Applications of Soil Physics

Daniel Hillel

Applications of Soil Physics

DANIEL HILLEL

DEPARTMENT OF PLANT AND SOIL SCIENCES
UNIVERSITY OF MASSACHUSETTS
AMHERST, MASSACHUSETTS

AP 1980

ACADEMIC PRESS
A Subsidiary of Harcourt Brace Jovanovich, Publishers
New York London Toronto Sydney San Francisco

COPYRIGHT © 1980, BY ACADEMIC PRESS, INC.
ALL RIGHTS RESERVED.
NO PART OF THIS PUBLICATION MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC OR MECHANICAL, INCLUDING PHOTOCOPY, RECORDING, OR ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT PERMISSION IN WRITING FROM THE PUBLISHER.

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Hillel, Daniel.
Applications of soil physics.

Bibliography: p.
Includes index.
1. Soil physics. 2. Soil moisture. 3. Soil management. I. Title.
S592.3.H53 631.4'3 80-535
ISBN 0-12-348580-0

PRINTED IN THE UNITED STATES OF AMERICA

80 81 82 83 9 8 7 6 5 4 3 2 1

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."

此为试读，需要完整PDF请访问：www.ertongbook.com

Contents

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.

此为试读，需要完整PDF请访问：www.ertongbook.com

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.

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).

Comprehensive reviews of the principles governing the infiltration process have been published by Philip (1969a) and by Swartzendruber and Hillel (1973).

B. "Infiltration Capacity" or Infiltrability

If we sprinkle water over the soil surface at a steadily increasing rate, sooner or later the rising supply rate will exceed the soil's limited rate of absorption, and the excess will accrue over the soil surface or run off it (Fig. 2.1). The *infiltration rate* is defined as the volume flux of water flowing into the profile per unit of soil surface area. This flux, with units of velocity, has also been referred to as "infiltration velocity." For the special condition wherein the rainfall rate exceeds the ability of the soil to absorb water, infiltration proceeds at a maximal rate, which Horton (1940) called the soil's "infiltration capacity." This term was not an apt choice, as pointed out by Richards (1952), since it implies an *extensive* aspect (e.g., one speaks of the *capacity* of a reservoir, when referring to its *total volume*) rather than an *intensive* aspect (e.g., a flow rate in terms of volume per units of area and time), as is more appropriate for a flux. Richards then proposed "infiltration rate" instead of "infiltration capacity," with "infiltration velocity" instead of "infiltration rate," but this suggestion has not been widely adopted.

More recently, Hillel (1971) has coined the term *infiltrability* to designate the infiltration flux resulting when water at *atmospheric pressure* is made *freely available* at the soil surface. This single-word replacement avoids the extensity–intensity contradiction in the term infiltration capacity and allows the use of the term infiltration rate in the ordinary literal sense to represent the surface flux under any set of circumstances, whatever the rate or pressure at which the water is supplied to the soil. For example, the infiltration rate can be expected to exceed infiltrability whenever water is ponded over the soil to a depth sufficient to cause the pressure at the surface to be significantly

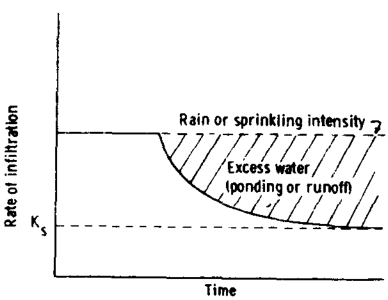

Fig. 2.1. Dependence of the infiltration rate upon time, under an irrigation of constant intensity lower than the initial value, but higher than the final value, of soil infiltrability.

greater than atmospheric pressure. On the other hand, if water is applied slowly or at a subatmospheric pressure, the infiltration rate may well be smaller than the infiltrability. In other words, as long as the rate of water delivery to the surface is smaller than the soil's infiltrability, water infiltrates as fast as it arrives and the supply rate determines the infiltration rate, i.e., the process is *supply controlled* (or *flux controlled*). However, once the delivery rate exceeds the soil's infiltrability, it is the latter which determines the actual infiltration rate, and thus the process becomes *surface controlled* or *profile controlled.* Horton, considered by many to be the father of modern physical hydrology, hypothesized that the soil surface zone determines what he called the infiltration-capacity, more or less apart from conditions within the soil profile. On the other hand, Childs (1969) regarded the infiltration process as a consequence of both the hydraulic conductivity and the hydraulic gradient prevailing in the soil's surface zone, allowing for the possibility that the gradient might be affected by the conditions existing throughout the profile.

If a shallow layer of water is instantaneously applied, and thereafter maintained, over the surface of an initially unsaturated soil, the full measure of soil infiltrability comes into play from the start. Many trials of infiltration under shallow ponding have shown infiltrability to vary, and generally to decrease, in time. Thus, the cumulative infiltration, being the time integral of the infiltration rate, has a curvilinear time dependence, with a gradually decreasing slope (Fig. 2.2).

Soil infiltrability and its variation with time are known to depend upon the initial wetness and suction, as well as on the texture, structure, and uniformity (or layering sequence) of the profile. In general, soil infiltrability is high in the early stages of infiltration, particularly where the soil is initially quite dry, but tends to decrease monotonically and eventually to approach asymptotically a constant rate, which is often termed the *final infiltration capacity*[2] but which we prefer to call the *steady-state infiltrability*.

The decrease of infiltrability from an initially high rate can in some cases result from gradual deterioration of the soil structure and the consequent partial sealing of the profile by the formation of a dense surface crust, from the detachment and migration of pore-blocking particles, from swelling of clay, or from entrapment of air bubbles or the bulk compression of soil air if it is prevented from escaping as it is displaced by incoming water. Primarily, however, the decrease in infiltrability results from the inevitable decrease in the *matric suction gradient* (constituting one of the forces drawing water into the soil) which occurs as infiltration proceeds.

[2] The adjective "final" in this context does not signify the end of the process (since infiltration can persist practically indefinitely if profile conditions permit), but it does indicate that soil infiltrability has finally attained a constant value from which it appears to decrease no more.

此为试读，需要完整PDF请访问：www.ertongbook.com