STATE OF HAWAII
DEPARTMENT OF LAND AND NATURAL RESOURCES
COMMISSION ON WATER RESOURCE MANAGEMENT
P.O. BOX 621
HONOLULU, HAWAII 96809

STAFF SUBMITTAL

for the meeting of the
COMMISSION ON WATER RESOURCE MANAGEMENT

March 28, 2012
Honolulu, Oahu

Request to Authorize the Chairperson to
Enter into an Agreement with U.S. Geological Survey to
Update Estimated Groundwater Recharge for Central and West Maui, Hawaii

SUMMARY OF REQUEST:

The Commission on Water Resource Management (Commission) proposes to authorize the Chairperson to enter into an agreement with the U.S. Geological Survey (USGS) to update the estimated ground water recharge for Central and West Maui.

BACKGROUND:

The State Water Code requires the Commission to establish hydrologic units and their sustainable yields in the Water Resource Protection Plan component of the Hawaii Water Plan to ensure the long-term protection and responsible management of Hawaii's ground water resources. Sustainable yield is defined as "the maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission." Haw. Rev. Stat. §174C-3

In setting sustainable yields, the Commission must first assess the quantity of ground water recharging the aquifer. Ground water recharge is the replenishment of fresh ground water. It depends on many natural and human-related factors. Recharge changes over time in response to climatological trends and land use.

The initial 1990 Water Resource Protection Plan (WRPP), adopted by the Commission, established ground water hydrologic units and their sustainable yields. However, the sustainable yield was based on best available information at the time. As new and better data becomes

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available, the Commission must periodically review and refine these estimates of sustainable yield. Haw. Rev. Stat. §174C-31(i)(2). In 2008, the Commission updated the WRPP, and adjusted sustainable yield estimates based on a reapplication of the Robust Analytical Model (RAM) and the best available recharge estimates at that time.

Hydrological data collection and analysis indicate that Hawaii's climate is changing. USGS reviewed daily mean discharge data at seven of its long-term-trend stations in Hawaii from 1913 to 2002. The study found statistically significant downward trends in annual base flow during the study period at all seven stations. This finding corresponds to independent research on rainfall by the University of Hawaii that has also documented downward trends in rainfall during this period. Recent studies also show that while overall rainfall totals have *declined*, rainfall event intensities and air temperatures have *increased*.

While further research is needed to determine whether the downward trends in rainfall and streamflow will continue or are part of a long-term cycle, any changes in rainfall, streamflow, and air temperature, will have significant impacts on ground water recharge and sustainable yields. It is imperative that the Commission review and refine recharge and sustainable yield estimates as ground water accounts for over 90% of our State's drinking water supplies. The Commission's 2008 Water Resource Protection Plan identified improvement of recharge estimates as a priority implementation action.

The most recent recharge estimates for West and Central Maui were done in 2007 as part of a water-budget study by the USGS. The study relied on hard-copy rainfall data maps and a base period of 1916 to 1983. That data is now more than 30 years old. Since then, not only has the USGS updated their methodology for estimating ground water recharge, but the University of Hawaii also released digital rainfall datasets for Hawaii. The new rainfall datasets cover a base period from 1978 to 2007 and provide the most current and scientific estimates of rainfall in Hawaii.

USGS will use the 2011 Rainfall Atlas of Hawaii to update the ground water recharge for Central and West Maui. The USGS will also use a refined water-budget model that introduces improved methods of estimating fog interception, forest canopy interception, and differentiates native from alien forests.

The Commission will use the results of this study in a separate exercise to refine its sustainable yield estimates of the areas investigated.

The proposed study will also coincide with the County of Maui Department of Water Supply's (Maui DWS) work with USGS to develop recharge estimates for parts of Northeast Maui. The results will be published together with the Commission's effort in a single USGS publication.

SCOPE OF SERVICES:

The proposed work involves a 14 month study to reassess the spatial distribution of ground water recharge for Central and West Maui (study area shown in Exhibit 1). The study will include the modification of an existing daily water-budget model and the processing of existing climatic, land use, land cover, soil, and streamflow data, including the new rainfall datasets from the updated Rainfall Atlas of Hawaii. Daily recharge estimates will be aggregated for each month of the year.

Future land use and drought scenarios will also be examined in the study. Future land use scenarios will be estimated using municipal zoning and planning documents from the County of Maui. Drought scenarios will be simulated using a period of extremely low rainfall selected from the historical record. A detailed explanation of the water-budget calculation methodology is included in the attached USGS proposal (Exhibit 2).

The results of the study will be made available to the public in a USGS Scientific Investigations Report. The report will include ground water recharge estimates for parts of Northeast Maui that area being developed in cooperation with the Maui DWS.

The total cost of this study will be $60,000. The Commission's share will be $30,000. The USGS will provide the remaining $30,000.

FUNDING:

Staff requests the Commission approve $30,000 to complete the study. Funding will come from the Commission's general fund, special fund, or a combination of both, depending upon available funding.

ENVIRONMENTAL REVIEW (CHAPTER 343, HRS)

HRS Chapter 343 does not apply because this is a planning study. Administrative Rule 11-200-5(d) provides:

"*For agency actions, chapter 343, HRS, exempts from applicability any feasibility or planning study for possible future programs which the agency has not approved, adopted, or funded. Nevertheless, if an agency is studying the feasibility of a proposal, it shall consider environmental factors and available alternatives and disclose these in any future assessment or subsequent statement. If, however, the planning and feasibility studies involve testing or other actions which may have significant impact on the environment, then an environmental assessment shall be prepared.*"

The proposed study is a planning study, which does not involve testing or other actions that will impact the environment. Therefore, HRS Chapter 343 is not applicable to this agency action.

RECOMMENDATION

Staff recommends that the Commission:

1. Authorize the Chairperson to enter into an agreement between the Commission and the U.S. Geological Survey to update the estimated ground water recharge distribution estimates for Central and West Maui and to approve funding not to exceed $30,000 to complete the study.

2. Authorize the Chairperson to amend or modify the joint funding agreement provided that such amendment or modification does not include any additional funding.

The terms of this agreement will be subject to the approval of the Chairperson and the Department's Deputy Attorney General.

Respectfully submitted,

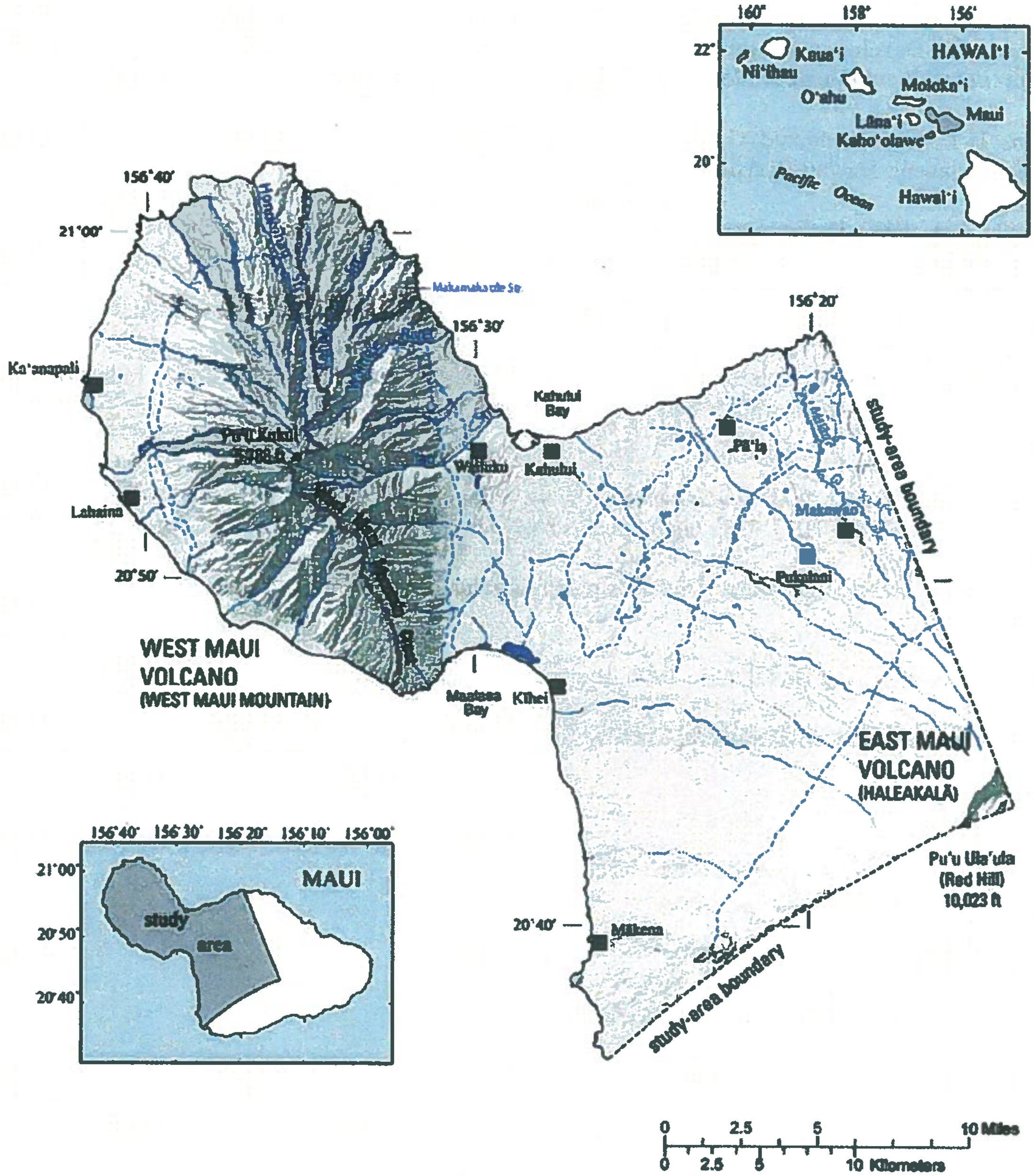
WILLIAM M. TAM
Deputy Director

Exhibits: (1) Map of the Central and West Maui study area
(2) USGS proposal for the reassessment of groundwater recharge for the Central and West Maui

APPROVED FOR SUBMITTAL:

WILLIAM J. AILA, JR.
Chairperson

Exhibit 1



HAWAI'I
Kaua'i
Ni'ihau
O'ahu
Moloka'i
Lāna'i
Maui
Kaho'olawe
Pacific Ocean
Hawai'i
Ka'anapali
Lahaina
Wailuku
Kahului
Kahului Bay
Pā'ia
Makawao
Pukalani
study-area boundary
WEST MAUI VOLCANO
(WEST MAUI MOUNTAIN)
Maalaea Bay
Kīhei
EAST MAUI VOLCANO
(HALEAKALĀ)
Pu'u Ula'ula
(Red Hill)
10,023 ft
Mākena
MAUI
study area
10 Miles
10 Kilometers

EXHIBIT 2

Reassessment of Groundwater Recharge for Central and West Maui, Hawaii

U.S. Geological Survey
Pacific Islands Water Science Center
Proposal, February 2012

SUMMARY

Recently published rainfall datasets for the Hawaiian Islands (Giambelluca and others, 2011) are more current and detailed than the ones used in the latest water-budget study of central and west Maui (Engott and Vana, 2007). Estimates of groundwater recharge could be substantially improved for all of central and west Maui (fig. 1) using these new rainfall datasets in combination with the refined water-budget model that was used for the update of recharge estimates in the Lahaina area of west Maui (Gingerich and Engott, 2012). The refined water-budget model for the Lahaina area introduced improved methods of estimating fog interception, the inclusion of forest canopy interception, and the differentiation of native and alien forests. Improved recharge estimates are recommended in the Water Resource Protection Plan (WRPP) (State of Hawaii, 2008). The State of Hawaii Commission on Water Resource Management (CWRM) periodically reassesses the sustainable yields of aquifer systems as updated recharge values and related information become available.

The newer rainfall datasets (Giambelluca and others, 2011) have increased spatial and temporal resolution. The newer datasets do not require digitizing and interpolation as process steps for creating water-budget model input. The base period from which normals were calculated for the newer rainfall datasets is 1978 to 2007, whereas the older datasets are 1916 to 1983. The newer datasets also include estimates of uncertainty, which are not included in the older datasets.

The groundwater demand for domestic water supply on Maui is increasing and likely will continue to increase in the future. Demand for water provided by the County of Maui Department of Water Supply (MDWS) in the Wailuku area is expected to increase from about 22 Mgal/d in 2005 to 34 Mgal/d in 2030 (Haiku Design and Analysis, 2009a). Demand from the MDWS in the Lahaina area is estimated to increase from about 5.1 Mgal/d in 2003 to 7 Mgal/d in 2030 (Haiku Design and Analysis, 2004).

The objective of this study is to update estimates of the spatial distribution of groundwater recharge in central and west Maui. Daily recharge estimates for current average climatic conditions and land use will be aggregated to determine an average recharge rate for current conditions. Several other scenarios will also be examined, including possible future land use and drought. The study will include the modification of an existing daily water-budget model and the processing of existing climatic, land use, land cover, soil, and streamflow data, including the new rainfall datasets from Giambelluca and others (2011), necessary to execute the water-budget model. Results of the study will be made available to the public in a USGS Scientific Investigations Report posted on the Pacific Islands Water Science Center website. It is anticipated that the study will take 14 months from the time work is commenced until the report is published. The report will include groundwater recharge estimates for parts of Northeast Maui that are being developed in cooperation with the County of Maui Department of Water Supply. The study cost is estimated to be $60,000 which takes advantage of cost savings by preparing one report for both studies.

PROBLEM

Recently published rainfall datasets for the Hawaiian Islands (Giambelluca and others, 2011) are more current and detailed than the ones used in the latest water-budget study of central and west Maui (Engott and Vana, 2007). Estimates of groundwater recharge could be substantially improved for all of central and west Maui (fig. 1) using these new rainfall datasets in combination with the refined water-budget model that was used for the update of recharge estimates in the Lahaina area of west Maui (Gingerich and Engott, 2012). The refined water-budget model for the Lahaina area introduced improved methods of estimating fog interception, the inclusion of forest canopy interception, and the differentiation of native and alien forests. Improved recharge estimates are recommended in the Water Resource Protection Plan (WRPP) (State of Hawaii, 2008). The State of Hawaii Commission on Water Resource Management (CWRM) periodically reassesses the sustainable yields of aquifer systems as updated recharge values and related information become available.

The newer rainfall datasets (Giambelluca and others, 2011) have increased spatial and temporal resolution. The newer datasets do not require digitizing and interpolation, which introduce unquantifiable uncertainty, as process steps for creating water-budget model input. The newer datasets consist of 8.1-arcsecond (770 by 820-ft) digital grids, whereas the older datasets (Giambelluca and others, 1986) used for the central and west Maui water-budget study (Engott and Vana, 2007) consist of hardcopy isohyet maps. The base period from which normals were calculated for the newer rainfall datasets is 1978 to 2007, whereas the older datasets are 1916 to 1983. The newer datasets also include estimates of uncertainty, which are not included in the older datasets.

The groundwater demand for domestic water supply on Maui is increasing and likely will continue to increase in the future. The resident population of the island has increased from

38,691 in 1970 to 144,444 in 2010, an increase of more than 273 percent (State of Hawaii, 2011, table 1.05). Demand for water provided by the County of Maui Department of Water Supply (MDWS) in the Wailuku area is expected to increase from about 22 Mgal/d in 2005 to 34 Mgal/d in 2030 (Haiku Design and Analysis, 2009a). Demand from the MDWS in the Lahaina area is estimated to increase from about 5.1 Mgal/d in 2003 to 7 Mgal/d in 2030 (Haiku Design and Analysis, 2004). Additionally, groundwater is pumped by several private water systems in the area, some of which may experience increased demand in the future. As of the end of 2011, MDWS withdrawals from the Iao aquifer system, the most important in central Maui, were about 79 percent of the sustainable yield, and MDWS withdrawals from the Kahului aquifer system were about 118 percent of the sustainable yield.

Description of Study Area

The study area (fig. 1) includes all of west Maui, the central isthmus, and about a third of east Maui. Maui is the second largest of the Hawaiian Islands and is located between longitude 155°57'W and 156°47'W and between latitude 20°32'N and 21°03'N. It is composed of two shield volcanoes, the older West Maui Volcano that rises to an altitude of 5,788 ft, and the younger East Maui Volcano (Haleakala) that rises to an altitude of 10,023 ft. The two volcanoes are separated by an isthmus, generally at altitudes less than 300 ft, which is covered with terrestrial and marine sedimentary deposits that are as much as 5 miles wide (Stearns and Macdonald, 1942).

West Maui Volcano has been deeply dissected by numerous streams, including Waikapu, Iao, Kahakuloa, and Honokohau, and Waihee River (fig. 1). These streams originate from near the summit of West Maui Volcano, where average annual rainfall exceeds 350 inches per year (Giambelluca and others, 2011). Above an altitude of about 2,000 feet, rainfall is supplemented by fog interception, which is water vapor and precipitation (not measured by rain gages) that is intercepted by vegetation. Historically, sugarcane was cultivated extensively on the western part of West Maui Volcano and pineapple on the northwestern and southeastern slopes.

Within the study area, the surface of East Maui Volcano is little dissected, and average annual rainfall over East Maui Volcano generally is less than 100 inches per year. Both pineapple and sugarcane are cultivated on the northwestern slopes of East Maui Volcano. In addition, sugarcane is extensively cultivated in the central isthmus of the island.

Geology.—The geology of Maui was described in detail by Stearns and Macdonald (1942), and some of the geologic units were subsequently reclassified by Langenheim and Clague (1987). West Maui Volcano has a central caldera and two main rift zones that trend in northwestern and southeastern directions from the caldera. Thousands of dikes exist within the rift zones, with the number of dikes increasing toward the caldera and with depth. Additional dikes exist outside the general trends of the rift zones, creating a radial pattern of dikes emanating from the caldera (Macdonald and others, 1983). Thousands of lava flows emanated from vents in and near the caldera and rift zones.

The rocks of West Maui Volcano consist of the mostly shield-stage Wailuku Basalt, which is overlain by the postshield-stage Honolua Volcanics and rejuvenated-stage Lahaina Volcanics. The Wailuku Basalt consists of tholeiitic basalt, olivine-tholeiitic basalt, and picritic tholeiitic basalt, and postshield-stage caldera-filling lava of alkalic basalt, and includes lava flows with associated intrusive rocks and pyroclastic and sedimentary deposits (Langenheim and Clague, 1987). The Honolua Volcanics consists of mugearite, trachyte, and hawaiite, and includes lava flows and associated domes, dikes, and pyroclastic deposits (Langenheim and Clague, 1987). The Lahaina Volcanics consists of basanite and picritic basanite, and includes lava flows and associated pyroclastic deposits (Langenheim and Clague, 1987).

East Maui Volcano has three rift zones that trend in northern, southwestern, and eastern directions. The rocks of East Maui Volcano consist of the shield-stage Honomanu Basalt, which is overlain by the postshield-stage Kula Volcanics and the younger rejuvenated-stage Hana Volcanics. The Honomanu Basalt consists of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt, and includes lava flows with associated intrusive rocks and rare pyroclastic deposts (Langenheim and Clague, 1987). The Kula Volcanics forms a veneer on the Honomanu Basalt, consists of hawaiite with some ankaramite and alkalic basalt, and includes lava flows with associated intrusive rocks and pyroclastic and sedimentary deposits (Langenheim and Clague, 1987). The Hana Volcanics consists mostly of alkalic basalt and basanite, and includes lava flows with associated intrusive rocks and pyroclastic and sedimentary deposits (Langenheim and Clague, 1987). The Kula Volcanics and the Hana Volcanics are the most widespread geologic units exposed at the land surface on Maui.

The central isthmus is formed by nearly flat-lying lava flows of the Honomanu Basalt, which are interbedded with consolidated and unconsolidated sedimentary deposits. Beneath the isthmus, Honomanu Basalt of East Maui Volcano overlies older Wailuku Basalt of West Maui Volcano.

Surface Water.—Much of the water used to irrigate sugarcane on Maui is diverted from streams, in both east and west Maui, with an extensive system of ditches (Wilcox, 1996). Within the study area, the U.S. Geological Survey (USGS) currently maintains stream gages on Waihee River and Honokohau, Kahakuloa, and Iao Streams in west Maui. In the past, the USGS has maintained numerous gages on other streams and ditches within the study area (Fontaine, 1996), although the periods of record for some gages are limited.

Perennial streams mainly exist where they intersect the groundwater table of either the freshwater-lens or dike-impounded groundwater systems or where rainfall is persistent. Some of the perennial streams in west Maui include the Iao, Honokohau, Kahakuloa, Makamakaole, Waiehu, and Waikapu Streams, and Waihee River (fig. 1).

Groundwater.—Fresh groundwater in the study area occurs mainly in freshwater-lens systems and dike-impounded systems (Yamanaga and Huxel, 1970; Takasaki, 1972; Meyer and Presley, 2000). A freshwater-lens system includes a lens-shaped freshwater body, an intermediate transition zone of brackish water, and underlying saltwater. The thickness of the transition zone is dependent on the extent of mixing between freshwater and saltwater. Within the study area, freshwater-lens systems are found in dike-free volcanic rocks of high permeability and sedimentary deposits. A thick wedge of sedimentary deposits forms a confining unit (caprock) over the high-permeability volcanic rocks near parts of the northeastern coast of West Maui Volcano and impedes the discharge of water from the freshwater-lens system. Where a coastal confining unit exists, water levels in the freshwater-lens system have exceeded 25 ft above sea level (Meyer and Presley, 2000). In areas of West Maui that lack a coastal confining unit, water levels in the freshwater-lens system generally are less than 5 ft above sea level. Water levels in the freshwater-lens system in the isthmus also are generally less than 5 ft above sea level. Burnham and others (1977) estimated a hydraulic gradient of about 1.6 ft/mi in the volcanic rocks in the isthmus near Kahului. The chemical quality of groundwater in the isthmus is highly dependent on irrigation and withdrawals for agricultural uses (Tenorio and others, 1970; Takasaki, 1972).

Dike-impounded systems are found near the caldera and rift zones of the volcanoes, where low-permeability dikes have intruded other rocks. The flow system includes a freshwater body, and where it exists, the underlying brackish water and saltwater. Near-vertical dikes tend to compartmentalize areas of more permeable volcanic rocks. Dikes impound water to thousands of feet above sea level on Maui.

In some areas, including the northern part of East Maui Volcano, low permeability rocks impede the downward movement of groundwater to allow a perched water body to develop within otherwise unsaturated rocks (Gingerich, 1999). Perched water recharges lower freshwater-lens systems or discharges directly to streams or the ocean.

Groundwater recharge is greatest in the inland mountainous regions where rainfall is highest. Fresh groundwater moves mainly from inland recharge areas to coastal discharge areas where springs and seeps exist both above and below sea level. In some stream valleys, where extensive erosion has exposed dike compartments, groundwater discharges directly to streams. Eastward flowing water from West Maui Volcano converges with westward flowing water from East Maui Volcano in the central isthmus, and water then flows to discharge areas near the northern and southern coasts (Tenorio and others, 1970; Takasaki, 1972).

Within the isthmus area, recharge from infiltration of rainfall is enhanced by irrigation return flow (Tenorio and others, 1970; Takasaki, 1972), injection of wastewater (Burnham and others, 1977), and disposal of stormwater (Hargis and Peterson, 1970; Peterson and Hargis, 1971). Prior to the early 1970s, about 190 Mgal/d of water diverted by ditches and 170 Mgal/d of groundwater withdrawn from shafts and wells was used to irrigate sugarcane fields in central Maui (Takasaki, 1972). Historically, excess water diverted from east Maui that was not needed for irrigation of sugarcane fields was used to recharge the groundwater body by discharging the water in gulches, irrigation ditches, and a cinder pit, and by seepage from reservoirs (Hargis and Peterson, 1970; Peterson and Hargis, 1971). If irrigation of sugarcane fields in central Maui is stopped, recharge will be reduced and the groundwater flow system will be affected.

OBJECTIVES

The objective of this study is to update estimates of the spatial distribution of groundwater recharge in central and west Maui. Daily recharge estimates for current average climatic conditions and land use will be aggregated to determine an average recharge rate for current conditions. Several other scenarios also will be examined, including possible future land use and drought. The study will include the modification of an existing daily water-budget model and the processing of existing climatic, land use, land cover, soil, and streamflow data, including the new rainfall datasets from Giambelluca and others (2011), necessary to execute the water-budget model. Results of the study will be made available to the public in a USGS Scientific Investigations Report posted on the Pacific Islands Water Science Center website. The report will document the recharge by State aquifer system.

APPROACH

A GIS-based water-budget model will be modified and used for this study to estimate the spatial distribution of recharge (see for example, Izuka and others, 2005; Engott and Vana, 2007; Engott, 2011). For this study, a daily time step will be used to avoid possible biases associated with monthly or annual time steps (Giambelluca and Oki, 1987). Daily recharge estimates for current average climatic conditions and land use will be aggregated for each month of the year.

Several other scenarios also will be examined, including possible future land use and drought. Future land use will be estimated using municipal zoning and planning documents. Drought will be simulated using a period of extremely low rainfall selected from the historical record.

The accuracy of recharge estimates from the water-budget model is limited by the accuracy of the input data. Sensitivity of recharge estimates to model input will be quantified.

Water-Budget Calculations

Groundwater recharge will be computed using the daily water-budget model and input data that quantify the spatial and temporal distribution of rainfall (Gimbelluca and others, 2011), fog interception, irrigation, evaporation, runoff, soil type, and land cover. Figure 2 shows the generalized water-budget flow diagram. Areas of homogeneous properties, termed "subareas", are generated by merging datasets that characterize the spatial and temporal distribution of rainfall, fog, irrigation, pan evaporation, runoff, soil type, and land cover in a GIS. For each subarea, recharge is calculated by the water-budget model. At the end of a simulation period, results for the subareas are summed over larger areas of interest, which can include entire aquifer systems.

For each subarea at the start of each day, the model calculates an interim moisture storage. Interim moisture storage is the amount of water that enters the plant-root zone for the current day plus the amount of water already in the zone from the previous day. For non-forest subareas, it is given by the equation:

$$X_i = P_i + F_i + I_i + W_i - R_i + S_{i-1}, \qquad \text{(1a)}$$

where:

X_i	=	interim moisture storage for current day [L],
P_i	=	rainfall for current day [L],
F_i	=	fog interception for current day [L],
I_i	=	irrigation for current day [L],
W_i	=	excess water from the impervious fraction of an urban area distributed over the pervious fraction [L],
R_i	=	runoff for current day [L],

$S_{i\text{-}1}$ = moisture storage at the end of previous day (i-1) [L], and

i = subscript designating current day.

For forest subareas, interim moisture storage is given by the equation:

$$X_i = (NP)_i - R_i + S_{i\text{-}1}, \qquad (1b)$$

where:

$(NP)_i$ = net precipitation for current day [L],

For forest subareas, net precipitation is computed as the sum of rainfall and fog interception less canopy evaporation, which is the amount of water from rainfall and fog that collects on the leaves, stems, and trunks of trees and subsequently evaporates. The equation is:

$$(NP)_i = P_i + F_i - (CE)_i, \qquad (2)$$

where:

$(CE)_i$ = canopy evaporation [L]

For urbanized subareas, the interim equation includes the factor W_i, which pertains to the fraction of urban subareas that are estimated to be impervious (see eq. 1a). In non-urban subareas where there is no impervious fraction, W_i is zero. Urbanized subareas are assigned a fraction (z) that is impervious. This fraction is used to separate, from the total rain that falls in an urbanized subarea, a depth of water that is treated computationally as though it fell on an impervious surface. Based on this impervious water fraction, some water is subtracted to account for direct evaporation. The remainder of the water (W_i) is added to the water budget of the pervious fraction of the model subarea. Thus, for the pervious fraction of an urban subarea, the total daily water input includes an excess of water from the impervious fraction.

For an urbanized model subarea, excess water, W_i, and water storage (ponded water) on the surface of impervious areas is determined using the following conditions:

$$X1_i = P_i - R_i + T_{i-1}, \tag{3}$$

for $X1_i \leq N$, $W_i = 0$, and

$X2_i = X1_i$,

for $X1_i > N$, $W_i = (X1_i - N)z / (1-z)$, and

$$X2_i = N, \tag{4}$$

where:

$X1_i$	=	first interim moisture storage on the surface of impervious area for current day [L],
$X2_i$	=	second interim moisture storage on the surface of impervious area for current day [L],
T_{i-1}	=	water storage (ponded water) on the surface of impervious area at the end of the previous day (i-1) [L],
N	=	rainfall interception capacity (maximum amount of water storage on the surface of impervious area) [L], and
z	=	fraction of area that is impervious [dimensionless].

The water storage on the surface of the impervious area at the end of the current day, T_i, is determined from the equation:

for $X2_i > V_i$, $T_i = X2_i - V_i$, and

for $X2_i \leq V_i$, $T_i = 0$, (5)

where:

V_i = pan evaporation for current day [L].

The next step in the water-budget computation is to determine the amount of water that will be removed from the plant-root zone by evapotranspiration (ET). Actual ET is a function of potential ET and interim moisture (X_i). A vegetated surface loses water to the atmosphere at the potential-ET rate if sufficient water is available. At all sites, potential ET is assumed to be equal to pan evaporation multiplied by an appropriate vegetation factor, termed a pan coefficient. For moisture contents greater than or equal to a threshold value, C_i, the rate of ET is assumed to be equal to the potential-ET rate. For moisture contents less than C_i, the rate of ET is assumed to occur at a reduced rate that declines linearly with soil-moisture content:

for $S \geq C_i$, , $E = (PE)_i$, and

for $S < C_i$ and $C_i > 0$ $E = S \times (PE)_i / C_i$ (6)

where:

E = instantaneous rate of evapotranspiration [L/T],

$(PE)_i$ = potential-evapotranspiration rate for the current day [L/T],

S = instantaneous moisture storage [L], and

C_i = threshold moisture storage for the current day below which evapotranspiration is less than the potential-evapotranspiration rate [L].

The threshold moisture storage, C_i, is estimated using the model of Allen and others (1998) for soil moisture. In this model, a depletion fraction, p, which ranges from 0 to 1, is defined as the fraction of maximum moisture storage that can be depleted from the root zone before moisture stress causes a reduction in ET. The threshold moisture, C_i, is estimated from p by the equation:

$$C_i = (1 - p) \times S_m \, , \qquad (7)$$

where:

S_m	=	moisture-storage capacity of the plant-root zone [L].

The moisture-storage capacity of the plant-root zone, S_m, expressed as a depth of water, is equal to the plant root depth multiplied by the available water capacity of the soil, ϕ. Available water capacity is the difference between the volumetric field-capacity moisture content and the volumetric wilting-point moisture content:

$$S_m = D \times \phi \, , \qquad (8)$$

where:

D	=	plant root depth [L],
ϕ	=	θ_{fc} - θ_{wp} [L^3/L^3],
θ_{fc}	=	volumetric field-capacity moisture content [L^3/L^3], and
θ_{wp}	=	volumetric wilting-point moisture content [L^3/L^3].

Values for p depend on vegetation type and can be adjusted to reflect different potential-ET rates. In the water-budget model, the ET rate from the plant-root zone may be (1) equal to the potential-ET rate for part of the day and less than the potential-ET rate for the remainder of the day, (2) equal to the potential-ET rate for the entire day, or (3) less than the potential-ET rate for the entire day. The total ET from the plant-root zone during a day is a function of the potential-ET rate ($(PE)_i$), interim moisture storage (X_i), and threshold moisture content (C_i). By recognizing that E = -dS/dt, the total depth of water removed by ET during a day, E_i, is determined as follows:

for $X_i > C_i$ and $C_i > 0$,

$$E_i = (PE)_i t_i + C_i\{1\text{-exp}[-(PE)_i(1\text{-}t_i)/C_i]\},$$

for $X_i > C_i$ and $C_i = 0$,

$$E_i = (PE)_i t_i,$$

for $X_i \leq C_i$ and $C_i > 0$,

$$E_i = X_i\{1\text{-exp}[-(PE)_i / C_i]\},$$

and

for $X_i = C_i$, and $C_i = 0$,

$$E_i = 0, \qquad (9)$$

where:

E_i = evapotranspiration from plant-root zone during the day [L],

t_i = time during which moisture storage is above C_i [T]. It ranges from 0 to 1 day and is computed as follows:

for $(X_i - C_i) < (PE)_i(1 \text{ day})$

$$t_i = (X_i - C_i)/(PE)_i,$$

and

for $(X_i - C_i) \geq (PE)_i(1 \text{ day})$,

$$t_i = 1. \qquad (10)$$

After accounting for runoff (eq. 1a or 1b), ET from the plant-root zone for a given day is subtracted from the interim moisture storage, and any moisture remaining above the maximum moisture storage is assumed to be recharge. The daily rate of direct recharge from anthropogenic sources is also added to daily recharge at this point. Recharge and moisture storage at the end of a given day are assigned according to the following conditions:

for $X_i\text{-}E_i \leq S_m$, $\quad Q_i = DR$, and

$$S_i = X_i - E_i ,$$

and

for $X_i\text{-}E_i > S_m$, $\quad Q_i = (X_i - E_i - S_m) + DR$, and

$$S_i = S_m , \tag{11}$$

where:

Q_i = groundwater recharge during the day [L], and

S_i = moisture storage at the end of the current day (i) [L],

DR = daily rate of direct recharge from anthropogenic sources [L] (water-main leaks, cesspool discharge, etc.).

Moisture storage at the end of the current day, expressed as a depth of water, is equal to the root depth multiplied by the difference between the volumetric soil-moisture content within the root zone at the end of the current day, and the volumetric wilting-point moisture content.

$$S_i = D \times (\theta_i - \theta_{wp}), \tag{12}$$

where:

θ_i = volumetric soil-moisture content at the end of the current day, i, [L^3/L^3].

PRODUCTS

The anticipated products of this study are a report in the USGS Scientific Investigations Report series. The report will describe the computation of groundwater recharge using a water-budget model. The report will be made available on the website of the Pacific Islands Water Science Center. The probable report title, report outlet, and milestone dates are listed in table 1.

Table 1. Milestone dates for planned report

Probable title	Report outlet	First draft	Review	Approval	Publication
An updated water-budget model and reassessment of groundwater recharge for central and west Maui, Hawaii	USGS SIR	12/2012	03/2013	04/2013	06/2013

BUDGET

A total of about $60,000 is needed for this 14 month study. The budget takes advantage of cost savings by combining groundwater recharge estimates for this study with those for parts of Northeast Maui that are being developed in cooperation with the County of Maui Department of Water Supply. A cost breakdown is provided in table 2. Labor includes salary and indirect costs for leave, facilities, and overhead assessments. Science support includes indirect costs for project management, technical services, and report processing fees.

Table 2. Project budget.

Category	Total
Labor	52,610
Science Support	7,390
Total	**$ 60,000**

WORK PLAN

The major tasks and associated periods of activity for this 14 month study are summarized in table 3. The anticipated study period is May 1, 2012 to June 30, 2013.

Table 3. Major work tasks and timelines

Task	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Month 13	Month 14
Recharge Modeling														
Prepare input datasets	x	x	x	x	x									
Modify water-budget model code			x	x	x	x								
Run model scenarios and analyze					x	x	x							
Report Preparation														
Writing							x	x	x					
Review and approval										x	x	x		
Publication													x	x

REFERENCES CITED

Allen, R.G., Pereira, L.S., Raes, Dirk, and Smith, Martin, 1998, Crop evapotranspiration; guidelines for computing crop water requirements: United Nations Food and Agriculture Organization Irrigation and Drainage Paper 56, 300 p.

Burnham, W.L., Larson, S.P., and Cooper, H.H., Jr., 1977, Distribution of injected wastewater in the saline lava aquifer, Wailuku-Kahului wastewater treatment facility, Kahului, Maui, Hawaii: U.S. Geological Survey Open-File Report no. 77-469, 58 p.

Engott, J.A., 2011, A water-budget model and assessment of groundwater recharge for the island of Hawaii: U.S. Geological Survey Scientific Investigations Report 2011–5078, 53 p.

Engott, J.A., and Vana, T.T., 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in central and west Maui, Hawaii, 1926-2004, U.S. Geological Survey Scientific Investigations Report 2007–5103, 56 p.

Fontaine, R.A., 1996, Evaluation of the surface-water quantity, surface-water quality, and rainfall data-collection programs in Hawaii, 1994: U.S. Geological Survey Water-Resources investigations Report 95-4212, 125 p.

Giambelluca, T.W., and Oki, D.S., 1987, Temporal disaggregation of monthly rainfall data for water balance modeling, in The Influence of Climate Change and Climatic Variability on the

Hydrologic Regime and Water Resources, International Association of Hydrologic Sciences Publication No. 168, p. 255-267.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawai`i: State of Hawaii, Department of Land and Natural Resources, Report R76, 267 p.

Giambelluca TW, Chen Q, Frazier AG, Price JP, Chen Y-L, Chu P-S, Eischeid J., and Delparte, D. 2011. The Rainfall Atlas of Hawai'i. *http://rainfall.geography.hawaii.edu*

Gingerich, S.B., 1999, Ground water and surface water in the Haiku area, east Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 98-4142, 38 p.

Gingerich, S.B., and Engott, J.A., 2012, Groundwater availability in the Lahaina district, west Maui, Hawaii: U.S. Geological Survey Scientific Investigations Report 2012–5010.

Haiku Design and Analysis, 2004, Maui County Water Use and Development Plan, Water Use and Demand, Preliminary Draft: Kahului, Maui, 71 p.

Haiku Design and Analysis, 2009a, Maui County water use and development plan, Central District, Final candidate strategies report, Upcountry Water Advisory Committee Review Draft: Haiku, 114 p.

Hargis, D.R., and Peterson, F.L., 1970, Artificial recharge practices in Hawaii: University of Hawaii, Water Resources Research Center Technical Report no. 43, 36 p.

Izuka, S.K., Oki, D.S., and Chen, Chien-Hwa, 2005, Effects of irrigation and rainfall reduction on ground-water recharge in the Lihue Basin, Kauai, Hawaii, U.S. Geological Survey Scientific Investigations Report 2005–5146, 48 p.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain, part II, stratigraphic framework of volcanic rocks of the Hawaiian Islands, chap. 1 of Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea, the geology of Hawaii (2d ed.): Honolulu, Hawaii, University of Hawaii Press, 517 p.

Meyer, William, and Presley, T.K., 2000, The response of the Iao aquifer to ground-water development, rainfall, and land-use practices between 1940 and 1998, island of Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 00-4223, 60 p.

Peterson, F.L., and Hargis, D.R., 1971, Effect of storm runoff disposal and other artificial recharge to Hawaiian Ghyben-Herzberg aquifers: University of Hawaii, Water Resources Research Center Technical Report no. 54, 51 p.

State of Hawaii, 2008, Water resource protection plan, June 2008: State of Hawai'i, Commission on Water Resource Management, variously paged.

State of Hawaii, 2011, 2010 State of Hawaii data book: State of Hawaii, Department of Business, Economic Development, and Tourism, http://hawaii.gov/dbedt/info/economic/databook/db2010/.

Stearns, H.T., and Macdonald, G.A., 1942, Geology and ground-water resources of the island of Maui, Hawaii: Hawaii Division of Hydrography Bulletin 7, 344 p.

Takasaki, K.J., 1972, Preliminary report on the water resources of Central Maui: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Circular C62, 59 p. plus appendixes.

Tenorio, P.A., Young, R.H.F., Burbank, N.C., Jr., and Lau, L.S., 1970, Identification of irrigation return water in the sub-surface, phase III Kahuku, Oahu and Kahului and Lahaina, Maui: University of Hawaii, Water Resources Research Center Technical Report no. 44, 53 p.

U.S. Geological Survey, 2007, Facing tomorrow's challenges—U.S. Geological Survey science in the decade 2007–2017: U.S. Geological Survey Circular 1309, x + 70p.

Wilcox, Carol, 1996, Sugar water: Hawaii's plantation ditches: Honolulu, University of Hawai'i Press, 191 p.

Yamanaga, George, and Huxel, C.J., 1970, Preliminary report on the water resources of the Wailuku area, Maui: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Circular C61, 43 p.

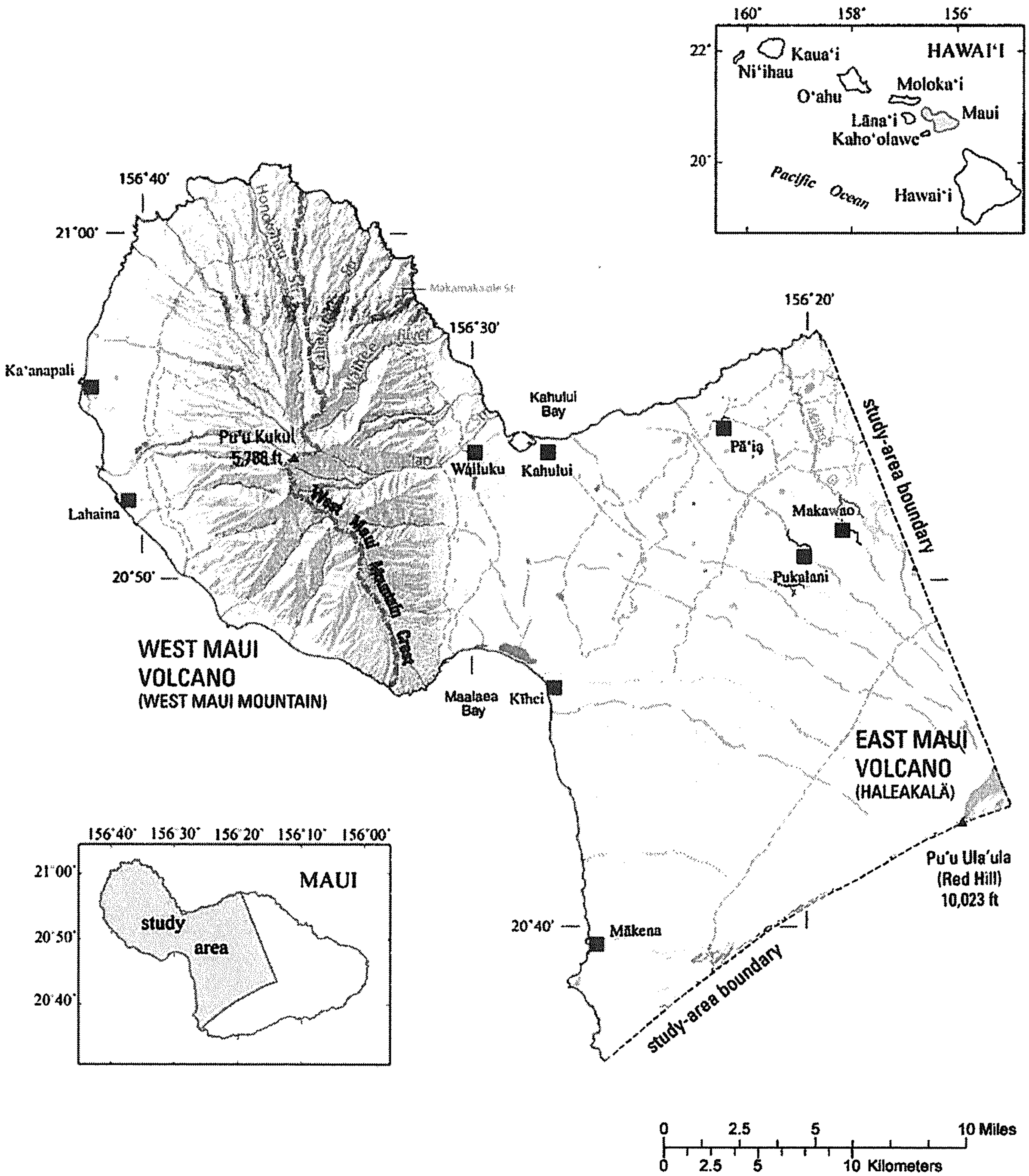
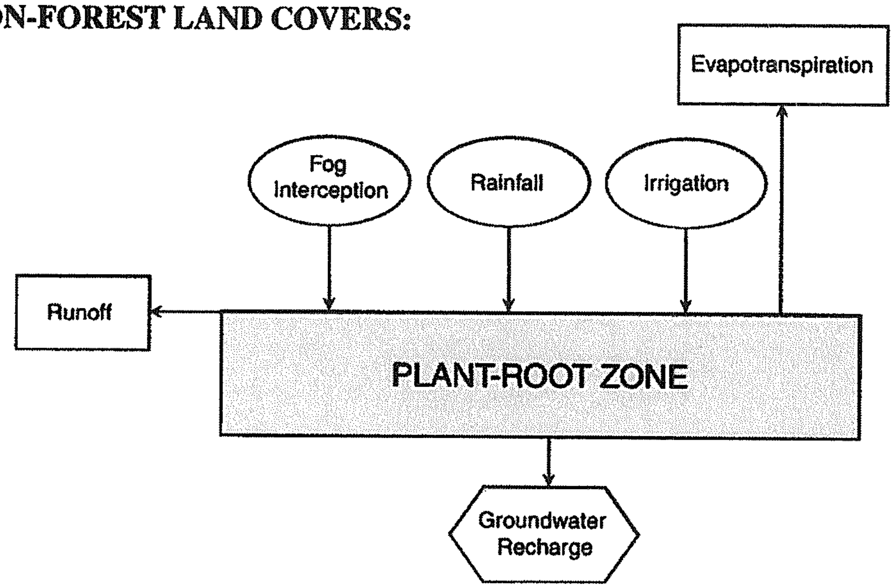


Figure 1. Map of the central and west Maui study area.

FOR NON-FOREST LAND COVERS:



FOR FOREST LAND COVERS:
(modified from McJannet and others, 2007)

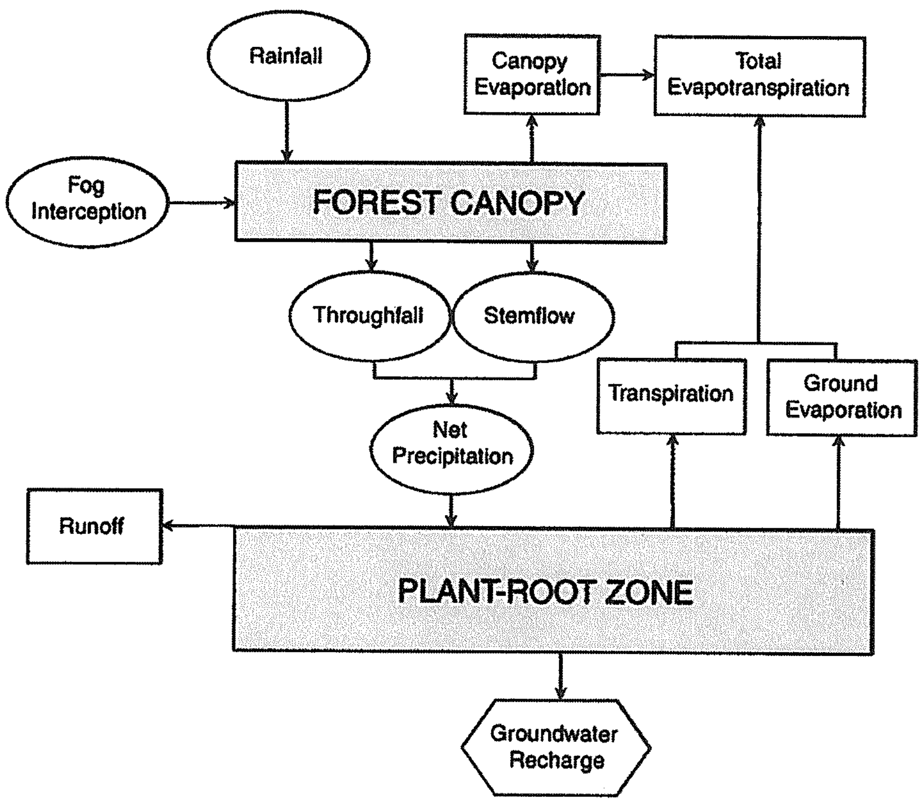


Figure 2. Generalized water-budget flow diagrams for forest and non-forest land covers.