



Applications of Soil Physics

Daniel Hillel

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Dedicated to my beloved children
Adi, Ron, Sari, Ori, and Shira
who have filled my cup with joy
and made all my trials worthwhile

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Say not; whenever I find the time
I shall study,
lest ye never find the time.

Hillel the Elder (in Avot 2:5)
1st century B.C.E.

Preface

This volume is a close sequel to, and should best be considered in conjunction with, a companion text entitled “Fundamentals of Soil Physics.” The two volumes share more than author, publisher, and date of publication. They both derive from and supersede an earlier text (“Soil and Water: Physical Principles and Processes”) published about a decade ago, and thus have a common philosophy, terminology, and format. Both are directed at the same constituency of upper-level undergraduate and graduate students of the environmental, engineering, and agronomic sciences. However, although this second treatise is based implicitly upon the fundamental principles enunciated in the first one, it differs sufficiently in aim and scope to justify separate publication. Whereas its forerunner primarily describes general principles, the thrust of the present work is to extend and direct those principles toward the understanding of phenomena that are likely to be encountered in the field, as a further step toward the definition and eventual solution of problems having practical importance.

The first and larger part of this book provides a systematic description of the field-water cycle and its management. It includes chapters on infiltration and runoff, redistribution and drainage, evaporation and transpiration, as well as irrigation and tillage. The second part of the book presents advanced expositions of transpiration from plant canopies, freezing phenomena, scaling and similitude analysis, spatial variability of soil physical properties, and movement of solutes during infiltration. As principal author, I consider myself fortunate to have been able to enlist the participation of several of my most highly regarded colleagues, whose contributions constitute the last

five chapters. These authors are, in alphabetical order, David E. Elrick, Edward E. Miller, Robert D. Miller, John L. Monteith, Donald R. Nielsen, and Arthur W. Warrick. Although no single book can ever be considered complete unto itself, it is my hope that the array of topics included herein provides a fairly comprehensive introductory survey of the applications of soil physics in the light of contemporary knowledge. In writing this, I am fully aware of the ephemeral nature of what I called "contemporary knowledge." As research progresses, even the most advanced exposition soon recedes into fading obsolescence. This may be a sad fate for authors to contemplate, but a happy one for science. So be it, then.

There is a special fascination in the topic of soil and water which, in any case, transcends the state of the science at any one moment. Perhaps it even antecedes every child's early interest in mud pies. Those of us who read the Bible cannot but note the powerfully symbolic account of creation in the first chapter of Genesis, which describes how the waters were divided and separated from dry land, and how man himself was created out of, and prefated to return to, "affar," which is, literally, the material of the soil. The primeval association of man with soil is manifested most strongly in the name *Adam*, derived directly from *adama*, a Hebrew word with the composite connotation of earth, land, and soil. Other ancient traditions evoke equally strong associations.

Our civilization seems to have drifted away from that intimacy with the soil which was the mark of our forebears in every land and culture. For that, we may be paying a heavier price than we realize. Seeing this, a philosopher and poet named Nietzsche felt driven to proclaim (in "Thus Spake Zarathustra"): "Man and man's earth are unexhausted and undiscovered. Wake and listen! Verily, the earth shall yet be a source of recovery. Remain faithful to the earth, with the power of your virtue. Let your gift-giving love and your knowledge serve the meaning of the earth." Perhaps our most precious possession and resource, both physical and spiritual, is contained in that most common substance that we sometimes call "dirt," but that is in fact the mother lode of life and the purifying medium wherein waste is recycled and productivity regenerated.

Would Montaigne forgive me? He was the man who wrote: "No one is exempt from saying silly things; the mischief is to say them deliberately."

Peruse me, O Reader, if you find delight in my work. . . . And come, men, to see the wonders which may be discovered in nature by such studies.

Leonardo da Vinci
Madrid Codex I

1 *Soil Physics Explores the Hidden Turmoil in the Field*

A poet gazing through his window might view the field lying outside as a place of pastoral serenity and restfulness. Not so the soil physicist. What he sees in the field is not rest but unceasing turmoil, a dynamic system in which matter and energy are in a constant state of flux. The soil physicist sees the radiant energy reaching the field and observes how this energy is transformed and what processes it powers. To be useful, the knowledge required by the soil physicist of this dynamic system must be quantitative. He strives to measure and to relate the variable rates of those simultaneous processes and to predict how these rates might change under possible control measures. Of particular importance are the processes of water and solute movement in the soil, and their combined effect on the growth of plants.

By some strange turn of historical and geographical fate, a sizable fraction of the world's population happens to be living in the globe's arid and semi-arid zones, where, by a cruel quirk of nature, the requirements of living things for water are greatest even while the supplies of water by natural precipitation are least. This discrepancy strongly affects agricultural plants, which, by their physiology and the nature of their interaction with the field environment, must transpire constantly and in fact must draw from the soil and transmit to the unquenchably thirsty atmosphere hundreds of times more water than they need strictly for their own growth. Thus in the arid zone the scales are weighted heavily against agriculture, and the imbalance must be rectified by intensive irrigation and water conservation. Nor is the problem confined to the arid zone alone. Such are the vagaries of climate that even so-called humid regions suffer periodic dry spells, or droughts.

It is the ability of the soil to serve as a reservoir for water and the nutrients dissolved in it which must bridge the gap between plant requirements, which are practically incessant, and the supply of water, which is intermittent and may be infrequent. But the soil is a leaky reservoir which loses water downward by seepage and upward by evaporation. To manage the system so as to maximize water use efficiency, we must monitor the balance of incoming versus outgoing water and the consequent change of moisture as well as nutrient storage in the root zone. This requires not merely a qualitative understanding of how the system operates, but also a quantitative knowledge of its mechanisms and the rates of its governing processes.

Being a vital link in the larger chain of interconnected media and processes comprising the biosphere, the soil interacts both with the atmosphere and with underlying strata. The soil also interacts in numerous ways with surface and underground bodies of water. Especially important is the interrelation between the soil and the microclimate. Radiant energy reaching the field is partly reflected and partly absorbed, depending on surface conditions. The energy absorbed is transformed into soil heat, “sensible” heat of the air, and latent heat of evapotranspiration. Only a minute fraction goes to photosynthesis, which, however, is the vital process of all agriculture, indeed of the entire biological cycle.

Modern society generates waste, and the problem of how to dispose of various waste materials has become increasingly acute in recent years. There is growing interest in the possibility of applying such materials to the land, in an attempt to utilize the soil’s ability to filter, retain, buffer, immobilize, decompose, or otherwise mitigate the hazards of polluting agents. However attractive the notion of the soil as “living filter,” the sad fact is that our knowledge of the processes involved is still woefully inadequate and serious misconceptions abound. Soils have been credited with an amazing, even mystical, capacity to purify contamination, albeit on the strength of very little conclusive long-term evidence. As often as not, the soil is only a way station in a continuous cycle, and its limited capacity to dispose of harmful pollutants can easily be overtaxed or abused. We mention this problem even though it does not lie within the recognized domain of soil physics but rather in the interdisciplinary realm which includes such related fields as soil chemistry and microbiology. Physical transport phenomena, however, are almost invariably involved and seldom very well defined in practice.

Part I:

THE FIELD WATER CYCLE AND ITS MANAGEMENT

The important role of the soil in the hydrologic cycle can hardly be overemphasized. Particularly crucial to this role is the soil surface zone, where the interaction of atmospheric water takes place with the lithosphere. It is here that the complex partitioning between rainfall (or irrigation), infiltration, runoff, evapotranspiration, and deep seepage is initiated and sustained. This zone is also a primary site for the management and control by man of that all-important resource, water.

The movement of water in the field can be characterized as a continuous, cyclic, repetitive sequence of processes, without beginning or end. However, we can conceive of the cycle as if it begins with the entry of water into the soil by the process of infiltration, continues with the temporary storage of water in the soil, and ends with its removal from the soil by drainage, evaporation, or plant uptake. Several fairly distinct stages of the cycle can be recognized, and, although these stages are interdependent and may at times be simultaneous, we shall attempt, for the sake of clarity, to describe them separately in the following several chapters.

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All the rivers run into the sea,
yet the sea is not full;
Unto the place whence the rivers come,
thither they return again.

Ecclesiastes 1:7

2 *Infiltration and Surface Runoff*

A. Introduction

When water is supplied to the soil surface, whether by precipitation or irrigation, some of the arriving water penetrates the surface and is absorbed into the soil, while some may fail to penetrate but instead accrue at the surface or flow over it. The water which does penetrate is itself later partitioned between that amount which returns to the atmosphere by evapotranspiration and that which seeps downward, with some of the latter reemerging as streamflow while the remainder recharges the groundwater reservoir.

Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface.¹ The rate of this process, relative to the rate of water supply, determines how much water will enter the root zone, and how much, if any, will run off. Hence the rate of infiltration affects not only the water economy of plant communities, but also the amount of surface runoff and its attendant danger of soil erosion. Where the rate of infiltration is restricted, plants may be denied sufficient moisture while the amount of erosion increases. Knowledge of the infiltration process as it is affected by the soil's properties and transient conditions, and by the mode of water supply, is therefore a prerequisite for efficient soil and water management.

¹ Water may enter the soil through the entire surface uniformly, as under ponding or rain, or it may enter the soil through furrows or crevices. It may also move up into the soil from a source below (e.g., a high water table).