Irrigation Management System, IMANSYS, a User-Friendly Computer Based Water Management Software Package

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Abstract

The IMANSYS model is an irrigation water requirements (IWRs) calculation model; it is an altered form of the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988). It calculates runoff, drainage, canopy interception, and effective rainfall based on plant growth parameters, soil properties, irrigation system, and long-term weather data (rain, evapotranspiration, and temperature). IWRs are calculated based on different water management practices. IMANSYS calculates evapotranspiration based on temperature data using different models. IMANSYS has several databases of, e.g., soil and plant growth parameters, irrigation systems, canopy interception. IMANSYS was implemented in JAVA object oriented language. IMANSYS output includes detailed net and gross IWRs, and all water budget components at different time scales (daily, weekly, biweekly, monthly, and annually) based on non-exceedance drought probability which is calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values.

Introduction

Plant water requirement is the amount of water, in addition to rainfall, that must be applied for a particular crop to meet its evapotranspiration needs and maintain optimum yield. It is usually called also net irrigation requirement (IRR_{net}) which is the irrigation water that is delivered to the rootzone and available for the plants to use. Estimates of irrigation requirements can be made based on site specific historical irrigation data or calculated using mathematical models. The latter method may be based on statistical methods or on physical laws which govern crop water uptake and use. Effective rainfall is that portion of rainfall which can be effectively used by a plant, that is, rain which is stored in the plant root zone. Therefore, effective is less than total rainfall due to canopy interception, runoff and deep percolation (or drainage) losses. A plant's irrigation requirement, as defined here, does not include water applied for freeze protection, crop cooling, or other purposes, even though water for these purposes is required for crop production and is applied through irrigation systems.

Estimates of irrigation requirements calculated using mathematical models use water budget models to historical climate data to obtain historical irrigation water demand. Water budget model refers to the accurate tracking of inputs, outputs, and soil water storage of an irrigated system. Water budget components include rainfall, irrigation, drainage below the root zone, runoff, canopy interception, evapotranspiration, and changes in soil water storage. These water budget models have been used for irrigation scheduling and crop water requirement estimation (Smajstrla, 1990; Obreza and Pitts, 2002; Fares et al., 200). Smajstrla (1990) developed the Agricultural Field Scale Irrigation Requirements

Simulation (AFSIRS) model that uses a water balance approach with layered soil column to simulate soil water infiltration, redistribution, and extraction by evapotranspiration as steady state processes on a daily basis. The AFSIRS model simulates the irrigation requirements for a crop based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The AFSIRS does not account for runoff and canopy interception and it cannot simulate multiple crops. It was designed for Florida's soils and crops.

The main goal of this paper is to give a detailed overview of the newly developed Irrigation water Management System, IManSys, model. IManSys is an irrigation water requirements (IWRs) calculation model; it is an altered form of the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988).

Model description

Irrigation Management System (IMANSYS)

IManSys is a Microsoft Windows based model that calculates irrigation requirements for regional crops on daily, weekly, monthly, and annual basis. Model also offers flexibility to add additional crops or modify the information about existing crops. The irrigation requirement from specific plants is calculated based on extreme value frequency analysis on long-term daily irrigation estimates. Detailed description of the model and its components are present below.

Water Budget in IMANSYS

Similar to AFSIRS, IMANSYS model uses the water balance approach with a two-layer soil profile to simulate the irrigation water requirement for specific plants on a daily basis. The plant specific irrigation requirements are calculated based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The daily water balance equation for the soil column defined by the crop root zone expressed in terms of equivalent water depth per unit area (cm) is:

$$\Delta S = P + G + IRR_{net} - (Q_D + Q_R + ET_c + I) \qquad (1)$$

where ΔS is the change in soil water storage expressed as equivalent water depth (cm), P is the gross rainfall (cm), G is the groundwater contribution (cm) from shallow water table, IRR_{net} is the net irrigation requirement (cm), $(Q_D + Q_R)$ is summation of groundwater drainage and surface water runoff (cm), ET_c is the plant evapotranspiration (cm), and I is canopy rainfall interception (cm). The water storage capacity (S) is amount of water that is available for plant uptake (cm). It is calculated as the equivalent water between field capacity and permanent wilting point for a given soil multiplied by the depth of the root zone.

The soil profile depth was assumed to be equal to the crop root zone depth. The plant root zone was divided into irrigated (upper 50 %) and non-irrigated (lower 50 %) zones based on the common practice of irrigating only the upper portions of the crop root zone where most of the roots are located (Smajstrla, 1990; Smajstrla and Zazueta, 1988). It is assumed that 70 and 30% of crop ET is extracted from these zones, respectively, when water is available (SCS, 1982). This pattern of water extraction is typically assumed for well-irrigated plants on non-restrictive soil profiles (Smajstrla and Zazueta, 1988).

Rainfall and canopy interception

Gross rainfall measured above canopy was adjusted with user defined canopy interception factor. If interception fraction is not available, model calculates it based on leaf area indices (LAI) and plant height (H) as described by Rutter et al. 1975. The basic interception calculation follows the following conditions:

$$I = I_{max} \quad \text{if } P >= I_{max} \qquad (2a)$$

$$I = P \quad \text{if } P < I_{max} \qquad (2b)$$

Where I is daily interception, Imax is the maximum daily interception calculating using the methods described below, P is the daily rainfall

During irrigation period, daily LAI value is obtained by the following equations:

$$LAI = K_c/K_{cmax} * LAI_{max} \quad \text{Perennial Crop} \qquad (3a)$$

$$LAI = DRZI/DRZI_{max} * LAI_{max} \quad \text{Annual Crop} \qquad (3b)$$

And interception is calculated as:

$$I_{max} = 0.2 * LAI \ (mm) \qquad (4)$$

Method based on plant height is only available for annual crops, using the following equation to obtain LAI to calculate interception using equation (2):

$$H = DRZI/DRZI_{max} * H_{max} \qquad (5a)$$

$$LAI = 24H \qquad (5b)$$

Where DRZI and $DRZI_{max}$ are the initial and maximum root zone depth for annual and perennial crops; K_c and K_{cmax} are the initial and maximum crop water use coefficients, respectively.

After subtracting the canopy interception, soil water contents are adjusted based on net rainfall (Gross rainfall-canopy interception). If effective rainfall (net rainfall-surface runoff) amount is sufficient to exceed field capacity in the irrigated root zone, the excess is added to the non-irrigated root zone. For micro irrigation systems, where the entire soil surface is not irrigated, rain is also added to the non-irrigated root zone, in proportion to the non-irrigated surface area.

Reference Evapotranspiration

IMANSYS provides options to select the appropriate model for ET calculation if the ET data is not available for the area. These ET models include the Hargreave-Samani (1985), the Evapotranspiration Prediction Model (ETM) based on Priestley-Taylor as detailed by Fares (1995), the FAO56-PM method (Allen et al., 1998).

Surface Runoff

Surface runoff (Q_R) was calculated using SCS curve number method (SCS, 1985 and 1993) using the following equation:

$$Q_R = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6}$$

where P is daily rainfall (cm), S is potential maximum retention (cm) which is related to SCS curve number as:

$$S = \frac{2540}{CN} - 25.4 \tag{7}$$

CN is the curve number which is related to the imperviousness of the surface. CN was determined based on hydrologic soil group and land use type.

Drainage

Drainage (Q_D) is the portion of rainfall in excess of rain stored in the soil profile to field capacity or depleted by crops (ET_c) as the water is redistributed in the soil. Drainage is calculated for days on which rainfall occurs and the amount of rain exceeds the soil water-holding capacity. When that occurs, the water which is percolating through the profile, is considered to be effective until redistribution to field capacity has occurred. Drainage from the irrigated and non-irrigated zones is calculated as the amount of water which is in excess of that required to restore the root zone to field capacity and to provide crop ET while it is redistributing. Drainage from these zones leaves the entire crop root system as leaching or groundwater recharge.

Gross Irrigation Requirement (IRR)

Irrigations were assumed to start when the available water for plant uptake decreases to a predetermined minimum allowable level, termed allowable soil water depletion (AWD) percentage. AWD values were determined from the literature and are fractions of the available soil water storage capacity that can be allowed to be depleted without significant reduction in crop yield. AWD values for the annual and perennial crops are user specific and can be provided with crop information. Model uses AWD 0.50 as default for all perennial crops. A value of 0.50 means that 50% of the available water in the irrigated crop root zone is allowed to be depleted between two consecutive irrigation events.

The irrigation requirement is calculated as the depth of water required to replenish the soil water content to field capacity in the irrigated crop root zone. Water losses occurred during irrigation due to irrigation system efficiencies were also added into irrigation requirements (i.e., gross irrigation water demand) by dividing IRR with a coefficient of irrigation system efficiency (f_i). The value of f_i varies with irrigation type between zero and one. The gross irrigation requirement (IRR) was calculated for each crop using the following equation, which is derived from Eq. (1):

$$IRR = \frac{ET_c - (P - Q_R - Q_D - I)}{f_i} \tag{8}$$

where f_i is the irrigation efficiency.

Statistical Analysis of IRR

Statistical analysis is performed on calculated IRR on weekly, bi-weekly, and monthly time steps based on long-term climate data. In addition to mean, median, minimum, maximum, and coefficient of variation of IRR, model also calculates IRR at 50%, 80%, 90%, and 95% using the least square fit to type 1 extreme value distribution. A 50% probability IRR will be expected to exceed once in every two years and if the data follows the normal distribution, 50% IRR will be equal to mean value. All the calculations were based on the methodology presented by James et al. (1983).

Materials and Methods: Case Study

Study Area

Irrigation requirements were estimated for ten locations across the state of Hawaii located between 18° 55′ N and 28° 27′ N latitude and 154° 48′ W and 178° 22′ W longitude. The study locations by island were: East Kauai, Kauai Coffee and Kekaha in Kauai Island; Waiahole and Waimanalo in Oahu Island; West Maui and Upcountry Maui in Maui Island; Molokai in Molokai Island; and Lower Hamakua and Waimea in Hawaii (Big) Island (Figure 1).

Crop Selection

In this study, 22 annual crops (Table 1a) and 11 perennial crops (Table 1b) that have high value for Hawaiian agricultural industry were selected. Irrigation requirements for all of the 33 crops were estimated for ten locations scattered on the Hawaiian Islands. The root zone information for the selected crops used in this study is provided in Table 1. The crop root zone for perennial crops was assumed to be constant. The crop root zone development for annual crops has four growth stages. The average growth stage lengths differ by crop and are given as fractions of the crop growing season. The root zone was held constant at the minimum depth throughout crop growth stage 1 that is crop establishment period. The root zone increases linearly to a maximum depth throughout growth stage 2 that is vegetative growth and development period. The maximum root zone is attained at the beginning of crop growth stage 3, which is peak of the growth period, and is maintained throughout growth stages 3 and 4. Growth stage 4 is the period of a crop from maturity to harvest (Smajstrla, 1990).

Soil

Representative soil series, textures, and water-holding capacities for each location were identified with the USDA Soil Survey of the State of Hawaii and supporting documents (USDA 1972; USDA, 1979). The water storage capacity within the crop root zone was defined as the product of the available water-holding capacity of the soil (Table 2), and the depth of the effective root zone for each crop (Table 1a and 1b).

Meteorological Data

Historical long-term daily rainfall data were obtained for stations within each system from the National Climate Data Center (NCDC) on-line database at http://www.ncdc.noaa.gov/oa/climate/climateinventories.html. Daily minimum and maximum temperature data was also downloaded from NCDC for Waimanalo and Upcountry Maui stations**.** Climate station location and climatic information are presented in Table 3.

Irrigation Requirement Calculations

IRR for annual crops were calculated for wet season (October to February) and dry season (April to August) whereas for perennial crops, they were calculated for the whole year. Hereafter the wet season will be referred as season-1 and dry season as season-2. Irrigations were assumed to start when the available water for plant uptake decreases to a predetermined minimum allowable level, termed allowable soil water depletion (AWD) percentage. AWD values were determined from the literature and are fractions of the available soil water storage capacity that can be allowed to be depleted without significant reduction in crop yield. AWD values for the annual crops used in this study are given in Table 1a whereas an AWD value of 0.50 was used for all perennial crops. A value of 0.50 means that 50% of the available water in the irrigated crop root zone is allowed to be depleted between two consecutive irrigation events.

Irrigation Systems

Drip and micro-sprinkler were the irrigation system types selected for most crops, with the former assigned primarily to vegetable crops and the latter to fruits and other perennials. Other irrigation system types assigned were; multiple sprinklers for alfalfa and lettuce, sprinkler–large guns for bana grass, and flood irrigation for taro. Irrigation system efficiency was assumed to be 85, 80, 70, 50, and 30 % for drip, micro-sprinkler, multiple sprinklers and sprinkler–large guns, flood, and nursery container irrigation systems, respectively (Tables 1a and 1b).

RESULTS AND DISCUSSIONS

Orthographic lifting and subsequent cooling of the moisture laden trade winds are the primary rainfall-producing mechanism over the islands. This results in substantially less rain on the leeward side due to a rain shadow effect. As a result, water deficits relative to potential ET are greater on the leeward, relative to the windward, sides of the Islands. At a single location, there is a significant temporal rainfall variability from month to month (Figure 2). In most of the location, rainfall maxima and minima occur in January and June, respectively. The difference between winter maxima and summer minima are greatest in dry areas, while wet areas are characterized by two peaks in precipitation throughout the year (Figure 2). At both Waiahole and Waimanalo, January and November were the wettest month. Spatial variability in rainfall occurs not just across mountain ranges and between islands, but also within individual watersheds and is primarily influenced by topography. In the Kauai Coffee, a gradient of approximately 122 m in the direction of mountains to ocean results in a difference of 1 m of rainfall (with little difference in ET).

The calculated IRR values differed temporally and spatially between locations due to the rainfall variation that occurs on each island. Climate station location and climatic information are presented in Figure 1 and Table 3. Historical annual rainfall is the lowest in the Waimea, West Maui, Waiahole, and Kekaha locations (42.9, 49.3, 52.8, and 54.1 cm, respectively) and highest in the East Kauai and Lower Hamakua systems (186.7 and 241.1 cm, respectively). ET_o data has less variability among systems than rainfall (ranging 120.6- 239.3 cm annually), and is generally inversely related to rainfall. Deficits between annual rainfall and potential ET were greatest in the West Maui and Molokai systems, averaging about 147.3 cm less rainfall than potential ET. The Lower Hamakua and East Kauai systems have clear water excess as they receive more annual rainfall than water losses through ET (78.7 and 38.1 cm more, respectively).

Hydrographically, the islands can be characterized into windward and leeward sides with the windward receiving significantly more rainfall compared to the leeward side. As a result, for both annual and perennial crops windward needs less IRR compared to leeward (Figure 3). Irrigation requirement for both annual and perennial crops at Waiahole, located in the leeward side is almost double as compared to Waimanalo which is located in windward side (Figure 3). IRR varies with the wet season (October to February) requiring less water and the dry season (April to August) requiring more. Variation in irrigation water requirement can vary not only with locations, but also with crops. For sweet corn the water budget component between two seasons are presented in Figure 4A and Figure 4B. Irrespective of location the mean, minimum, and maximum IRR can be more than double during summer season as compared to winter season. This difference is mostly due to low rainfall and higher ET during summer months as compared to winter.

IRR requirement for selected annual and perennial crops are presented in Figure 5. Water requirement for pineapple is significantly lower but it can vary from one location to another. The IRR requirements for some crops can be 4 to 5 times higher between one location to another. Irrespective of crop type, IRR for East Kauai was lowest among all twelve stations and Molokai had the highest (results not shown). For the same crops Dendrobium and Draceana, IRR varied significantly due to difference in irrigation system type (micro-spray vs nursery sprinkler). The IRR calculations show some crops needs less water such as pineapples than others, and some crops such as taro, need more water than any other crops within a single location. The IRR requirement varies with location, planting periods and crop types. Therefore, if a water thirsty crop is planted in wet season and a plant with less water requirement is planted in the following dry season, a considerable overall cost reduction in irrigation water requirement can be obtained.

In Hawaii seed corn can be grown any time during the due to suitable climatic condition throughout the year. When IRR requirement was compared with different sowing date, May and November, resulted in highest and lowest IRR, respectively (Figure 6). IRR for seed corn sown in May is 2.5 times higher than that of sown in November. This variably is consistent with the monthly variability in rainfall and ET during the year.

SUMMARY AND CONCLUSION

This manuscript summarized the main steps of the development the Irrigation Management System (IManSys) software which uses weather, soil and crop databases, e.g., daily rainfall and evapotranspiration, soil physical properties, irrigation system characteristics, and crop parameters to calculate site and plant specific irrigation requirements. IManSys is proven to be a reasonable management tool, an effective teaching software for different users. This package might require several modifications to allow it use in different environment and help answer multiple questions.

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Table 1a: Annual crop Kc values and stage lengths as a fraction of growing period

Crop	Root depth (cm)		Crop Kc			Duration (fraction of crop cycle)				Allowable water depletion (fraction of total)				Irrigation type*	Irrigation efficiency (%)
	Irrigated Depth	Total Depth	$Kc_{initial}$	Kc_{mid}	Kc_{late}	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4		
Alfalfa, initial	20.32	60.**96**	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	S	70
Alfalfa, ratoon	60.96	60.96	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	S	70
Banana, initial	60.96	121.92	0.5	1.1	1	0.31	0.23	0.31	0.15	0.35	0.35	0.35	0.35	MS	80
Banana, ratoon	121.92	121.92	1	1.05	1.05	0.33	0.16	0.49	0.01	0.35	0.35	0.35	0.35	MS	80
Cabbage	20.32	30.48	0.7	1.05	0.95	0.24	0.36	0.3	0.09	0.45	0.45	0.45	0.45	D	85
Cantaloupe	20.32	30.48	0.5	0.85	0.6	0.08	0.5	0.21	0.21	0.35	0.35	0.35	0.35	D	85
Dry Onion	20.32	30.48	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.9	D	85
Eggplant	20.32	30.48	0.7	1.05	0.9	0.21	0.32	0.29	0.18	0.4	0.4	0.4	0.4	D	85
Ginger	20.32	30.48	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.25	D	85
Lettuce	20.32	30.48	0.7	1	0.95	0.2.7	0.4	0.2	0.13	0.3	0.3	0.3	0.3	S	70
Other melon	20.32	30.48	0.5	1.05	0.75	0.21	0.29	0.33	0.17	0.35	0.35	0.35	0.35	D	85
Pineapple, yr1	30.48	30.48	0.5	0.3	0.3	0.16	0.33	0.26	0.25	0.6	0.6	0.6	0.6	D	85
Pineapple, yr2	60.96	60.96	0.3	0.3	0.3	0.38	0.32	0.27	0.03	0.6	0.6	0.6	0.6	D	85
Pumpkin	20.32	30.48	0.5	1	0.8	0.2	0.3	0.3	0.2	0.35	0.35	0.35	0.5	D	85
Seed Corn	30.48	45.72	0.4	1.2	0.5	0.16	0.28	0.32	0.24	0.6	0.6	0.6	0.8	D	85
Sugarcane, New- year 1	45.72	91.44	0.4	1.25	1.25	0.21	0.29	0.25	0.25	0.65	0.65	0.65	0.65	D	85
Sugarcane, New- year 2	91.44	91.44	1.25	1.25	0.75	0.14	0.14	0.14	0.59	0.65	0.65	0.65	0.65	D	85
Sugarcane, ratoon	91.44	91.44	0.4	1.25	0.75	0.1	0.15	0.46	0.29	0.65	0.65	0.65	0.65	D	85
Sweet potato	20.32	30.48	0.5	1.15	0.65	0.12	0.24	0.4	0.24	0.65	0.65	0.65	0.65	D	85
Taro	20.32	30.48	1.05	1.15	1.1	0.2	0.13	0.4	0.27	0	0	0	0	F	50
Tomato	20.32	30.48	0.6	1.15	0.8	0.2	0.27	0.34	0.19	0.4	0.4	0.4	0.65	D	85

Watermelon	20.32	30.48	0.4	1	0.75	0.15	0.26	0.26	0.32	0.26	0.32	0.26	0.32	D	85

* MS = micro spray, NS = nursery sprinkler, S = Sprinkler, D = Drip, F = Flood

Table 1b: Perennial crop effective root depth Kc values by month of the year.

Crop	Root depth (cm)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Irrigation type*	Irrigation efficiency
	Irrigated Depth	Total Depth														
Coffee	60.96	121.92	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	MS	0.8
Dendrobium,	20.32	20.32	1	1	1	1	1	1	1	1	1	1	1	1	MS; NS	0.80, 0.20
Draceana, pot	20.32	20.32	1	1	1	1	1	1	1	1	1	1	1	1	MS; NS	0.80, 0.20
Eucalyptus closed canopy	182.88	182.88	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8
Eucalyptus young	121.92	182.88	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	MS	0.8
Guava	76.2	152.4	8	0.9	1	1	9	0.8	0.8	0.9	1	1	9	8.5	MS	0.8
Heliconia	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8
Kikuyu grass	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	S	0.75
Lychee	76.2	152.4	0.95	1	1	1	0.95	0.9	0.9	0.85	0.8	0.8	0.9	0.9	MS	0.8
Macadamia nut	76.2	152.4	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	MS	0.8
Ti	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8

* MS = micro spray, NS = nursery sprinkler, S = Sprinkler

Table 2. Representative soils for each of the ten target locations.

Location	Weather Station	Soil series	Texture	Water holding capacity ($cm^3\ cm^{-3}$)
East Kauai	Lihue Variety	Kapaa	Silty clay	0.14
Kauai Coffee	Wahiawa	Makaweli	Stony silty clay loam	0.15
Kauai Coffee	Brydswood	Koloa	Stony silty clay	0.11
Kekaha	Kekaha	Kekaha	Silty clay	0.105
Kekaha	Mana	Lualualei	Clay	0.115
Waiahole	Kunia.Sub	Kunia	Silty clay	0.13
Waimanalo	Wai.Exp.Sta	Waialua	Silty clay	0.14
Molokai	Kaunakakai	Molokai	Silty clay loam	0.12
West Maui	Pohakea	Pelehu	Clay loam	0.13
Upcountry	Kula	Kula	Loam	0.14
Waimea	Lalaumilo	Waimea	V. fine sandy loam	0.14 at 0-1.27 m 0.02 at 1.27-2.29 m
Lower Hamakua	Paauilo	Paauhau	Silty clay loam	0.14 at 0-1.27 m 0.06 at 1.27-2.29 m

Table 3: Climate stations and characteristics of the ten target locations.

ID	Location	Climate Station	Island	Latitude	Longitude	---------Rain-----	
						Years of record	Annual mean (cm)
1	Kekaha	Mana	Kauai	22.04	-159.77	(1950-95)	72.1
2	Kekaha	Kekaha	Kauai	21.97	-159.71	(1950-99)	54.1
3	Kauai Coffee	Wahiawa	Kauai	21.9	-159.56	(1950-04)	89.7
4	Kauai Coffee	McBryde Station	Kauai	21.92	-159.54	---	--
5	Kauai Coffee	Bydswood Station	Kauai	21.93	-159.54	(1952-04)	150.4
6	East Kauai	Lihue Variety Station	Kauai	22.03	-159.39	(1964-99)	186.7
7	Waiahole	Kunia Substation	Oahu	21.39	-158.03	(1994-05)	52.8
8	Waimanalo	Waimanalo Experiment Station	Oahu	21.34	-157.71	(1970-00)	107.9
9	Molokai	Kualapuu Res.	Molokai	21.16	-157.04	---	--
10	Molokai	Kualapuu	Molokai	21.16	-157.04	(1950-77)	85.9
11	West Maui	Pohakea Bridge	Maui	20.82	-156.51	(1950-04)	49.3
12	West Maui	Field 906	Maui	20.83	-156.5	---	--
13	Up-country	Kula Branch	Maui	20.76	-156.33	(1979-05)	60.5
14	Waimea	Lalaumilo Field Office	Hawaii	20.01	-155.69	(1981-04)	42.9
15	Lower Hamakua	Hamakua Makai	Hawaii	20.05	-155.38	---	--
16	Lower Hamakua	Paauilo	Hawaii	20.04	-155.37	(1950-05)	241.1

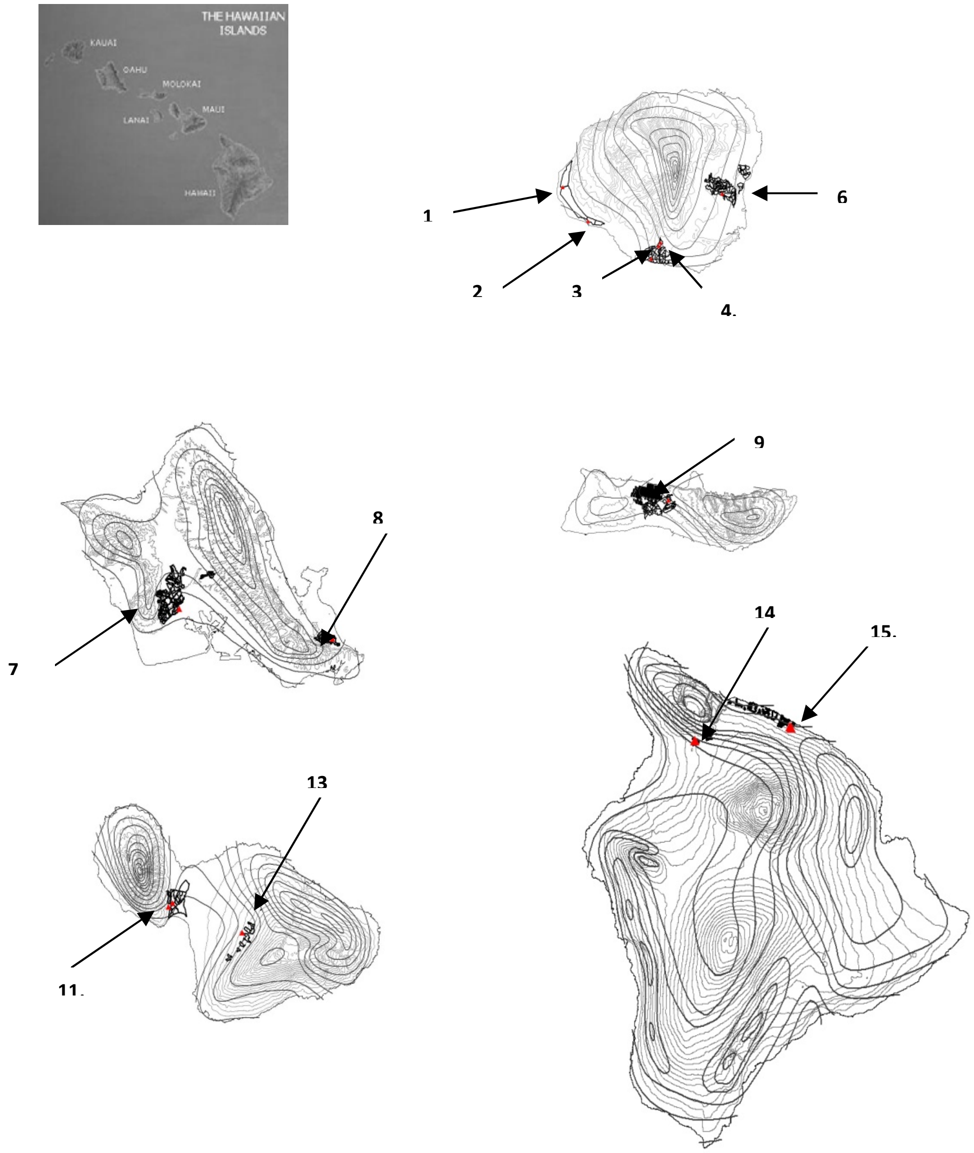

Figure 1. Selected 10 locations and climate data stations for the Hawaiian Islands. Stations are represented by the numbers their information is given in Table 3. Dark contours indicate isohyets gradients in rainfall and light contours indicate elevation. a) Kekaha and East Kauai in Kauai Island, b) Waiahole and Waimanalo in Oahu Island, c) Molokai in Molokai Island, d) West Maui and Kula in Maui Island, and e) Kamuela and Lower Hamakua in Hawaii (Big) Island.

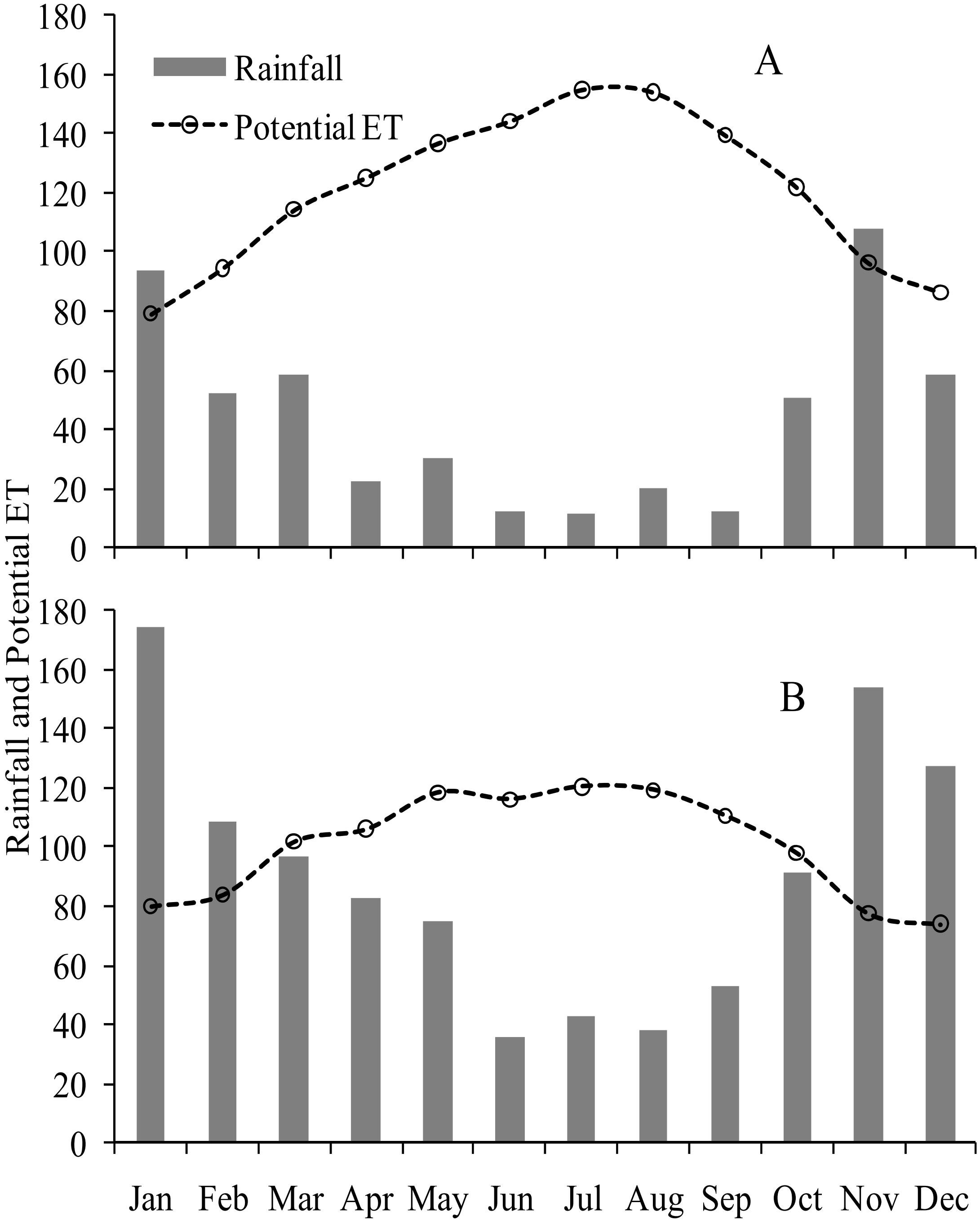

Figure 2. Intra-annual variability in rainfall (bars) and potential evapotranspiration (line) for a representative leeward (A, Waiahole) and windward (B, Waimanalo) locations.

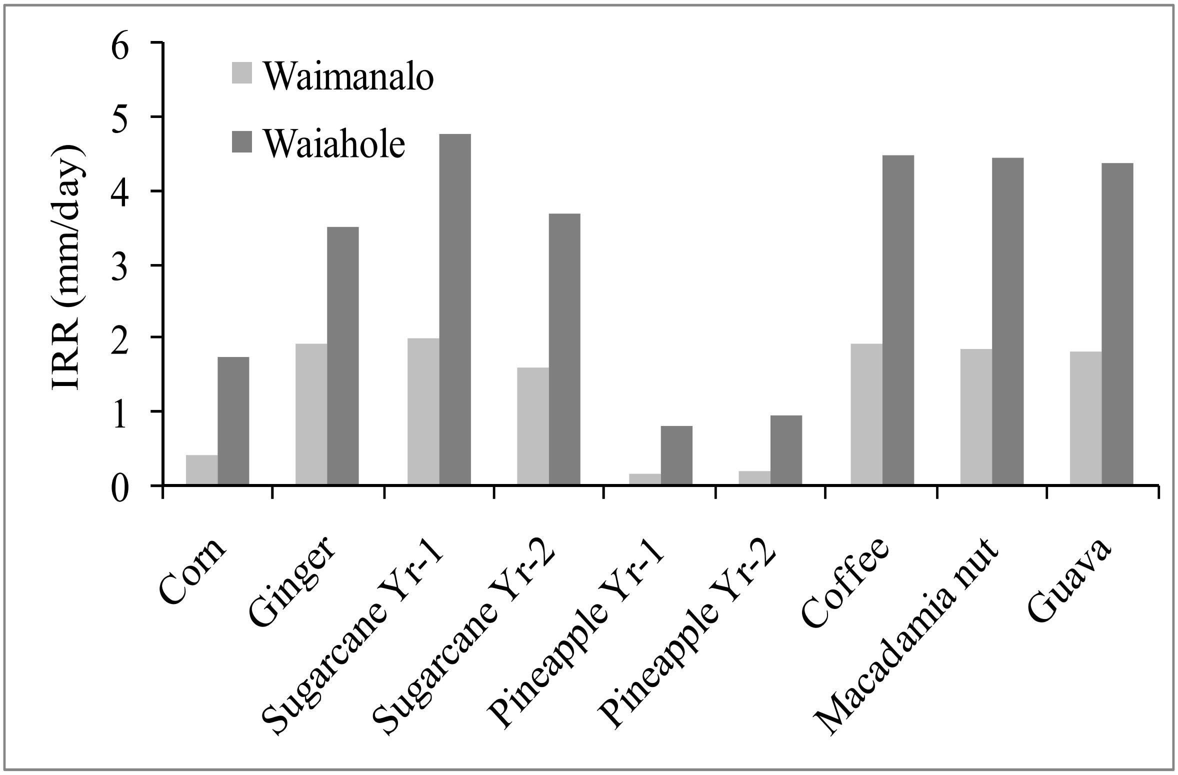

Figure 3: Comparisons of IRR calculated for Waimanalo and Waiahole locations for annual and perennial crops.

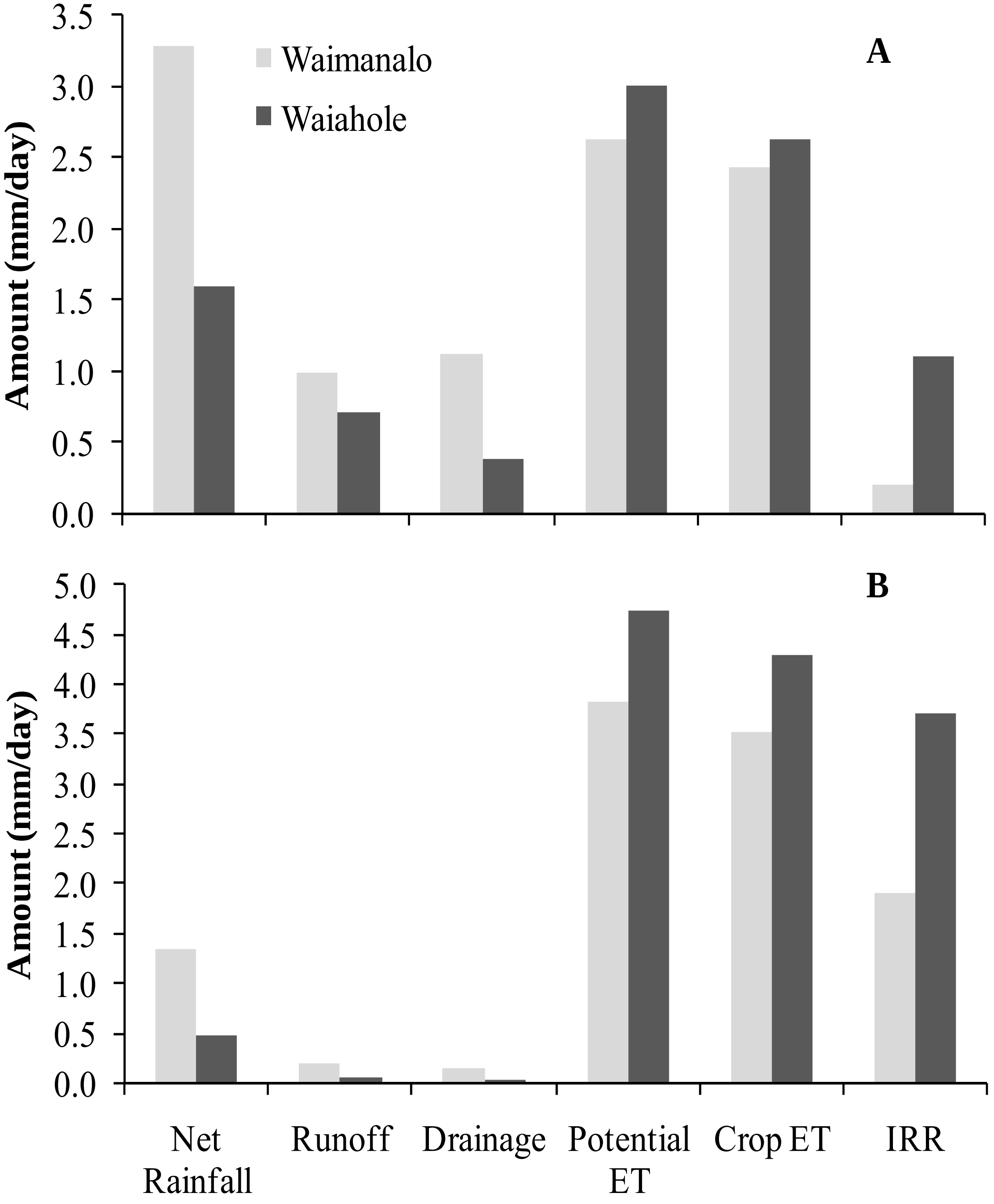

Figure 4: Water balance components and estimated IRR for Seed Corn using IMANSYS for Season-1 (A) and Season-2 (B) for Waimanalo and Waiahole locations.

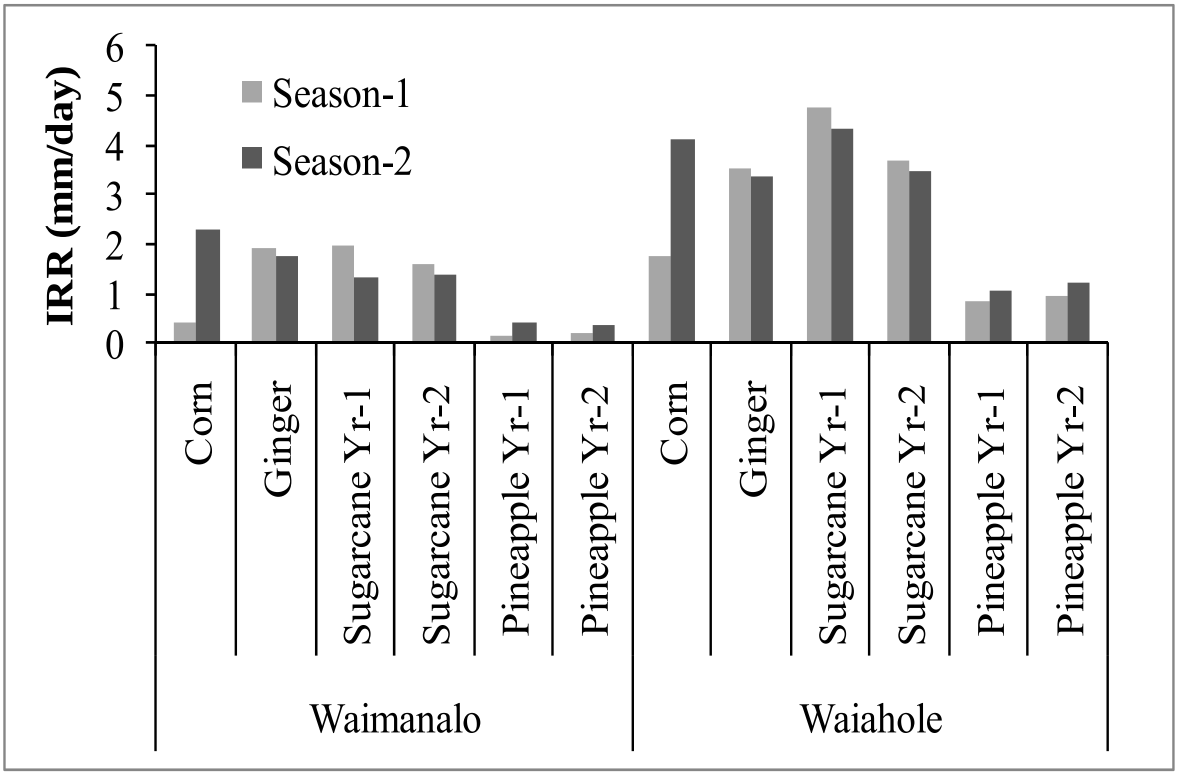

Figure 5: Variability in IRR between seasons at Waimanalo and Waiahole location on the Island of Oahu.

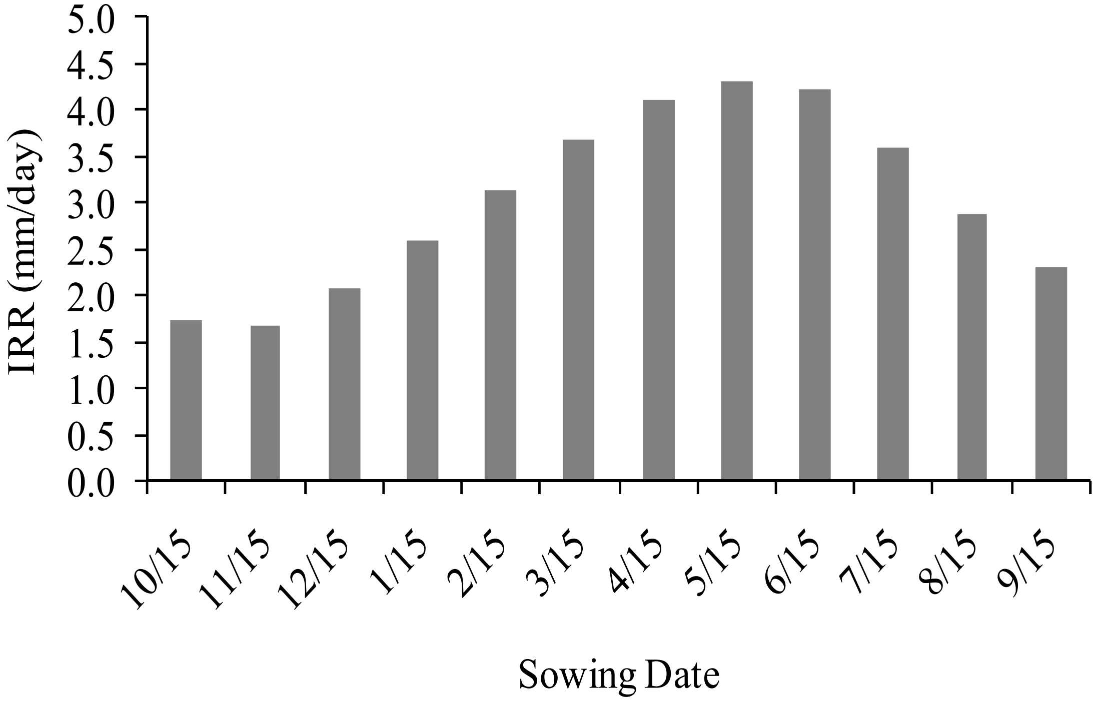

Figure 6: Variability in IRR with date of sowing for seed corn at Waiahole location on the Island of Oahu.