serve as energy sources. Explain.
4. Discuss how geoscience fits into pollution studies.
5. Outline the merits and drawbacks of deep subsurface disposal of wastes.
6. Compare and contrast the concepts of “dilute and disperse,” “concentrate and contain,” and “resource recovery” relative to waste disposal.
7. List the five most common types of solid waste in North American disposal sites.
8. Recycling is now a popular method of disposing of some types of wastes. What are some the major drawbacks associated with recycling?
9. Explain residence time with respect to a pollutant.
10. What is BOD?

Notes

Unit 8
Hazardous Wastes

Topics

Introduction to hazardous wastes
Mining and environmental pollution
Acid precipitation
Radioactive wastes
Love Canal example

Introduction

In this unit we will continue with our discussion of the geoscience of pollution and waste disposal but will focus on the broad topic of hazardous wastes.

Learning objectives

A hazardous waste is one that contains one or more substances that represent a particularly *serious* threat to the environment or to human health. Particularly troublesome are those wastes that were introduced in unit 7: soluble or able to produce a mobile fraction through their decay, which can then lead to the pollution of groundwaters, surface waters, or land-water ecosystems. The handling of materials that are either radioactive, strongly acidic, or very poisonous in small amounts often requires an in-depth understanding of the geology and geochemistry of the environment.

By the end of this section you should be able to:

- describe the various types of radioactive waste;
- differentiate between toxic waste, hazardous waste, and intractable waste;
- list the major sources of radioactive wastes with reference to their relative importance;
- discuss the problems with interim storage;
- summarize mining activities in Canada with respect to processes and techniques that give rise to pollution;
- use specific chemical reactions to explain the generation of acid mine drainage;
- describe how acid mine drainage affects the environment;
- discuss how bedrock geology can influence the environmental effects of acid rain; and
- using the Love Canal episode, show how proper geological investigation plays a pivotal role in land use studies.

Learning activities

1. Finish reading chapter 13, chapter 14 and chapter 15 in your textbook and answer the study questions at the end of each of these chapters.
2. Read the study notes and answer the review questions.
3. Finish Assignment 3 and submit it to the Student Services Office no later than the due date indicated in the Assignment due dates.

Study notes

Introduction to hazardous wastes

During the 1970s a new, previously unheard of, waste problem appeared on the scene: hazardous waste. The infamous Love Canal disaster in 1976 captivated the attention of both Canada and United States and served as a doom warning of future problems. The first quantitative evaluation of the magnitude of the problem was a 1979 U.S. EPA report which estimated that over 50,000 sites in the United States contained hazardous wastes and that about 2,000 of these posed significant risk to human health. Over the past decade, relatively little advance has been made in the routine handling of hazardous wastes.

A *hazardous waste* is one that may present a danger to human health because of its toxic, explosive, or corrosive/reactive nature. A separate category of hazardous wastes is *toxic wastes* that are poisonous. *Intractable wastes* are those for which there are currently no environmentally acceptable disposal facilities in the region. The terms are often used interchangeably, but they are not the same. By definition, all intractable wastes are hazardous, but relatively few are toxic. For example, most of North America's intractable wastes are nontoxic CFCs (chlorofluorocarbons) and halons. However, the toxicity of the toxic wastes cannot be overlooked. Dioxins, for example, are among the most lethal compounds in existence. There are about 75 chemical compounds belonging to the dioxin family. They are colourless, odourless, and tasteless. By themselves they have no known use or value and are produced as an unintentional by-product in the manufacture of herbicides, detergents, pesticides, disinfectants, and wood preservatives. One-millionth of a gram can kill a guinea pig; a concentration of one part per billion (ppb) is considered hazardous to humans. They are insoluble in water but relatively soluble in fats and organic tissue. Thus, dioxins are not readily leached out of the soil but they can bioaccumulate in the food chain. One positive feature of the compounds is that they are effectively destroyed by photodecomposition. When exposed to sunlight they have a very short half-life (approximately one hour); in soils, however, the half-life ranges up to decades.

The handling of hazardous wastes varies greatly from region to region. High temperature incineration is a common method of disposal in eastern North America and parts of Europe. However, fears of air pollution, leaks, spills, and other contamination problems as well as the NIMBY (not in my back yard) syndrome have curtailed widespread use of this type of disposal. Many regions are simply stockpiling hazardous wastes. They are being kept in storage until a better disposal method becomes available. Unfortunately, leakage and contamination at the storage site is a common occurrence. For example, in Sydney, Australia, some 100,000 tonnes of intractable wastes are stored at a single site near the ocean. Leakage from this site has contaminated the soils of a large area surrounding the site. Last year a fire in a PCB (polychlorinated biphenyl) waste storehouse in Ontario forced large-scale evacuation and fears of widespread contamination.

Mining and environmental pollution

The minerals industry is very important to Canada's economy. Few other industries have had as much impact on the development of Canadian society and economics than mining. However, mining in Canada, as in much of North America, has a particularly notorious reputation from the standpoint of pollution. It has been commonly held for many years that it is impossible for the mining industry and "nature" to exist side by side. It is often assumed that the requirements of the two are mutually exclusive. But as we approach the end of the twentieth century, it must be concluded that the technology now exists for industry to maintain adequate production levels and at the same time act responsibly, with the longer-term interests of the environment at the forefront.

Mining has been a major environmental concern for many years. The major problems created by mining activities are:

- increased erosion and sedimentation;
- water pollution; and
- aesthetic degradation.

In most cases of environmental damage attributed to the minerals industry, it is not so much the actual extraction of the mineral that is most damaging, but rather the disturbances caused by the processes associated with upgrading and processing of the ore. For example, 70 years after the cessation of mining activities in regions of Québec, the waters draining out of these areas are still heavily polluted due to the occurrence of spoils heaps and waste material.

In Canada most of the environmental degradation problems associated with mining are associated with extraction and processing of:

- Metals, specifically nickel, copper, zinc, and lead.
- Coal.

The minerals industry in Canada basically consists of five main stages:

a. **Exploration:** The geological, geochemical, and geophysical surveying of an area to identify and delimit ore bodies including exploratory drilling, stripping of overburden, and excavation.

b. **Development**: The preparation of the site for mine activities including road and surface facility construction.

c. **Extraction:** Removal of the ore.

d. **Beneficiation:** The concentration of the ore from low or medium grade deposits.

e. **Processing:** Any additional modification required to create a usable product.

Each of these stages involves environmental disruption; however, the precise impact and relative intensities of the activities are variable depending on the nature of the topography and ore body, the remoteness of the site, and the material being mined. As a broad generalization, the most significant potential for environmental damage is associated with the extraction, beneficiation, and processing stages.

Water is essential for most aspects of modern mining. It serves both as a vital raw material and as a vehicle for waste disposal. Hence, many of the major environmental problems associated with mining involve water pollution. In particular, water from mining activities is often charged with unacceptable levels of mineral and trace metals. Metals ores are usually crushed and milled at the mine site. These actions tend to produce very fine-grained waste, or tailings, which are allowed to settle out in tailings ponds before the water is re-used. Chemical reagents added to the ores during processing also are an important source of water contamination. Although most mines today attempt to reduce the contamination by discharging the water and tailings waste from the mining and milling operations into settlement and treatment lagoons (tailings ponds). These lagoons are very often poorly designed, insufficient in size or retention times, or leak into the subsurface. Other important sources of pollution are from:

- The storage piles where water and wind can transport the concentrated ore into streams or onto surrounding soil.
- Transportation of the ore.
- Smelter emissions.

In the case of coal mining, additional problems are associated with the size of the mines: coal mining is nearly always a much larger scale operation than metal mining. Coal strip mines commonly extract 40,000 to 60,000 tonnes per day compared with only about 6,000 tonnes for underground base metal mines. It is predicted that oil shale mining will require removal and processing of nearly 200,000 tonnes of shale per day. Excavations of this size result in large piles of waste and overburden that are usually prone to erosion by water and wind and leaching by rainwater and drainage.

Acid mine drainage

One of the most damaging and far-reaching environmental problems associated with mining is the generation of *acid mine drainage*. Although any mineral deposit which contains sulphide is a potential source of acid mine drainage, certain types of mining are more prone to generating acidic conditions than others. In general, the extraction of coal, copper, zinc, silver, gold, lead, and uranium are the greatest potential contributors of acid drainage.

Acid mine drainage is usually the result of a complex series of geochemical reactions. Pyrite (FeS_2) is certainly the most common and volumetrically most important mineral contributing to the reactions, but there are over 20 other sulphide minerals that are susceptible to weathering and oxidation. Basically, the sulphide minerals oxidize in the presence of water upon exposure in the mining process to create sulphuric acid. The reactions are straightforward:

$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$
(production of sulphuric acid by oxidation of pyrite)

$Fe^{2+} + 0.25O_2 + H^+ \rightarrow Fe^{3+} + 0.5H_2O$
(oxidation of ferrous iron, Fe^{2+}, to ferric iron, Fe^{3+})

$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$
(precipitation of ferric hydroxide)

$FeS_2 + 14Fe^{3+} + H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2+} + 16H^+$
(reaction of ferric iron with pyrite)

The key point that these reactions demonstrate is that pyrite and the reduced sulfur can remain stable in anaerobic conditions. However, as soon as these reduced sulphide mineral species are exposed to oxidizing (atmospheric) conditions, decomposition to H_2SO_4 occurs. Thus, the limiting step in the reaction series is the combination of the metallic sulphide with oxygen. This oxidation process, in turn, is controlled to a major degree by the surface area of the sulphide: in general, the finer the grain size, the greater the surface area and the greater the rate of reaction.

Acid mine drainage affects the environment is a number of ways:

- The acidity itself.
- Fe^{3+} precipitates.
- Heavy metals.
- Turbidity.

The most significant impact of the acidity factor, which is normally assessed by measuring the pH of the stream, lake, or soil, is to substantially reduce the bicarbonate buffer system. This buffer system, present in most natural settings, is a feedback mechanism that controls the magnitude of the shifts in pH. However, below a pH of about 4.2 all carbonate and bicarbonate is converted to carbonic acid. This acid readily dissociates to water and free carbon dioxide, which is then lost to the atmosphere. Thus, the water looses its capacity to buffer changes in pH. Also, many photosynthetic organisms use bicarbonate as their source of inorganic carbon. Bringing the pH of the aqueous environment down to 4 eliminates the bulk of photosynthesis. On the other hand, flocculation of silt and clay is increased at low pH, resulting in a much clearer aqueous medium, greater light penetration, and the potential for greater photosynthesis.

A more general problem with acid mine drainage (or any other process that reduces the pH such as acid precipitation) is that it increases the rate of decomposition of carbonates, feldspars, and clay minerals. The elements released by this enhanced chemical weathering often include potentially toxic metals such as aluminium. In addition, the dissolution releases large quantities of dissolved silica that, in the aqueous environment, can stimulate blooms of diatoms. Conversely, the lowered pH will result in dissolution of the shells of many molluscs and crustaceans.

The classic orange to red colored flocs of Fe^{3+} (ferric) precipitates associated with most acid mine drainage areas are composed mainly of $Fe(OH)_3$ which, as shown in the equations above, is a result of the oxidation of pyrite. At very low pH values the iron ions are soluble, but as the pH rises they begin to precipitate out. The critical pH for iron is 4.3 in normal fresh water. Thus, it is possible to roughly gauge the severity of the acid drainage very quickly by simply looking for the orange ferric precipitates. More importantly, however, is that when the pH does rise and the ferric salts come out of solution, the fine precipitates and colloidal gels have severe effects on the biota of the streams and lakes. In suspension, the precipitates reduce light penetration and interfere with photosynthesis. When the precipitates settle out they can smother the benthic biota.

A decrease in pH is often accompanied by a significant rise in the solubility of heavy metals. Thus, very high concentrations of relatively toxic substances can occur in acid drainage. For example, unpolluted streams in northwestern Ontario have an average nickel concentration of about 0.01 mg/l; acid drainage streams (pH 3.9) near Sudbury contain Ni in excess of 10 mg/l.

In addition to the turbidity associated with ferric iron precipitates, there are several other causes of turbidity associated with mining operations. Where the acid drainage is being treated with lime to increase the pH, large amounts of calcium sulphate, aluminium hydroxide, and, at relatively high pH (greater than 9) iron hydroxide, are precipitated, which can remain in suspension for some time. The tailings ponds and spoil heaps themselves are not only sources of acid but also can be easily eroded to give high levels of turbidity to the surrounding lakes and streams.

Acid precipitation

The contamination of water and soils by deposition of contaminants from atmospheric sources is important. The phenomenon of radioactive fallout has been well studied in many parts of North America and Europe for over twenty years. Similarly, the acidification of surface waters and soil by low pH precipitation, popularly known as acid rain, was a severe environmental problem recognized in the 1950s in Norway and Sweden. Indeed, much of what is known about the processes of acid rain stem from investigations and research in northern Europe during the past several decades.

The cause and effect relationship of acid rain and the disappearance of fish and degradation of forests were first scientifically documented in Scandinavia in 1959, although suggestions of the influence of acid rain were made as early as 1920. Also in the late 1950s and early 1960s, episodes of highly acidic precipitation were documented in Belgium, the Netherlands, Luxembourg, Germany, France, and Britain. It was not until the late 1960s, however, that abnormally low pH rainfall was identified in North America.

Normal rain is weakly acidic with a pH of about 5.5 due to the presence of carbonic acid. However, when the oxides of sulfur and nitrogen, which are created mainly by combustion of fossil fuels, react with water and oxygen in the atmosphere, sulphuric acid and nitric acid are created. These additional sources of acid can lower the pH of precipitation to less than 4.0.

The environmental effects of acid rain are, to a major degree, controlled by the geochemistry of the water, soils, and rocks upon which the precipitation is falling. One of the major reasons the effects of acid rain are so devastating in Scandinavia, eastern Canada, and northeastern United States is that the bedrock of these regions is mainly igneous crystalline type. Thus, the soils derived from these rocks and the surface and shallow subsurface waters of these regions are lacking in any type of buffering agent, such as carbonate ions, which compensate for changes in pH. With increased acidic precipitation, the threshold level for many fish and plants is soon reached, thereby causing drastic changes in the ecology.

In Canada numerous studies have now shown that from southwestern Ontario eastward to Nova Scotia over 50% of the lakes have pHs of less than 5, and 90% of these lakes have become devoid of fish. As indicated in the newspapers and popular ecojournals during the past several years, this has become a point of considerable international aggravation to Canadians because the dramatic increase in sulfur oxides and nitrogen dioxide can be traced to the highly industrialized Ohio River valley area. Unfortunately, the fact that the single 400 m high smokestack at Sudbury, Ontario, is responsible for over 1% of the entire world's SO_2 emissions tends to negate the Canadian concerns.

The environmental problems associated with acid precipitation go far beyond fish kills. Alteration of the soil chemistry upsets the normal cycling of metals in the soils and accelerates the leaching and dissolution of minerals. Many types of bacteria are eliminated because most cannot tolerate a pH of lower than 5. This ultimately results in a decrease in the amount of organic debris decomposed, which, in turn, decreases the amounts of nutrients put back into the aqueous and soil environments. Damage to buildings and other man-made structures also occurs. It has been estimated that over \$10 x 10^9 damage occurs to city buildings in eastern North America per year.

Radioactive waste

High-level and low-level radioactive wastes and uranium mine tailings are the undesirable by-products produced by the various stages of the nuclear power industry. These by-products are generated at the mining and milling site as well as during the processing of the fuel, the actual use of the uranium in the reactors, and after the fuel is spent.

The types of waste are conventionally differentiated simply on the basis of the intensity of radiation they emit. *High-level radioactive wastes* are generated by the actual use and operation of nuclear reactors. Spent reactor fuel contains highly radioactive elements: it comprises over 99% of the total radioactivity of all the radioactive waste. *Low-level radioactive wastes* are composed mainly of materials and liquids that come in contact with radioactive material during the operation and maintenance of the reactor. These wastes are composed of such things as filters, clothing, washes, containers and other maintenance materials. Finally, the uranium *tailings* are a by-product of the mine, which removes the metallic mineral from the large amount of ore. The situation with U mining is a bit unusual in that exceedingly small amounts of uranium must be extracted from huge volumes of ore. Most uranium mining and mill tailings are composed of common minerals such as quartz, feldspar, micas, pyrite, and calcite, plus very small quantities of unrecovered radioactive minerals (e.g., radium–226, lead–210, thorium–232). These latter components can represent a modest amount of radioactivity. The solid and liquid wastes, including all contaminated waters and reagent chemicals from the milling processes, are pumped as viscous liquid slurries to large settling ponds.

To appreciate the problems with radioactive waste it is important to realize that radioactive elements are found naturally in the environment. However, it is not until they are concentrated by mining and milling or produced in reactors that their existence requires special handling. The storage and disposal of radioactive wastes affects both land use and land value.

The amounts of the various radioactive wastes are continuously growing as more and more power is being generated through the use of nuclear energy. While storage sites for high- and low-level wastes need not occupy large areas of land, uranium mine tailings, conversely, require thousands of hectares of land. Obviously the most important aspect affecting the disposal of nuclear wastes is the fact that they are radioactive. Land utilized for the disposal of the wastes is likely to be unsuitable for other uses.

Since the beginning of the nuclear industry in North America in the early 1940s, radioactive wastes have been produced essentially without consideration to their disposal. The industry began during the Second World War with the mining of relatively small amounts of uranium ore for military uses. The demand increased after the first atomic bombs were used and especially as the arms race accelerated and more nuclear weapons were developed. The use of uranium for the generation of electricity further increased the volume of wastes and as more nuclear power plants came into operation, it became evident that there was a more pressing need for a disposal method.

Low-level radioactive wastes

Low-level wastes are generated by a number of sources, including reactor operations and maintenance, uranium refineries and fuel manufacture. The Atomic Energy of Canada Limited research and development activities also generate waste materials, as do users of radioisotopes in medical and research laboratories. Most of the volume of low-level wastes, however, is produced in nuclear reactor operation. In reactor operations, small quantities of fission products escape from the fuel elements and contaminate the coolant. The contaminated coolant is treated to remove the radioactive components. Materials used in the cleaning and maintenance of the reactor plant and in treating the coolant are all considered to be low-level radioactive wastes.

The radioactivity in these low-level wastes ranges from barely detectable to relatively high values, with hazardous lifetimes from a few hours to tens of thousands of years.

Two key features of radioactive wastes must be evaluated:

1. Their level of radioactivity.
2. The time over which the material will be hazardous.

These two characteristics determine the extent and period of isolation required. Radioactive wastes containing radionuclides that have short half-lives (half-life is the period that would have to pass before the radioactivity of the element would be halved) pose relatively little problem. Clearly, the most serious concerns are with radioactive wastes containing nuclides having long half-lives.

In reactor operations, the fission process, or the splitting of the atomic nucleus for the production of energy, generates a large number of highly radioactive fission products. Radioactive elements are also formed by other processes in the reactor such as neutron activation of the fuel, heat transfer and the reactions within the moderator medium (heavy water). Depending on the origin of the waste, the composition and radioactivity level of the low-level wastes vary considerably. Nonetheless, even low radiation levels pose a health and environmental hazard.

Disposal methods

No completely satisfactory disposal method has been developed for low-level radioactive wastes, but several options have been proposed. These include:

- Depositing the wastes, suitably contained, into the sea.
- Shallow land burial.
- Burial in sanitary landfill sites.
- Placement in inactive mines.

Although sea dumping was common during the 1960s and 1970s, the method most technologically promising for Canada is probably shallow land burial or utilization of existing sanitary landfill sites. Although there appears to be no adverse effects with this type of disposal, it has been shown that some low level wastes can bioaccumulate in the food chain.

Mine and mill tailings

Uranium mine and mill tailings comprise the largest volume of wastes produced by any component of the nuclear fuel industry. The milling of uranium ore produces enormous volumes of coarse-grained sandy tailings with low levels of radioactivity.

In Canada there are several main uranium mining areas: open pit mines at Wollaston Lake and Cluff Lake, Saskatchewan, and the underground mines at Elliot Lake and Agnew Lake, Ontario. Although the mining operation itself can generate waste, it is the milling of the ore that creates most of the volume of waste. Milling is the process by which the uranium content in the ore is extracted and concentrated into a substance known as yellowcake. The ore enters the mill, where it is crushed and ground. Following this, the crushed ore is subjected to a sequence of chemical treatments to separate the uranium.

Two waste types are produced: solid wastes, composed of the residue from the ore, and liquid wastes, composed of water, components leached from the ore and chemicals used in the extraction process. The two waste products are combined into a slurry and transferred to tailings ponds, where the solids are allowed to settle out and the liquids are separated. The bulk of the radioactivity in the uranium tailings is in the form of radium-226 although this will vary depending on the on the mineralogy of the ore body. In addition to the radioactive waste, the tailings, like that from any other mine, contain a wide variety of heavy metals, pyrite, and other reactive materials. Furthermore, because an acid leach solution is often used in the milling process, both the solids and liquid radioactive wastes are also acidic and must be treated with lime or crushed limestone to neutralize the acidity.

Since their first operation in the 1940s, uranium mills in Canada have produced 300 million tonnes of tailings. However, as demand increases corresponding to gradual decrease in usage of fossil fuels, lower grade ores will have to be mined, and the waste generated in the milling process increased significantly. At present, the mill waste disposal sites are isolated from human access in order to protect people from radioactivity. In addition to the tailings ponds and effluent lagoons, several other methods of disposal have been proposed. These include: backfilling of the mine (either subsurface or open pit) and underwater storage. Unfortunately, little is known about the potential long-term reactions between the tailings, water, and bacteria in an active or inactive mine or subaqueous setting. The major concern with respect to uranium tailings being handled this way is the long-term release of radioactivity. Radium and thorium, because of their very slow decay rates, will not have reduced their radioactivity to half the present level for roughly 100,000 years, and even then the radioactivity is too high for the tailings to be left in a condition that would be accessible to the general public. Also important are the nonradiological properties of the tailings, especially their heavy metal components and the acidic nature of the tailings—factors that are in common with other mining operations but nonetheless constitute serious health and environmental hazards.

High-level radioactive wastes

The operation of a nuclear reactor generates a certain amount of irradiated fuel, commonly referred to as spent fuel. Whether this spent fuel is discarded in its present form or reprocessed to recover useful constituents, it is designated as high-level radioactive waste. Over 99% of the radioactivity resulting from the operation of a nuclear generating station is in the spent fuel. Of the three types of nuclear wastes, high-level radioactive wastes constitute the greatest potential hazard to the public.

Reactor fuel, before being introduced in the reactor core, is composed of uranium oxide pellets that were produced from the yellowcake. The pellets are placed in zirconium tubes assembled in fuel bundles. Zirconium is relatively immune to radiation damage and interferes very little with the fission process. Each bundle of zirconium fuel rods is sealed to prevent leakage and then placed in the reactor. After about a year inside the reactor, the fuel bundles become spent and must be replaced. When a fuel bundle is removed, it is highly radioactive and produces heat.

The spent fuel contains a wide variety of radionuclides. Some of them decay to half their original level in a short time (e.g., iodine-131 has a half-life of 8 days and krypton-85 has 10 years). Others, such as plutonium, which has a half-life of 24,400 years, take thousands or millions of years to decay to insignificant quantities. These, therefore, require complete isolation from the environment.

You are certainly already aware of the debates that are raging in both Canada and united about the final storage of this material simply by reading the newspaper or watching television; your textbook provides a good overview of the present suggested storage methods. Most of Canada’s spent fuel is currently stored underwater in large tanks, known as fuel bays, at the sites of the nuclear generators. The spent fuel bundles are placed in baskets, which are stacked on the bottom of the tank of water and are continually cooled by circulating water. In addition, the water acts as a shield against radiation. Water leaving the pool is treated to remove radioactive elements that may have accumulated by contact with the spent fuel baskets. However, as the quantity of spent fuel produced increases, a permanent method that requires no monitoring for disposal of the high-level wastes is being actively sought. Many methods of permanent disposal have been considered, including:

- Placing the wastes in scaled canisters and leaving them in various designated locations to be monitored for as long as necessary.
- Transporting the wastes in suitable containers to the Antarctic or to Greenland for burial in continental ice sheets.
- Transporting the wastes into space.

Few of these methods are feasible. Surface disposal is obviously rejected because future generations would have to continue monitoring the hazardous wastes. Moreover, surface disposal would be vulnerable to man-made hazards such as wars and accidents. The use of the ice sheets is rejected because of the dynamic nature of continental ice and also because the Antarctic is covered by an international treaty that forbids the disposal of nuclear wastes. The use of rockets is eliminated because of the high cost and the possibility of accident.

There are currently two options that are receiving consideration throughout the world: disposal of the wastes, suitably contained, either into the sea or into terrestrial geological media. Canada has spent considerable effort investigating the disposal of wastes in crystalline rocks. The method requires the construction of a vault in undisturbed rock in the Canadian Shield. The vault would be 500–1,000 m below the surface. The high-level wastes would then be scaled into containers, placed in the vault, and once the vault is filled, the repository would he backfilled.

At the present time all HLW produced is being stored until suitable geologic disposal environments are evaluated. Most of this temporary storage in North America is in cooled, stainless steel or concrete underground tanks.

As discussed in your textbook, there are a number of other long-term storage possibilities for high-level wastes presently being considered in the United States. In general, for underground storage and long-term disposal of nuclear wastes to be feasible the following requirements have to be met:

- The rock mass has to be homogeneous for at least a km^3.
- The upper surface of the area in which storage will take place should be at least 1 km deep.
- The rock should not have any major discontinuities, faults, or fractures.
- The rock should have very low permeability and negligible through-flow of groundwater.
- The rock should be overall chemically stable and should provide a geochemical barrier prohibiting the transmittance of radioactive products by ion exchange or adsorption.
- Chemical reactions within the waste should not affect the integrity of the rock.
- The area should be free of seismic activity and be of low commercial value.
- The underground storage should be able to withstand long-term climatic changes and sea level changes.

Love Canal example

The Love Canal disaster has become a classic and well-known example of subsurface waste disposal. Although similar problems have occurred repeatedly throughout the past several decades in many other places in eastern and central United States and Canada, Love Canal was so well publicized it is now a symbol of man’s ability to degrade his environment and the repercussions of this degradation.

The Love Canal story starts in the late nineteenth century with W. T. Love. Mr. Love planned an “ideal” or model city in the area of Niagara Falls, New York: the location would be adequately served by electric power and water from the Niagara River that would support not only the city but also industry. Central to

Love's plan was the construction of a navigable canal bypassing the falls and connecting the Niagara River above and below the falls. Approximately two kilometres of this elaborate water diversion canal were dug before Love's company went bankrupt and the entire project was abandoned and forgotten.

Periodically during the 1920s and 30s, the trench was used by both the nearby towns and local industry as a waste disposal site. In 1947 the property was acquired by the Hooker Chemical and Plastics Corporation. Hooker, often painted as the villain in the story, simply continued to use the canal as a convenient and economical disposal site. Over the next six years about 20,000 tonnes of liquid wastes were placed in steel drums and buried in the old canal. In 1953, after the canal was filled, a clay cap was placed on top of the trench and the site closed.

At this time there were few houses in the vicinity and no roads or other municipal construction near the site. However, with urban expansion, the vacant land soon became valuable. Two years after Hooker closed the site the city of Niagara Falls acquired the canal land and the property surrounding it from Hooker for the token price of $1. It must be stressed that the Hooker Corporation made the city aware of the fact that the site was used for disposal of liquid wastes. Despite this, the city undertook no scientific investigation before constructing a school, roads, sewer, water, and electrical servicing, and selling the remaining land to private housing developers. Both single-family dwellings and apartment blocks were built on or immediately adjacent to the canal. By 1971 one school and a total of 100 houses had been built directly on the canal, with another 235 houses constructed on land immediately adjacent to the canal.

As early as 1966 things started going wrong. Residents of the new homes began to complain of fumes and odours in their basements. By 1973 the complaints escalated to actual seepage of foul smelling and, in some cases, caustic liquids into the basements. In 1975 and 1976, after a period of exceptionally heavy snowfall melt and heavy spring rains, subsidence of the land surface occurred that damaged many of the 100 houses sited directly on the canal. Associated with this subsidence were the appearance of the metal storage drums at the surface, and the presence of pools of liquid chemicals in yards. Several of the house's basements were flooded with chemicals.

Although not noticed at the time, subsequent studies have shown that the area had an unusually high incidence of certain diseases during the 1966–76 period: the Love Canal residents had three times the national average rate of miscarriages, nearly four times the normal rate of birth defects, and ten times the average number of people with nerve diseases. Finally, in 1980, after twice being declared a health hazard, the area was closed, the residents relocated, and measures begun to isolate and correct the contamination problem. Even today the legal aspects are not yet settled. Estimates of the cost of the disaster run as high as $\$100 \times 10^6$.

As devastating as the Love Canal episode was to the local New York and Ontario residents, the real impact of Love Canal was the realization of the true nature and extent of the waste disposal problem in North America. Surveys and studies done after Love Canal have suggested that there may be as many as 20,000 such sites in North America, some still active but many forgotten. During the past decade other “Love Canals” have come to light: Times Beach, Missouri; Woburn, Massachusetts; Waukegan, Illinois.

Key concepts and terms to remember

acid drainage
acid precipitation
background level
CFC
dioxin
flocculation
half life
hazardous waste
heavy metals
HLW
incineration
intractable waste
leachate
LLW
Love Canal
PBB
PCB
pH
photo-decomposition
tailings pond
toxic waste

Review questions

1. Evaluate the advantages, disadvantages, and possible concerns related to disposal of HLW in:

   Oceans
   Basalt
   Salt beds
   Space

2. Define “half-life.”
3. What are the differences between toxic wastes and hazardous wastes?
4. Summarize the main tasks undertaken by a mining complex.
5. What is the difference between high-level radioactive waste and low-level radioactive waste?

Assignment 3

1. (10) What is the Superfund, what is the legislation behind it, who manages it, and has it been successful?
2. (10) On which type of sedimentary rock would you choose to develop a sanitary landfill and why?
3. (10) What are the minerals and other substances in sedimentary rock that may emit radon?
4. (10) The greatest potential petroleum deposits in North America lie under government-owned North Slope areas of Alaska and Yukon. Environmental groups generally oppose any drilling in these areas because of the high potential for damaging sensitive ecosystems, interference with caribou herds, and the escape of toxic wastes into the environment from drilling. Similarly, movement of the oil south to market via Pacific Ocean oil tankers is problematic because of the likelihood of oil spills. The oil industry, however, wishes to lease, explore, and develop these regions. Is there any way to resolve these conflicting attitudes? Explain.
5. (5) What was the Australian doctrine of Terra Nullis (also spelled Nullius) and what are the consequences of the High Court of Australia's decision on this matter? (Hint: you may have to do some basic library or online researching to properly answer this question.)
6. (10) Do all mine waste produce toxic materials to the environment? Explain. Which kind(s) of ore bodies are of special concern in regard to acid mine drainage?
7. (10) Summarize the measures for control and reduction of AMD.
8. (10) Without any question, mining and petroleum exploration during the nineteenth and twentieth centuries were responsible for broadening the industrial base of Canada, for causing the nation's economic expansion, and contributed to its emergence as a world leader. The results were an increase in the nation's wealth and development of the west and north. What were the major environmental legacies that are left from these mining and petroleum efforts in Canada?
9. (25) Trashmore is a city of 50,000 located in central Canada. As the newly hired environmental geologist for the municipality, you have been asked to determine the most suitable plan for disposal of the city's solid waste for the next few years. Since Trashmore is not a wealthy urban area, you plan to look into the possibilities for sanitary landfill rather than incineration or other more costly techniques. After looking at the geologic map and cross section (Figures A1, and A2), you conclude that for environmental reasons, one of the potential sites is much better than the other two.
    a. Which of the following sites did you select and why?: Cheryl's Aggregate Co.; Kitty Litter Clay Co.; Nancy's Limestone, Inc.

b. Summarize the major hazards that might be at the other sites.

c. Some of the members of the city council of Trashmore have suggested that the landfill should be located close to a river so that the liquid wastes can be diluted and dispersed. On Figure A3, draw in the water table and add several arrows to show the likely direction of the groundwater flow and the path of the rainwater that falls on the surface of the landfill.

d. Comment on the suitability of this type of site.

e. You have now selected a site for Trashmore's landfill. You must convince the members of city council to change the name of the site from "dump" to "landfill." What are some of the major differences between a sanitary landfill and a dump?

Figure A.1

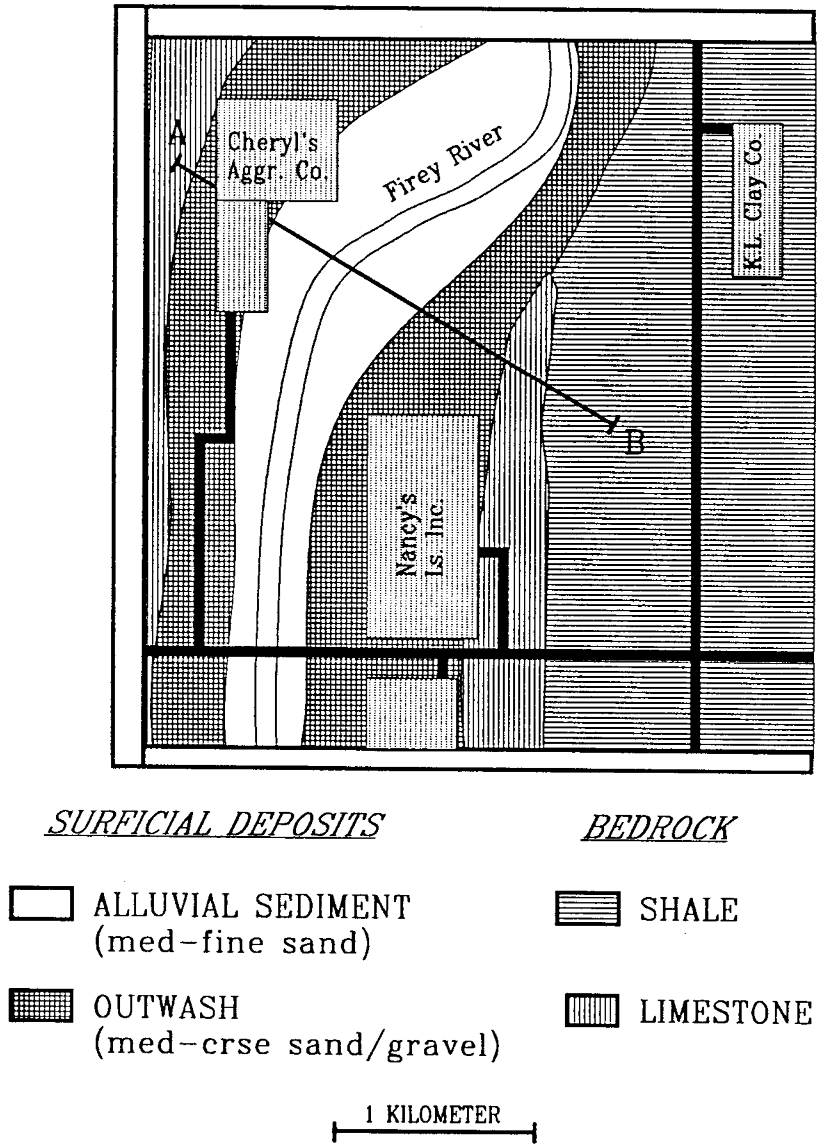

Cheryl's
Aggr. Co.
Firey River
K.L. Clay Co.
A
B
Nancy's
Ls. Inc.
SURFICIAL DEPOSITS
BEDROCK
ALLUVIAL SEDIMENT
(med-fine sand)
SHALE
OUTWASH
(med-crse sand/gravel)
LIMESTONE
1 KILOMETER

Figure A.2

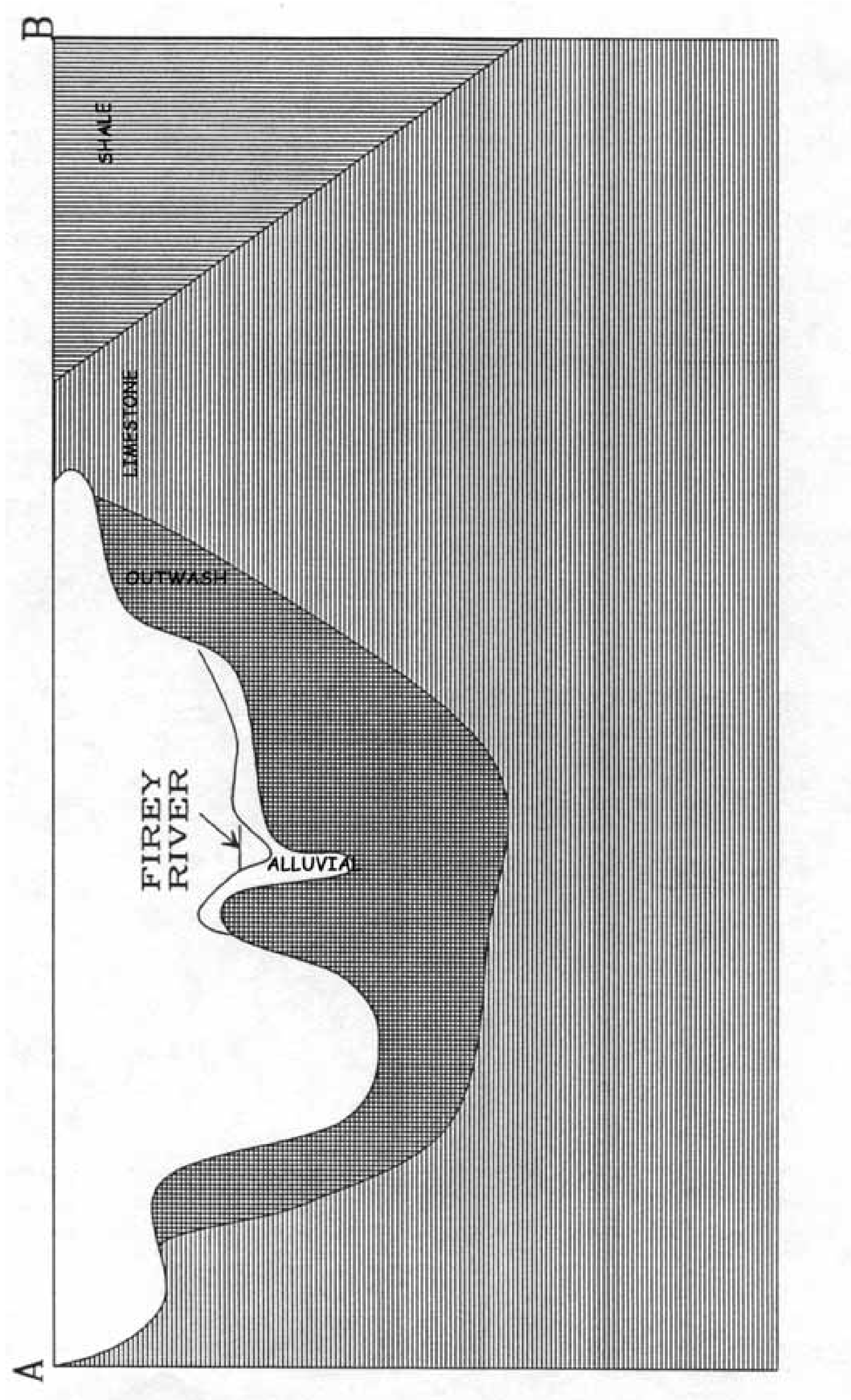
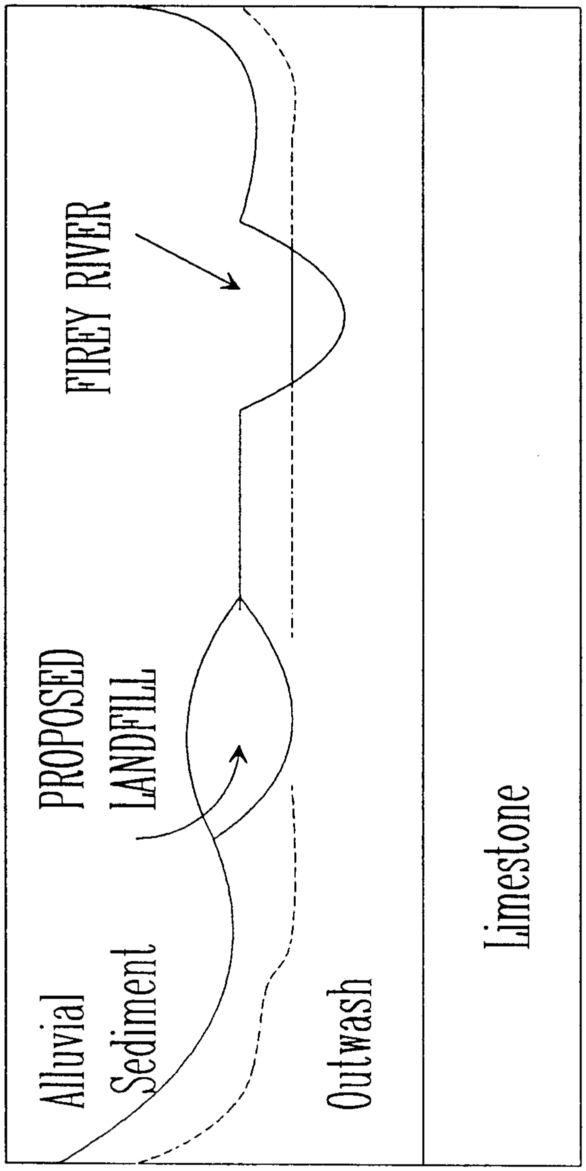


Figure A3



FIREY RIVER
PROPOSED LANDFILL
Alluvial Sediment
Outwash
Limestone

Notes

Module 5
Water Resources and Environmental Geology

Notes

Unit 9
Water Geoscience

Topics

Hydrologic cycle

Groundwater

Water use

Wetlands

Introduction

This module considers the use (and misuse) of water as a natural resource. We have already considered some aspects of surface water flow in connection with the exogenic geologic hazard of flooding. We now want to broaden our perspective. The importance of water availability for domestic use, agriculture, and industry is apparent, particularly in water stressed areas of the world. A satisfactory water supply is dependent upon a number of factors; among these, however, geologic considerations play a pivotal role. Thus, the environmental geologist is becoming more and more involved directly with the design of ecologically acceptable systems of collection, transmission, purification, and distribution of water for society.

Learning objectives

Water is one of the fundamental substances necessary for life. The availability of water has not only permitted great civilizations to flourish, but has also been a key factor in their destruction. The overall objectives in this section are first to familiarize us with the different settings in which "usable" water exists in near-surface environments of the Earth and how we, as environmental geologists and hydrologists, recognize and evaluate this resource. We will then turn our attention to understanding how society uses this water and specifically how the scientists and engineers who are charged with the task of providing a supply of this resource for society cope with an ever-increasing demand. Finally, we will study some classic efforts in water management schemes in order to emphasize the absolute necessity of sound management practices.

By the end of this section you should be able to:

- describe the principal modes of occurrence of water on the planet;
- discuss the hydrologic cycle;
- explain why water is essential on Earth and list the most important properties of this unusual substance;
- illustrate and discuss the occurrence of water in the subsurface;

- describe, with the aid of appropriately labelled diagrams, the flow of water in the near-surface environment;
- construct a contour map of the water table on the basis of drill data;
- explain how Darcy’s law is applied to the flow of groundwater through porous media;
- calculate the discharge from an aquifer;
- describe and draw a diagram that shows a cone of depression resulting from drawdown around a pumping well;
- predict how salt water might intrude a freshwater aquifer in a coastal area;
- quantify the various uses of water on a global and regional basis;
- differentiate off-stream uses from in-stream and consumptive uses; and
- show how wetlands perform an invaluable service to society;

Learning activities

1. Begin reading chapter 8 (pages 213–245) in your textbook and answer the study questions. You should plan to finish this reading by the end of unit 10.
2. Read the study notes and answer the review questions.
3. Start working on Assignment 4; this assignment is due no later than the due date indicated in the Assignments due date box.

Study notes

Introduction

Water is one of the most vital resources we have. It is essential for life: a person can live for perhaps a month without food, but only for a few days without water. Water is also the primary controlling factor in the transfer of nutrients from the lithosphere to the biosphere; it plays a major role in dissolution and dilution of waste products; it serves as a raw material for photosynthesis. In many parts of the world it is the availability of usable water, rather than food, energy, or raw materials that acts as the limiting factor for population growth, urbanization, and most other human activities. As important as it is to have a constant source of usable water, many problems can arise if there is too much of it. Thus, water can take on a schizophrenic personality: lack of it causes drought and severely limits human occupation of an area; too much creates floods, triggers landslides, and destroys property; poor quality can lead to disease and sickness, poor crops, degraded landscapes, and even eventual destruction of manmade structures and habitats.

The study of water as a resource has historically been within the domain of engineers. However, the proper maintenance of this resource implies the detailed knowledge of several important geologic principles and concepts.

Indeed, the Earth sciences are particularly well suited for this investigation because:

- Much of the world's supply of usable water is derived from geologic materials.
- Many aspects of the hydrologic cycle are directly influenced by the geologic setting.
- Like flooding, many of the problems associated with the scarcity of this resource are related to basic geologic processes.

Water, a combination of the elements hydrogen and oxygen, is a compound that makes Earth unique compared with other planets of the solar system. It is so common that over 70% of the earth's surface is covered by water. Unfortunately, most of this water is either saline or locked up in ice sheets and therefore not usable to man. As discussed in your textbook, of the enormous amount of water present on Earth (about 1.5×10^9 km^3), only about 0.3% of it is usable for most of man's purposes. Of this small amount, about 99% is either so remote that it has not yet been easily accessed, is too deep to effectively use, or is already polluted. This leaves approximately 0.003% of the earth's total water supply to draw from.

Water is a rather unusual substance. It is the only material that exists at the earth's surface temperatures in all three physical states. Unlike other geologic resources such as oil, gas, metals, or coal, water is a renewable resource, capable of recharge in a time period ranging anywhere from a few days (as is the case for atmospheric and fluvial H_2O) to thousands of years (for groundwater and deep ocean water). It is a conducive medium for plant growth because it is clear and colourless. Likewise, it is a very attractive medium for transportation because it has a very low viscosity. Water is one of the very few compounds that expands when it solidifies, thereby making the solid material less dense than the liquid. This property is extremely important for aqueous plants and animals; if ice did not float on water, it would accumulate at the bottoms of lakes, rivers, and ponds, and many lakes in temperate regions would never thaw completely. Water has a very high heat capacity, which means that it can absorb large quantities of heat energy without itself becoming hot. This property accounts for the moderating climatic effect that large bodies of water have on nearby cities. Finally, water is "wet." This may seem obvious, but it also means that water is "reactive"; it is eager to adhere to other substances and to enter new chemical bonding, thereby making it the "universal" solvent.

Hydrologic cycle

Your first course in Earth sciences discussed the details of the hydrologic cycle, so only a very brief summary will be given here. However, it must be emphasized that virtually any type of examination of water resources must begin with a thorough understanding of this important cycle. Indeed, much of the work of environmental geologists associated with water resources involves simply the measuring, documentation, and assessment of the flow of water from one part of the cycle to another.

Water is continually cycled through the lithosphere, hydrosphere, and atmosphere by an immense distillation and distribution system. Water is put into the atmosphere by evaporation from oceans, lakes, rivers, and soils and by transpiration from plants. This component of the cycle is termed evapotranspiration and is driven by solar energy. Cooling and condensing results in precipitation that falls back onto the land surface or ocean (meteoric water). Some of the precipitation moves overland as runoff to rivers and finally to the sea. Some of the precipitation also moves down into the ground through the zone of aeration (vadose groundwater) where the soil is not saturated with water. The infiltrating water may reach the level at which the sediment and/or rock is saturated with water. This is phreatic groundwater, and the upper surface is termed the groundwater table. Phreatic groundwater moves slowly within porous and permeable units (aquifers). The flow rate and direction are controlled by elevation differences between where the aquifer is being recharged and where it is exiting the subsurface hydrologic system (i.e., a river, lake, or ultimately the sea).

All of the world's water supply is eventually cycled through this sequence but at much different rates. Atmospheric water, river water, shallow lake water, and shallow groundwater are all recycled fairly rapidly (a few days to a few weeks to a few hundred years). In contrast, ocean water and deep groundwater require thousands and in some cases millions of years for renewal. For example, the groundwater in the Ordovician carbonate aquifers beneath Winnipeg, which comprise a valuable source of water for both industrial and domestic purposes in southern Manitoba, is estimated to be some 15,000 years old.

Groundwater

Nature of the resource

The water table represents the top of the zone in which the pores in the soil, sediment, and rock are completely saturated with water. Unlike surface water, the movement of groundwater is very slow, usually measured in millimetres or centimetres per day rather than centimetres per second. An important point that must be kept in mind when working with groundwater is that however slow the movement is, the water in the pore system IS moving and its flow is controlled by gravity. Thus, much of the work of the environmental geologists and hydrologists involved with the use of groundwater is mapping the occurrence of the water in the various subsurface aquifers and identifying the rate and direction of flow of the water.

The use of groundwater as a water resource is increasing in North America. Presently, about 25% of the water demand in North America is met by groundwater sources. Nearly three-quarters of this groundwater is used for agricultural purposes. However, in areas of stressed surface water supplies, such as western Canada and western United States, the use of groundwater for municipal and industrial purposes is much higher.

Groundwater holds several distinct advantages over surface water sources:

- Groundwater is usually free of toxic organisms and other contaminants and therefore needs relatively little treatment or purification before use.
- Groundwater sources supply water of a constant temperature and composition.
- Groundwater is less significantly affected by short-term droughts relative to surface water impoundments.
- When it is available relatively near the surface, it is much less expensive to acquire than the construction of pipelines, diversions, dams, and reservoirs.

The problems with groundwater are that it is not always present relatively close to the surface and that the supply is not easily and quickly recharged. Because of this slow recharge, once the groundwater does become polluted, it cannot readily be flushed or cleaned up. Finally, in much of western Canada, the groundwater is (naturally) of poor quality, often too saline for use by humans.

Groundwater hydrology

Whatever is known about the groundwater in a particular region must be derived by drilling. As a well is drilled, the cutting bit will pass through the unsaturated *vadose zone* and then encounter the sharp boundary of the water table marking the top of the *phreatic zone*. The elevation of the *water table* is an important reference point. As more wells are drilled the elevation of more points on the surface of the water table are known. Eventually, enough data points are available to plot on a map and contour. This elevation contour map portrays the highs and lows on the water table surface, just as a topographic map illustrates the highs and lows on the land surface. In fact, often the water table elevation contour map will simply be a subdued and smoothed version of the topographic map: where the land rises in a hill, the water table elevation will mimic this rise.

In addition to topography, the depth to the water table is largely a function of climate. In humid regions it is normally within about 10 m of the land surface, whereas in arid areas it can hundreds of metres below the surface. Because of the high costs of drilling deep wells, it is rare to attempt to produce water from aquifers more than 300 m deep.

Finally, unlike the land surface, the level of the water table varies with time. The groundwater is affected by atmospheric pressure changes, and by input and withdrawal from the system. Input can come from seepage and infiltration from above through the vadose zone, and from recharge by precipitation or streams and lakes. Withdrawal of water occurs by drilling a well and pumping water to the surface, and by natural discharge into a lake or stream.

If the aquifer in which the groundwater is flowing is in direct contact with the earth's surface, then the pressure on the water at the water table is nearly equal to the atmospheric pressure. This is termed an unconfined aquifer. Many of the shallow aquifers in southern Manitoba are unconfined. If, however, the aquifer is overlain by strata of very low permeability (*aquicludes*), then the pressure of the water will likely be greater than that of the atmosphere. The aquifer in this case is confined. If our well is drilled into this confined aquifer, the groundwater will rise in the hole. The amount of rise is dependant on the pressure differential between the aquifer pressure and the atmospheric pressure; the elevation to which it will rise is termed the piezometric or *potentiometric surface*. An artesian system is one in which this piezometric surface is at a higher elevation than the ground surface.

The movement and flow of groundwater in the subsurface is controlled ultimately by two very simple factors:

1. The nature of the material through which it is flowing.
2. The pressure exerted on the water to make it flow.

Quantitative studies of the flow of a fluid through a porous aquifer are based on an empirical relationship known as *Darcy's law* or Darcy's equation (see also the examples and discussion in Case Study 8.2 (page 228) of the assigned reading for this unit). Henri Darcy, a French engineer, was able to show experimentally over a century ago that the discharge of water through a tube of a certain cross sectional area that was packed with porous, granular material was proportional to the difference in elevation of the two ends of the tube and inversely proportional to the length of the tube. Specifically, the Darcy equation is:

$$Q = KA\frac{\nabla h}{\nabla L}$$

where Q is the rate of flow (m^3/day), K is the *hydraulic conductivity* (m/day), A is the cross sectional area through which the flow occurs (m^2), and the quantity $\Delta h/\Delta L$ is the *hydraulic gradient* (i.e., the change in elevation, Δh, per distance, ΔL). The hydraulic conductivity, like permeability, depends on both the nature of the material and on the characteristics of the fluid flowing through the material. Finally, the Δh component of the hydraulic gradient is not merely an elevation difference but rather is the difference in head, or the level to which the water will rise in an observation well. Head is easily observed and measured in the well, or it is calculated by:

$$h = \frac{P}{\tau} + Z$$

where P is the pressure, τ is the specific weight of the water, and Z is the elevation of the water above some arbitrary datum. By measuring the hydraulic gradient and experimentally evaluating the hydraulic conductivity, we can easily calculate the average velocity (V) of groundwater flow using:

$$V = Kx\frac{\nabla h}{\nabla L}$$

This calculation is critical if, for example, a harmful substance is accidentally introduced into the aquifer. It is important that the environmental geologist is able to evaluate how long it will take that substance to reach nearby groundwater wells or surface streams that perhaps are being used for municipal water supplies.

The Darcy equation allows us to examine the flow in one linear section of path of the water in the subsurface. However, by using the potentiometric surface map that we created by observing the elevation of the water table in a series of wells, we can easily evaluate the direction of flow or the three-dimensional flow paths in a specific map area. The contour lines on this map join points of equal head and are termed *equipotential lines*. The groundwater in the aquifer will always move in a direction that is perpendicular to these lines, assuming, of course, that the material in the aquifer is homogeneous. Thus, a network of equipotential lines and orthogonal flow lines can be drawn and a flow net created.

This *flow net* is two-dimensional in the horizontal plane but we can just as easily create a two-dimensional flow net in the vertical plane. To do this, we use a cross section of the aquifer and plot the various equipotential lines that can be determined from the well data. The same rules are followed in drawing the flow lines perpendicular to these equipotential lines, except that now we are showing the movement of water in the vertical plane. The construction of these flow nets is important because not only does it help us to graphically visualize the complex three-dimensional flow of groundwater, but it also allows the geologist to independently evaluate the hydraulic conductivity. This latter calculation can be made using:

$$q = Kh\frac{nf}{nd}$$

where q is the discharge per unit width, K is the hydraulic conductivity, h is the total head drop over the region of interest, nf is the number of flow channels (i.e., the number of zones between the flow lines), and nd is the number of head drops (i.e., the number of equipotential lines crossed over the region of interest).

Water use

Human use of water has increased dramatically during this century. Today we use approximately twice as much water as we did just two decades ago. The three major uses of water by people (other than transportation) are:

1. Industrial use.
2. Municipal and domestic use.
3. Agricultural use.

About half of this use consists of water lost to the atmosphere by evapotranspiration. The other half consists of degraded use: the water is contaminated by dissolved salts, other chemicals, heat, or biological components before being returned to the hydrologic cycle.

On a global scale, people use only about 8% of the total annual freshwater runoff, suggesting that there is an ample supply for human use. Furthermore, estimates indicate that it is economically feasible to tap as much as 20% of the world's annual runoff. Of course, the major problem with this large supply of usable water is that it is unevenly distributed. Ultimately, this is due to the uneven distribution of precipitation and the variable rates of evaporation at the surface of the earth. Consequently, many areas of the world are now withdrawing more water than can be replenished on an annual basis. Parts of western North and South America, Australia, and the Mediterranean, northern Africa, and Middle East regions have all experienced severe water shortages in the past decade. A recently compiled united Nations report paints a rather pessimistic picture for the future. It is predicted that within the next ten years, most of the Soviet Union, Europe, India, Australia, northern and western Africa, about two-thirds of North America, and substantial parts of Argentina and Brazil will experience severe water shortages. Superimposed on this are estimated increases of 100% in the demand for irrigation water, 2,000% increase for industrial water, and 500% increase for domestic and municipal use. Finally, the increased urbanization, particularly in developing nations, will lead to pollution of approximately 40% of the world's freshwater supply.

The use of various components of the hydrologic cycle vary greatly from one place to another. In North America, people now use about 2×10^9 m^3 of water per day or roughly 12,000 litres per person per day. Most of this total is, of course, for industrial and agricultural purposes; the actual per capita use for purely domestic activities is only about 1,000 litres per day. Up to 1950 more water was used for agriculture than for industry. Today, however, industrial uses account for about twice as much withdrawal as agriculture. Most of this industrial use is associated with power plants and the water is mainly used for cooling purposes. The other large industrial use is manufacturing with the production of metals (245 m^3 of water per tonne of steel produced, 1,200 m^3 per tonne of Al), plastics (2,000 m^3 per tonne), and pulp/paper (450 m^3 per tonne) being the biggest consumers. However, a relatively small amount of this industrial water is degraded. The largest concern is an increased temperature of the waste water, which presents problems for recycling and disposal.

Municipal use in North America amounts to about 1,000 litres per person per day. Of course, the biggest problem is maintaining an adequate supply for the large metropolitan areas. Some very elaborate water diversion schemes have been constructed to assure the major cities (primarily in California) of a supply of water. Even more grandiose diversions have been seriously proposed such as the infamous NAWAPA (North American Water and Power Alliance) designed to divert water from northern Canada to western United States at a cost of about $\$500 \times 10^9$, and diversion of the Mississippi River into western Texas. Of the 100 largest cities in North America, most (70%) get their water from surface sources alone, while only 20% depend exclusively on groundwater sources. Of the 70 cities using surface water, 40 tap man-made reservoirs, 18 use river water, and 12 use lake water.

With increasing urbanization and industrialization, the relative proportion of water used in rural areas has decreased substantially. About half of the water used outside of cities and industry is used for irrigation. Irrigation began in western North America in the early 1800s and has continued to expand gradually since then. Today, the source of irrigation water is mainly from surface reservoirs and rivers, with the Colorado River forming the world's single largest irrigation management system.

There are several basic types of irrigation used today. The oldest but one of the least efficient techniques is simple diversion and channelization of surface water using a system of canals and ditches to funnel the flow into crop furrows. However, salinisation, or the gradual build-up of salts in the soil, is a major problem because evaporation losses in this type of irrigation are relatively high. It is estimated that up to 50% of the water is wasted by leakage, infiltration into noncrop sites, and excessive water being applied to some areas of the cropland. The use of sprinkler systems to distribute the water has become very popular in the past several decades. In fact, the development of the large circular sprinklers so commonly used and easily identified from the air by their unique geometry, has been called the most significant mechanization development in agriculture since the invention of the tractor! These circular sprinkler systems permit accurate and uniform application of water to the crops, can be used in rolling terrain (which obviously cannot be irrigated by conventional canals-ditches), decreases the evaporation losses, and is relatively inexpensive. Finally, drip irrigation uses a system of low-pressure, underground pipelines to apply the water directly to the roots of the crops. This irrigation technique is expensive to install and maintain but is extremely efficient. It uses much less water and creates better crop yields because the water application is more constant. It is used in very arid climates.

Wetlands

Wetlands are areas that are transitional between terrestrial and aquatic systems where the water table is at or very near to the surface of the land. There are various types of wetlands including:

- Riverine wetlands associated with the floodplain and channel systems of streams.
- Lacustrine wetlands.
- Marine intertidal and estuarine wetlands.

Historically, wetlands have rarely been treated as a resource, but rather were generally viewed as something to be drained, filled, or dredged. For example, in the United States, the "Swamp Reclamation Act" of 1849 gave jurisdiction for the sale and/or disposal of some 130 million acres of wetlands to the individual states. This resulted in the conversion of about half of all of the wetlands in the United States. About 60 million acres remain.

Today, it is generally recognized that wetlands perform many important physical and biological functions. They are economically important because they form the spawning grounds for about 65% of all the fish and shellfish harvested in North America. Their role in the ecological functioning of waterfowl is even more impressive: the many wetlands of the north central part of the continent are a duck factory, acting as staging grounds for over 90% of North America's ducks. The wetlands are a hydrologic buffer in that they store water during floods and release water during dry periods, thereby reducing the severity of both floods and droughts. Recently, it has been shown that wetlands provide a way of mitigating water pollution by trapping, retarding and transforming many types of pollutants such as silt, toxic metals, pesticides, and excess organics. These pollutants are then broken down into less harmful constituents by microorganisms in the wetlands sediment. Ducks Unlimited has estimated that it would cost about $75,000 per acre to design and construct an "artificial" wetlands that would provide these same services.

Key concepts and terms to remember

- acre-foot
- aquiclude
- aquifer
- aquitard
- artesian
- Central Arizona Project
- cone of depression
- confined aquifer
- Darcy's law
- dipolar
- discharge
- equipotential lines
- flow net
- flow velocity
- hydrologic cycle
- hydraulic conductivity
- hydraulic gradient
- meteoric water
- phreatic groundwater
- pressure differential
- potentiometric surface
- recharge
- residence time
- specific heat
- unconfined aquifer
- universal solvent
- vadose zone
- water table
- watershed
- wetlands
- Δh
- ΔL
- Q
- K
- nf
- nd

Review questions

(Some of these questions also refer to Unit 8 and Unit 10.)

1. What is the difference between velocity and discharge of water through a river channel?
2. What do Darcy's Law and river discharge have in common? How do they differ?
3. What is the significance, in terms of geological time, of the word "temporary" in temporary base level?
4. What is the ultimate base level and why is it called that?
5. How do oxbow lakes form?
6. What causes point bars and cut banks to form?
7. Why is a longer historical record of peak discharge preferred for a given river when determining the statistical recurrence interval for flood events?

8. Given a rank, for a particular flood event, of 25 and a record of 24 years duration, what is the recurrence interval for a flood of this size?
9. What are two benefits and two negative aspects of large dams on rivers?
10. Building artificial levees has been said to be “self-perpetuating.” Why does building a levee in one place along a river system prompt the construction of another downstream?

Notes

Unit 10
Geology of Water Resources Modifications

Topics

Types of dams

Impact of dams

Introduction

In this unit we will continue with our discussion of the geoscience water resources by examining the role that geologists play in helping to ensure suitable delivery of this resource.

Learning objectives

By the end of this section you should be able to:

- classify the various types of dams;
- discuss the major controversies surrounding dam construction;
- critically evaluate the widespread use of dams in North America;
- distinguish upstream problems associated with dams/reservoirs from downstream problems;
- critically examine the impact of the Aswan High Dam on the Nile River; and
- show with a sketch and discussion the management scheme of the Colorado River.

Learning activities

1. Finish reading chapter 8 in your textbook and answer the study questions.
2. Read the study notes and answer the review questions.
3. Do assignment 4 and submit it to the Student Services Office no later than the due date indicated in Assignment due dates.

Study notes

Introduction

Ever since people started living in cities they have attempted to alter the normal drainage systems by the construction of dams. The dam-aqueduct systems of the ancient Romans, built between about 300 B.C. and 100 A.D., are well known and, indeed, remarkable even by today's high-tech standards. The concept of irrigation also necessitated building dams to provide a satisfactory constant supply of water when it was needed. Reservoirs impounded behind dams have become the most common water storage system in the world. There are about 70,000 large (greater than 7 m high) dams in North America with over 1,500 major reservoirs (greater than 1,000 km^2). The first dam constructed in North America was in 1634 in New England and was used for waterpower for a mill. In the last three decades, dam construction has progressed at a rate of about 5 dams per day. This is hardly surprising; if water is the single most essential ingredient for civilization, society must have a means of obtaining, storing, and distributing it. Dams and reservoir systems provide this means. However, in altering the flow of a drainage system, inevitable changes are made in the hydrologic character of the stream on which the dam is located. These changes provide both positive and negative feedback mechanisms. A good dam is obviously one in which the negative feedback is minimized or one in which the positive features so overwhelm the negative aspects that the overall impact of the dam on society is positive.

Types of dams

While this is not an advanced course in river hydraulics or river management engineering, it is within the domain of an environmental geologist to understand the basic types of dams and to be able to discuss the attributes of the various types with the engineers. There are essentially three types of riverine dams: gravity, arch, and embankment.

Gravity dam

A gravity dam resists the forces of the water in the reservoir simply by its weight or mass. In other words, the dam stays in place because the shear stresses of the combined water and sediment in the reservoir behind the dam are overcome by the shear resistance of the vertical component of the dam's mass on the floor of the river. It is absolutely essential that the underlying bedrock at a gravity dam site be sufficiently strong to resist the added stress of the water, sediment, and mass of the dam.

Arch dam

An arch dam, in contrast, gets its strength from the arcuate shape. The shape is designed such that the curvature transmits most of the water/sediment forces to the adjacent rock abutments. Consequently, arch dams can be much lighter, thinner, and easier to construct. Of course, it is essential that the rock abutments on either side of the river be strong enough to resist the added stress. There are also combinations of arch and gravity dams, such as the large Hoover Dam on the Colorado River, which use components of each of these types.

Embankment dam

An embankment dam is made simply of excavated material (Earth fill, rock fill) without any additional binding substances. These dams “work” because the accumulated earth/rock fill retards more water than can leak through the structure. Embankment dams are usually used on small streams, whereas arch and gravity dams are most often constructed on large rivers.

Impact of dams

Positive aspects

Dams and reservoirs have numerous positive aspects and are, in many ways, extremely beneficial to society. The reservoir can capture high spring flows from heavy rain or melting snow and release the water from these high flows gradually over time during periods when the it is most required. Thereby dams also reduce the danger of flooding in downstream areas at the same time as providing a controllable and reliable flow of water for agricultural, industrial, and municipal uses. Some dams also supply “renewable” hydroelectric power and many reservoirs serve an important recreational purpose.

Dam failures

Despite these many positive aspects of dams and reservoirs, there is still a considerable amount of controversy over dam construction, as has been demonstrated by numerous water resources dam-reservoir projects in western Canada in recent years. One of the first problems that the public identifies is the safety aspect of dams. Although considering the number of dams and reservoirs that are constructed in North America, this probably should not be a major consideration, however, the fact remains that there have been “numerous” dam failures with, of course, catastrophic downstream repercussions. In short, dams are often perceived to significantly increase the downstream flood hazard risk in an area. Whether or not the other benefits (including flood protection, hydroelectricity, recreation, source of water) outweigh this negative aspect of increased risk must be carefully analysed.

One of the most startling and unfortunate factors of past dam failures is that nearly 65% of them were due to either faulty design, poor construction, improper operation and maintenance, or foundation failure that should have been anticipated. In North America today, it is estimated that there are about 10,000 dams that have a high probability of failure. One of the more classic examples of dam failure due to a lack of geological input into the construction is that of the St. Francis Dam in California in the late 1920s. This dam was sited at the contact of two lithological units: part of the foundation was a micaceous schist, the other part was conglomerate. The conglomerate contained abundant gypsum veins, partings, and cement. When this rock was dry it was quite strong, but wetting the rock led to dissolution of the soluble gypsum, disintegration of the conglomerate, and failure of the dam. In addition to property losses of about ten million dollars, some 500 lives were lost in the catastrophe. Unfortunately, this is not an isolated example; there are many other examples of dam siting on improper foundation. Some of the better known are:

- The Aswan Dam on the River Nile in Egypt that is located on the porous and permeable Nubian Sandstone Formation.
- The Elwha River Dam in Washington that is sited on gravels and sands that are so porous and permeable that the reservoir water undercut the dam.
- A series of dams and reservoirs sited on karst-prone limestone terrain in which the reservoir water simply drains away.

Flood control

A second major problem with many dams is that they are designed to prevent and control small- and medium-sized floods (i.e., high frequency floods), but cannot prevent very large floods. People often mistakenly believe that the presence of a dam on a river will protect them from all floods. Thus, urbanization of the floodplain below the dam proceeds without consideration for the true potential flood hazard risk. When a low-frequency, large flood does occur, the damage is much greater than if the dam had not been built.

Water supply

Although the construction of a dam and reservoir will usually help to maintain a constant supply of water, it will not increase the amount of water available. In fact, because large reservoirs in arid regions suffer considerable loss of water by evaporation, many times there is actually a net decrease in the water supply. Reservoirs also loose water by infiltration and seepage into the subsurface, thereby further decreasing the supply. Even the reservoir itself is sometimes controversial. While a dam offers some measure of downstream flood protection, it does this at the expense of permanently flooding large areas upstream from the dam. This dramatic change in ecosystems has been vigorously protested by many people because it displaces human and wildlife habitats and destroys scenic natural areas. Although the reservoir will create habitats for other organisms, these other species are often viewed as less desirable.

An example of this type of ecological change that caused a considerable amount of scientific and political controversy is the Tellico Dam on the Little Tennessee River. The dam was begun in 1963 and construction proceeded as part of the Tennessee Valley Authority until conservationist groups successfully acquired an injunction to halt construction in 1973. The reason for this injunction was that the reservoir would have destroyed the habitat of a fish that was on the endangered species list. Legal battles continued until mid-1978 when the U.S. Supreme Court ruled that it was acceptable to finish the dam. In late 1978, however, Congress effectively overruled the Supreme Court decision by temporarily cutting funds for the project and turned the case over to a cabinet level inquiry board. This board unanimously agreed to recommend halting the dam construction even though it was over 90% complete. By the end of 1979 Congress reallocated sufficient funds to complete the dam.

Reservoir problems

Another major problem with the construction of reservoirs is that they fill up. The first effect of a dam on a river is to reduce the flow velocity of the river upstream from the dam. As the river enters the newly created reservoir it drops its sediment load in the form of a delta. Delta progradation can significantly shorten the life of a reservoir and hence its usefulness. For example, the Anchicaya Dam on the Columbia River was built in 1955. By 1957 the reservoir was a quarter filled with sediment; 8 years later it was completely filled. The reservoir of the Shihmen Dam in Taiwan was filled in 10 years despite an anticipated 70–year life span when it was constructed. Lake Nasser behind the Aswan Dam receives an incredible 13 x 10^6 m^3 of sediment per year. This was sediment that was originally carried down the Nile to be deposited in the large Nile Delta.

Downstream problems

In addition to these upstream problems, the areas downstream from the dam also suffer. One of the biggest downstream problems is increased erosion and downcutting by the rejuvenated river. The construction of a dam dramatically changes the hydrologic and geomorphologic balance of the stream system. Water that is released from the dam is usually devoid of sediment, and is often at a much lower temperature than the original stream water. These factors combine to give the stream much more erosive power below the dam. For example, after construction of Hoover Dam, the Colorado River channel below the dam was lowered over 3 m. This resulted in substantially increased siltation farther downstream, which, in turn, increased the flood hazard downstream.

Economics

Finally, many groups of society question the economic basis and benefit-cost ratios that are incurred by the building of some (many!) dams. Opponents cite many examples of “pork barrel” legislation and make-work projects in dam construction efforts. Some of the many examples include the following:

- A \$48 x 10^6 dam on the Glover Creek in Oklahoma was constructed supposedly to supply water to the region. Nevertheless, only 6,000 people live in the vicinity and their needs are already served by a reservoir designed to supply water for 90,000 persons.
- The Hillside dam in Kansas was constructed at a cost of \$55 x 10^6 to protect 7,000 acres of downstream farmland from flooding, but the reservoir behind the dam flooded 14,000 acres of productive upstream land.
- The Bayou Bodcau project in southern Louisiana was to supply downstream flood protection for farmers; the cost was an incredible $300,000 per landowner.
- The Fruitland Mesa project in southern California cost about \$130 x 10^6 and supplied water for 60 farmers.

Garrison dam/diversions

Somewhat closer to home, residents of the northern Great Plains will remember the great amount of controversy that raged about 10 to 15 years ago over the Garrison dam and associated diversion schemes. Indeed, this project has had a long and controversial history. The project actually began with the first U.S. Congressional approval for funding in 1887. However, because of a lack of demand for the water, work on the project did not begin until 40 years later. In 1944 additional money was allocated to the project, which was then known as the Pick-Sloan Missouri River irrigation project. By 1955 the Garrison dam on the Missouri was finally completed at a cost of \$300 x 10^6 (1955 U.S. dollars). The reservoir behind this dam flooded over 300,000 acres of productive farm and ranch land, and, according to opponents of the scheme, land that was invaluable for wildlife habitat and historical/archaeological reasons. In an attempt to compensate for at least part of this loss, the U.S. Congress authorized the diversion of some of the impounded reservoir water across North Dakota to irrigate 200,000 acres of land in eastern North Dakota. Unfortunately, this major diversion scheme called for the construction of some 7,500 km of canals and artificial drainage systems, and the loss of another 65,000 acres of farmland in the central part of the state. In addition, the canals, which are up to 35 m deep in places, intersect bedrock aquifers, and thereby lower the water table of the surrounding prairie. This has resulted in the draining of many of the wetlands surrounding the diversion route. Superimposed on these geologic/ecological problems was the dramatic increase in costs of the project. The funding requests went from \$250 x 10^6 in 1968 to \$400 x 10^6 in 1973 to \$1 x 10^9 in 1979. The complete story and ultimate impact of the Garrison dam and diversions is still not known. A major environmental impact study was conducted in the 1970s that identified severe water quality degradation as well as significant negative biological repercussions that would be inflicted on the drainage systems.

Aswan dam

The Aswan High dam and Lake Nasser in Egypt have become a classic example of problems and negative feedback mechanisms that can arise from construction of major dam-reservoir systems. This massive, 150 m high dam on the Nile River, completed in 1967 at a cost of over one billion dollars, is truly a remarkable engineering feat. It was designed and constructed for several very worthwhile purposes:

- To help control the annual flooding on the Nile.
- To provide a constant supply of water for irrigation of the Nile valley.
- To generate electricity.

Unfortunately, like many other large river control systems, these benefits have only been partially met and many of the positive features of the dam have been overshadowed by a plethora of unanticipated negative aspects caused by its construction.

One of the major problems with the construction of the Aswan dam is that it was undertaken without a proper knowledge base and without a sufficient understanding of the impact of such a major feature on the Nile drainage system. Many of the problems outlined below could have been anticipated if more study would have been conducted before construction. On the positive side, the dam has partially accomplished several of its goals: it provides about 50% of Egypt's electrical power and has eliminated downstream flooding along the Nile. Also, the water from Lake Nasser has been used to irrigate nearly a million acres of land, thereby substantially increasing the food production and cotton yield from the Nile valley. Finally, the impact of several major droughts in the region in the last 20 years has been significantly decreased because of the ability to release water from the 50,000 km^2 reservoir.

Notwithstanding these benefits, however, it is predicted that the dam will likely be an ecological and economic disaster for Egypt. For example, it was realized soon after construction started that the dual purposes of hydroelectric power generation and irrigation were not compatible in this area. The power generation has to be strongly seasonal because of the draw down of the reservoir during the summer months for irrigation. In contrast, while the climate of Egypt would permit year-round cotton and food production if sufficient irrigation water was provided, crop planting has to be limited because of the necessity to keep the reservoir as high as possible in order to provide hydroelectricity during at least part of the year. Similarly, one of the biggest problems to be faced in using the dam and reservoir is that, after 25 years of operation, Lake Nasser has never been more than half filled; there is simply insufficient water to fill the reservoir! This may seem incongruous considering the size and drainage basin area of the Nile, one of the largest and longest rivers in the world. However, the large expanse of open lake undergoes water losses of as much as 4 m per year in the hot, dry climate of central Egypt. Substantial losses are also incurred by seepage into the very porous and permeable Nubian Sandstone, a major aquifer in the North Africa region.

The most costly problem of the Aswan dam is in the downstream end. Before the dam was built, the annual flooding of the Nile River, while problematic from a human occupation perspective, was important: it provided an annual supply of nutrient-rich sediment to the floodplain and washed accumulated salts out of the soil. Now, with the downstream floodwaters more or less eliminated, the nutrient-rich sediment is being deposited in the upper end of Lake Nasser. To compensate for the lack of natural nutrients, Egypt has had to spend about $\$300 \times 10^6$ per year on artificial fertilizers. Although these synthetic fertilizers are locally made, the fertilizer plants use much of the electrical power generated by the dam. The salinisation in the downstream "floodplain" is significantly decreasing the yields of the previously very productive farmland. To date about 700,000 acres of land have been lost, offsetting by about 70% the amount of new land opened by irrigation from the reservoir. In order to correct for this build-up of salts in the soils, the construction of a complex artificial drainage system has been proposed that would annually flush the soils. The estimated cost for this project is about $\$1 \times 10^9$—as much as the dam itself!

The construction of irrigation canals and ditches in the downstream areas of the floodplain has provided ideal conditions for the rapid spread of schistosomiasis, a disease transmitted to humans by freshwater snails living in the slow-moving waters of the canals. The infection rate in people living below the dam has risen from less than 10% before dam construction to about 90% today.

Because much of the sediment load of the Nile River now is being deposited in Lake Nasser rather than being carried downstream to the Nile Delta, numerous additional problems have been created:

- The reservoir is filling much faster than originally anticipated. Because the Aswan Dam was built without sluices, it will be virtually impossible to "flush" the sediment from the reservoir.
- The Nile Delta is foundering due to a lack of sediment. The Mediterranean Sea is very rapidly transgressing inland by as much as 2 m per year in the Delta area, resulting in further loss of productive agricultural land.
- The lack of nutrients being delivered to the Delta and offshore area has resulting in loss of Egypt's sardine, mackerel, lobster, and shrimp industries. Not only were these fish an important source of food for the 40 million people in the metropolitan areas of the Delta and Nile River valley, but they also provide jobs for some 40,000 persons.
- The lack of sediment in the Nile River below the dam has caused considerable downstream downcutting and erosion. A possible solution to this is to build more dams below the Aswan structure. Ten addition dams are planned for the area between Aswan and Cairo at a cost of $500 x 106 each.

Colorado River

This final example is not so much an example of a single dam but rather the regulation and manipulation of a major river system. The Colorado River drains an area of over 600,000 km^2 in six states of western United States and Sonora and Baja of Mexico. The bulk of the drainage basin is within an arid region, with rainfall averaging only about 20 cm over much of the area. Evaporation rates are high.

The river and its drainage basin have a relatively long and complex history of scientific investigation and engineering manipulation. River explorer, geologist, and director of the U.S. Geological Survey, J. W. Powell, was one of the first scientists to visit and study the basin. Direct and continuous monitoring of the flows at various places in this large basin was begun about 100 hundred years ago. Problems with conflicting views of the management of this river began almost immediately upon European settlement in the basin. The main problems have centred on diversions of water from the upper, more humid parts of the basin, thereby causing low supplies and flows in the downstream areas. The first diversions took place in Wyoming and Utah as early as 1840. Later in the 1800s more Colorado River water was tapped for use in agricultural areas of California and Arizona. A major large-scale diversion system supplied water to the Imperial Valley in California in 1901. In 1905 this diversion actually took all of the Colorado River and allowed it to flow into the Salton Sink (thereby creating the Salton Sea). Urbanization in the southern California and Arizona areas caused the further diversion of Colorado River water into Lake Havasu and via various aqueducts to Los Angeles, Tucson, and Phoenix.

The management of the Colorado River and its watershed is a classic example of evolutionary concepts of water resources management coupled with legislative and jurisdictional controversies and agreements. The key principle that has evolved over the past 100 years is the doctrine of prior appropriation, which basically confirms "first rights" to the water. Specifically, the doctrine, which is the backbone of much of western U.S. and Canada water law, indicates that a user who has once established a pattern of beneficial use of previously unappropriated surface water has established a future right to continued water use on the scale initially established. For example, in the case of the Colorado River, the early demands for water by the "upstream" states (Wyoming, Utah, and Colorado) and Mexico was much less than the demand by the "downstream" states (California, Arizona, New Mexico) and specifically the huge demand for irrigation water for the Imperial Valley/Salton Sea area. Because these use requirements had been established relatively early in the history of management of the basin, it would be very difficult to modify the allocations in light of new demands or a changing hydrologic budget, despite the fact that nearly all of the water originates in the highland areas of the upstream states.

By federal law and international agreement, the upstream states can "use" (i.e., extract for irrigation, municipal, or industrial purposes)
7.5×10^6 acre-feet (an acre-foot is a commonly used hydrologic volumetric unit equivalent to the amount of water one foot thick covering one acre of land); the downstream states can extract 8×10^6 acre feet; Mexico can use 1.5×10^6 acre feet. This totals an annual use of the Colorado River water of 17.0×10^6 acre-feet. Unfortunately, it is now realized that the Colorado system cannot supply that quantity of flow in a normal year. The average annual discharge of the Colorado before any diversions or human uses was about 13.0×10^6 acre-feet. Thus, the various states and regions of southwestern U.S. and northern Mexico have the legal right to consume more water than can be delivered by the Colorado system in an average year. This incredible situation came about by unintentionally using average flow records for the Colorado during a rather long period of high water discharge in the basin (1900–1930). In retrospect, it is now clear that these three decades unfortunately had the highest flows on record.

The Colorado River reservoirs have experienced a similar type of problem to that of Lake Nasser with respect to conflicts over multiple uses. A major feature of the Colorado system is nine dams, which can hold over 60×10^6 acre-feet at maximum capacity. However, because these reservoirs are also to be used for flood control as well as power generation and recreation, there is usually only about 50×10^6 acre feet of storage. Again the doctrine of prior appropriation dictates that the additional storage must be kept available in case of flood. The remarkable near-failure episode of the Glen Canyon dam in 1983 demonstrates the conflicts that arise in managing this major drainage basin and the scientific and technical constraints that must be placed on the legally assured rights of the water resource users.

It is evident that the Colorado River water supply system is being placed under considerable stress, in part from existing “legal” demands for its water and from the additional demands from the expansion and urbanization that is going on in southwestern United States and northern Mexico. These demands and inevitable conflicts have forced geologists and hydrologists to closely examine not only the relatively short-term historical record of flows in the Colorado River basin (i.e., from 1880 to present), but also by using geologic “proxy” data, identify the approximate level of flows over a much longer time frame. Geologists have now accumulated reasonably accurate flow information going back over 400 years. Any future water allocation schemes must use this database and must attempt to arrive at a compromise with legal and social implications of water use within the constraints of lowered water availability.

The realization that the Colorado River cannot supply the existing demand has also generated some rather interesting alternatives and suggestions of ways of enhancing the flows. One of the most reasonable approaches sought is the termination of all future water resource development plans for the basin. Any further water consumption by either the upstream or downstream states will only deplete the balance even more than it already is. Land developers and those responsible for acquiring additional sources of water for existing urban areas obviously find this alternative difficult to accept. Proponents of the Central Arizona Project, which is to divert an additional 1.2 x 10^6 acre-feet of water to the Phoenix-Tucson area, have been particularly vocal in their opposition.

There has been serious consideration given to a major diversion of water from the Columbia and Snake Rivers of northwestern United States into the headwater areas of the Colorado. As with the more grandiose NAWAPA scheme, this proposal has met firm opposition from hydrologists, geologists, conservationists, and ecologists. Many scientists suggest that the only resolution to the Colorado River water supply problem is in changing existing patterns of land use and water consumption. Agricultural use (i.e., irrigation) accounts for between about 70 and 90% of the total water withdrawal from the basin. At the present time the fee structure for the Colorado River water is such that farmers can purchase water for irrigation purposes much cheaper than the water that is being used for municipalities. Thus, there has been little incentive among the agricultural groups to install more efficient irrigation systems or to improve the existing systems that are already there. Other ways of improving the efficiency of agricultural use have been suggested including augmenting the Colorado River water with groundwater, recycling and desalination the water after irrigation, and installing a distribution system consisting of covered pipelines rather than open ditches.

Summary

No segment of environmental geology is fraught with as many problems and controversies as water resources management. A reliable and consistent source of usable water is an absolute essential commodity for society. Thus, elaborate water source projects have been proposed and created, some with disastrous environmental and ecological repercussions. Historically, water resource management has been built around engineering control structures such as dams, reservoirs, canals, and diversions. The future of water availability in many parts of the world is bleak. Thus, other management techniques have recently been proposed including large-scale desalination plants, towing icebergs, controlling weather patterns, and conservation.

Superimposed on this increasing demand is the conflict within societal groups over the use of the water. In general, domestic, industrial, and agricultural uses are not compatible and compromises among all groups have been difficult to make in a water stressed environment.

Key concepts and terms to remember

- acre-foot
- arch dam
- artesian
- Aswan High Dam
- Central Arizona Project
- embankment dam
- gravity dam
- residence time
- schistosomiasis
- St. Francis Dam
- water table
- watershed

Review questions

(Some of these questions also refer to Unit 9.)

1. What physical property (or properties) of water:
    a. Allows lakes to freeze from the top down?
    b. Helps moderate the weather and protect us from the shock of sudden atmospheric temperature changes?
    c. Accounts for its widespread use as a solvent?
2. Critically evaluate the following statement: “Many areas of the world will run out of water within the next decade.”
3. If water is indeed a renewable resource, how can groundwater be depleted?
4. What are the main functions of dams?
5. Summarize the problems that dams create.
6. Explain why dams, despite, providing flood control, may lead to more flood damage than if they had not been built.
7. From where do most of the cities in North America get their water?
8. What is “unusual” about the use of water in the Colorado River basin?
9. What advantages are there to the drip irrigation system?
10. Summarize the advantages of the rotary or circular sprinkler irrigation system.

Assignment 4
Groundwater Flow

1. (5) What areas in Canada and United States are experiencing groundwater overdraft? What are some management techniques that could slow or stop this overdraft?
2. (10) Flowing artesian wells were common in the early days of settlement on the Northern Great Plains. Now water almost always has to be pumped. Why?
3. (10) Are there any situations in which rocks may have high porosity but are not good aquifers? Explain.
4. (5) Tables are flat! But groundwater tables are not. Explain.
5. (10) What is the Ghyben Herzbeg relationship? Using this relationship, calculate the thickness of the lens of freshwater that is under an island off the coast of Nova Scotia that has a water table level 3 m above sea level.
6. (5) You have been asked to drill a well for your penny-pinching uncle who lives on a farm in eastern Saskatchewan. He insists that you stop drilling as soon as you strike water. Is this wise? Explain?
7. (15) Discuss the effects to groundwater recharge in a region that is undergoing urbanization. What procedures might you suggest to city council to mitigate any potentially harmful effects?
8. (20) A confined aquifer has a hydraulic head of 10 m between two wells that are 2 km apart. The hydraulic conductivity of the aquifer is 5 m/day. What is the apparent velocity between the two wells?
9. (20) What volume of water per day will flow beneath a valley filled with permeable and porous sandy alluvium 150 feet thick and 1 mile wide, where the hydraulic conductivity is 400 ft/day and the potentiometric gradient is 10 feet/mile?

Notes

Module 6
Drought, Desertification, and Salinisation

Notes

Unit 11
Drought

Topics

Introduction to drought

Changes in circulation patterns

The Sahel example

Introduction

The earliest civilizations grew up beside great rivers: the Tigris, the Euphrates, the Nile, the Indus, and the Yellow. But the land that supported these civilizations was marginal. In this unit we will explore the complex subject of drought and the related aspects of desertification and salinisation.

Learning objectives

By the end of this section you should be able to:

- characterize the concept of drought;
- illustrate how large scale atmospheric circulation patterns help explain the occurrence of drought;
- critically evaluate the roll of ENSO, both spatially and temporally, in drought development; and
- show, with an example from Africa, how feedback loops are important in drought formation.

Learning activities

1. Begin reading chapter 12 (pages 351–369) and chapter 6 (pages 148–177) in your textbook and answer the study questions. You should plan to finish this reading by the end of unit 12.
2. Read the study notes and answer the review questions.

Study notes

Introduction

Ever since human society first started developing organized agricultural systems, we have been plagued by drought. Today there is strong evidence to suggest that both floods and drought are intricately linked to large-scale global atmospheric condition.

Drought is a concept not easy to delimit satisfactorily. Like floods, which can occur in dry areas as well as wet one, drought can affect areas with high rainfall as well as arid lands. While many definitions of drought exist, it can be defined simply as an extended period of rainfall deficit during which time agricultural biomass is severely affected. In some parts of the world, such as northeast United States and eastern Canada, a drought may have more of an effect on urban water supplies than on agriculture. The actual period of rainfall deficit before a drought exists also varies widely. In Britain, a drought is a period of more than 15 days with a total of less than 4 mm of rain. In the prairie region of Canada a drought is any period where no rain has fallen in at least 30 days. Lack of rain for this length of time can severely reduce crop yields in an area where crops are sown, grown, and harvested in the short period of three to four months. In Libya droughts are defined as periods of greater than 2 years without rain! In contrast, in Australia, for example, such definitions are meaningless, as most of the country receives no rainfall for at least one 30–day period each year. Indeed, in tropical areas subject to monsoons, drought conditions appear each dry season. Consequently, drought there is usually is defined as a 12–month period in which precipitation amounts are in the lower 10% of recorded annual rainfall. In India, a drought is declared if the annual rainfall is less than 75% of the long-term average. The point here is that drought is not some definite point on a scale but rather simply as a perceived water shortage. Terms associated with water shortage are often used indiscriminately:

- **Aridity:** a permanent shortage of water caused by a dry climate.
- **Drought:** an irregular phenomenon occurring in exceptionally dry periods or dry years.
- **Desiccation:** the drying up of the landscape and various components of the landscape such as soils, lakes, and rivers.

However drought is defined, one aspect should be emphasized. We tend to think of climate as a constant background over which drought (and periods of excessive rainfall) occurs. Clearly, this is not true. In fact, we depend on relatively short historical records to define climate. For example, “normal climate” is often viewed as the average of weather conditions and observations at a locale for a 30–year period. We now realize there are two major problems with this: Firstly, climate at most places in the world during the most recent decades was very different from the preceding 30–year period or the entire rest of the century. Secondly, conditions within these past three decades have varied greatly. The point here is that changes in precipitation regimes in terms of both long-term and short-term changes in general air circulation patterns and human land-use are factors that must be evaluated in drought definition and mitigation.

Changes in circulation patterns

Regional climatic changes responsible for drought reflect changes in general air circulation patterns. Intense heating by the sun at the equator causes air to rise and spread out poleward in the upper troposphere. As this air moves toward the poles, it cools and begins to descend back to the Earth's surface at about 20–30^o North and South of the equator. Upon reaching the Earth's surface, this air either returns to the equator or moves further toward the poles.

Within this large-scale atmospheric circulation system, where the air rises, low-pressure systems form and there is instability and condensation of moisture, resulting in heavy rainfall. Where air descends, high-pressure areas form accompanied by high evaporation, clear skies, and atmospheric stability. This circulation system comprises the Hadley cells, which encircle the globe. At the pole, air cools and spreads towards the equator along the Earth's surface. Where it meets warmer air from the tropics, a cold polar front develops with strong uplift and generation of other low-pressure systems. Between the polar front and the Hadley cell, strong westerly winds develop in both hemispheres. Controlling the position of this polar front is the jet stream in the upper troposphere. The path of this jet stream is not constant around the Earth. Instead, it and the corresponding westerlies follow a meandering and highly looping path as they encircle the globe. The meanders in the jet stream are termed Rossby waves.

Within this very general picture of the Earth's atmospheric circulation there are several complications. First of all, the Hadley cells migrate annually with the movement of the sun north and south of the equator. Obviously, most of the Earth's heating occurs in the equatorial regions, nonetheless, there are subtle but important shifts in the most intense location of that heating. For example, in the northern hemisphere summer, heating shifts from equatorial regions to the Indian mainland. Air is sucked onto the Indian subcontinent from adjacent oceans and landmasses and returns via upper air movement to either southern Africa or the central Pacific. In contrast, during the northern hemisphere winter this intense heating area shifts to the Indonesian-northern Australian maritime region.

In both these situations above, an area of high pressure develops over the equatorial ocean west of South America as part of the Hadley cell. This high pressure off the Peruvian coast is quite intense because the cold upwelling ocean water helps cool the air. Thus, air flows from this region, westward across the Pacific as an "easterly trade wind." In doing so these easterlies, referred to as Walker circulation, blow warm surface water across the Pacific Ocean, where it piles up in the Coral Sea area offshore from Australia. As a result, sea level is slightly depressed off the South American coast and slightly raised in the Coral Sea area. The easterlies also cause the upwelling of cold water along the South American coast, which feeds back on the stability of the system. Indeed, these pools of distinctly different temperature water form one of the Earth's major positive feedback loops, reinforcing the east to west circulation: the cold water in the eastern Pacific creates high pressure that induces the air flow; this process causes upwelling of cold water along the coast, which in turn further cools the air. On the western side of the Pacific, easterlies pile up warm water, thus creating convective instability: rising air and low pressure.

ENSO

The phenomenon of El Niño has been experienced by generations of Peruvians—the fishing grounds off the coast of Peru are among the richest in the world. This fishery is sustained by upwelling cold water filled with nutrients. Periodically, a mass of warm water appears off the coast, which has devastating affects on the economy. Today, El Niño/Southern Oscillation (ENSO) is regarded as one of the most important elements in year-to-year variations in the climate, with over half of the Earth being subjected to weather anomalies associated with this phenomenon.

The large-scale atmospheric circulation system described above is very stable and stationary, and is able to exist well beyond any annual cycle. However, for some inexplicable reason, the heating/circulation process weakens in intensity, or completely breaks down every 2 to 7 years or so. This results in high pressure becoming established over the Indonesian-Australian area, while low pressure develops over the warmed waters off the South American coast. The easterly trade winds abate and are replaced by westerly winds (i.e., winds blowing from west to east) in the tropics. In the western part of the Pacific, the rainfall belt shifts to the central Pacific and drought replaces normal (heavy) rainfall in northern Australia and Indonesia. This fluctuation is called the "Southern Oscillation" (SO), and as we all now know, is the cause of extreme climate changes on a worldwide basis.

Because the SO historically caused the appearance of warm water along the Peruvian coast at around Christmas time, the term El Niño (in Spanish, the boy child) has been applied. Until just a few years ago, the appearance of El Niño was thought to be the *triggering mechanism* for the Oscillation. Now, however, we realize that most El Nino events appear several months *after* warming in the central Pacific has been initiated. Because extreme El Nino events are so well documented in the historical record and are preserved in sedimentary deposits going back at least 5,000 years, it is common to refer to the entire anomalous system as the El Niño-Southern Oscillation or ENSO for short.

The effects of an ENSO event are widespread; global in many instances. It has been estimated that the Southern Oscillation is responsible for about 30% of the variance in rainfall records on a global basis. In South America, Peru, Bolivia, Venezuela, and Brazil are all affected by ENSO-induced drought. However, the greatest impact occurs in the western part of the Hadley cell in Africa, India, Indonesia, and Australia. In Indonesia more than 90% of the monsoon droughts and complete monsoon failures are associated with El Niño. Failure of the Indian monsoon is believed to be have been responsible for the deaths of millions of people over the past 100 years as a result of drought and famine. Drought in the African Sahel region (particularly Ethiopia and Sudan) and floods/drought in the lower Nile are ENSO-related.

The Sahel example

While there is no uniform definition of drought that can be applied to all regions of the world, clearly it can be viewed (rather than defined) on the basis of its effects: drought is an extended period of rainfall deficit that results in the curtailment of the "natural" growth of vegetation (and organisms) in a region. If the region is an agricultural one, a drought can extensive damage to crops.

Over the past several decades one of the greatest droughts to occur has affected the Sahelian area of sub-Saharan Africa. The drought began in the late 1960s and continues today. So far it has killed about 250,000 people and 10–12 million cattle. The Sahel is at the southern margin ("shore"; Sahel is Arabic for shore) of the Sahara Desert. It is a semiarid transitional zone between the true desert to the north and forested regions to the south.

The conversion of the Sahel from semiarid to arid environment is, at least in part, almost certainly related to changes in large-scale pattern of atmospheric circulation such as discussed above. However, this decreasing precipitation in the Sahel has also generated a negative biogeophysical feedback loop: decreased annual rainfall reduces biomass growth, which leads to reduced evapotranspiration, and overall decreased moisture content in the atmosphere and a further decrease in rainfall. As the loop intensifies, soil moisture diminishes, adding further to the reduction in evaporation and cloud cover. As the surface dries out, vegetation dies, and the surface albedo (the degree to which shortwave solar radiation is reflected off the surface) is reduced, leading to an increase in ground heating and a rise in air temperatures near the ground. This process also exposes the ground to wind, permitting more dust in the atmosphere, which causes heating of higher levels of the atmosphere. This heating has the effect increasing the stability of the atmosphere, reducing the possibility of precipitation. Thus, once initiated, these feedback mechanisms work to enhance droughts in the area presumably until some significant change occurs in the major tropical air circulation pattern.

However in the case of the Sahel region over the past 40 years, another factor must be assessed: increased human population combined with poor "management" of the original semiarid land. Shortly after the beginning of the drought in the Sahel, world fuel prices escalated dramatically (the so-called "energy crises" of the 1970s and 1980s) and people switched from a largely fossil fuel base to one entirely dependent on wood for cooking and heating. This change led to rapid deforestation of shrubs and trees. Increased population also meant that even greater stress was put on the land to supply food. In this area traditionally about a quarter or more of the available agricultural land was normally left fallow. However, during the 1970s and 1980s nearly all available land was continuously cultivated, leading to decreased fertility, and further enhancement of drought conditions.

Key concepts and terms to remember

albedo
arid
drought
El Niño
El Niño-Southern Oscillation
ENSO
Hadley cell
Rossby wave
Sahel
semiarid
SO
Southern Oscillation
Walker circulation

Review questions

(Some of these also refer to Unit 12)

1. How does the intertropical convergence zone (ITCZ) relate to deserts?
2. What are some ways that sand dunes can be stabilized?
3. What facilitated the natural recovery of desert land in Kuwait?
4. What can you conclude about the process that shaped Mushroom Rock in Death Valley, California?
5. What is the Sahel?
6. Why has the Sahel been a focus of attention in recent times?
7. Why is South America the recipient of North African dust rather than the other way around?
8. Explain how coastal dune fields need not originate in desert climates.
9. What are some of the potential health hazards from wind-blown dust apart from respiratory and eye irritation?
10. What is the best program for reversing desertification?

Unit 12
Desertification, Salinisation, and Problem Soils

Topics

Desertification

Salinisation

The Aral Sea example

Processes of salinisation

Characteristics of saline and sodic sediments and soils

Salinisation of water resources

Management

Other problem soils and expansive soils and permafrost

Introduction

This unit will continue our exploration of geoenvironmental problems related to dryland settings with discussions of desertification, salinisation, and expansive soils. Desertification (and the related salinisation) is essentially the conversion of formerly productive land to a state more resembling a desert. Although it is clearly rooted in human use and abuse of the landscape, we will see that it is a complex phenomenon driven by such diverse factors as overgrazing, deforestation, overuse of limited water resources and natural shifts in climate. Expansive soils, somewhat surprisingly also a "dryland" problem are a phenomenon familiar to many in western Canada.

Learning objectives

By the end of this section you should be able to:

- summarize the global extent of arid and semiarid regions;
- differentiate arid, semiarid, and hyperarid settings with respect to rainfall;
- illustrate the various causes of desertification with specific examples;
- critically evaluate the role that humans have in the desertification process;
- calculate SAR and ESP of saline and sodic sediments;
- outline the history of salinisation;
- show how salinisation and desertification influences humans by using the Aral Sea catastrophe;
- describe how salinisation occurs from both natural causes and secondary causes;

- calculate how much salt accumulation would result from precipitation and irrigation of a given quality of water;
- specify how salinisation can be properly managed;
- describe the most common mineralogies that are associated with expansive soils;
- differentiate 1:1 clays from 2:1 clays;
- summarize what other factors in addition to clay mineralogy are important in the phenomenon of expansive soils; and
- explain how climate and what climatic conditions most affect permafrost.

Learning activities

1. Finish reading chapters 12 and 6 in your textbook and answer the study questions.
2. Read the study notes and answer the review questions.

Study notes

Desertification

As you learned in your first-year geoscience courses, every continent has a desert. We often think of deserts as regions heat and sand, yet many deserts are cold and most are not composed mainly of sand. Deserts are usually classified on the basis of their average annual rainfall: *hyperarid* deserts receive less than 25 mm of rain annually; *arid* areas get annual rainfalls of 25–200 mm; *semiarid* areas receive 200–500 mm.

Arid regions make up about 40% of the total land area of the Earth. Over 80% of these are located on the continents of Africa, Asia, and Australia. The most noteworthy desert regimes include huge Afro-Asian belt that extends from the Atlantic Ocean to China. This zone includes the Saharan, Arabian, Iranian, and Gobi deserts. In North America are the Great Basin and the Mojave Desert of the United States and the Sonoran and Chihauhuan deserts of Mexico. The arid lands of South America are the Atacama and Patagonian deserts of Chile and Argentina.

However, it is the semiarid regions of the world that are most threatened by desertification. Semiarid regions are usually covered by a wide variety of vegetation and are suitable for some agricultural purposes. Unfortunately, they are particularly vulnerable to erosion when their vegetative cover has been removed.

Desertification is a general term applied not only to the expansion of the true desert conditions into previously semiarid regions, but also to general degradation of land in semiarid areas that often lie along the margins of deserts. Contrary to popular press, desertification is a global phenomenon that has been operating for at least several thousand years.

Causes

Droughts by themselves are not the major cause of desertification. Rather, onset of desertification is probably more attributed to abuse of the land during droughts, which, in turn, hastens degradation of the drylands. The most famous instance of desertification in North America, the Dust Bowl of the 1930s, was created by a combination of drought and poor farming practices.

Indeed, the world's semiarid regions are very delicately balanced ecosystems. Even relatively minor activities such as cultivation, grazing, change in vegetation cover, or irrigation projects can stress the land and contribute to degradation and desertification.

Probably one of the major causative factors in most semiarid regions is *overcultivation*: the practice of attempting to grow more crops than the natural fertility of soil can support. Overcultivation, ultimately leading to loss of fertility, soil damage, and subsequent exposure to erosion, generally occurs in systems characterized by rapidly growing populations. Historically it has also been common where societies have switched from subsistence farming (mainly drought-resistant crops) to raising cash crops (e.g., nuts, cotton, rice, wheat) that require irrigation. Extensive growing of irrigated crops strains the already fragile semiarid environment.

In many areas of the world, *overgrazing* is also a major contributor to desertification. Placing too many animals on the land, which ultimately kill off the shrubs and grassland vegetation, leads to soil erosion. Once the vegetation is gone, remobilization of the bare sediment by wind can occur. Also, the simple pounding of hooves decreases the particle size and compaction of the top layer of soil, making it more susceptible to wind erosion. Likewise, large-scale clearing of brush and "deforestation" (although most semiarid regions are not heavily forested) further leads to massive soil erosion and desertification.

What can be done?

There is still considerable debate about whether desertification, such as is currently affecting areas like the Sahel, is permanent or reversible. Certainly under the existing poor land management and use, conditions in the Sahel are probably not reversible within a reasonable time scale. In other areas it may be possible to halt the desertification process, but only if society can accept that semiarid environments are exceedingly fragile and their exploitation can proceed only with appropriate land use planning. Several steps that must be taken to reverse the process include:

- Improvement of soil fertility and conservation.
- Substitution of other fuels for wood.
- Revegetation in order to stabilize soils.
- Elimination or significant decrease in free-range cattle, sheep, and goat herding.

Obviously, most of these measures are difficult or impossible to implement in poorer or developing countries, where population pressures and already limited resources, often combined with civil unrest, make the situation desperate.

Salinisation

Salinisation has contributed to the demise of many agricultural-based societies throughout history, including the decline of ancient civilizations of the Mesopotamia area (centered around the Tigris and Euphrates rivers) and the Inca Empire in Peru. Many agricultural areas of North America, Egypt, Arabia, India, and Australia have been degraded by salinisation.

Salinisation is the increase in concentration of salts (total dissolved solids or TDS) in the pore waters of the near surface sediments and soils. In fact, both land (soils and sediment) and water resources can be salinised by naturally occurring physical and chemical processes and by human activities. Sometimes human-induced salinisation is referred to as *secondary salinisation*.

History of salinisation

As indicated above, a well documented case of salinisation leading to collapse of a human society occurred in Mesopotamia where early cities in the valleys of the Tigris and Euphrates rivers emerged about 4000 BC. The initial development of human settlement in this area was based on irrigation farming and the main crop was wheat. However, in response to an increasing concentration of sodium chloride (NaCl) in the soil, wheat was gradually replaced by barley, which is more salt-tolerant. By about 2100 BC wheat production had decreased further and it accounted for only a small proportion of the grain production. Finally by 1700 BC the cultivation of wheat was abandoned completely. However, as salt continued to accumulate it eventually reached such concentrations that even the barley would not grow, and much of the population was forced to abandon the area. Similar histories of crop production leading to soil infertility due to salinisation are present from parts of China, the Indus River Basin, South America, and the Southwest of United States.

The Aral Sea example

Human-induced salinisation is not confined to ancient cultures. The British developed large-scale irrigation projects during the nineteenth century in India and Pakistan to increase food production (partly in response to recurring ENSO-induced droughts and famine). These led to the rise of saline groundwater and to widespread salinisation. Probably one of the most spectacular (catastrophic) modern examples is that of the Amu Darya and Syr Darya rivers in eastern Asia. In the 1950s these rivers, which previously had flowed into the Aral Sea, were diverted for use on irrigated crops. These irrigated lands produced 90% of the (former) USSR's cotton and 40% of its rice. Due to these major diversions, the Aral Sea began to shrink. Between 1960 and 2,000 its level dropped 20 m and its area decreased by over 60%. Salinity of the Sea, previously one of the worlds largest “brackish water” (TDS ~10 ppt), has increased by 500%. In places the shoreline has regressed (moved basinward) as much as 40 km, leaving former coastal fishing towns and ports without access to the Sea.

This shrinking has had obvious catastrophic effects on the flora and fauna of the Aral Sea and watershed and devastating effects as the human inhabitants. The ecosystem is now greatly degraded; health and climate problems plague the region:

1. Salt and dust storms arising from the newly exposed sediments of the former Aral Sea now affect large areas of eastern and central Asia.
2. There has been nearly complete destruction of the Aral's former ecosystem and complete loss of the once important commercial fishery.
3. The decreased flow of the Amu and Syr Dar'ya has caused significant erosion and degradation of their delta areas—formerly rich agricultural land.
4. The climatic around the Aral Sea has become harsher, hotter, more arid summers and colder winters.
5. There have been substantial declines in groundwater levels around the Aral Sea, whereas in irrigated areas rising water tables have led to water-logging and salt increases.
6. The region now has poor quality drinking water with most sources coming from polluted and saline rivers, irrigation canals, and shallow wells.
7. The population has experienced declines in health and increases in mortality in response to environmental degradation and contamination. The major problems are increases in respiratory ailments (caused by blowing salt and dust), viral hepatitis (caused by contaminated water and poor hygiene), typhus/paratyphus (caused by contaminated water and poor hygiene), liver and esophageal cancer (caused by blowing salt and dust), intestinal disorders and infections (caused by contaminated water, poor hygiene, and blowing salt and dust), kidney problems (caused by poor diet and heavily mineralized water), maternal anemia (caused by poor diet and frequent pregnancies), tuberculosis (caused by poor medical and health care), congenital abnormalities (caused by toxic contaminants) and plague (caused by explosion of rodent population on dry bottom sediments and poor hygiene.

Irrigation is frequently cited as the cause of reduced inflow to the Aral Sea. This certainly is true but we must be careful not to place blame entirely on the 1950–60 irrigation expansion. Irrigation in the Aral Sea basin has a long history, dating back at least two millennia. However, irrigation, itself, did not have significant effects on sea level in the more distant past. This is because the irrigation projects were *restricted* to the floodplains and deltas of the rivers. Consequently, a large proportion of the water used for irrigation was simply diverted and ultimately much of it made its way to the Sea. However, when irrigation was expanded into the true desert areas away from the rivers' floodplains and deltas, reductions in river flow were sizable and the Aral began to recede. Even during the last four decades of the twentieth century the “linkage” between irrigation and level of the Aral Sea has not been uniform. Indeed, we now realize that there are two distinct factors involved:

1. Problems began when irrigation was expanded beyond the deltaic and floodplain areas of the Amu Dar’ya and Syr Dar’ya and into the open desert. This resulted in the *net loss* of a much of the water due to a substantial reduction of return flow.
2. The lowered water levels of the fluvial systems fed back via a variety of linkages to further decrease the natural counterbalance of loss of irrigation water: lowered groundwater tables, change of vegetation and overall decrease in vegetation cover, change in surface albedo, etc.

Processes of salinisation

As mentioned above, salinisation is the process whereby the concentration of total dissolved solids in water and soil is increased due to natural or human-induced processes. We must emphasize here that salinisation can be an entirely natural process: salt-affected soils are formed as a result of the long-term influence of natural processes leading to an accumulation of salts in a region. Natural processes can also be gradual, the accumulation of salts as a result of a gradual addition of weathering, or rapid as might be the case of a temporary submergence of soils under marine. Natural salt-affected soils have a wide distribution on all continents and are very common in some countries in Europe, Asia, Africa, North and South America, and Australia.

Secondary or human-induced salinisation is the result of either addition of salts or the mobilization of salts that might be stored in the soil profile, shallow subsurface sediments or groundwater. Paradoxically, this mobilization is usually due to the *addition of extra water* provided by human activities such as irrigation or land clearing and conversion of bush and natural vegetation to crops. The extra water raises water tables or increases the pressure of subsurface confined aquifers, thereby creating an upward movement (leakage) to the surface. When the water table becomes close to the sediment or soil surface, the water is evaporated, leaving salts behind and causing salinisation. The mobilised salt can also move laterally or vertically toward streams or lakes and increase their salinity.

Closely associated with salinisation is the process of *alkalisation*, whereby the clay fraction of the sediment/soil becomes saturated with sodium. The effect of Na^+ is to disperse the fine clay particles and cause the soil’s desirable “crumb-like structure” to collapse or disintegrate. As a result, the particles of sediment tend to swell, thereby expanding into the pore space of the soil and clogging natural porosity. This lower porosity leads to lower permeability, which ultimately restricts water and air penetration. These soil/sediment conditions also favour water logging.

Source of salt

Dissolved solids exist in rainwater, within the soil profile, in the sediments and rocks into which the soils are forming, in groundwater, and, of course, in water used for irrigation. Rainwater generally contains 10–30 mg/l TDS or sometimes as much as 50 mg/l in coastal areas. The distribution of atmospheric salt decreases with increasing distance from the coast. However, even these small amounts can accumulate to large quantities in a drainage system. Consider a salinity of only 10 mg/l in rainwater. This would add 10 kg/ha of salt to the soil for each 100 mm of rainfall per year. Accumulation of this salt over several thousand years would be considerable.

Salt stored in the soil profile depends mainly on the nature of the soil and the average annual rainfall. Salt content is generally low for sandy soils and high for soils containing a high percentage of clay minerals. Salt content varies inversely with average annual rainfall.

Groundwater aquifers can store substantial amounts of salt, depending on their salinity, porosity, thickness and extent. For example, a 40 m thick aquifer with a porosity of 10% and salinity of 1,000–10,000 mg/l could store 40–400 tonnes of salt per hectare.

Finally, irrigation water adds salt to the soil in proportion to the soluble salt content and the annual application scheme of the irrigation water. Even in the case of good quality irrigation water, which might contain as low as 200–500 mg/l TDS, the amount of salt added per ha and per year is substantial. For example, irrigation water with a salt content of 500 mg/l contains 0.5 tonnes of salt per 1,000 m^3. Since most crops require about 6,000–10,000 m^3 of water per hectare each year, one hectare of land may receive 3–5 tonnes of salt.

Salt mobilisation

Mobilising salt stored in the soil profile and aquifers due to human activities such as irrigation is a major problem in semiarid regions of the world. In nonarid areas where the rainfall and, consequently, the leaching of substances through the soil is more substantial, salinisation can be avoided.

As we learned earlier in this course, many surface irrigation methods that are used widely have low efficiencies. The diversion of irrigation water to fields requires a network of canals, which are commonly unlined, resulting in high seepage rates. The lost water often gradually accumulates, thereby raising the water table. Even in relatively arid conditions, continued use of irrigation without periodic drainage of accumulated seepage water, will result in the groundwater closely approaching the surface. Once the water table is close to the surface, further upward movement is due to *evaporative pull-up*. Evaporation takes place and results in the accumulation of salt in the upper part of the soil/sediment. Indeed, the increase of evaporation rates with respect to the decrease in water table depth is very significant and can very quickly result in considerable loss of fertility. Of course, the system is self-looping: the closer the water table is to the surface, the higher the rate of evaporation, which results in further pull-up of the water table. Unfortunately, the problems associated with the raising of the water table by irrigation are almost always underestimated initially. Even when the natural water table is 10–20 m below the land surface, it can easily be elevated to within a meter of the surface by prolonged use of irrigation systems.

Land clearing for farming and grazing activities also changes the hydrologic balance and can be a major cause of rising water tables. In this case the actual mechanism is a bit different: there is usually less evapotranspiration from crops and pastures than from the native vegetation in semiarid and arid regimes. Thus, clearing increases the amount of water percolating through the surface sediments to recharge the aquifers. Groundwater table elevations can rise very rapidly in this situation. In places where natural bush has been cleared for agriculture in Australia, the groundwater surface rose at a rate of 2–3 m/yr!

Characteristics of saline and sodic sediments and soils

Salt-affected soils can be classified into two broad groups: *saline* and *sodic*, or alkaline, soils. The main criteria used in this classification are:

1. **Sodium adsorption ratio** (SAR): This is the relation between Na^+ and the major divalent cations (Ca^{2+} and Mg^{2+}) of the soil (actually of the solution extracted from the soil or sediment). It is expressed as:

   $SAR = (Na^+)/[(Ca^{2+} + Mg^{2+})/2]^{0.5}$

   where the cations are expressed in milliequivalents per litre.

2. **Exchangeable sodium percentage** (ESP): This is the ratio (or percentage) of exchangeable Na^+ to the total exchangeable cations of all types in the soil. It is expressed as:

   $ESP = \text{exchangeable } Na^+/\text{total soil cation exchange capacity}$

3. **Salinity:** Saline soils and sediments are defined by the presence of an excess of soluble salts. The dominant soluble salts in saline soils are mainly chlorides, sulphates, and bicarbonates of sodium, calcium, and magnesium. Soil and sediment is considered saline when the electrical conductivity of the soil 4,000 µS/cm. Although this value of conductivity is almost universally applied, in fact crop damage can occur at salinities corresponding to much lower conductivities (remember from your physics and chemistry courses: conductivity decreases with decreasing TDS). A value of 2,000 µS/cm usually corresponds to an ESP value of about 15 and an SAR value of 13. Alkaline soils have electrical conductivities generally less than 4,000 µS/cm, ESP of greater than 15, and SAR of more than 13.

4. **pH:** Alkaline soils and sediments have values of greater than pH of 8.5, whereas saline soils generally are less than that.

Salinisation of water resources

Rising water tables of saline aquifers due to increased recharge or upward leakage from deeper aquifers not only causes land salinisation, but will also increase the seepage of saline groundwater into rivers and lakes, thereby increasing their salinisation. Furthermore, the direct discharge of saline effluents from irrigation drainage systems and diffuse run-off from irrigated fields can also contribute to increased salinity of the streams and lakes. Likewise, construction of flood or water resource structures such as dams, weirs, and locks in semiarid and arid regions aggravate salinisation problems.

As we discussed earlier in the course, not only is evaporation greatly enhanced from these open water reservoirs, but dams and reservoirs create a hydrodynamic head of water usually several metres high, which causes saline groundwater to flow into the rivers downstream from structures. Behind the dam, increased water level will raise water table levels in surrounding regions leading to expansion of soil salinisation problems.

Other common causes of increased river and lake salinity are direct discharge of industrial saline water that can also cause increases in river salinity and intrusion of seawater in coastal areas. For example, in many active mining areas, the salinity of effluents exceeds 10,000 mg/l. The saline effluent from extraction and treatment of potash in western Canada can be exceptionally high. Countries with seawater intrusion problems are many, but most noteworthy are Australia, Belgium, France, Germany, the Netherlands, Egypt, Iran, Israel, Libya, and Lebanon. In most coastal situations, freshwater aquifers overlie the saline seawater. However, domestic, agricultural, and industrial overpumping in the freshwater zone can easily change the equilibrium between fresh and saline water and cause intrusion of seawater.

Finally, the application of millions of tonnes of de-icing agents, usually in the form of NaCl, to highways and urban areas in the snow-belt regions of Europe, Canada, and United States contributes to the accumulation of salt in the soil profile and the salinisation of groundwater resources.

Management

Obviously, the best management strategy is simple: do not irrigate or significantly alter the natural cover of land in semiarid or arid regions. In many cases, however, this cannot be done because of historical settlement or modern population growth pressures. Thus, other geoengineering techniques may be used to help curtail the problem.

Drainage

Drainage is as necessary as irrigation for the maintenance of plant growth, prevention of water-logging and soil salinisation. The major drainage techniques are:

1. **Surface drainage:** Surface drainage is the removal of excess water by artificially shaping the land in order to make the water flow. In general, the deeper the drain, the greater is the width of adjacent land affected by the drawdown of the groundwater. Although surface drains can be used efficiently to control the water table, their main disadvantages are loss of land, hindrance to farming operations and overland traffic, and significant maintenance requirements due to factors like weed growth or bank erosion.
2. **Horizontal subsurface drainage:** Horizontal subsurface drainage is the technique of controlling the water table and salinisation by installation of horizontal drains at some depth (usually about 2 m) below the surface. The drains are installed at intervals designed to ensure the water table in the space between the drains does not rise above a given height. Tile and

concrete pipes historically were the most common materials for subsurface drainage, however, today plastic (polyvinylchloride, polyethylene, and polypropylene) tubes and pipes are common. The main disadvantage of subsurface drainage systems is that installation is very labour intensive.

3. **Vertical drainage systems:** These are most applicable if the water table is relatively deep. Basically these are water wells drilled on a grid that act to bring any lost or ponded irrigation water down to the deep water table quickly rather than having the water evaporate at the surface.

Dilution flow

The intentional release of freshwater from reservoirs in a dammed fluvial system during periods of low river flow (i.e., high river salinity) can reduce potential salinisation. The obvious drawback to this is that the reservoirs may already be stressed due to intense use for water supplies, hydroelectricity, and recreation purposes.

Improving irrigation efficiency

In many irrigated areas, seepage loss is a significant contributor to the regional water table. Eliminating channel seepage can, therefore, have a significant effect on rising water tables and salinity. The main types of channel lining include: concrete, masonry, synthetic membrane, bentonite membrane, and compacted clay. Alternatively, channels can be completely replaced by pipelines.

Changing irrigation method

The method of irrigation affects both the efficiency of water use and salt accumulation. However, as we learned in earlier discussions, each irrigation method has advantages as well as disadvantages. Thus, care and study should be applied before trying to improve salinity control by simply changing the irrigation method. For surface flooding or sprinkler irrigation, salt accumulation increases with length of time or volume of water used. For furrow irrigation, which applies water to only part of the field surface, salt accumulates in the ridges (evaporative pull-up) but not usually in the furrows. Differences in the rate of infiltration are, in part, controlled by slope, compaction, texture, and sediment chemistry and, in part, by the time that infiltration can take place (i.e., the upper end of the field nearest the water source usually has much longer infiltration time than does the lower end of the field).

River and lake disposal

Effluents from either diffuse drainage or concentrated surface collection facilities are very commonly released to fluvial systems. Obviously, this common practice, if uncontrolled, merely passes the salinisation problem on to vital water supplies or to persons who happen to be located downstream from the point of disposal. Indeed, the lower reaches of many fluvial systems have become unfit as a water source because of this. The river is converted into a saline stream, which in turn has feedback repercussions on any aquifers, lakes, or estuaries into which the river flows.

Disposal into lakes or swamps is also an attractive option, but mainly for the same environmental reasons discussed above should not be considered without detailed study on the effects of added nutrients, pesticides, and other chemical components. Similarly, drainage water can be disposed of in evaporation basins or ponds. These are often natural depressions or perhaps already existing saline lakes. However, one of the major problems associated with the maintenance of large evaporation basins is leakage. Both lateral and vertical seepage can create a saline groundwater mound beneath a surface basin, which could interact with and contaminate natural groundwater. The other criticism is that the ponds can be large. For example, in the San Joaquin Valley of California, the area of the evaporation basins is about 20% of the total irrigated land.

Deep-well disposal

Disposal of water and liquid wastes in wells drilled relatively deep into the subsurface is a technique that has been commonly used since the 1930s. The geology and hydrogeology of the deep subsurface aquifers must be carefully assessed. In particular, it is imperative that the waste fluid should be physically, chemically, and biochemically compatible with the host rock. A detailed knowledge of the expected chemical and biological reactions between the liquid waste, host rock, and natural pore fluids is required.

Other problem soils: Expansive soils and permafrost

Nature of the problem

Expansive soils, or surficial sediments that undergo significant volume changes depending on the moisture content, are common in large areas of western North America. As with all soil properties, the ability to swell and contract is inherited directly from the parent material in which soil is developed. In North America, two main groups of parent materials lead to expansive soils:

1. Volcanic ash and other deposits from volcanic eruptions.
2. Shales with high smectite content.

These two types of parent material are regionally abundant throughout most of the Great Plains, Great Basin, and Rocky Mountain areas, much of the Gulf of Mexico Coastal Plain, the Mississippi, Missouri, and Red River drainage basins, and the Pacific coast area. Estimates of annual damage to structures due to expansive soils run as high ten billion dollars. Approximately 10% of all structures constructed on or in expandable soils undergo significant damage (i.e., beyond reasonable repair) and another 60% sustain moderate to minor damage. This includes houses, commercial buildings, roads, streets, and buried utilities and pipelines.

Clay mineralogy of expansive soils

A clay mineral is a class of alumina-silicate minerals having its chemical units arranged in a layered structure. The basic structural units or building blocks comprising the layers are:

- Silica tetrahedrons ($SiO4$).
- Aluminium and magnesium hydroxide octahedrons.

The various groups of clay minerals are a function of how these structural units are arranged in the crystal. A *1:1 type* of clay, the simplest structure, is a mineral made up of layers of one octahedral sheet alternating with one tetrahedral sheet. The mineral kaolinite is the most commonly occurring 1:1 layered silicate. These clays are characterized by their stability (i.e., they do not undergo extensive volume changes upon hydration or dehydration).

A *2:1 clay* has a structure in which there is an octahedral sheet between two tetrahedral sheets. The most common and important 2:1 layered silicate mineral is smectite (sometimes called montmorillonite). These clays are extremely susceptible to significant volume changes due to substitution of ions and water molecules within the structure. The most common substitutions are:

- Aluminium for the silica in the tetrahedral sheet.
- Iron and magnesium for the aluminium in the octahedral sheet.
- Various metallic ions and water in between the layers.

When this substitution occurs there is an expansion of the crystal structure and therefore an increase in the volume of the sediment in which the clay is present.

All clay-rich soils swell or shrink to some extent when subjected to moisture change. This is because of the large amount of pore space present between the clay-sized particulate materials of the soil. This type of expansion/contraction is known as *interparticle volume change*. Interparticle swelling and shrinking are controlled only by the physical properties of the soil, specifically the porosity and particle size of the material. Importantly, the swelling is not a function of mineralogy. A soil made up of quartz and one composed of smectite will undergo the same amount of interparticle volume change if the two deposits have the same particle size and porosity.

In contrast, the physicochemical changes induced within the clay minerals themselves, which are termed *intracrystalline volume changes*, are controlled only by the mineralogy of the clays. Two soils, both composed entirely of the same clay minerals, will undergo the same amount of intracrystalline volume change regardless of their grain size characteristics. The potential for volume change of a soil composed of smectite is about 1,000 times greater than one composed of kaolinite.

In addition to clay mineralogy and particle size of the soil, other factors that help to determine the amount of expansion/contraction are:

1. **Density:** In general, the higher the density or consolidation, the more expansion that will occur per unit volume of sediment.
2. **Amount of moisture:** Obviously, the greater the amount of moisture available for intralayer substitution, the greater the amount of volume expansion.
3. **Amount and type of loading of the soil:** In general, soils that are lightly loaded by foundations and structures show the greatest amount of swelling and shrinking.

4. **Geometry of the soil mass:** A thick layer of expansive soil has the potential for much greater total volume change than a thin layer.

Mitigation

The best method of preventing damage from expansive soils is to avoid them. However, considering the large geographic area characterized by expansive soils, this is not possible in most cases. If it is necessary to place a structure on or in a potentially expansive soil the following remedial measures can be applied to reduce the damage:

- Replace the expansive soil with nonswelling material. Usually, however, the expansive material extends to such great depths that complete removal and backfill are not practical.
- Provide sufficient load to withstand and counteract the expansive forces of the soil. This is usually done in the construction of large commercial buildings, but is not practical in house or road construction.
- Flood the area, either with water or some other type of chemical injection, before construction in order to cause maximum expansion of the soil. The potential for further expansion will be greatly reduced, assuming that the expansive soil is not allowed to desiccate.

Permafrost

Permafrost, or perennially frozen ground, presents many special problems for construction and is a major environmental concern in large parts of North America and Europe-Asia. About 24% of the land surface of the world is characterized by permafrost. There has been a tremendous amount of research directed at understanding permafrost and the geotechnical aspects of constructing on it.

A typical section through a permafrost soil shows three basic units or divisions: the uppermost layer, called the *active zone* or *suprapermafrost zone*, freezes and thaws on a seasonal basis. It is separated from the lower, *perennially frozen ground* by the *permafrost table*. The perennially frozen ground grades downward into the *talik*, which is the unfrozen zone underlying the permafrost.

Climate is the single most important factor in dictating the presence of permafrost. Optimum conditions for the development and maintenance of permafrost are:

- Long, cold winters.
- Short, cool summers.
- Little precipitation.

In addition, the water content, mineral composition, and texture of the sediment and soil play key roles in permafrost formation by controlling the thermal conductivity of the ground. A thick vegetation cover tends to produce a thinner active zone and a thinner perennially frozen zone. However, complete removal of the vegetation, such as takes place during construction, results in a large increase in the thickness of the active zone. This, then, is the main problem with working with and constructing in permafrost terrain: thawing of the ice in the active zone releases water. This water cannot penetrate into the underlying perennially frozen ground and therefore stays near the surface in the active zone. This increase in moisture content leads to a loss of cohesion of the soil and solifluction.

Mitigation techniques of permafrost problems fall into three main categories:

1. Active measures involve replacing the entire active zone with material less susceptible to large moisture release upon thawing. Most commonly this is done by replacing the high water content clay-rich soils with sandy or silty sediments, which hold less water.
2. Passive measures attempt to eliminate the increase in active zone thickness that is associated with permafrost melting by the use of insulation, stilts, or pilings.
3. Design measures try to produce a structure that withstands the freeze-thaw and solifluction cycles.

Key concepts and terms to remember

active zone
expansive soil
fabric
hydrocompaction
intracrystalline swelling
interparticle swelling
kaolinite
layered silicate mineral
montmorillonite
permafrost
permafrost table
smectite
suprapermafrost zone
talik
1:1 clay structure
2:1 clay structure

Review questions

(Some of these questions also refer to Unit 11.)

1. Sketch a profile through a typical permafrost zone.
2. Differentiate 1:1 clays from 2:1 clays.
3. Describe the conditions most favorable for permafrost development.
4. Differentiate interparticle swelling from intracrystalline volume changes.
5. What are the features of the general circulation of the atmosphere that account for the location of the world’s major deserts?
6. Yuma, Arizona, and Point Barrow, Alaska, both receive about the same amount of annual rainfall, yet the country around Point Barrow is largely swampy and Yuma is in a parched desert. Why?
7. Where is the Sahel? Discuss the climate changes there and use examples of feedback or loops to explain these changes.
8. Where is the Gobi Desert? What factors account for its existence?
9. Explain how spheroidal weathering occurs?

10. Where on Earth do you think chemical weathering processes would be most active and why?
11. How do the layers in exfoliation domes differ from the layers visible in spheroidally weathered outcrops?
12. What is a transported soil?
13. Where are the highest sheet and rill erosion rates and resultant loss of cropland in the USA?
14. Where are the highest rates of wind erosion in the Great Plains area of the USA?
15. What is the difference between rill and sheet erosion?
16. What are the advantages of strip cropping?
17. What is the fundamental advantage of the ancient technique of terrace farming?
18. Why has total U.S. cropland been decreasing?

Notes

Answers Appendix

The following answers are brief suggestions only. Complete answers would require more detail.

Unit 1 Basic Concepts and Historical Development

1. Any of:
   - Not all geology is environmentally related.
   - Reinforces the environmental interaction of the science.
   - Emphasis is on both social impact of hazards and on society's impact on environment.
   - Numerous other "problem" terms.
2. If stress is applied to a system such that it exceeds a critical point, the system changes rapidly. There are many examples; see textbook and notes.
3. The amount of time required for a quantity to double in size.
4. Populations grow exponentially, whereas most resource growth is only arithmetically.
5. There are many possible examples; see text and notes. Overpumping a groundwater aquifer leading to decreased carrying capacity of the land; use of off-road vehicles leading to increased siltation and high erosion rates.
6. Man is superior attitude; nature is self-healing attitude; nature is cyclic attitude; the now generation philosophy; the infinity complex.
7. Battle of Gettysburg in the U.S. Civil War; Allied landings in France during WWII; many others.
8. It has the ability to be predictive as well as historical.
9. Uniformitarianism most simply stated is: "The present is the key to the past." It is the basic guiding principle in all aspects of Earth science. In environmental geology studies it is very important not to confuse rates of processes with uniformitarianism.

Unit 2 Introduction to Geologic Hazards

1. Endogenic (earthquake, volcano) and exogenic (flood, landslide).
2. No 'set' answer; you should try to provide a logical and factual reason for whichever hazard you pick as the 'worst'.
3. Often this is simply due to the extremely rapid global communications we are now used to; other reasons might include increased population, urbanization, poor technological planning, etc.

Unit 4 Exogenic Geologic Hazards

1. Speed of movement: fast to slow; Type of material involved: unconsolidated to bedrock; Geometry of movement: homogeneous and fragmented to nonfragmented; Type of movement: slide to fall.
2. Adds nutrients to floodplain soils; flushes away accumulated salts.
3. The forces that promote movement and the forces that resist movement.
4. Changing slope configuration by undercutting and/or adding weight to the slope, and changing the internal moisture conditions of the slope material.
5. Many possible answers: tilted trees, tilted utility poles, taut and sagging wires, hummocky topography, leaks in pools, breaking pipes, poor alignment of fences, doors, walls.
6. By putting more people on the floodplain; by channelization and decreased infiltration.
7. Recurrence interval is the reciprocal of the probability;

$$RI = \frac{N+1}{M} = \frac{1}{P}$$

Unit 5 and Unit 6 Coastal Environmental Geology

1. Waves of oscillation occur in relatively deep water whereas waves of translation are shoreline phenomena in shallow water. Waves of oscillation do not actually move the water mass, as they pass by, except in a circular oscillatory pattern. Waves of translation physically move shoreward and break as the top of the wave outruns the base.
2. The wave base of a long wavelength wave lies at greater depth than that of a shorter wavelength wave. This means that it will “feel bottom” farther off shore than shorter waves. This gives the wave more time to build as it approaches shore and affects the underwater beach profile over a greater area.
3. Waves crests approach shorelines at an angle most of the time. Because of this, part of a wave will reach the shore before the rest of it does. The end of the wave entering shallower water will “feel bottom” at a depth equal to half its wavelength and begin to slow down. The rest of the wave will continue to advance at the original velocity creating a curve or bend in the wave crest which is called refraction.
4. An estuary is a semi-enclosed basin in which river water mixes with sea water.
5. The northeast quadrant of a hurricane is in reference to the direction that the storm is moving over the sea or land surface, where “north” refers to the direction the storm is headed. The direction that the storm came from, in this frame of reference, would be south. In other words, it is a relative frame of

reference that has to do with the way the storm is tracking. The wind in a hurricane circles the center of the storm in a counterclockwise direction in the northern hemisphere. This means that the net wind velocity in the northeast quadrant will be the sum of the rotational velocity of the storm plus the velocity of its forward motion. If, for example, the forward velocity is 50 kms per hour and the rotational velocity is about 145 kms per hour, the wind velocity in the northeast quadrant will be the sum of these which would be over 190 km per hour. The reverse situation is true in the northwest quadrant where the net wind velocity would be only 100 kms per hour.

6. Storm surge is the leading cause of death and destruction. It is a mound of water, in front of and under the storm that has the effect of significantly raising sea level. This basically brings storm waves inland and causes structures near the shore line to be subjected to the direct force of the waves. Destruction under these circumstances can be near total. The greatest death toll from an American natural disaster happened in Galveston, Texas, in 1900, in just this way. Over 6000 people drowned. What may be the deadliest coastal flooding of all time also occurred this way in East Pakistan (now Bangaladesh) in 1970, where more than 300,000 people lost their lives.
7. The short answer to this question is that they are classified on the basis of wind velocity. A longer answer is that there are 5 categories referred to by number beginning with 1 being the weakest and 5 the strongest. This is referred to as the Saffir-Simpson Hurricane Scale.
8. Some areas benefit while others suffer. Although Hawaiian hurricanes only occur during El Niño years, hurricanes actually decrease in the Atlantic. Fishing suffers during El Niño years in Peru but improves off California. Drought and flooding are negative effects of El Niño years, but tornados decrease in the central USA.
9. The relatively small first wave was mistakenly thought to be the extent of the danger by some residents. Many returned home prematurely and then fell victim to the much larger waves that followed. Sadly for those who died, it was the third wave that was the biggest.
10. Dredging is commonly used. At Santa Barbara, a dredge works year round to remove sand from a growing spit at the mouth of the harbor.

Unit 7 Geology of Pollution

1. Many possible answers; some of the more obvious are: contain all wastes at the site; reduce the amount of surface and groundwater water contamination.
2. No, because it simply transforms the problem from solid waste disposal to liquid waste disposal.

3. Flammable gases, such as methane, are by-products of both disposal techniques.
4. Geology must play a central role in all aspects of waste and pollution management and contamination documentation, including the physical siting of waste management installations, diagenetic alteration of the wastes, and the movement and subsequent confinement of wastes.
5. Advantage: very effective, cheap; Disadvantage: groundwater contamination, subsidence, earthquakes, toxic gases.
6. Dilute and disperse: small volume, no longer possible in urban areas; concentrate and contain: problems with leakage, storage; resource recovery: conversion of the waste into something useful.
7. Paper products, food products, metals, glass/ceramics.
8. Not presently cost-effective, sometimes creates more pollution.
9. Residence time is the amount of time it takes for the particular material to be cycled through a specific defined system, cycle, or pool. The residence time of "pollutants" varies greatly depending on the geochemical reactivity of the material and on the characteristics of the other components in the system or pool.
10. Biochemical oxygen demand.

Unit 8 Hazardous Wastes

1. a. Cheap, efficient, not effectively segregated from the hydrologic cycle, large potential for global contamination.
   b. Abundant at the site, relatively large groundwater flow systems, large potential for groundwater contamination.
   c. Relatively low groundwater flow, very efficient heat dissipation character, self-healing fractures, abundant, unstable over long periods, very soluble, potential for contamination of highly populated areas.
   d. Effective, expensive, chance of accident.
2. The amount of time required to decrease the activity of a radioactive element by 50%.
3. Toxic wastes are hazardous wastes that are poisonous.
4. Essentially exploration, development, extraction, benefication, and processing.
5. Very simply their relative levels of radioactivity and/or half-lives.

Unit 9 Water Geoscience

1. Velocity, of a river, is the speed of travel of water through its channel in, for example, feet per second. Discharge, of a river, is the volume-rate of flow through the channel in, for example, cubic feet per second. Mathematically, you get discharge by multiplying the velocity times an area reflecting the shape of a two-dimensional cross section through the channel. This results in an answer expressed in cubic units of volume, such as cubic feet, per second which is an expression of volume-rate of flow.
2. Both have to do with the volume-rate of flow of water. Darcy's Law pertains to groundwater flow. River discharge, in contrast, is open-channel flow. The fundamental difference in the equations governing the two is that Darcy's Law considers the effect of the substrate through which the water is flowing. Considering this difference, it is not surprising that the rates of groundwater flow are extremely slow compared to river discharge.
3. Features associated with temporary base levels are geologically impermanent or "temporary." Lakes, for example, may last for a considerable length of time from a human perspective, but will eventually disappear over the course of geological time. Even mountain ranges are temporary features when viewed this way. Other causes for temporary base levels are even shorter lived. A landslide that blocks a river, for example, will soon be removed by erosion. Hydroelectric dams also form temporary base levels of very short duration (geologically).
4. The ocean is called the "ultimate base level" because the ocean is here to stay geologically. This is not to say that sea level itself is constant. It varies as a function of climatic fluctuations that affect global ice volume. But the ocean is where river erosion ultimately ceases. Perplexingly, there are temporary base levels that lie below sea level. The Dead Sea in the Middle East is a good example of this. It is a body of water in an arid region that has no outlet to the ocean.
5. Low gradient river systems are commonly dominated by meandering channel patterns characterized by tight looping bends shaped like curves in a winding mountain road. These channels migrate through time. In some instances, the curvature of the channels becomes so pronounced that two channels will actually intersect each other and form what is called a "cut off." The term cutoff is applied because one bend of the river gets essentially amputated and isolated from the rest of the river. As water continues to flow through the cutoff, the water left in the abandoned channel becomes a stagnant lake. This lake is called an "oxbow lake."
6. There is a general tendency for rivers and streams to form curved rather than straight channels. Once channels become curved, the water current moving through them shifts from one side of the river to the other in a regular and predictable way. For example, a passenger riding in a car following a curving road will be alternately swayed from one side of the car toward the other and back again by inertia. Similarly, water in a curving river channel

will be shifted from one side of the channel to the other by inertia, as the river changes direction. The net result of this is that the outboard sides of river bends receive the lion's share of the energy as the river water gets shifted to that side. A consequence of this is accelerated erosion in the form of a cut bank. On the inboard side, current energy is predictably decreased. A consequence of this is deposition of sediment in the form of point bars.

7. Short records may not include less frequent large flood events. As a result there is a danger of underestimating the size of future events and their recurrence intervals.
8. On the average, a flood of this size would be expected to occur once a year. This is calculated by adding 1 to the duration of the record in years (24 + 1) and then dividing this result by the rank of the event (25).
9. The benefits could include cheap electricity, clean electricity, flood control, irrigation, recreation, and drought prevention. The negative aspects could include loss of habitats, endangerment of species, loss of natural flooding, sediment deposition, increased erosion below the dam, negative effects to delta areas downstream, and, in some cases, loss of life from failure of dams.
10. Where new levees are built, usually on top of natural ones, flood water is prevented from entering the adjacent flood plain. This water is then forced to flow downstream to other areas. Natural levees in those areas will then experience higher than normal water levels and may be overtopped. The typical solution to this flooding problem is construction of an artificial levee. During the next high water period the story is repeated, thus perpetuating levee construction in the downstream direction.

Unit 10 Geology of Water Resources Modifications

1. a. Decrease in density upon freezing.
   b. High heat capacity.
   c. Wettability.
2. On a global scale, the supply of fresh, potable water many times exceeds the existing and projected demands. However, this usable water is very poorly distributed giving rise to local and regional shortages as the demand in "marginal" areas increases.
3. The renewal times are long thus permitting an aquifer to be temporarily depleted.
4. Flood control, recreation, power generation, water supply.
5. Upstream: ecological/habitat changes, loss of land, increased seismic activity; downstream: increased erosion, downcutting, loss of sediment, loss of nutrients, increased flood hazard.
6. Unrestricted downstream development on the assumption that the dam will protect the development against all flood hazards; dam failure.

7. Surface water sources.
8. It is "legal" to use more water than normally flows in the river.
9. Very efficient, creates better crop because the water is applied directly to roots, less salinisation.
10. Can be used in rolling terrain, less evaporation, inexpensive.

Unit 11 Drought

1. Trade winds converging toward the equator feed atmospheric upwelling that rises and moves into the northern and southern hemispheres. The upwelling is the result of more efficient heating of the earth by the sun in equatorial areas which produces a warm low-pressure air mass. This area is called the ITCZ or intertropical convergence zone. The high level air flow away from the equator eventually cools and sinks back to earth at about 30 degrees north and south of the equator as a cool-dry high pressure air mass. This explains the concentration of deserts at these latitudes.
2. Methods used to stabilize sand dunes include barriers, tree lines and other wind breaks, planting plants, oil, or in some cases paving. The Chinese have even used straw barrier mats along rail lines. In general the approach is either to deprive the dune of its mobilizing wind or to immobilize the sand grains themselves.
3. Exploitation was halted by land mines. These explosives made it dangerous for people to travel into desert areas.
4. The lower part or stem is much more abraded than the upper part, suggesting that wind erosion in the desert is concentrated at near ground level.
5. The Sahel is a region of Africa located south of the Sahara Desert and north of the humid savannah grasslands.
6. This is an area of human-induced desertification where there is a delicate balance between survival and disaster. Poor farming and grazing practice in combination with climate variation has caused deterioration of the land. It is the famine resulting from this that has attracted the world's attention.
7. The prevailing wind direction is toward the west because there is a general westward convergence of air flow toward the equator due to the coriolis effect. These winds are called the trade winds. They occur both north and south of the equator.
8. All you need for dunes to form is an abundance of sand, a lack of stabilizing vegetation, and wind. In non-desert coastal dune fields, the sand supply simply overwhelms the vegetation.
9. A disturbing finding has been the identification of pesticides, herbicides, viruses, bacteria, and fungi in wind-blown dust. African dust in the Caribbean, for example, contains microbes that are about 25% plant pathogens and 10% human pathogens.

10. The first step is to halt exploitation immediately. Other steps include planting trees of an appropriate type, water resource management, development of ecologically viable windbreaks, and stabilizing dunes.

Unit 12 Desertification, Salinisation, and Problem Soils

1. Profile should show the active layer overlying the perennially frozen ground that grades downward into the talik. The permafrost table should be shown.
2. 1:1 clay is made up of layers of an octahedral sheet alternating with a tetrahedral sheet; a 2:1 structure has an octahedral sheet between two tetrahedral sheets. The 2:1 structure allows for more volume change due to substitution of ions or water.
3. Long, cold winters, short, cool summer, little precipitation; high sediment moisture content, thin vegetation cover.
4. Interparticle: movement because of loss or gain of pore water; Intracrystalline: movement due to physicochemical changes in the clay mineral lattice.
5. Descending (warming) air masses.
6. Evaporation and relative humidity.
7. Central Africa along the southern edge (shore) of the Sahara Desert. Land clearing and replacement by crops; overgrazing; many possible feedback mechanisms could be cited.
8. Mongolia and NW China; continental interior; rain shadow.
9. Jointed masses of rock tend to be broken up into blocks. This increases the surface area that can be affected by chemical weathering. The corners of blocks have three surfaces compared to two for edges and one for the sides. Because of this the corners weather faster than the edges which, in turn, weather faster than the sides. The resulting weathering surface becomes spherical, from which the word spheroidal is derived. Spheroidally weathered rock masses have a concentrically layered appearance. Many times the original shape of the individual blocks can still be seen.
10. Topical areas such as the Amazon or Congo River basins are places where chemical weathering processes progress rapidly. The common denominator there is climate with rainfall being most significant.
11. The layered appearance of exfoliation domes derives from tension cracks produced by relieved stress. Exfoliation domes are usually made up of rock masses formed deep underground where pressures were higher. Once the overlying rock mass is eroded away, the load decreases and the remaining rock mass is able to expand and crack. Speroidally weathered outcrops form mainly by chemical weathering. Where pressures come into play, they are the result of mineralogical changes such as clay formation.
12. The word transported refers to the substrate upon which the soil is developed. In place granite, for example, is not considered transported. Ash,

dust, river sediment, and glacial sediment are all examples of transported materials upon which transported soils can develop.

13. In the central Mississippi River basin and Hawaii. The top 5 states, excluding Hawaii, are Iowa, Missouri, Kentucky, Tennessee, and Mississippi.
14. In the arid southern part of this area including parts of Texas, New Mexico, and Colorado.
15. Rill erosion happens in discrete streams of water ultimately leading to gullying. Sheet erosion removes soil particles in thin layers more or less uniformly over a sloping surface.
16. It helps catch soil washed off of bare areas and it provides some wind protection.
17. It prevents the negative effects of run off such as rill and sheet erosion. Both soil and water are conserved.
18. Soil erosion is part of the problem but other important factors include urbanization, and conversion to other uses. Urbanization has taken some of the best soil in the USA out of production and is likely to continue to do so.

Notes

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Notes

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