data for some 400 U.S. evaporation-pan stations in its *Climatological Data* series, and pan coefficients and annual free-water evaporation have been summarized and mapped by Farnsworth and Thompson (1982). Figure 7-7 shows free-water evaporation for the contiguous United States. Chow (1994) described an automated evaporation pan that, while relatively costly, is sufficiently accurate and reliable to make it attractive for use in an observation network.

Since year-to-year variations of pan evaporation are usually not large, observations for a few years can provide a satisfactory estimate of annual values, which can then be adjusted by the appropriate regional pan coefficient to give an estimate of free-water evaporation. While such information might be useful in planning for a water-supply reservoir, advection and storage could cause actual lake evaporation to be considerably different from pan-estimated free-water evaporation: Derecki (1981) computed 483 mm average annual evaporation for Lake Superior by the mass-transfer approach, whereas free-water–surface evaporation is about 554 mm. Based on the Lake Hefner study, M.A. Kohler concluded that "Annual lake evaporation can probably be estimated within 10 to 15% (on the average) by applying an annual coefficient to pan evaporation, provided lake depth and climatic regime are taken into account in selecting the coefficient" (Harbeck et al. 1954, p. 148).

Van Bavel's (1966) results and other studies indicate that free-water–surface evaporation calculated by the combination method closely approximates pan evaporation on an annual basis and for shorter periods if heat exchange through the pan is accounted for via Equations (7-41) and (7-42). This correspondence is seen in the results of Examples 7-3 and 7-4.

7.4 BARE-SOIL EVAPORATION

More than one-third of the earth's land surface consists of Entisols, Inceptisols, and Aridisols supporting little or no vegetation (Table 3-9; Figures 3-40, 3-41). In addition, most agricultural lands have meager vegetative cover much of the time. Thus evaporation from bare soil is globally significant and vitally important to farmers, especially in the management of irrigation.

Following infiltration due to rain, snowmelt, or irrigation, evaporation from bare soil (also called **exfiltration**) generally occurs in two distinct stages:

Stage 1: an **atmosphere-controlled stage,** in which the evaporation rate is largely determined by the surface energy balance and mass-transfer conditions (wind and humidity) and is largely independent of soil-water content. Evaporation in this stage occurs at or near the rate of free-water evaporation; and

Stage 2: a **soil-controlled stage,** in which the evaporation rate is determined by the rate at which water can be conducted to the surface in response to potential gradients induced by upward-decreasing soil-water contents [Equation (6-16)] rather than by atmospheric conditions. The evaporation rate in this stage is less than the free-water rate.

The transition from the first stage to the second is typically quite abrupt and can often be visually detected as an increase in the brightness (albedo) of the soil surface (Figure 7-8a).

As implied above, soil evaporation during stage 1 can be estimated by the approaches appropriate for free-water evaporation, of which the Penman Equation [Equation (7-33)] usually gives the best results (Parlange and Katul 1992a). Thus the remainder of this section will focus on evaporation during the soil-controlled stage.

Following an infiltration event, the soil dries both by drainage and by evaporation. If stage-1 evaporation has occurred at the average rate $\overline{E}_1$ for a duration t_1, then the total stage-1 evaporation, F_1, is

$$F_1 = \overline{E}_1 \cdot t_1, \qquad \textbf{(7-43)}$$

and the water content at the end of stage 1 is designated θ_1 (assumed uniform with depth). Salvucci (1997) showed that the modeling of stage-2 soil evaporation can be greatly simplified by (1) invoking a relationship between the duration of stage-1 evaporation, soil properties, and soil moisture; and (2) assuming that the rate of soil drainage due to gravity is much greater than the exfiltration rate. This leads to a cumulative evaporative loss, $F_{soil}(t)$, given by

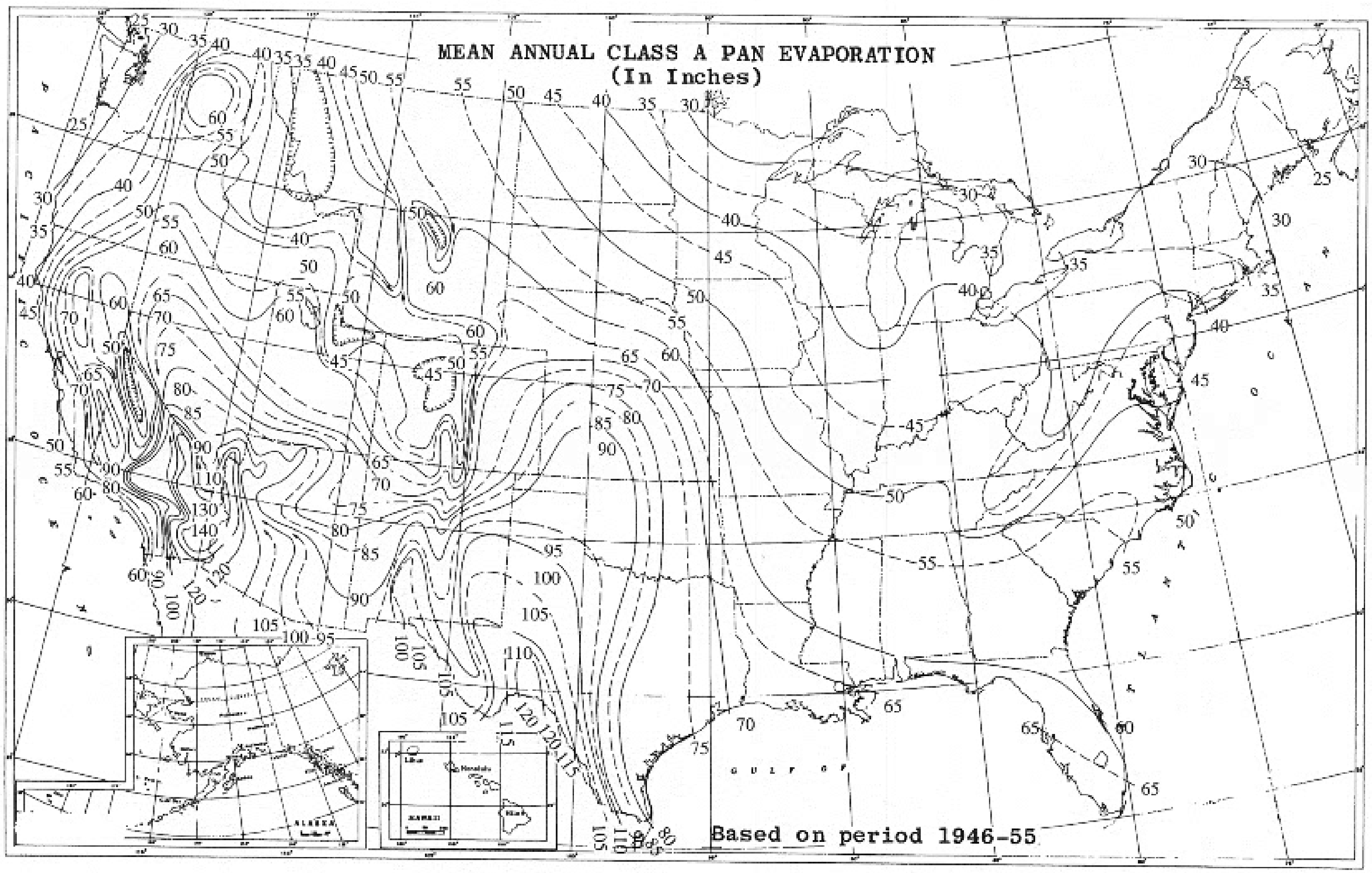

FIGURE 7-7
Average annual pan (= free-water-surface) evaporation (in. yr^{-1}) for the 48 contiguous United States based on data for 1946–1955. Map provided by U.S. National Weather Service.

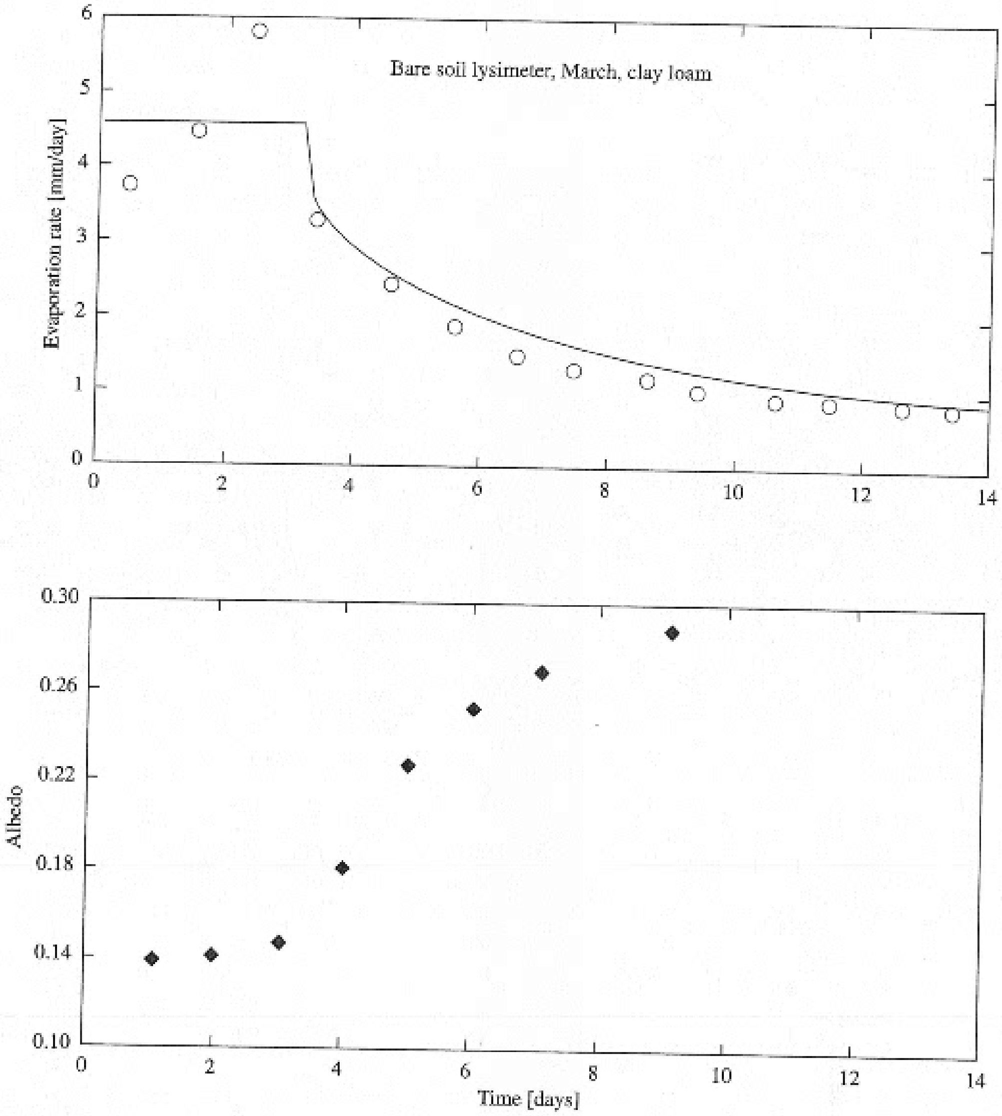

FIGURE 7-8
(a) Bare-soil evaporation following irrigation as measured in a lysimeter (circles) and computed via Equation (7-45) (line). (b) Concurrent soil-surface albedo. Figure provided by Guido Salvucci, Boston University.

$$F_{soil}(t) = F_1 \cdot \left[1 + \left(\frac{8}{\pi^{1/2}}\right) \cdot \ln\left(\frac{t}{t_1}\right)\right], \quad t \geq t_1 \quad \textbf{(7-44)}$$

and a stage-2 evaporation rate, $E_2(t)$, of

$$E_2(t) = \left(\frac{8}{\pi^{1/2}}\right) \cdot \overline{E}_1 \cdot \frac{t_1}{t} = 0.811 \cdot \frac{F_1}{t}, \quad t \geq t_1. \quad \textbf{(7-45)}$$

With Equations (7-44) and (7-45), one can estimate stage-2 evaporation based only on estimates of the stage-1 evaporation rate and observation of the time at which stage 1 ends—which, as noted, can usually be readily done from ground or satellite observations of albedo. This simplified approach gave estimates that compared well with observations in several field experimental situations (Figure 7-8).

EXAMPLE 7-5

During the infiltration event of Example 6-7 a total of 81.4 mm infiltrated. Following this, stage-1 evaporation lasted for $t_1 = 3$ days and occurred at an average rate of $\bar{E}_1 = 10$ mm day^{-1}. Compute the stage-2 evaporation rate over the next 10 days in which no rain fell.

Solution From Equation (7-43), the stage-1 evaporation is

$$F_1 = 10\,\text{mm day}^{-1} \cdot 3\,\text{day} = 30\,\text{mm}.$$

For stage 2, Equation (7-44) gives the cumulative evaporation:

$$F_{soil}(t) = 30\,\text{mm} \cdot \left[1 + 0.811 \cdot \ln\left(\frac{t}{3\,\text{day}}\right)\right];$$

and Equation (7-45) gives the evaporation rate:

$$E_2(t) = 0.811 \cdot 10\,\text{mm day}^{-1} \cdot \frac{3\,\text{day}}{t} = \frac{24.3\,\text{mm}}{t}.$$

The results are tabulated as follows:

t (day)	3.0	3.5	4.0	4.5	5.0	5.5	6.0	
$E_2(t)$ (mm day^{-1})	8.11	6.95	6.08	5.40	4.86	4.42	4.05	
$F_{soil}(t)$ (mm)	30.0	33.8	37.0	39.9	42.4	44.7	46.9	
t (day)	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
$E_2(t)$ (mm day^{-1})	3.74	3.47	3.24	3.04	2.86	2.70	2.56	2.43
$F_{soil}(t)$ (mm)	48.8	50.6	52.3	53.9	55.3	56.7	58.0	59.3

7.5 TRANSPIRATION

7.5.1 The Transpiration Process

Transpiration is the evaporation of water from the vascular system of plants into the atmosphere. The entire process (Figure 7-9) involves **absorption** of soil water by plant roots; **translocation** in liquid form through the vascular system of the roots, stem, and branches to the leaves; and translocation through the vascular system of the leaf to the walls of tiny **stomatal cavities,** where evaporation takes place. The water vapor in these cavities then moves into the ambient air through openings in the leaf surface called **stomata.**

Plants live by absorbing carbon dioxide (CO_2) from the air to make carbohydrates, and that gas can enter the plant only when dissolved in water. The essential function of the stomatal cavities is to provide a place where CO_2 dissolution can occur and enter plant tissue; the evaporation of water is an unavoidable concomitant of that process. However, transpiration also performs the essential functions of maintaining the turgor of plant cells and delivering mineral nutrients from the soil to growing tissue.

Air in stomatal cavities is saturated at the temperature of the leaf, and water moves from the cavities into the air due to a vapor-pressure difference, just as in open-water evaporation. The major difference between transpiration and open-water evaporation is that plants can exert some physiological control over the size of the stomatal openings, and hence the ease of vapor movement, by the action of **guard cells** (Figure 7-10). The major factors affecting the opening and closing of guard cells are (1) light (most plants open stomata during the day and close them at night), (2) humidity (stomatal openings tend to decrease as humidity decreases below its saturation value), and (3) the water content of the leaf cells (if daytime water contents become too low, stomata tend to close).[7]

It is important to emphasize that transpiration is a physical, not a metabolic, process: Water in the **transpiration stream** is pulled through the plant by potential-energy gradients that originate with the movement of water vapor into the air through the stomata in response to a vapor-pressure difference. When vapor exits through the stomata, water evaporates from the walls of the stomatal cavity to replace the loss; this loss of liquid water causes a potential-energy decrease that induces the movement of replacement water up through the vascular system; this movement ultimately produces a water-

[7] Several other factors are known to affect the opening and closing of stomata, including wind, CO_2 levels, temperature, and certain chemicals. A mathematical representation of the effects of the factors most important in hydrological modeling is given later.