CHAPTER 1

INTRODUCTION TO HYDROLOGIC OPTICS

1.0 Hydrologic Optics: Definition, Domain, and Desiderata

As the earth swings round the sun, it continuously turns its atmosphere, its lands and its seas to face into the steady torrent of energy streaming from that radiant star. Of the nearly 65,000,000 watts of radiant power of all wavelengths emitted from each square meter of the sun's surface, about 1,400 watts are incident on each square meter of the upper levels of the earth's atmosphere directly facing the sun, there to initiate and sustain the complex chains of meteorologic and hydrologic events among which are the important biologic links evolving in the atmosphere and the seas. In the meteorologic domain, the radiant flux from the sun is partly absorbed to warm the earth's gaseous mantle so as to generate winds and habitable climes; and partly scattered so as to help grow plants and light the ways of the creatures of the air and earth below. In the hydrologic domain the radiant flux, when in sufficient abundance, is partly absorbed to help keep the seas and lakes and other natural hydrosols in their fluid state, and is partly scattered about in their upper levels so as to light the ways and help provide sustenance for the creatures of these watery domains.

Hydrologic optics is the quantitative study of the interaction of radiant energy with hydrosols, especially the natural hydrosols of the earth such as its seas, lakes, ponds, rivers, and bays. Hydrologic optics is part of a broader discipline known as *geophysical optics* which studies the common physical and geometrical principles governing radiant energy fields in both the meteorologic and hydrologic domains. Geophysical optics together with *astrophysical optics*--in which the emission, absorption and scattering of radiant energy within general planetary and stellar atmospheres is of primary concern--fall under the aegis of *radiative transfer theory,* which is defined as the quantitative study, on a phenomenological level, of the transfer of radiant energy through media that absorb, scatter, or emit radiant energy. Radiative transfer theory, in turn, is viewable as a logical descendent of electromagnetic theory, and in this way hydrologic optics, and more generally radiative transfer theory, may take its place among the theories of modern physics. These interrelations are summarized in Fig. 1.1.

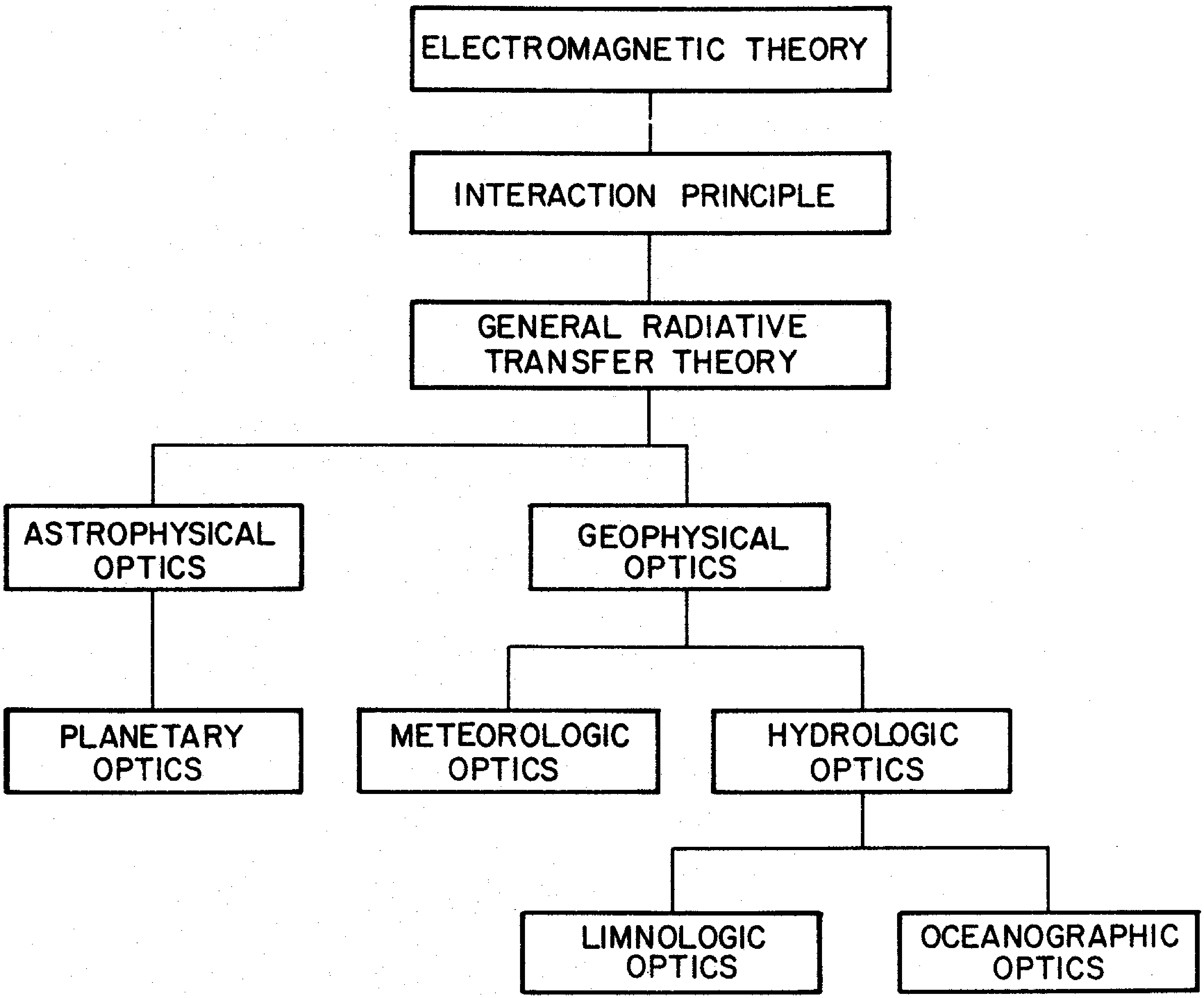

FIG. 1.1 Hydrologic optics as a logical descendant of radiative transfer theory and electromagnetic theory.

The Problems of Hydrologic Optics

The theoretical and empirical studies comprising hydrologic optics arise in the attempts to answer several diverse types of questions such as the following. How much radiant energy of a given wavelength is reflected from a sea or lake surface, and how much penetrates this surface and reaches each depth of the sea or lake? How does the amount transmitted depend on the surface winds and other factors affecting the physical, geometric, and dynamic state of the moving surface? Does the light penetrate the body of the ocean or lake in some general and predictable manner as regards depth dependence and directional dependence of the light distribution? If so, what are the pertinent physical measurements that must be made to facilitate such predictions? What effects on the light field are engendered by the proximity of the shores, bottoms and other boundaries of the hydrosols? What are the pertinent optical properties of natural hydrosols by which oceanographers and limnologists can characterize these waters? How may these scientists usefully employ these concepts in the pursuit of their special interests such as marine biology, geology, and hydrodynamics? How far can a diver or submariner expect to see a given submerged object as he maneuvers in the submarine world of blue-green lights and shadows? How far can one expect to communicate underwater by means of given types of light sources such as lasers, point sources, etc.? Of what significance is the polarized light field to the denizens of the deep and to enterprising humans interested in navigating through the submarine world by unconventional means? These summarize some of the basic types of questions with which hydrologic optics is concerned. The questions have many variations and their resolutions are often of great difficulty,so that the theory of radiative transfer which underlies hydrologic optics is often taxed to its limits in the attempts to provide quantitative or even qualitative answers. As the discussion proceeds, we shall make clear the present status of the solutions to the general problems listed above.

The Aims and Desired Goals of This Work

In this work we shall be concerned with the systematic development of the basic physical principles and mathematical procedures of radiative transfer theory which have been found effective in solving the general types of problems cited above. The reason for selecting the domain of hydrologic optics for specific study rather than meteorologic optics or any other branch of general radiative transfer rests simply in the fact that it is in this domain that most of the practical experience of the author lies.

It should be emphasized at the outset that our primary concern is with the *principles* of hydrologic optics rather than the detailed numerical and experimental aspects of the state of the art of the discipline. These latter procedures, as important as they are in the various stages of securing our knowledge, both theoretical and empirical, are in the last analysis meaningful and efficacious only if they are based on sound physical principles and mathematical techniques. Repeated direct experiences of the author in pursuing complete or partial solutions of problems of the types listed above, have demonstrated the importance of having a well-grounded knowledge of the principles of radiometry and radiative transfer theory during the search for the solutions. It would seem to follow that anyone faced with similar problems and armed with a comparable battery of principles and laws of the subject will also eventually find his way to his own desired experimental or theoretical goals. This, then, leads to the primary aim of the present work: *to give a systematic development of the fundamental principles and procedures of radiative transfer theory which may be employed by students of the subject in the pursuit of solutions of their particular theoretical and experimental problems of geophysical optics, and especially hydrologic optics.* It has also been the experience of the author that both the theoretical and experimental practitioners of the arts of radiometry and radiative transfer are singularly independent individuals, each in his own way, and in view of this it would be somewhat futile to preoccupy the potential student and researcher with anything but the most pertinent and general principles and procedures. This observation is cited to reinforce our aim enunciated above.

The Plan and Scope of This Work

It is in the nature of the theory of hydrologic optics that the full founding and delineation of its basic principles is tantamount to a full founding and delineation of the basic principles of radiative transfer theory itself. This fact rests on the observation that the physical-geometric problem of completely describing the structure of the scattered light field in a sea or lake is just as complex a task as that of describing the light field in the atmosphere, or for that matter in any real medium that emits or scatters light. This realization dawned very early in the author's studies of oceanographic and limnologic optics and in his theoretical excursions into the problems of meteorologic optics. It was eventually realized that the appropriate direction of study was not a problem-by-problem horizontal advance through the everyday jungle of examples, cases, and counter-examples, but rather the direction required a sharp vertical tack, straight up into the heights of abstraction, from whence one could most economically view the radiometric scenes spread out below from horizon to horizon. This attempt to escape into the thin air of general constructs and guiding principles was made as often as the exigencies of daily problems and consultations would allow, and eventually as reports and papers accumulated, there emerged a pattern of principles and procedures which could be seen to apply to all the special principles and special procedures accumulated to that time. Interestingly, it was found that the abstract principles could be phrased and assembled using very meager amounts of advanced mathematical machinery. This, coupled with the author's classroom experience that the basic constructs of radiative transfer, namely *radiant flux, scattering, absorption, volume, area,* and *length* are all readily visualizable, resulted in a theoretical framework which was readily understood and applied once a small number of academic prerequisites had been dispatched, namely the equivalent of a one year course in advanced calculus, which includes vector analysis, and first and second order ordinary differential equations.

For all these reasons it was decided in the planning stages of this work that its scope be widened to embrace, whenever possible, the completely general principles of radiative transfer theory, and to attempt a systematic development of the subject by starting from a single fundamental principle, namely that which eventually came to be called the *interaction principle* (Sec. 3.2). For, it would be inefficient and unesthetic to base a science on many seemingly unrelated principles when it is possible to employ merely one. Accordingly, in Chapter 3, after a thorough grounding in geometrical radiometry, the reader is lead through a methodical construction program of general radiative transfer theory. The elaboration of the details of this task will occupy most of the remainder of the work, with several important chapters, included as integral parts of the main discussion, which are devoted to the richer theoretical details made possible by adopting the plane-parallel settings indigenous to hydrologic optics.

It was found possible to adopt the preceding form of development of radiative transfer theory provided some care was taken at the outset to equalize the backgrounds and intuitions of potential students of the subject. It is to such students and to the general reader that we devote this chapter. In the following sections we shall acquaint these readers with the general outlines of hydrologic optics by supplying representative radiometric examples of natural light fields and typical magnitudes of optical properties encountered in natural hydrosols. We shall also present three of the simplest models of light fields which are capable of describing a very wide number of situations encountered in practical hydrologic optics. We shall in addition illustrate the use of these models by means of explicit deductions and calculations. We shall also present graphs and tables based on these models which have been found useful in practice. Then with these introductory developments completed, we shall feel free to start from scratch in Chapter 2 and proceed rigorously with the systematic construction of the modern theory of

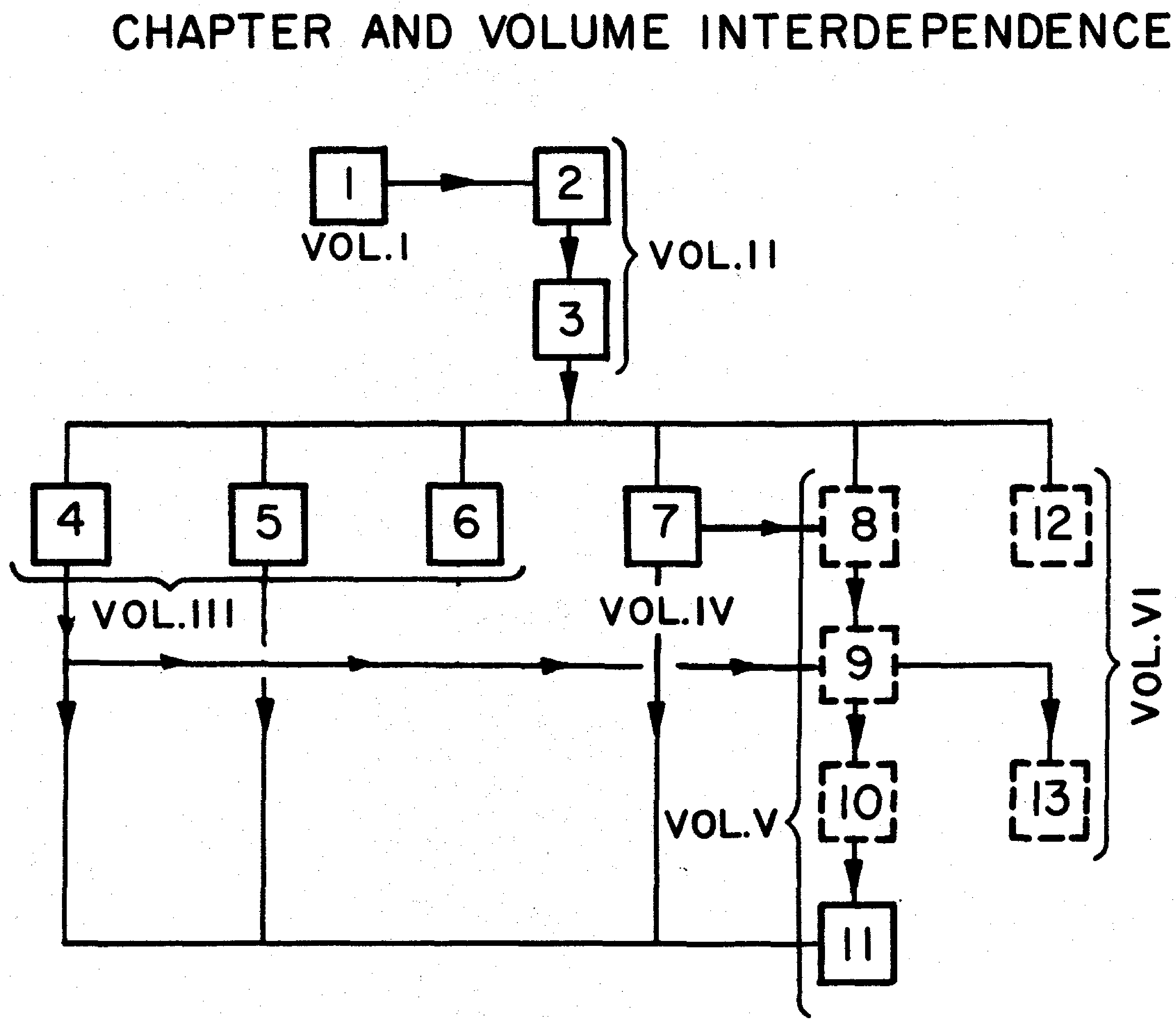

FIG. 1.2 Interdependence of the chapters of this work.

radiative transfer. The results will embody powerful extensions which appear to be capable of solving--in principle and in practice--every known current problem of applied radiative transfer theory in the domains of the air and the sea.

As an aid in studying the present work Fig. 1.2 indicates the *logical interdependence* of the various volumes and chapters. Actually every chapter is connected in some way with every other; however, some connections are stronger than others, and these are shown in the diagram. Thus the prerequisite most essential to understanding a given chapter is the chapter (or chapters) which stand immediately above it via the horizontal and vertical lines in the diagram. For example Chapter 11 depends directly on 4,5, 7 and 10, while 6 depends directly only on 3. Furthermore, the chapters whose contexts are developed on the level of general radiative transfer theory (Fig. 1.1) are outlined in heavy boxes; those that are more directly concerned specifically with hydrologic optics (or the theory of stratified plane parallel media) are outlined in the dashed boxes.

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1.1 A Primer of Geometrical Radiometry and Photometry

After the solar radiant energy incident on the upper levels of the atmosphere has rapidly percolated down through the atmosphere and redistributed itself via scattering processes throughout the lower reaches and in the upper layers of the seas and lakes, its flow within these media assumes an intricate, and relatively steady geometric pattern. A particularly useful mode of representation of this flow of scattered radiant energy is possible by means of the concepts of geometrical radiometry, whose definitions and interrelations we shall now briefly study. A relatively complete and detailed study of geometrical radiometry and photometric concepts is reserved for Chapter 2.

The Nature of Radiant Flux

The radiant energy streaming in from the sun is understood to be electromagnetic energy. The atomic radiative processes of the sun generate a wide range of frequencies (or wavelengths) of electromagnetic energy, only a small part of which is visible to the human eye, or detectable by human skin, or usable by the plants and animals of the earth. The part of the electromagnetic spectrum visible to normal human eyes lies essentially in the range from 400 to 700 millimicrons wavelength, the 400 mμ light being deep blue-violet, the 700 mμ light being deep red, with all the colors of the rainbow ranging continuously between these extremes. The wavelength of electromagnetic energy evoking the greatest sensation of brightness is the yellow-green at 555 mμ under normal daylight conditions. If radiant energy of wavelengths much less than 400 or much greater than 700 mμ fall on normal retinas, there is relatively no conscious awareness of such an event by the associated brain, though--in some extraordinary cases, some ultra violet (380 mμ) and some infra red (780 mμ)