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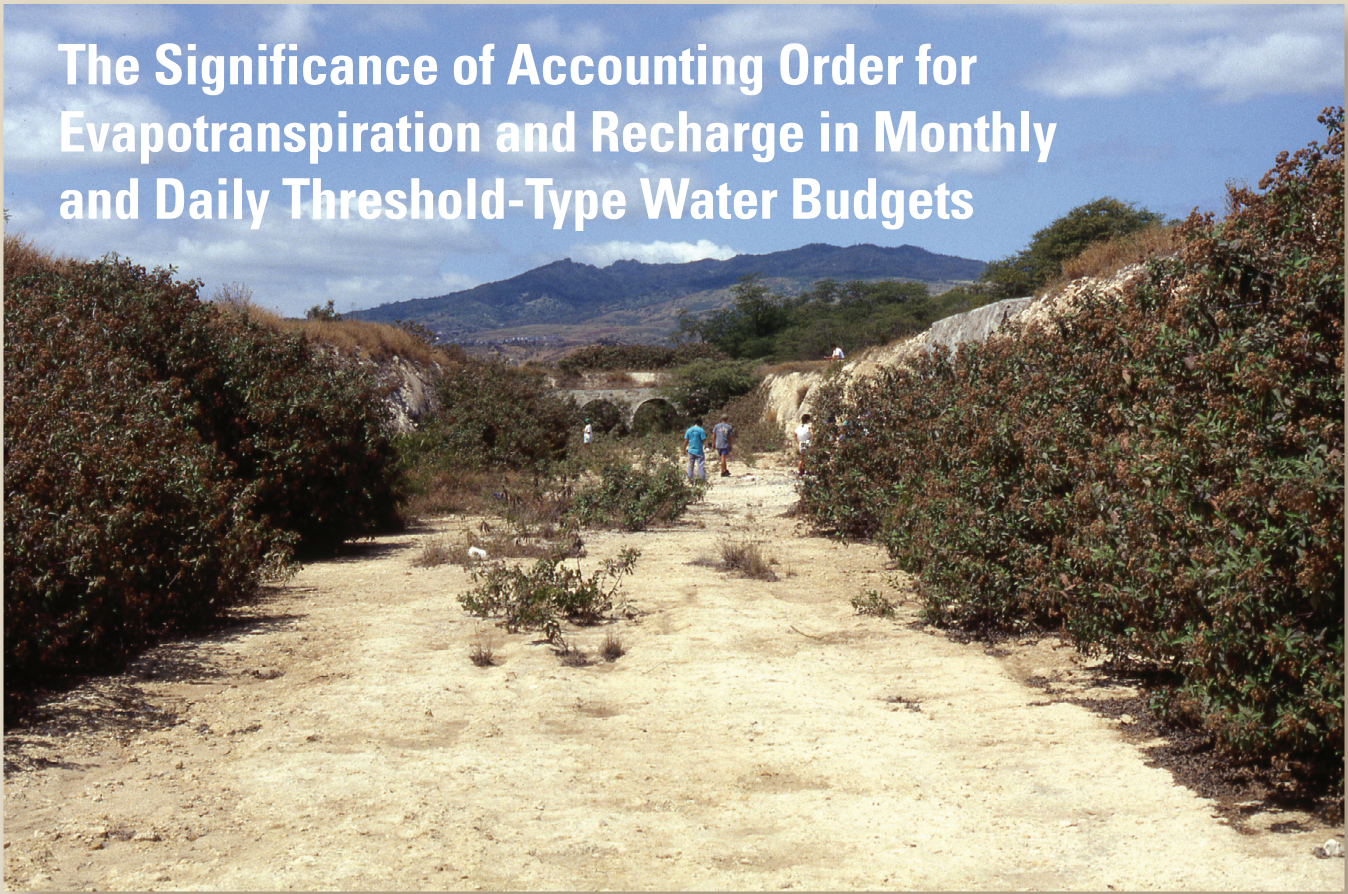
The Significance of Accounting Order for Evapotranspiration and Recharge in Monthly and Daily Threshold-Type Water Budgets



Scientific Investigations Report 2008-5163

U.S. Department of the Interior
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COVER

The order of accounting for evapotranspiration and recharge in threshold-type water budgets can have an effect on ground-water recharge estimates, which is a concern for evaluating water availability. For monthly water budgets, accounting for recharge before evapotranspiration is most appropriate in areas where rainfall occurs infrequently (such as southwest O`ahu, top), whereas accounting for evapotranspiration before recharge is most appropriate where rainfall occurs relatively uniformly throughout the month (such as the eastern part of the Island of Hawai`i, bottom). USGS photos by D.S. Oki (top) and D.C. Nishimoto (bottom).

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By Delwyn S. Oki

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Flowrate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Vertical coordinate information is referenced to mean sea level.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

The Significance of Accounting Order for Evapotranspiration and Recharge in Monthly and Daily Threshold-Type Water Budgets

By Delwyn S. Oki

Abstract

Most threshold-type water-budget models account for the loss of water by evapotranspiration before accounting for recharge. Recharge estimates can differ substantially, depending on whether recharge is counted before or after evapotranspiration in the water budget. This disparity is the source of uncertainty and is most pronounced for areas where soil-moisture storage capacity is small or for water budgets computed using a large time interval (such as monthly). Water budgets that account for recharge before evapotranspiration provide higher estimates of recharge and lower estimates of evapotranspiration relative to water budgets that account for evapotranspiration before recharge. The choice of accounting method is less significant for a daily computation interval than for a monthly computation interval. In general, uncertainty in recharge estimates is least for water budgets computed using the shortest computation interval that the data allow and that is consistent with the physical processes being represented. If the data only allow for long (weekly or monthly) computation intervals, then selecting the appropriate accounting order for the study area may be critical. For monthly water budgets, accounting for recharge before evapotranspiration is most appropriate in areas where rainfall occurs infrequently, whereas accounting for evapotranspiration before recharge is most appropriate where rainfall occurs relatively uniformly throughout the month.

Introduction

Regional estimates of ground-water recharge generally are needed for water-availability assessments and as input to numerical ground-water models. A simple water-budget model of the plant-soil system is a commonly used tool to estimate ground-water recharge (Thornthwaite and Mather, 1955). These water-budget models generally use annual, monthly, weekly, or daily bookkeeping procedures that account for inflows (precipitation and irrigation) and outflows (runoff, evapotranspiration, and recharge) of water from the plant-soil system and changes in soil moisture within the plant root zone (fig. 1). The choice of time interval used in the water-budget computation commonly is based on data availability, although the physical processes being represented (for example timing of precipitation, evapotranspiration, or drainage) also may need to be considered. Simple water-budget models are useful for regional assessments of ground-water recharge, although complex, data-intensive, computationally less efficient numerical models of the unsaturated zone may provide more accurate representations of the physical processes of soil-water movement.

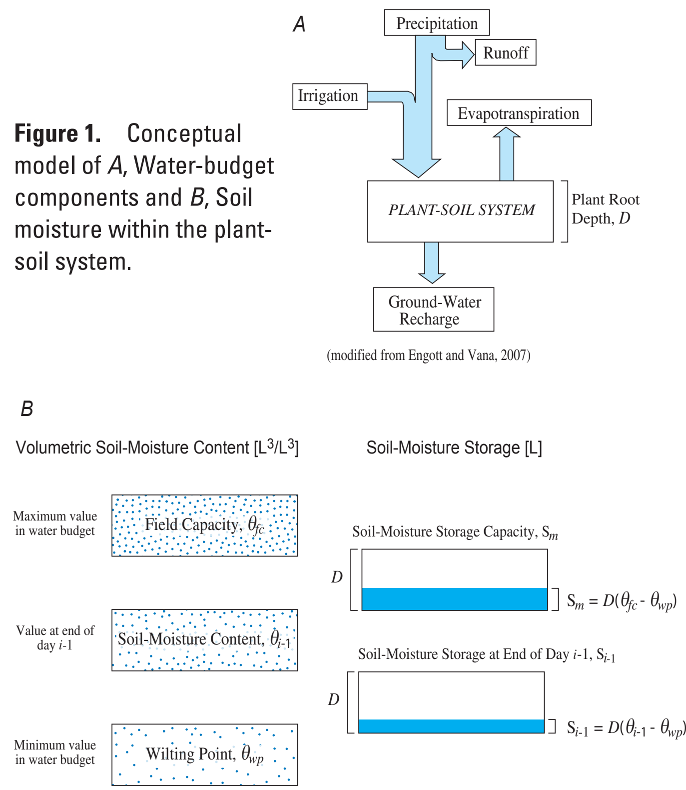

Figure 1. Conceptual model of *A*, Water-budget components and *B*, Soil moisture within the plant-soil system.

In threshold-type water-budget models, ground-water recharge occurs when available water exceeds the soil-moisture storage capacity. Most threshold-type water-budget models account for the loss of water by evapotranspiration before accounting for recharge, although in some cases it has been suggested that the water budget should account for recharge before evapotranspiration. Eyre and others (1986) indicated that accounting for recharge before evapotranspiration may be reasonable if (1) recharge occurs mainly during storms, when rainfall intensity is high and evapotranspiration is low, and (2) the saturated infiltration capacity of soils greatly exceeds the rate of evapotranspiration. For these conditions, much of the soil water may rapidly drain past the plant root zone before it can be lost to the atmosphere by evapotranspiration. Accounting for recharge before evapotranspiration in threshold-type water-budget models may be less appropriate for areas where drainage is slower.

In a monthly water budget of the plant-soil system, the two accounting methods can produce markedly different recharge estimates. For example, a monthly water budget was computed for the Island of Moloka‘i, Hawai‘i, and the average island-wide recharge estimate ranged from 11 to 19 in/yr (140 to 237 million gallons per day), depending, respectively, on whether evapotranspiration was assumed to occur before recharge or recharge was assumed to occur before evapotranspiration (Shade, 1997). Thus, considerable uncertainty may be associated with the accounting method in monthly water budgets.

Water budgets that account for evapotranspiration before recharge tend to provide lower estimates of recharge and higher estimates of evapotranspiration than water budgets that account for recharge before evapotranspiration. Water budgets that account for evapotranspiration before recharge have the potential to underestimate recharge and overestimate evapotranspiration, particularly as the length of the time interval used in the computation increases (Giambelluca and Oki, 1987; Alley, 1984; Rushton and Ward, 1979; Howard and Lloyd, 1979). Water budgets that account for recharge before evapotranspiration have the potential to overestimate recharge and underestimate evapotranspiration, although the conditions for which this is the case have not been documented.

Purpose and Scope

The U.S. Geological Survey (USGS) undertook the present investigation in response to a need for additional information on the effects of accounting order for evapotranspiration and recharge in water-budget computations for island settings. The objectives of this study are to (1) quantify the effects of water-budget accounting method on recharge estimates, and (2) evaluate the appropriateness of the two accounting methods relative to climatic setting. The analyses for this study used existing daily rainfall and pan-evaporation data.

Methods

Ground-water recharge was estimated using both daily and monthly water budgets and two methods of accounting for evapotranspiration and recharge. In this report, the water-budget computation method that accounts for recharge before evapotranspiration is referred to as method 1, and the water-budget computation method that accounts for evapotranspiration before recharge is referred to as method 2.

Evapotranspiration was determined as a function of potential evapotranspiration and soil moisture. Most evapotranspiration models that are based on potential evapotranspiration and soil moisture incorporate aspects of the extreme models of Veihmeyer and Hendrickson (1955) and Thornthwaite and Mather (1955), hereinafter referred to as the VH and TM models, respectively. Veihmeyer and Hendrickson (1955) suggested that evapotranspiration occurs at the potential rate when soil moisture is between field capacity and the wilting point, but that evapotranspiration is zero when soil moisture is at or below the wilting point. Thornthwaite and Mather (1955) suggested that the rate of evapotranspiration decreases linearly as soil moisture is reduced from field capacity to the wilting point. Both of these extreme models were tested.

Daily Water Budgets

The water-budget method used in this study is a variant of the Thornthwaite and Mather (1955) bookkeeping procedure. A water budget of the plant-soil system was computed on a daily basis in the following manner. For a given area, runoff was subtracted from daily rainfall, and the difference was added to the beginning soil-moisture storage for the day to determine interim soil-moisture storage:

$$X_i = P_i - R_i + S_{i-1},$$

where: X_i = interim soil-moisture storage for current day [L],
S_{i-1} = ending soil-moisture storage from previous day (i–1), equal to the beginning soil-moisture storage for current day (i) [L],
P_i = precipitation for current day [L],
R_i = runoff for current day [L], and
i = subscript designating current day number.

All volumes of water are expressed as an equivalent depth of water over an area, and therefore have units of length [L]. Irrigation, snow melt, and interception of rainfall by vegetation were ignored for this analysis.

The ending soil-moisture storage from the previous day is equal to the plant root depth multiplied by the difference between the ending volumetric soil-moisture content within the root zone from the previous day and the volumetric wilting-point moisture content (fig. 1):

$$S_{i-1} = D \times (\theta_{i-1} - \theta_{wp}),$$

where: D = plant root depth [L],
θ_{i-1} = ending volumetric soil-moisture content from previous day (i–1), equal to the beginning volumetric soil-moisture content for current day (i) [L^3/L^3], and
θ_{wp} = volumetric wilting-point moisture content [L^3/L^3].

The soil-moisture storage capacity is equal to the root depth multiplied by the difference between the volumetric field-capacity moisture content and the volumetric wilting-point moisture content:

$$S_m = D \times (\theta_{fc} - \theta_{wp}),$$

where: S_m = soil-moisture storage capacity [L], and
θ_{fc} = volumetric field-capacity moisture content [L^3/L^3].

Method 1

Method 1 assumes that any interim soil moisture greater than the soil-moisture storage capacity will be recharge, and evapotranspiration is then subtracted from the remaining soil-moisture storage. Recharge for the current interval, i, is determined as:

$$Q_i = X_i - S_m \quad \text{for } X_i > S_m,$$
$$Q_i = 0 \quad \text{for } X_i \leq S_m,$$

where: Q_i = depth of recharge for the current day, [L].

Evapotranspiration is estimated on the basis of the VH and TM models. Using the VH model, evapotranspiration and soil-moisture storage at the end of the day are estimated as:

for $X_i - Q_i \geq PE_i$,

$$E_i = PE_i \text{ and}$$
$$S_i = X_i - Q_i - PE_i;$$

for $X_i - Q_i < PE_i$,

$$E_i = X_i - Q_i \text{ and}$$
$$S_i = 0,$$

where: E_i = depth of water lost to evapotranspiration during the current day [L],

PE_i = potential evapotranspiration for current day [L], and

S_i = soil-moisture storage at the end of the day [L].

Using the TM model, evapotranspiration and soil-moisture storage at the end of the day are estimated as:

$$E_i = (X_i - Q_i)[1 - \exp(-PE_i/S_m)] \text{ and}$$
$$S_i = X_i - Q_i - E_i .$$

The equation for E_i associated with the TM model is derived by recognizing that (1) the instantaneous rate of evapotranspiration, E, is linearly related to the instantaneous soil-moisture storage, S, by the relation $E=(PE_i/S_m)S$, (2) $E=-dS/dt$, and (3) E_i also is equal to the difference between available soil moisture after accounting for recharge ($X_i - Q_i$) and S.

Method 2

In method 2, evapotranspiration is first subtracted from the interim soil-moisture storage, and any soil moisture remaining above the soil-moisture storage capacity is assumed to be recharge. Using the VH model, evapotranspiration is estimated as:

$$E_i = PE_i \text{ for } X_i \geq PE_i \text{ and}$$
$$E_i = X_i \quad \text{for } X_i < PE_i.$$

Using the TM model, evapotranspiration is estimated as:

$$E_i = PE_i t_i + S_m\{1 - \exp[-PE_i(1 - t_i)/S_m]\} \text{ for } X_i > S_m ,\ t_i < 1,$$
$$E_i = PE_i \quad \text{for } X_i > S_m ,\ t_i \geq 1,$$
$$E_i = X_i[1 - \exp(-PE_i/S_m)] \quad \text{for } X_i \leq S_m, \text{ and}$$
$$t_i = (X_i - S_m)/PE_i .$$

Recharge and soil-moisture storage at the end of the day are determined as:

for $X_i - E_i > S_m$,

$$Q_i = X_i - E_i - S_m$$
$$S_i = S_m ;$$

for $X_i - E_i \leq S_m$,

$$Q_i = 0$$
$$S_i = X_i - E_i.$$

Monthly Water Budgets

Monthly water budgets for methods 1 and 2 were computed using the same procedure as described for the daily budgets. However, instead of computing the water budgets using daily rainfall, runoff, and potential evapotranspiration, the daily values were aggregated into monthly totals, and these monthly values were used in the water-budget equations described above, except a monthly computation interval was used.

Data

For the water budgets, pan evaporation was used as an estimate of potential evapotranspiration. Daily rainfall and daily pan-evaporation data (National Climatic Data Center, 1995) from three sites in Hawai‘i (fig. 2) were used to compare recharge estimates from the daily and monthly water budgets. The Hilo Airport site (National Weather Service Station 1492) is located on the wet, windward (northeastern) side of the Island of Hawai‘i, the Honolulu Observatory (Station 1918) is located on the dry, leeward (southwestern) side of O‘ahu, and the Līhu‘e Airport (Station 5580) is located on the eastern side of Kaua‘i. For each site, the longest available period of record (as of 2000) without missing rainfall data was selected for analysis.

During the periods of record used, average annual rainfall ranged from a low of 20 in. at Honolulu Observatory (January 1982 to December 1993) to a high of 123 in. at Hilo Airport (November 1961 to August 1965). Average annual rainfall at the Līhu‘e Airport was 40 in. (June 1974 to June 1993). Average annual pan-evaporation rates were 66, 84, and 101 in. at Hilo Airport, Honolulu Observatory, and Līhu‘e Airport, respectively. The monthly mean pan-evaporation value was used to estimate pan evaporation on days with missing data.

Ranges of soil-moisture storage capacity values and runoff-to-rainfall ratios were used to test how these factors affect the recharge estimates. Soil-moisture storage capacity values ranging from 0.1 to 20 in. were used with two constant runoff-to-rainfall ratios of 0.05 and 0.5. Use of constant runoff-to-rainfall ratios resulted in consistent runoff estimates among the different water-budget models and isolated the water-budget method, rather than the runoff model, as the main factor affecting the recharge estimate.

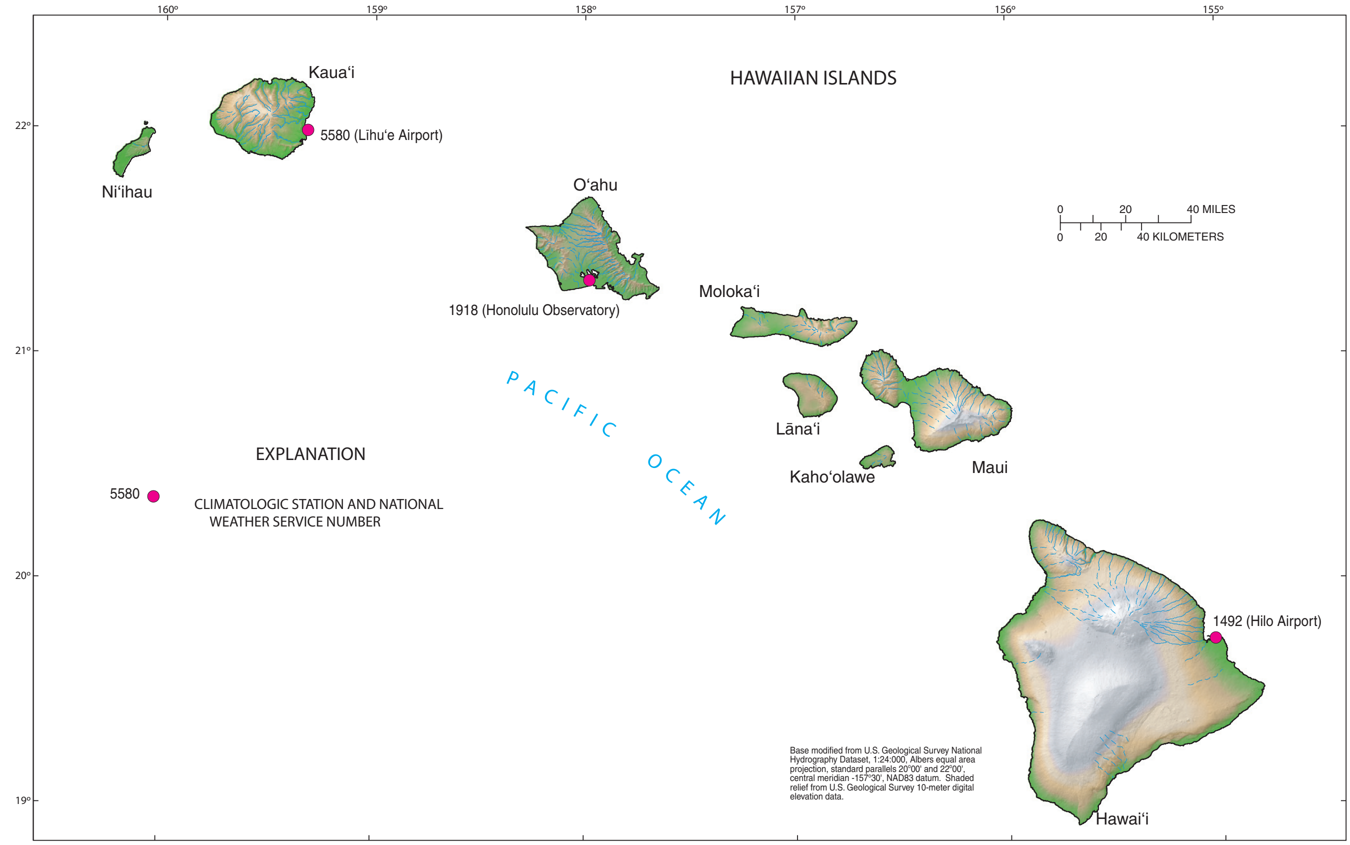

Figure 2. Selected climatologic stations, Hawai‘i.

Results and Discussion

Recharge was estimated by methods 1 and 2 using both daily and monthly water budgets with the VH and TM evapotranspiration models. Of the three sites, estimated average annual recharge was greatest for the Hilo Airport site and least for the Honolulu Observatory site (figs. 3–5). Recharge estimates decrease with increasing values of soil-moisture storage capacity and increasing runoff-to-rainfall ratios. For a given site, the difference between average annual recharge estimates from daily and monthly water budgets decreases with increasing soil-moisture storage capacity values.

Effect of Accounting Method

Over a single computation time interval (one day or one month), recharge estimated using accounting method 1 will be greater than or equal to that estimated using method 2, all other factors being equal (including soil-moisture storage at the beginning of the interval). If soil-moisture storage at the beginning of an interval differs for methods 1 and 2, then it is possible for estimated recharge using method 2 to exceed that using method 1 for the interval. On average, however, recharge estimated using method 1 is greater than or equal to recharge estimated using method 2 for a given computation-interval length and evapotranspiration model (figs. 3–5).

The difference between average annual recharge estimated from water budgets using methods 1 and 2 is greatest for small values of soil-moisture storage capacity, S_m (figs. 3–5). For example, for the Hilo Airport site, average annual recharge estimated with monthly water budgets using methods 1 and 2 differed by more than 40 in. for a soil-moisture storage capacity of 0.1 in., but it differed by less than 10 in. for a soil-moisture storage capacity of 20 in. (fig. 3).

Over a single computation interval, evapotranspiration estimated using method 1 cannot exceed the soil-moisture storage capacity. This can result in an artificial limiting of evapotranspiration, especially for small soil-moisture storage capacity values. For example, if the soil-moisture storage capacity is 0.1 in., then the estimated annual evapotranspiration from a monthly water budget cannot exceed 1.2 in. (= 12 months × 0.1 in.). Because annual rainfall and potential evapotranspiration greatly exceed 1.2 in. for most settings, use of method 1 can artificially limit estimated evapotranspiration and, thus, overestimate recharge. This artificial limiting of evapotranspiration associated with method 1 becomes less significant with decreasing computation intervals and increasing values of soil-moisture storage capacity. Over a single computation interval, evapotranspiration estimated using the VH model and method 2 will exceed the soil-moisture storage capacity if interim soil-moisture storage, X_i, and potential evapotranspiration for the interval, PE_i, both exceed the soil-moisture storage capacity. Over a single computation interval, evapotranspiration estimated using the TM model and method 2 will exceed the soil-moisture storage capacity if (1) X_i and PE_i both exceed the soil-moisture storage capacity and (2) X_i minus the soil-moisture storage capacity is greater than or equal to PE_i. Over a single computation interval, evapotranspiration estimated using the TM model and method 2 also will exceed the soil-moisture storage capacity if (1) X_i and the quantity $(PE_i t_i + S_m\{1-\exp[-PE_i(1-t_i)/S_m]\})$ both exceed the soil-moisture storage capacity and (2) X_i minus the soil-moisture storage capacity is less than PE_i. These conditions most commonly are met for small values of soil-moisture storage capacity. Thus, for small soil-moisture storage capacity values, recharge estimated using method 1 may greatly exceed recharge estimated using method 2. For large soil-moisture storage capacity values, recharge estimated using methods 1 and 2 are in closer agreement, because soil-moisture storage capacity is less likely to limit evapotranspiration with method 1.

Effect of Computation Interval

The difference in recharge estimates between accounting methods is more pronounced with monthly water budgets than with daily water budgets (figs. 3–5), which indicates that selecting an appropriate accounting method for a monthly

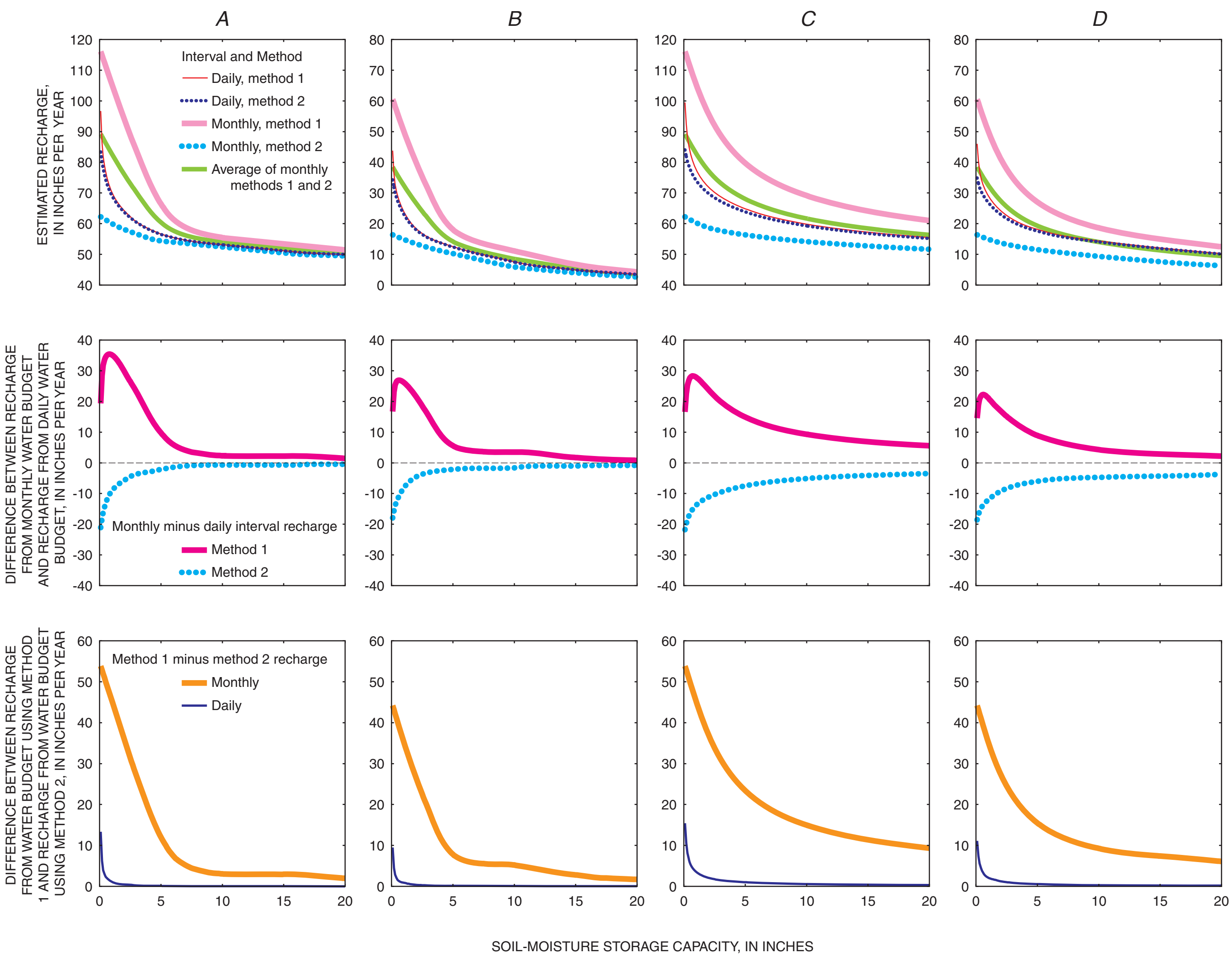

Figure 3. Variations in estimated average recharge as a function of soil-moisture storage capacity using rainfall and pan-evaporation data (November 1961 to August 1965) from Hilo Airport (National Weather Service Station 1492), Island of Hawai‘i, Hawai‘i. Water-budget method 1 assumes recharge occurs before evapotranspiration, and method 2 assumes evapotranspiration occurs before recharge. Potential evapotranspiration is assumed to be equal to pan evaporation. *A*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.05, *B*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.5, *C*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.05, *D*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.5.

water budget is critical for accurate recharge estimates. The choice of accounting method is less critical for daily water budgets, particularly for soil-moisture storage capacity values greater than about 1 in.

Over a single month, recharge estimates from monthly water budgets using methods 1 and 2 will bracket the monthly recharge estimates from daily water budgets using the two methods, all other factors being equal (including soil-moisture storage at the beginning of the month). Use of method 1 with monthly data results in high recharge estimates, whereas method 2 results in low recharge estimates. On a short-term basis, recharge for a particular month estimated from a daily budget may fall outside the range of estimates from the monthly budgets if soil-moisture storage at the beginning of the month varies among the different water budgets. In general, however, for a given soil-moisture storage capacity, runoff-to-rainfall ratio, and evapotranspiration model, long-term average recharge estimates from the monthly water budgets using methods 1 and 2 bracket the recharge estimates from the daily water budgets.

The difference between estimates of average annual recharge using monthly and daily data with a common accounting method is greater for small values of soil-moisture storage capacity. Results using data from a given site

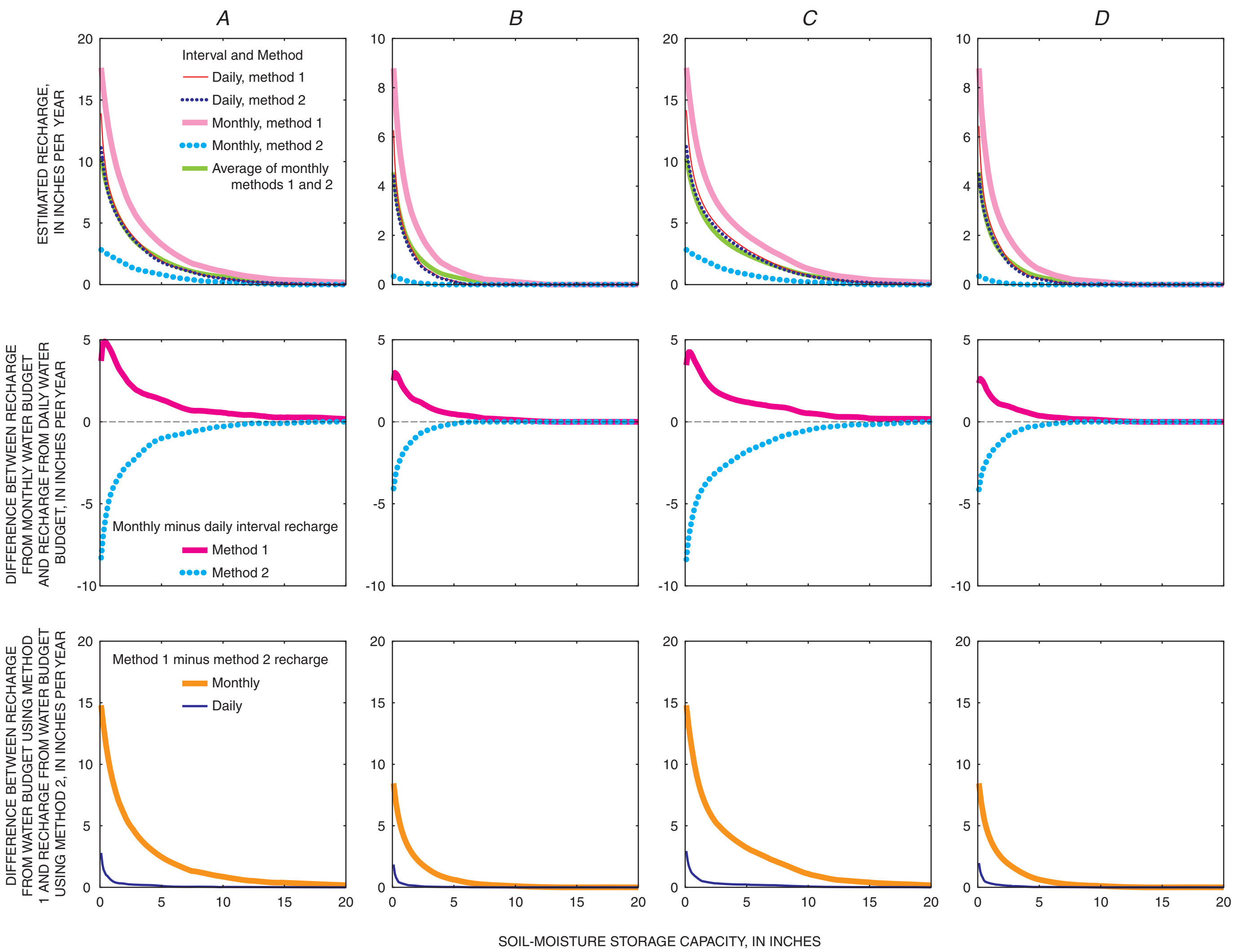

Figure 4. Variations in estimated average recharge as a function of soil-moisture storage capacity using rainfall and pan-evaporation data (January 1982 to December 1993) from Honolulu Observatory (National Weather Service Station 1918), Island of O‘ahu, Hawai‘i. Water-budget method 1 assumes recharge occurs before evapotranspiration, and method 2 assumes evapotranspiration occurs before recharge. Potential evapotranspiration is assumed to be equal to pan evaporation. *A*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.05, *B*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.5, *C*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.05, *D*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.5.

generally indicate that (1) the maximum difference between average annual recharge estimates from monthly and daily water budgets using a common accounting method is at or near the lowest soil-moisture storage capacity value tested (0.1 in.) and (2) the minimum difference is at the highest soil-moisture storage capacity value tested (20 in.) (figs. 3–5).

Effect of Evapotranspiration Model

For a single time interval, the VH model produces evapotranspiration estimates that are greater than or equal to estimates from the TM model. Also, for a single time interval, the VH model produces recharge estimates that are less than or equal to estimates from the TM model. Long-term average recharge estimated using the TM model exceeds recharge estimated using the VH model for a common computation interval, soil-moisture storage capacity, and runoff-to-rainfall ratio. The difference in recharge estimates from the TM and VH models is most pronounced using data from the wettest site (Hilo Airport) (figs. 3–5). For a common computation interval and soil-moisture storage capacity, the difference in recharge estimates from the TM and VH models at the Honolulu Observatory and Līhu‘e Airport sites is greater for the larger runoff-to-rainfall ratio tested (0.5), which is not always the case at the Hilo Airport.

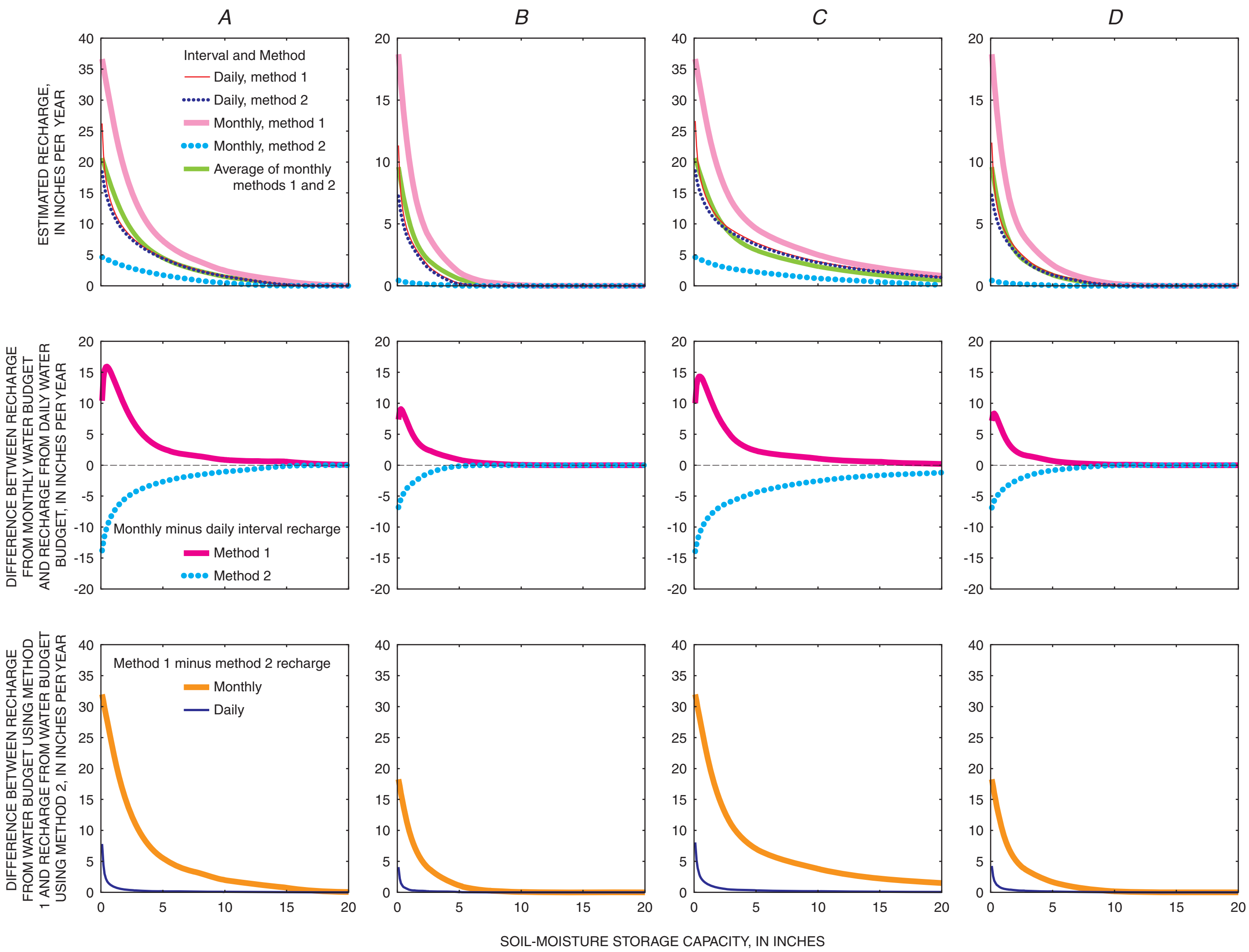

Figure 5. Variations in estimated average recharge as a function of soil-moisture storage capacity using rainfall and pan-evaporation data (June 1974 to June 1993) from Līhu‘e Airport (National Weather Service Station 5580), Island of Kaua‘i, Hawai‘i. Water-budget method 1 assumes recharge occurs before evapotranspiration, and method 2 assumes evapotranspiration occurs before recharge. Potential evapotranspiration is assumed to be equal to pan evaporation. *A*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.05, *B*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.5, *C*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.05, *D*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.5.

Selection of Appropriate Accounting Method

The order in which recharge and evapotranspiration are assigned has less of an effect on the recharge estimate in daily water budgets than it does in monthly water budgets. Thus, whenever monthly water budgets are used, it is important to recognize the conditions for which each accounting method is most appropriate. Because daily water budgets can account for intramonth variability in rainfall, evapotranspiration, and soil-moisture conditions, it is reasonable to expect a more realistic recharge estimate from a daily water budget than from a monthly water budget. By treating estimated recharge values from the daily water budgets as standards for comparison, the reliability of estimated recharge from monthly water budgets can be assessed.

At the smallest soil-moisture storage capacity value tested (0.1 in.), the absolute difference between recharge estimated from monthly and daily water budgets (with a common evapotranspiration model) using method 1 is less than the absolute difference using method 2, except at the Līhuʻe Airport for a runoff-to-rainfall ratio of 0.5. For soil-moisture storage capacity values greater than 0.1 in., results using data from the wet site (Hilo Airport) for a runoff-to-rainfall ratio of 0.05 indicate that the absolute difference between recharge estimated from monthly and daily water budgets using method 2 is less than the difference using method 1 (fig. 3*A* and *C*). Results from the Hilo Airport also indicate that, for conditions that produce less frequent recharge (runoff-to-rainfall ratio of 0.5), the absolute difference between recharge estimated from monthly and daily water budgets using method 2 is less than the difference using method 1 for soil-moisture storage capacity values greater than 0.1 in. and less than about 19 in. (VH model) or 9 in. (TM model). Thus, results from the Hilo Airport indicate that where soil-moisture storage capacity values are greater than 0.1 in. and less than 9 in., the absolute difference between recharge estimated from monthly and daily water budgets using method 2 is less than the difference using method 1 for the runoff-to-rainfall ratios tested.

Monthly water-budget results using data from the dry site (Honolulu Observatory), where recharge occurs infrequently, indicate that the absolute difference between recharge estimated from monthly and daily water budgets (with a common evapotranspiration model) using method 1 is slightly less than the difference using method 2 for low soil-moisture storage capacity values (fig. 4). At the Honolulu Observatory and for a runoff-to-rainfall ratio of 0.05, the absolute difference between recharge estimated from monthly and daily water budgets using method 1 is slightly less than the difference using method 2 for soil-moisture storage capacity values less than about 4 in. (VH model) or 10 in. (TM model). Results from the Honolulu Observatory also indicate that, for conditions that produce less frequent recharge (runoff-to-rainfall ratio of 0.5), the absolute difference between recharge estimated from monthly and daily water budgets using method 1 is slightly less than the difference using method 2 for soil-moisture storage capacity values less than about 1 in. (VH model) or 2 in. (TM model). For soil-moisture storage capacity values greater than about 4 in., the magnitude of the difference between average recharge estimated from monthly and daily water budgets using a common accounting method is less than 1 in/yr, regardless of evapotranspiration model or runoff-to-rainfall ratio tested.

Annual rainfall at the Līhuʻe Airport is greater than rainfall at the Honolulu Observatory but less than rainfall at the Hilo Airport. Thus, water-budget results using data from

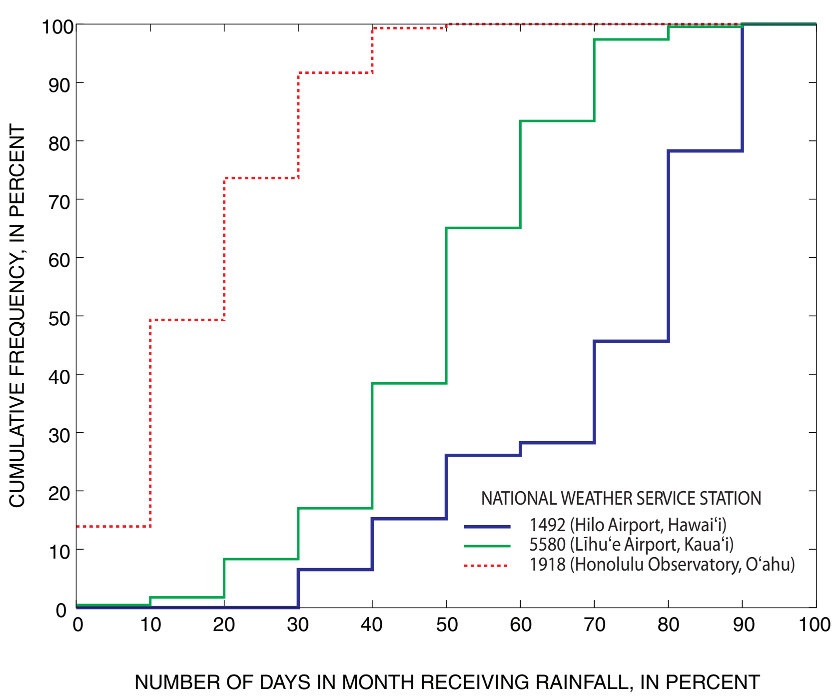

Figure 6. Cumulative frequency distribution of rainy days in a month at selected sites in Hawaiʻi. Periods of record: Hilo Airport, Hawaiʻi (National Weather Service Station 1492, State key 87) November 1961 to August 1965; Līhuʻe Airport, Kauaʻi (National Weather Service Station 5580, State key 1020.1) June 1974 to June 1993; and Honolulu Observatory, Oʻahu (National Weather Service Station 1918, State key 702.2) January 1982 to December 1993.

the Līhu‘e Airport are expected to have some of the characteristics from each of the other sites. Results using data from the Līhu‘e Airport generally indicate that either method 1 or method 2 may produce a smaller absolute difference between recharge estimated from monthly and daily water budgets depending on the evapotranspiration model, amount of runoff, and soil-moisture storage capacity.

Hilo Airport receives considerably more rainy days in a month than Honolulu Observatory (fig. 6). For such sites with frequent rainfall throughout each month, a monthly water budget using method 2 generally would be preferred over one using method 1. For sites with infrequent, episodic rainfall, a monthly water budget using method 1 may be preferred if the runoff-to-rainfall ratio and soil-moisture storage capacity are small. To verify this, monthly rainfall data from Hilo Airport were disaggregated into two extreme daily sequences to more readily assess the effects of rainfall distribution on water-budget recharge estimates. At one extreme, all of the monthly rainfall was assumed to occur on the first day of the month. At the other extreme, the monthly rainfall was uniformly distributed throughout the month. The daily pan-evaporation data were not adjusted.

For the case in which all of the rainfall in a month consistently falls on the first day of the month, (1) average

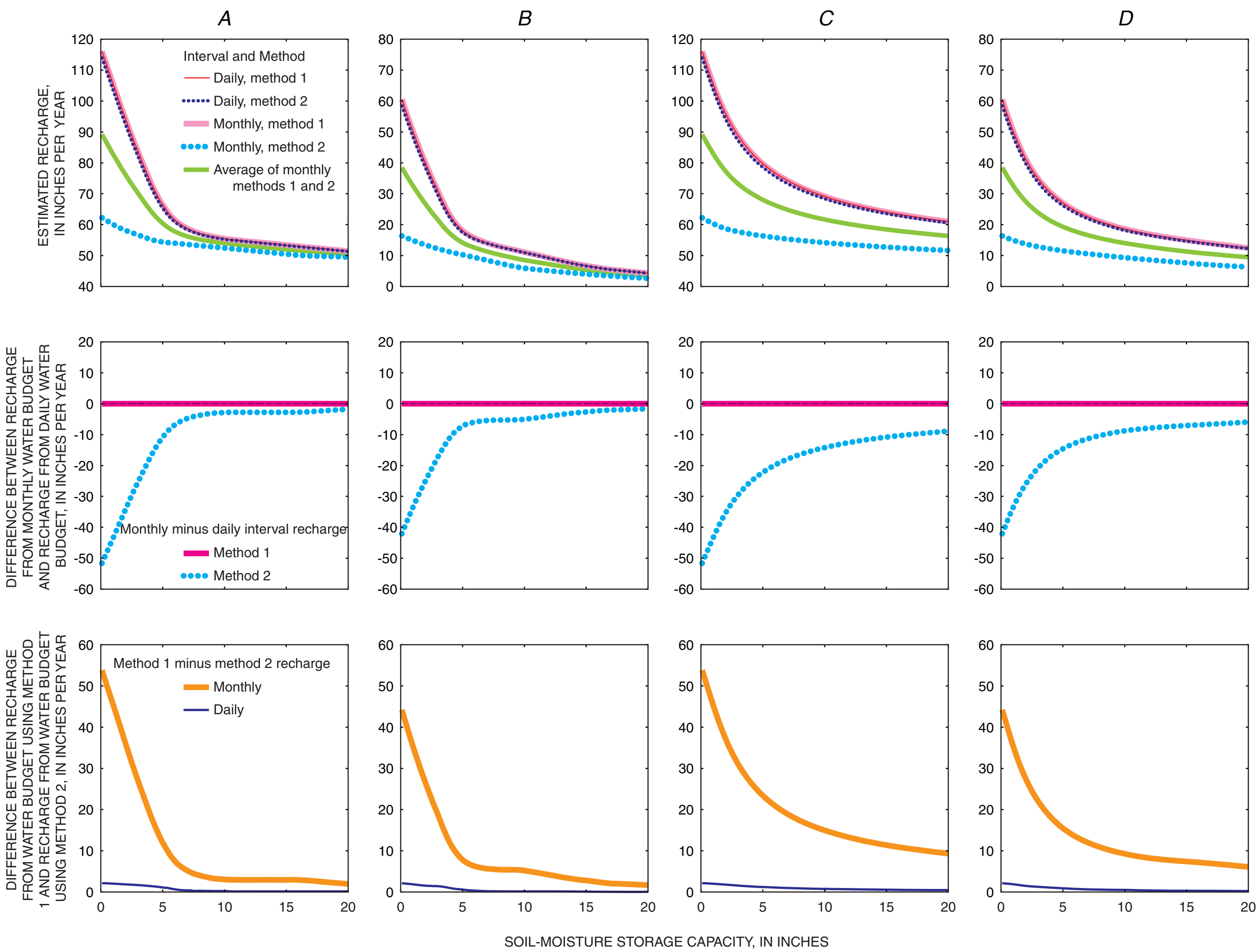

Figure 7. Variations in estimated average recharge as a function of soil-moisture storage capacity using synthetic daily rainfall distributed as one storm on the first day of the month (all of the rainfall in a month distributed to the first day of the month) and pan-evaporation data (November 1961 to August 1965) from Hilo Airport (National Weather Service Station 1492), Island of Hawai‘i, Hawai‘i. Water-budget method 1 assumes recharge occurs before evapotranspiration, and method 2 assumes evapotranspiration occurs before recharge. Potential evapotranspiration is assumed to be equal to pan evaporation. *A*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.05, *B*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.5, *C*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.05, *D*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.5.

recharge estimated from monthly and daily water budgets using method 1 are nearly identical, regardless of whether the VH or TM model is used, and (2) average recharge estimated from a monthly water budget using method 2 is consistently lower than recharge from daily water budgets (fig. 7). For the other extreme case, in which rainfall in a month occurs at a uniform rate on each day, (1) monthly and daily water budgets using method 2 produce similar recharge estimates and (2) the difference between recharge estimated from monthly and daily water budgets using method 1 is consistently greater than that derived with method 2, regardless of whether the VH or TM model is used (fig. 8). In general, results indicate that method 1 is most appropriate for monthly water budgets in areas where rainfall occurs infrequently, whereas method 2 is most appropriate for monthly water budgets where rainfall occurs uniformly throughout the month.

Given that long-term recharge estimates from monthly water budgets using methods 1 and 2 bracket the recharge estimates from daily water budgets, the average of the recharge values from the two monthly water budgets may better approximate recharge from daily water budgets (figs. 3–5). However, in some cases, recharge from a monthly water budget using just one of the methods may better approximate recharge from daily water budgets than the

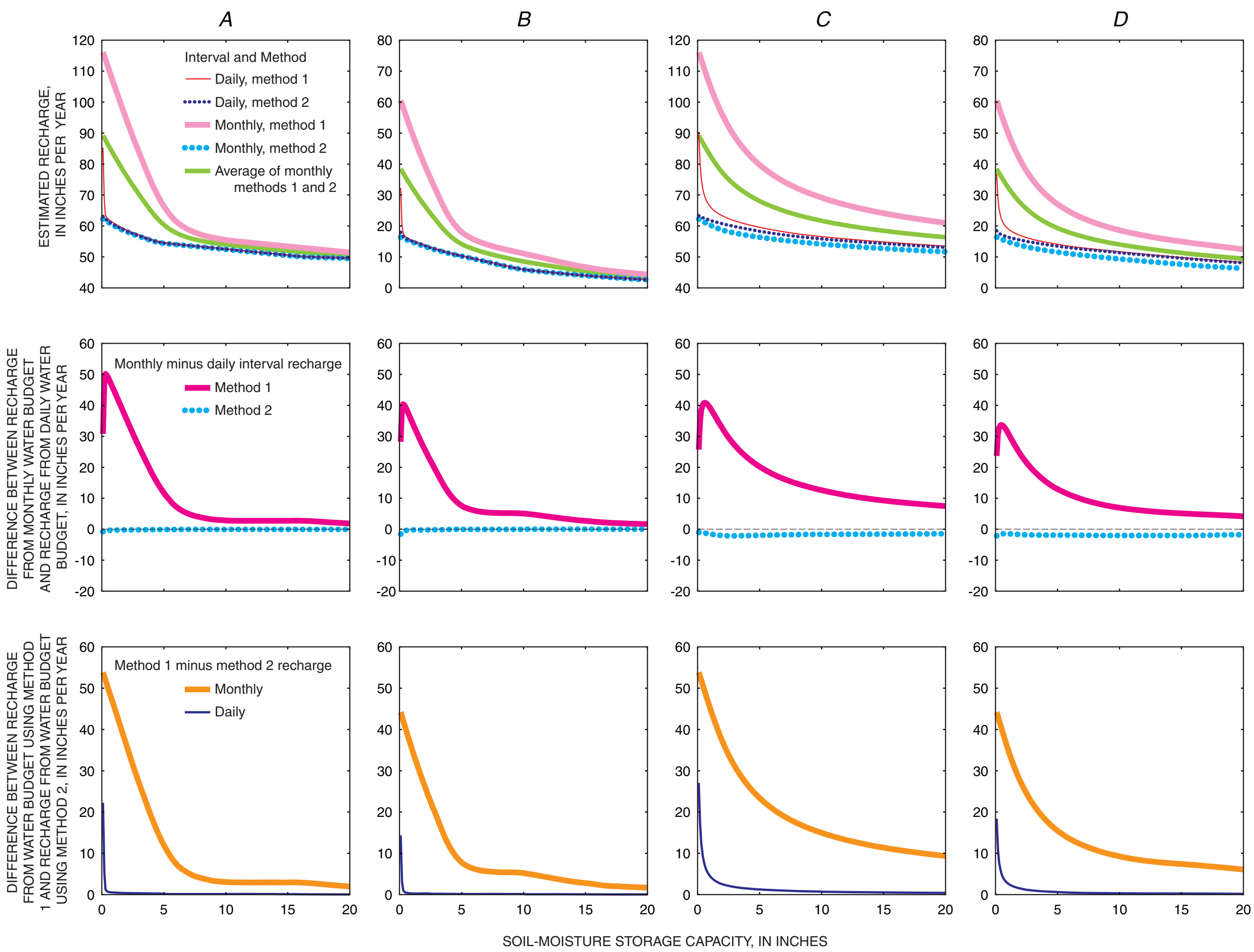

Figure 8. Variations in estimated average recharge as a function of soil-moisture storage capacity using synthetic daily rainfall distributed uniformly throughout the month and pan-evaporation data (November 1961 to August 1965) from Hilo Airport (National Weather Service Station 1492), Island of Hawai‘i, Hawai‘i. Water-budget method 1 assumes recharge occurs before evapotranspiration, and method 2 assumes evapotranspiration occurs before recharge. Potential evapotranspiration is assumed to be equal to pan evaporation. *A*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.05, *B*, Evapotranspiration model of Veihmeyer and Hendrickson (1955) and runoff-to-rainfall ratio of 0.5, *C*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.05, *D*, Evapotranspiration model of Thornthwaite and Mather (1955) and runoff-to-rainfall ratio of 0.5.

average of the recharge values from the two monthly water budgets (figs. 7–8). Thus, use of the average of the recharge values from the two monthly water budgets (using methods 1 and 2) may contain uncertainty that can be avoided with use of a daily water budget.

Summary and Conclusions

Most threshold-type water-budget models account for the loss of water by evapotranspiration before accounting for recharge. For water budgets computed using short time intervals (daily), the accounting order is less critical than it is for water budgets computed using longer time intervals (monthly). In a monthly water budget of the plant-soil system, the two accounting methods can produce significantly different recharge estimates. Relative to daily water budgets, monthly water budgets that account for recharge before evapotranspiration (method 1) provide higher estimates of recharge and lower estimates of evapotranspiration, whereas monthly water budgets that account for evapotranspiration before recharge (method 2) provide lower estimates of recharge and higher estimates of evapotranspiration. The difference in recharge estimates from daily and monthly water budgets is most pronounced for areas with small soil-moisture storage capacity values. The difference between methods 1 and 2 is smaller using a daily water budget than it is using a monthly water budget. Thus, the choice of accounting method is less significant for a daily computation interval than for a monthly computation interval. In general, uncertainty in recharge estimates is least for water budgets computed using the shortest computation interval that the data allow and that is consistent with the physical processes being represented. If the data only allow for long (weekly or monthly) computation intervals, then selecting the appropriate accounting order for the study area may be critical. In general, results indicate that method 1 is most appropriate for monthly water budgets in areas where rainfall occurs infrequently, whereas method 2 is most appropriate for monthly water budgets where rainfall occurs uniformly throughout the month. The average of the recharge values from the two monthly water budgets (using methods 1 and 2) may better approximate recharge from daily water budgets, although the average value contains uncertainty that can be avoided with use of a daily water budget.

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