WATER AT THE SURFACE OF THE EARTH

An Introduction to Ecosystem Hydrodynamics

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PREFACE

I have tried to express in this book some of the ways that biological, physical, cultural, and urban systems at the surface of the earth operate. Of the many different forms of mass and energy these systems receive and transform, this book deals primarily with water seen in association with other forms of matter, including pollutants, and with several forms of energy; in other words, with the hydrodynamics of ecosystems.

Since it concentrates on the reception, processing, and transformation of water by ecosystems at the earth/air interface, the book is not a conventional hydrology or hydrometeorology text. It considers off-site flow, for instance, not from the viewpoint of channel hydrology, but as ecosystem yield, which is a counterpoint to input in these systems and a consequence of the modes of transformation.

The book approaches the dynamics of water in terrestrial systems through the budgets of water in each zone or environment of a system, e.g., the canopy, the ground surface, the soil, and so on. These zones extend the overall water budget in hydrology, which, expressed in numerous models and prediction procedures, long ago proved its worth, and which I met in flood engineering in 1941. Shortly thereafter I saw its association with the energy budget at the earth's surface in the generation of snow-melt floods. My view of these interface budgets from experience in engineering groups was later expanded as I worked with land managers, principally foresters, and with meteorologists. Each of these groups—engineers, meteorologists, and foresters—has from both pragmatic and fundamental standpoints contributed much to the study of hydrology in the United States and indeed throughout the world. In particular, I owe much to such people as Cleve Milligan, S. E. Rantz, the late Bill Bottorf, Henry

Anderson, and Frank Snyder, hydrologists in the Corps of Engineers, Forest Service, and Geological Survey.

In a different perspective, I have tried to blend the contributions of these hydrologists with those of such research workers, geographers, and meteorologists as John Leighly, Gilbert White, the late C. W. Thornthwaite, J. R. Mather, K. R. Knoerr, IUrii L'vovich Rauner, R. A. Muller, Gene Wilken, and Canute VanderMeer, working with rainfall, floodplain management, applications of the water budget in many areas, forest hydrology, and techniques of water management.

Many of the ideas in this book were first expressed in a manuscript that I wrote under the twin stimuli of viewing Australian water problems during a Fulbright year and the thoughts of Alan Tweedie and Alec Costin. Expansion of the material during a second Fulbright year and a term at Hawaii reflects the encouragement of James Auchmuty at Newcastle and Jen-hu Chang at Hawaii. I have also profited from comments and questions from my students in hydrology, meteorology, and climatology classes and seminars at Clark, Georgia, Berkeley, Newcastle, Macquarie, Hawaii, and, of course, Milwaukee. I am grateful to the Fulbright-Hays program and its Australian counterpart, the Australian-American Educational Foundation, for the years in Australia, and to the encouragement of my wife Enid for the whole book.

The drawings have been prepared under the able supervision of James J. Flannery, and photographs not otherwise credited were made by Enid Miller.

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Chapter I

INTRODUCTION

Water at the surface of the earth represents a convergence of two objects of highest human interest: water, and the outer active surface of our planet.

Water is a unique molecule, present in three physical states and in bulk quantities on the earth. The outer active surface of our planet is the place where intense physical and chemical changes and almost all biological and cultural phenomena are concentrated.

This essential substance, water, is of obvious practical importance in ecosystems at and near the earth's surface. Its manifestations in these systems also present problems of intellectual significance, which have been studied by many fields of science —hydrology and oceanography, climatology and micrometeorology, soil science, geology and geophysics, ecology, and geography. Other problems have been examined (although sometimes incompletely) by practitioner disciplines—civil engineering, forestry, agronomy, resource management, city planning, and sanitary or environmental engineering. Each field, having its own focus elsewhere, fails to a degree to follow through on the coupling stated above: water as it is manifested in systems at and near the surface of the earth.

JUST WHAT IS THE EARTH'S SURFACE?

We will focus here on the complex outer skin of the earth and its ecosystems through which the pulses of water delivered by rainstorms make their ways. It is the earth's surface and its mantling ecosystems that are emphasized. We are less concerned about water in channels or captive in the hands of man than with water at the surface.

Such an examination of on-site processes identifies a series of water storages at different levels in ecosystems. These storages are seen on the leaf canopy, on the litter and ground, and in the soil of the ecosystems that cover the lands. The term "ecosystem" in the subtitle of the book encompasses the set of environments through which water moves. The term "hydrodynamics" indicates the movements themselves. Associated with the biological realm of the ecosystem are two zones that are connected with it; both the local air and the rock formations underlying the soil hold, take in, and give out water.

The storages of water in ecosystems are connected by water fluxes. Rain and snow are impacted from the atmosphere onto foliage; water blows or drips from leaves to the ground; water is infiltrated into the soil from which it percolates deeper into the ground or is extracted by transpiring plants. Movement of water off the site to which the atmosphere delivered it finally takes place in the form of vapor, surface or near-surface runoff, or groundwater movement.

The approach we are taking to water at the earth's surface does not follow the so-called hydrology "cycle," that often-cited, little used relic of the 17th century. Instead, we seek to follow the sequence of events occurring as water moves through ecosystems—a sequence that provides a chronological framework in which we can pursue the successive storage of water in the different levels and the fluxes that connect them. This framework of alternating storages and fluxes demonstrates the now rapid, now halting, progress of water through the ecosystems of the interfacial zone between the atmosphere and the bedrock of our planet.

THE BUDGET IDEA

Before we can discuss water in each of these ecosystem environments, we must understand that all the mass and energy of an ecosystem are as carefully counted as a miser's hoard. For every input there are equivalent outgoes; for a credit there is a balancing debit. Ecosystems operate on a budget of water as well as of nitrogen, carbon, or other forms of matter. Everything has a price and everything has to be paid for.

So in each environment at and near the earth's surface we will try to strike an account of inflows and outflows. We speak, in general, of "the water budget," but in actuality we make a budget for each environment within an ecosystem. For example, we make quantitative statements about the snow mantle on a meadow by measuring the input to it from snowstorms and the outputs from it by evaporation, off-site drifting, and downward movement of meltwater. Following this, we can strike another budget for the underlying soil, totting up inputs and outputs. We can use the same procedure for the deeper groundwater. In each environment, the water budget simply states the law of the conservation of matter. Its value is limited only by the accuracy with which we measure each flux or storage of water. In fact, casting a budget often warns us to look for unreliable measuring instruments or procedures.

Concommitant Budgets

The movement of water through the sequence of storages and fluxes is accompanied by the movement of waterborne materials of many kinds: dissolved gases and salts, nutrients, eroded soil particles, and even man-made molecules of the new biocides. These flows are nearly ubiquitous companions of the water flows. For instance, the salt that is spread on the roads inconsiderately moves into the groundwater body. Such mass budgets are a useful means of analyzing problems of environmental pollution.

We also recognize that no form of matter moves unless energy in some form is being expended. Therefore in each environment where we construct a water budget, say for the snow intercepted by trees in a winter storm, we can also construct an energy budget. The movement of intercepted snow out of the tree crowns is powered by applications of energy and does not take place otherwise. Evaporation of intercepted snow, for instance, is not as common as was once thought, because the large energy supply required is usually just not available.

Energy takes many forms. Some of those associated with water budgets are radiation, both short wave (solar energy with wavelengths shorter than 3 μm) and long wave (emitted by clouds, surfaces, and some atmospheric gases at wavelengths greater than 3 μm), and the sensible and latent forms of heat. Sensible heat is perceived as warmth of air or soil.

Latent heat, a form connected in many ways with water, represents the heat added to water when it changes physical state, as from liquid to gas. This is the heat of vaporization, 2500 kJ kg^{-1} of water. It is also, in the reverse process, the heat of condensation, released in clouds when vapor condenses into droplets.

The first law of thermodynamics states that the energy inputs and outputs to a system, plus the change of stored energy, add to zero at any instant. The amount of energy used in vaporizing 1 kg of water is equaled by the energy inputs, e.g., from solar radiation (or reduced heat storage in the water), received in the same period of time. If inputs fall short, evaporation does also. Analogies to the water budget are plain.

Joint analysis of energy and water budgets provides a double-barreled attack on many hydrologic problems, with a better chance of success because both fundamental continuity equations—of mass and of energy—have to be satisfied. A proposed water budget that does not check out in terms of inputs and outputs of energy is telling us that some of our measurements are wrong and need to be checked and improved.

Patterns of the Water Budget in Time

Solution of the water budget in a specific environment for long-term conditions, let us say over an entire year, must be compatible with its solution minute by minute. The law of conservation of mass applies as much to short periods of time as to long ones. Especially in short periods, the absence of steady-state conditions is compensated for by fluctuating amounts of water held in storage in the local environment.

Local storages in the environmental sequence through which water progresses sometimes tend to smooth the initial fluctuations fed into terrestrial systems by the episodic deliveries of water from rainstorms. The soil holds water from sporadic rain, feeding it out more gradually as vegetation transpires during succeeding days. On the other hand, some local storages generate their own fluctuations; snow builds on a fir branch during a storm, then suddenly slides to the ground.

The water budget helps us characterize the regular regimes of the day and the year insofar as they emerge in the various water fluxes. Seasonality over the span of the year is evidenced in many of the interactions between water and ecosystem processes, and is succinctly expressed in budget terms.

Similarly, the effects brought about by climatic change or by man over time can be examined by constructing water budgets for conditions before and after the change. This means of assessing the consequences of man's impact on the environment has been applied where logging, severe grazing, prescribed use of fire, clearing a forest for cultivation, urbanization, or other alterations of ecosystems have occurred. The budget is a powerful tool for analyzing these impacts on the environment.

Spatial Patterns of the Water Budget

Patterns in the landscape can be made concrete if we examine the spatial distribution of components of the water budget. We can depict the areal pattern of snowfall in a mountain valley, or radiant energy and other forms of heat supplied to the melting snow cover, and therefore the pattern of meltwater formation and the generation of off-site flow. While the budgets in each ecosystem in the valley are in balance, the mix of components will vary from place to place. We have a quantitative means of comparing ecosystems on north and south slopes, on ridges, in valleys, on granite or andesitic agglomerate, and in forest and cleared land, and we can see how they differ. On a medium spatial scale we can then construct a single water budget for the whole mosaic of ecosystems in the valley and its drainage basin. This areally averaged budget can then be compared with those characterizing other drainage basins to explain why one yields more streamflow than another, or sends it out sooner in the spring.

Similarly, we can strike a water budget for a large region, such as the snow zone of the California Sierra Nevada. On a still larger scale, we can make one for all of eastern North America, for a whole continent, or a whole ocean. For the entire earth, the budget is simple; an annual precipitation input to the surface of 1000 kg m^{-2} approximates the annual output by evaporation from the surface—the budget idea again!

WATER IN SYSTEMS

Although the earth's surface and its lower atmosphere taken together form a virtually closed system for water, the surface alone represents an open system, as does any sector of it or any ecosystem. Water moves in and out of each of these systems. Inputs and outputs can also be defined for levels or environments within each ecosystem, a set of environments that provides a logical sequence of water budgets, which feed one another. The outflow from the forest canopy becomes the inflow into the water system at the forest floor, infiltration through the forest floor becomes the input into the soil, and so on.

WATER SUPPLIED BY THE ATMOSPHERE TO THE EARTH'S SURFACE

Rain and Snow

The principal input of water to ecosystems on the earth's surface is rain and snow extracted by systems of vertical motion from vapor in the moving currents of the atmosphere. Although it is an areal phenomenon, rainfall is mostly known to us from measurements at specific points where rain gages are located. At these points the rain pattern has the dimensions of duration, depth during a storm, and intensity. From point data we can reconstruct the individual rain area or hydrologic storm. Over a period these provide a picture of seasonal and yearly rainfall to a whole region and its ecosystems.

We begin by describing storms in the atmosphere. These are systems that convert inflows of water vapor into outflows of raindrops and snowflakes that are precipitated to the underlying surface. Their budgets, involving the rates of inflow and outflow, are the fundamental idea in the next chapter. The chapter sequence in this book follows this downward progress of water from the lower atmosphere, through ecosystems at the earth's surface, through the soil and mantle rock, to the "waters under the earth." Four chapters describe how water is delivered from the atmosphere to surface ecosystems; four describe water budgets at the surface and in the soil; three describe evaporation from these systems back to the atmosphere; the following three discuss water in the local air and rocks, zones associated with ecosystems; and the last two chapters describe horizontal movement of water transformed by ecosystems where the preceding storages and fluxes were located. The book begins with input of water to ecosystems, then describes how it is processed in these systems, and ends with the liquid water yield from them.

Chapter II

ATMOSPHERIC VAPOR FLOWS AND ATMOSPHERIC STORMS

WATER VAPOR AND ITS MOVEMENT OVER THE EARTH'S SURFACE

Water vapor emanating from water bodies and vegetation systems covering the earth's surface is mixed upward into the earth's atmosphere. Sometimes it enters a storm cell in the same day and is precipitated back to the earth in the same region of the world. More often it gets caught in one of the great airstreams that move restlessly over the globe and is carried a great distance. Sooner or later, however, it is pulled into a cell of vertical motion, lifted, and cooled by expansion to the temperature of condensation. When amalgamated into snowflakes or raindrops the condensed water falls to the ground, perhaps a thousand kilometers from where it became airborne.*

Atmospheric Water Vapor

One characteristic of the amount of vapor in the atmosphere is its small mass. The areal average over the conterminous United States is 17 kg m^{-2}; Table I shows how it varies throughout the year. In the cold season it is about one-third of what it is in the warm season, an

* A great 17th century work by John Ray, analyzed by Tuan (1968, p. 104), distinguishes between "the rain that moistens the soil, thus making it productive, and the rain that causes rivers to flood." The former, beneficial, type comes from "vapours that are exhaled out of dry land; the latter is caused by the condensation of 'surplus' vapours which the Winds bring over the land from the great oceans." While we still try to distinguish local and remote sources of vapor, we do not associate either with beneficial or harmful hydrologic effects.

TABLE I

Atmospheric Content of Water Vapor over the Conterminous United States from the Surface to the 300-mb Level[a]

Month:	D	J	F	M	A	M	J	J	A	S	O	N	D	Mean
Water vapor:	11	10	9	10	14	19	25	30	29	23	17	12	11	17

[a] Unit: kg m^{-2}. Source: Reitan (1960).

expression of the relation between vapor pressure and temperature. The warm-season increase is particularly large in the interior of the continent because here in winter the air was dry at all levels.

Regions of small vapor content are those like the Arctic Archipelago of Canada in winter (only 2 kg m^{-2}). Here the atmosphere receives little vapor from the cold underlying surface or by transport from distant warm and moist surfaces (Hay, 1971). Even here the content increases in summer to 16 kg m^{-2} as the underlying surface of the whole continent becomes warm and wet.*

Over the northern hemisphere, the yearly average vapor content varies with latitude approximately as follows (kg m^{-2}):

North Pole	5
60N	10
45N	20
30N	30
Equator	45

The annual average over the entire earth is about 25 kg m^{-2}. This represents a total mass of about 13×10^{15} kg. When this number is compared with those characterizing masses of water in other locations, it is seen to be minute (see Table II).

In mass, atmospheric water exceeds only the water in river channels. Both these locations, however, are important beyond what is suggested by the momentary mass of water in them because this water is in rapid motion. Its turnover is short.

A small amount of water is airborne in liquid or solid state. Clouds contain liquid droplets and solid crystals of water, mostly in forms so

* In spite of the dominant long-distance movement of vapor molecules, it is clear that a large regional deviation in evaporation from the underlying surface is important. For example, slow evaporation from the cold surface of the Great Lakes in summer is evidenced in Hay's map as a depression of 2–3 kg m^{-2} in atmospheric vapor content; that is, about 0.1.