Engineering Hydrology for Natural Resources Engineers

Second Edition

Ernest W. Tollner

WILEY Blackwell

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This edition first published 2016

Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Library of Congress Cataloging-in-Publication Data applied for.

A catalogue record for this book is available from the British Library.
ISBN: 9781118928721

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: © Adventure_Photo/Getty images.

Set in 8.5/12pt, MeridienLTStd by SPi Global, Chennai, India.

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Part Two: Field- and Farm-Scale Water Quality

Acknowledgments

The general farm and dairy background made possible by my parents, Ernest and Ruby Tollner, both now deceased, was of incalculable value to this undertaking. This view has sharpened as time passed. Likewise, the broad-based agricultural and biological engineering experiences gained while studying under the guidance of B.J. Barfield, Tom Haan (The University of Kentucky), Charlie Busch and Dave Hill (Auburn University) were formative. Colleagues Brahm Verma and Dale Threadgill, who mentored me for some 35 years at the University of Georgia, have been helpful in numerous ways. Discussions with colleagues in the UGA water faculty group were stimulating and influential in charting the discussion pathway of many topics presented in this work. Mr. Harry Langford, a technical editor for John Wiley and Sons, provided superb editorial guidance and support. I deeply appreciate the patience and encouragement of my wife, Caren. I dedicate this effort to the memory of my parents, my mentors, to Caren, UGA water faculty colleagues, and to the glory of our creating and sustaining God. I put this work forward as an offering to all. May all on His journey leave behind a more sustainable environment! May we dress and keep His magnificent creation in a sustainable way for all to better serve!

Preface

The definition of Natural Resource Engineering proposed in the previous edition has become fairly well accepted. One could easily call the Natural Resources Engineer an Ecological Engineer, particularly at the basin scale. The difference between the two designations is mainly one of starting point. Most of those pursuing Natural Resources Engineering began with a physics view of engineering and have since picked up much ecology along the way. Many Ecological Engineers started their careers in ecology and then incorporate necessary physical processes as they practice. The end is often similar for both pathways except that registration as a Professional Engineer (PE) is easier to obtain via the physics-based engineering route.

The goal of this revision is threefold. The text reflects new developments in discipline knowledge and ever-changing regulation. The book now more thoroughly presents the similarity of many agricultural and urban processes. The text introduces up-to-date and accessible software tools. The text includes manual calculation examples for clearly demonstrating solution methods. We have simplified the writing. The revised edition incorporates comments received from instructors and students in programs across the United States and around the world.

As in the first edition, this revision first provides a quantitative overview of the hydrologic processes. We then discuss runoff, erosion, and water-quality implications. The book moves to field-scale water management, including structures, drainage, and some irrigation topics.

At the basin scale the text covers some stream and lake ecology topics for supporting the Ecological Engineering discipline. A summary of Ecological Engineering, as viewed by an ecologist, concludes the book. The goal remains to aid students and practicing professionals help their clients reach rural and urban environmental stewardship objectives. The text is a survey of the field of Natural Resources Engineering. Chapters in the latter half of the book support detailed topical instruction when coupled with indicated web resources.

Online Supplementary Material contains access to Excel spreadsheets and other selected software: Appendix B contains additional details. Internet links are provided relating to the main topics. Users may obtain current information on each subject using the revised Internet links.

It became evident in the revisions that the physics of hydraulics and sedimentation is nearly identical, be it on the farm or in the city. The universal physical principles at work in the farm and urban environments guided the revision of many chapters. There is an increased emphasis on the urban environmental problems. However, traditional agricultural problems remain. The common physics is a potential venue for kindling the urban student's desire to consider agricultural topics. Likewise, the rural student can see how practices applied on the farm can contribute to environmental stewardship in urban environments.

Climate change potentially influences economic well-being and holistic satisfaction. The climate-change phenomenon thereby impacts Natural Resources Engineering practices. Thus, a revisit of the robustness of civil, environmental, and agricultural engineering designs on the landscape is in order. Reflecting on process commonalities should engender stronger, more robust design concepts over the scope of the text.

The desired outcome of this book is to provide the background for using the standard references associated with each subject area of the text. This background includes online resources such as the *National Engineering Manual* of the US Natural Resources Conservation Service (NRCS). A second desired outcome is to develop skills to move the content towards more urban and ecological engineering applications (as the NRCS is now doing incrementally). A third desired outcome is to prepare one for applying sophisticated public domain and commercially available software packages for natural resources engineering design and watershed assessment.

As the author, I am solely responsible for errors and omissions. Please notify me of errors in text or the artwork. I would also welcome input regarding significant omissions.

About the companion website

This book is accompanied by a companion website:

www.wiley.com/go/Ernest/EHNRE

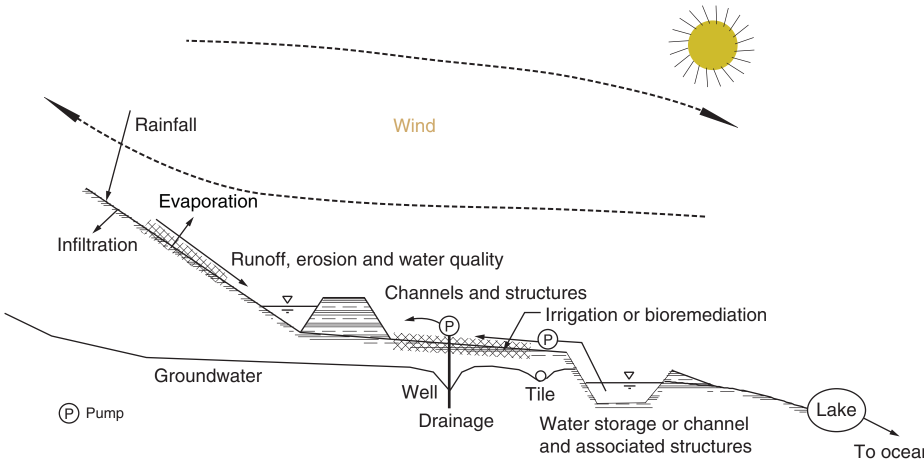
The website includes

- Software
- Excel

Scan this QR code to visit the companion website

CHAPTER 1

Natural resources engineering opportunities



Water, soil, air, plants, animals, other people, are each necessary for our existence. They form our collective environment. Since the dawn of history, humankind has been cultivating food and fiber, domesticating animals, and developing resources. Providing tools facilitating "dressing and keeping" the planet while meeting feed, food, and fiber needs is the overarching vision for this text. Since the 2002 edition, bioenergy production, sustainability, and climate-change pressures have stimulated increased realization of the necessity for responsible natural resource engineering.

Where do we begin? The study of natural resources engineering starts primarily with the study of the physical, biological, and chemical modalities operating in the environment. Physical effects are manifest in the **hydrologic cycle** (see NOAA, 2014). In a survey of the holdings of the University of Georgia Libraries under "land use change," some 8000 articles discuss the hydrologic cycle. The near uniform distribution of books and microfilms dated from 1833 to 2014. There were an additional 500 items going back to 1569. Land-use change has exercised public debates for many years. According to Biswas (1970), philosophers have documented natural forces since the time of Hammurabi (circa 1700 B.C.E.). Solomon (circa 900 B.C.E.) made one of the most elegant statements pointing toward the hydrologic cycle:

> A generation goes, and a generation comes, but the earth remains forever. Also, the sun rises and the sun sets; and, hastening to its place, it rises there again. Blowing toward the south, then turning toward the north, the wind continues swirling along. On it circular courses the wind returns. All the rivers flow into the sea yet the sea is not full. To a place where the rivers flow, there they flow again.
>
> *Ecclesiastes* (1:4-7)

Humankind establishes boundaries in time and space not respected by water, soil, and air. People cannot completely control the biotic or chemical components. We focus mainly on water and soil. Impacts spread across humankind's

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boundaries, spatially and temporal. Effects become manifest in the face of population increases. Developing nations desire to achieve a standard of living of developed countries, which results in additional pressure. Society looks for the path of moderation between development and conservation. Engineers and other professionals contribute to the identification of that moderate path. The text omits the components of natural resource engineering that link heavily to the airshed.[1] The text also does not present other well-developed topics in classic environmental engineering curricula such as waste management, even though all these satisfy the adapted definition of Natural Resources Engineering.

GOALS

- To define fundamental issues and scales associated with Natural Resources Engineering.
- To evaluate how land use is changing in response to societal forces and visualize the resulting opportunities for Natural Resource Engineering.
- To overview the scope of Natural Resources Engineering.

1.1 Definitions

Natural Resources Engineering – the design of planned activities complementary to or in opposition to physical and societal forces leading to modifications of the soil, water, biota, and air environment. The natural forces relate to the hydrologic cycle. Societal forces stem from the desires of people. The Natural Resources Engineer practices on scales ranging from the field, farm, to basins. The purpose is resource development and environmental management.

Ecological Engineering – natural resources engineering practiced largely at the basin scale. Ecological Engineers come from an ecology background, but practice the same art and science as a Natural Resources Engineer.

The foregoing definition of Natural Resources Engineer broadens the scope of natural resources from resource extraction. The text emphasizes more general activities such as crop production and urban development, while the definition also includes activities such as bioremediation and bioconversion. The following terms often appear in the Natural Resources Engineering literature.

Biological remediation (bioremediation) – the application of plant materials, organic amendments, and microbial organisms in order to sequester or transform toxins.

Bioconversion – the biologically mediated physical and chemical conversion of municipal, agricultural, and industrial organics to useful products.

Climate change – the established notion that temperature and precipitation patterns evolve over time as a rsult of solar irradiation changes, volcanism, and other earth movements, and possibly human-induced changes: urban heat islands, impacts of reservoir installation, sea-level rise, and changes in monsoonal rainfall timing appear to be the documented climate-change effects that directly or indirectly intersect topics discussed in this text.

Farm, field, and factory scale – refers to typical problem size: the problem scope lies among the regional and greenhouse, room, or microbial scales.

Hydrology – the scientific study of water: the properties, distribution, constituents, and transport in the atmospheric, surface, and subsurface realms.

Urban agriculture – the development of organic agricultural production, often within urban areas or on the urban fringe.

[1]Works such as Cooper and Alley. (1994) provide an excellent overview of the physical, biological, and chemical forces at work in predominantly urban settings. Principles, however, are broadly applicable to any region.

1.2 The hydrologic cycle and the water–soil–air–biotic continuum

Water and wind are the driving forces for production and pollution. Thus, one must be concerned with the hydrologic cycle. For example, consider the continental United States. The equivalent depth of water passing over the United States in the atmosphere is 300 in. Average annual precipitation over the US land mass is about 30 in (762 mm), partitioned as follows:

- 26 in (660 mm) as rain;
- 4 in (102 mm) as snow, sleet, hail;
- 9 in (229 mm) percolate to groundwater or runs off;
- 21 in (533 mm) returns to the atmosphere;
- 0.73 in (18.5 mm) is consumptively used.

Agriculture consumes 83% of the consumptively used water, but competition is increasing. Agricultural irrigation requires about 40% of consumptively used water. About 40% of the atmospheric return is due to inefficient irrigation. Some corresponding partitions for the world are (Maidment, 1993):

- 31 in (800 mm) falls as precipitation;
- 12 in (320 mm) as runoff to the land;
- 5 in (130 mm) as runoff to the oceans.

Figure 1.1 schematically shows the hydrologic cycle and highlights water management engineering addressed in this work.

- Water falls to earth as precipitation: rain, drizzle, snow, sleet, hail; water also forms directly by condensation – dew.
- Plants may intercept precipitation reaching the ground surface. Water may infiltrate and percolate into the soil, run off the surface, or evaporate.
- Evaporation may occur directly from the precipitation, from plant leaves (wetted leaves and due to transpiration), from the soil surface, from storage structures, from streams and water bodies and the ocean.
- Winds transport moisture, wind-eroded and human-activity-sourced particulates, and odors.
- Plants use infiltrated water (transpiration).

Water may seep into the groundwater, streams, and surface water bodies. It may also move laterally after infiltrating and reappear on the surface at some point downslope (interflow). A complete development of wind erosion and air quality aspects are left to other texts.

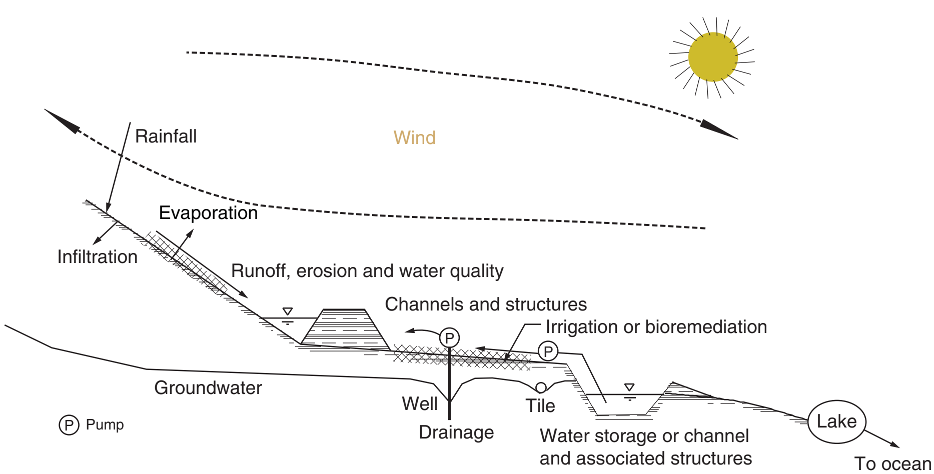

Figure 1.1 Schematic view of the hydrological cycle and related engineering topics associated with Natural Resources Engineering.

Standard hydrologic measurements include the following:

- precipitation, by rain and snow gages;
- accumulated snow, by snow surveys;
- runoff at outlets, using various weirs or related devices;
- evaporation measured using evaporation pans;
- evapotranspiration, by lysimeters or more advanced techniques;
- groundwater level, with monitoring wells and piezometers;
- wind speed and direction, with anemometers and wind vanes;
- humidity, with hygrometers or other electronic means; and,
- solar radiation, with radiometers.

Class A weather stations and some state environmental networks contain instrumentation for many of these measurements. A visit to the US Geological Survey (USGS) home page provides much information relating to runoff and groundwater levels at sites around the United States.

1.3 Changing land uses due to societal forces

In the United States we are diverting forests and prime farmlands to urban developments, designated wetlands, reservoirs, and the like. Change in land use implies a change in land ownership. Change in land use may trigger legally mandated assessments related to environmental appropriateness for the intended use. Requests for financial assistance for making the change may trigger assessments. A visit to the National Resources Inventory of the US Department of Agriculture (USDA, 2013) provides a summary of current trends in the United States.

The application of soil conservation practices to cropland area in the United States is increasing. Total rural land in the United States has decreased about 3% from 1982 to 2010: from approximately 1.41×10^9 to 1.37×10^9 acres. Of the cropland, pastureland, rangeland, and other rural land categories, only forestland coverage increased. Bioenergy mandates apply pressure to cropland resources. In a study of resources required for meeting bioenergy targets, the US Environmental Protection Agency (USEPA, 2009) anticipated significant demand for converting traditional farmland to bioenergy plant production. Thus, the observed decline in cropland would likely level or reverse.

Urbanization results in cover removal and exposure to erosive rainfall. Urbanization and the need to bioremediate environmental spills go together. Urbanization also increases the population segment having heightened sensitivities to unhealthy streams. The change of land use in and around another owner's real estate provides opportunities for Natural Resource Engineers. Outcomes of management changes on soil, water, air, and biotic state must be anticipated. In an agricultural sense, management change may only apply to crop rotations. In contrast moving from agricultural use to residential, commercial, waste treatment or environmental remediation application requires management system, as opposed to individual, responses.

Accelerated land-use change is a worldwide phenomenon due to population increasing 2% annually. Along with all the US land-use-change motivators, developing nations around the world face major problems related to infrastructure development. Increased needs for increased food, fiber, and energy apply stress to production agriculture around the world. Environmentally conscious production and manufacturing are now becoming a priority, although many regions are struggling valiantly to catch up even with tremendous population growth.

The climate-change debate is forcing revisits to current ways of interacting with the environment. The transformation from coal to "green" energy sources is impacting land use in coal-mining regions. The "fracking" boom is significantly influencing land use in many areas of the United States. Proven oil reserves in the United States have increased 7.1% in 2013 alone.[2] Solar and wind energy transitions are pointing to effects only now beginning to unfold in natural resources engineering.

[2] See http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy/review-by-energy-type/natural-gas/natural-gas-reserves.html.

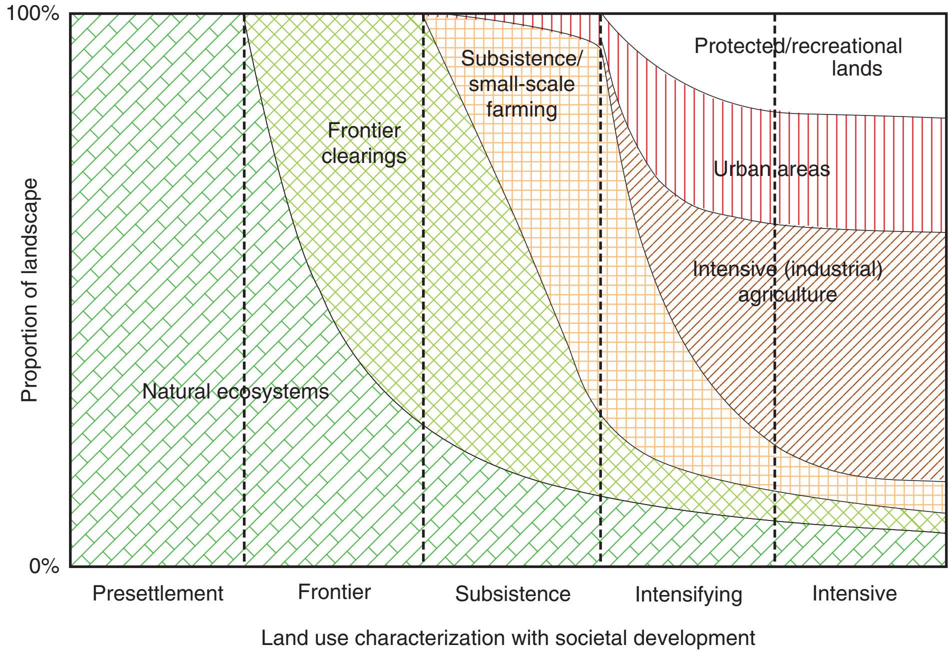

Figure 1.2 Land development relating to the social development of human societies.

World land-use and climatic indicators have been changing since the dawn of human civilization. Deforestation began to happen on a large scale at the birth of modern agriculture. As machine power replaced human power, energy demands of agriculture increased dramatically. Foley *et al*. (2005) provide a summary graphic of worldwide land-use change that is shown as Figure 1.2. These patterns include outward expansion of the rural–urban "fringe," the increasing concentration of animal production, and the applications of agricultural and municipal wastes to land. Changing land ownership and use creates a demand for engineering services.

The Global Harvest Initiative 2014 GAP Report (Zeigler, 2014) provides a concise summary of forces driving the need for sustainability and productivity in our worldwide food supply. These same forces, along with environmental stewardship, mandate that we dress and keep planet Earth.

1.4 Natural resources and ecological engineering scope addressed in this text

The purpose of this section is to establish technological pathways available to natural resources engineers to meet global feed, food, and fiber needs in a sustainable way. Each example listed below ties in with one or more components of the hydrological cycle. We primarily address humid, regions in this text. Of the water–soil–air continuum, the book does not address air quality due to space constraints.

1.4.1 Flood prevention

Flooding in upstream watersheds results in loss of life, property damage, and crops. Flooding causes loss of services and blocks access to remote areas. Flood damage in rural areas costs an estimated $2 billion annually in the United States. Losses are even more problematic with continued development. Flood losses are catastrophic in terms of human life and property around the world. As an extreme example, in 1998 the country of Bangladesh was 70% inundated by floodwater of the Ganges River, with tens of millions of people homeless and thousands dying by drowning or from disease. Deforestation and mountainside cultivation in the Himalayas has increased the amount of sediment carried by the rivers to three billion tons annually, raising the rivers beds, and increasing the likelihood of flooding. Deforestation due to population pressure often precedes catastrophic flooding events.

1.4.2 Erosion control

Erosion occurs when rainfall or wind dislodges soil particles, which are then transported by water or wind. Here we confine the discussion to water erosion.[3] Figure 1.3 shows an example of catastrophic flooding and sediment deposition. Estimates of rates of global soil loss range from 0.09 mm/yr to 0.3 mm/yr (Lal, 1994). Terracing, conservation tillage, and application of soil stabilizers are useful strategies for erosion control in urban or rural settings. The annual erosion from agricultural fields and pastures is about 4 189 500 000 tons. Erosion from cropland and construction is declining due to control measures (NRCS, 1998). Chemical-based no-tillage systems effectively address the erosion problem in many field crops. Challenges remain for specialty crops such as vegetables. Urban construction sites generate some 48 000 tons of soil per square mile annually. Urban construction, mining reclamation, and forestry production pose issues germane to Natural Resources Engineers.

1.4.3 Water quality renovation and management

Water quality suffers when it contains dissolved or suspended pollutants. Researchers have detected at least 16 different pesticides in the groundwater in 26 different states (Leeden *et al.*, 1990). Poor water quality is a consequence of runoff transporting surface or subsurface pollutants. The development and adoption of best management practices have resulted in improving water quality in the United States. Water quality is a continuing problem in much of the developing world. Wetlands, riparian zones, and vegetation strips trap sediments and remove nutrients and organics. Erosion due to urban construction is an issue of water quality. The usual approach for dealing with these problems is

Figure 1.3 Flooding in 2011 near the entrance of the Nzoia River to Lake Victoria near Kisumu, Kenya.

[3]Wind erosion in the humid eastern United States is not a predominant concern like it is in the western states. However, damage to crops in the emergence phase is sometimes significant in the US Coastal Plain (van Donk and Skidmore, 2003; Wagner, 2013).

to extend the extensive experience base for agriculture to include these activities. Research is identifying technologies for reducing inputs and conserving resources, or that lead to useful byproducts, all of which involve Natural Resources Engineers.

1.4.4 Drainage

Surface and subsurface drainage is often beneficial for timely field operations and high yields. Figure 1.4 shows the result of attempted operations of large equipment in wet areas. In arid areas, salinity potential also demands subsurface drainage. Of 260 million irrigated hectares worldwide, 60 million suffer from salinization (Jensen, 1993). Drainage was a primary tool for increasing cropland area in the middle of the last century. Drainage decreased in importance for conventional agriculture in the mid-1980s in response to environmental pressures to protect wetlands. Drainage has many uses in the urban environment. Irrigation projects usually require drainage for managing salinity build-up. We present an introductory treatment of well hydraulics and tile line drainage as potential components of bioremediation systems.

1.4.5 Irrigation

The irrigated area of the world approaches 270 million hectares. It is expanding at 2% per year. The United States has approximately 22.5 million irrigated hectares (Hoffman *et al.*, 2007). Less than an estimated 2% of potentially productive land receives irrigation in many developing countries. Worldwide, surface irrigation is predominant, even though it is much less efficient compared to sprinkler or drip irrigation. Developing countries are potential markets for irrigation engineering, particularly as they move towards sprinkler and drip modalities. Bioremediation schemes employing irrigation would most likely use a sprinkler system. This chapter covers traditional sprinkler irrigation (see Figure 1.5), because the sprinkler entails a comprehensive treatment of infiltration, soil storage, and water usage, The reader can then easily bridge to systems more thoroughly discussed in other water management or irrigation texts referenced in Chapter 14.

Figure 1.4 Tractor and trailer in a very wet field, reflecting that lack of drainage negatively affects the accomplishing of timely field operations. (Courtesy of https://www.youtube.com/watch?v=NHKTbT8fYYM, where additional images are also available.)

Figure 1.5 Center pivot-irrigated peanut production in South Georgia.

1.4.6 Bioremediation

Bioremediation is an emerging new application of drainage and irrigation. The purpose is to apply nutrients and collect effluents from contaminated spaces. The *in situ* bioremediation technique is shown schematically in Figure 1.6. This scheme employs microbes to convert contaminants into innocuous constituents. The Natural Resources Engineer designs drainage and irrigation projects. Specifications of the amendments to the system remain with the microbiologist and other specialists. Our immediate interest is in surveying tools and techniques for providing the required nutrients and water.

1.4.7 Watershed–stream assessment

A discipline of watershed assessment is emerging which serves as a bridge between the field and basin scales. Prichard *et al*. (1998, 2003) provide an easily read overview of watershed assessment methods. Pollution abatement and watershed aesthetic improvement require coordinated physical and model-based assessment. The discipline Ecological Engineering received much impetus from this desire. Assessment of watershed health focuses on streams conveying runoff. A healthy watershed is one with a high number of species and ecosystems within the terrestrial and aquatic realms. Other indicators of health include ratios of organisms attracted to polluted waters versus those attracted to nonpolluted waters. Jorgensen *et al*. (2010) provide a concise compilation of indicators useful for the assessment of ecosystem health. Engineers assist in developing comprehensive nutrient management plans (CNMPs) for large animal-based agriculture (see Figure 1.7). CNMPs provide for the safe application of manures. Engineers likewise assist in restoring natural streams following exhaustive guidelines in NRCS (1998). See Figures 1.8 and 1.9).

1.4.8 Ecological Engineering

The Ecological Engineer (or, the Natural Resources Engineer at the basin scale) focuses on holistic approaches. Self-design within broadly defined units is fostered (Mitsch and Jorgenson, 2004). Ecological Engineering minimizes the classical linear, unit operations approach. The Natural Resource Engineer works with ecologists and other