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Irrigation Water Requirement Estimation Decision Support System (IWREDSS) to Estimate Crop Irrigation Requirements for Consumptive Use Permitting In Hawaii

Final Report

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STATE OF HAWAII
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EXHIBIT X-24

EXECUTIVE SUMMARY

This report gives a detailed over view version 2.0 of the Irrigation Water Requirement Estimation Decision Support System (IWREDSS, 2.0) – an ArcGIS-based numerical simulation model was developed to help estimate crop irrigation requirements for consumptive use permitting in Hawaii. The model estimates irrigation requirements (IRR) for perennial and annual crops grown on Hawaiian soils. The model estimates IRR and other water budget components including net irrigation water requirements (*NIR*), gross irrigation water requirements (*GIR*), water duty in inches of 1000 gallons per acre (GAL_A), gross rain (G_RAIN), net rain (N_RAIN), effective rain (*ER*), runoff (*RO*), canopy interception (*INT*), potential evapotranspiration (ET_O), reference evapotranspiration (ET_C), and drainage (*DR*). The model uses various irrigation application systems (i.e., trickle-drip, trickle-spray, multi sprinkler, nursery/container sprinkler, large gun sprinkler, seepage/sub irrigation, crown flood, and flood (Taro)), growing seasons, and irrigation practices (e.g. the usual practice of irrigating to field capacity, applying a fixed depth per irrigation event, and deficit irrigation).

IWREDSS uses different databases for weather, crop water uptake parameters, irrigation systems, and soil physical properties. These databases and other information used in IWREDSS are summarized in this report and include 1) potential evapotranspiration, 2) rainfall 3) soil physical properties, e.g., water holding capacities, and 5) crop water up take parameters (length of growing season, crop coefficient, and rooting depth).

IWREDSS 1.0 runs as an extension of the ESRI ArcGIS 9.2 software and IWREDSS 2.0 runs as an Adds-In of the ESRI ArcGIS 10.x. This report includes a step by step guide on how to use IWREDSS to simulate IRRs for a specific area based on its Tax Map Key (called in this document TaxID), or included in a digitized may as a GIS layer. IWREDSS results are presented in a text (ASCII) file and graphically as a GIS layer/map.

IWRDESS was calibrated and validated with irrigation data estimates from Hawaii USDA-NRCS Handbook 38 (USDA-NRCS, 1996). These data include irrigation requirements maps for some crops on the major Hawaiian Islands. A sensitivity analysis was also carried out to test the effect of the timing of growing seasons on the IRRs for seed corn (a four month growing

season) with twelve different starting dates throughout the year (January through December). IRR estimations were also calculated for different bioenergy crops under windward and leeward conditions on the islands of Maui, Kauai, Oahu, and Hawaii. Irrigation requirements calculated with IWREDSS for different crops grown under specific to Hawaiian Islands are in close agreement with those estimated by USDA-NRCS Handbook 38. The relative small differences between the two datasets could be due to several factors including spatial and temporal variability of rainfall, evapotranspiration, and soil physical properties, and interpolation methods used to estimate rainfall and evapotranspiration.

The Summary of improvements/changes in IWREDSS 2.0 is shown in the following table:

Comparison of different features of IWREDSS 1.0 and IWREDSS 2.0

Features	IWREDSS 1.0	IWREDSS 2.0
1. Soil data	Soil data of all islands as of May, 2008.	Updated soil data of all islands as of February 6, 2013, downloaded from the webpage of the Natural Resources Conservation Service, United States Department of Agriculture.
2. TaxID	TMK Parcels of all islands as of May, 2008	Updated TMK Parcels of all islands as of February 8, 2013, downloaded from the webpage of the Office of Planning, Department of Business, Economic Development & Tourism, State of Hawaii
3. Rainfall Atlas of Hawaii	Rainfall Atlas of Hawaii – R76 (Giambelluca et al., 1986)	Updated Rainfall Atlas of Hawaii - 2011 (Giambelluca et al., 2012)
4. Climate stations	Twelve climate stations with daily rainfall and potential evapotranspiration data.	Sixty seven climate stations with daily rainfall and potential evapotranspiration data.
5. Software for user interface	ESRI ArcGIS 9.2	ESRI ArcGIS 10.x
6. Crops data	16 Perennial and 23 annual crops	27 Perennial and 28 annual crops
7. Aquifers	No Aquifers data	Aquifers of DLNR and DOH were added for reference
8. Output format	Old output format	Format of output changed according to requirement of Commission of Water Resources Management.

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GLOSSARY:

- ALISH: Agricultural Lands of Importance to the State of Hawaii.
- AWD (Allowable Water Depletion): Fraction of the available soil water storage capacity that can be allowed to deplete without significant reduction in crop yield.
- DR (Drainage): Portion of incoming water that drains below plant root zone.
- ER (Effective Rain): Portion of water that is stored in the root zone and used by the plants.
- ET_C (Reference Evapotranspiration): Portion of water that vaporizes back to the atmosphere via plants. The ET_C is the amount of ET_O occurring from a specific crop.
- ET_O (Potential Evapotranspiration): Evapotranspiration to the given atmospheric conditions.
- G_RAIN (Gross Rain): The rain that falls from the clouds and reaches the crown of plants.
- GAL_A: Water duty in inches of 1000 gallons per acre.
- GIR (Gross Irrigation Requirements): NIR divided by the application efficiency of irrigation application system.
- GIS: Geographic information system.
- INT (Canopy Interception): Portion of G_RAIN intercepted by the plant canopy or crown.
- IWREDSS: Irrigation Water Requirement Estimation Decision Support System.
- IRR: Irrigation requirements
- K_C: Crop coefficient.
- LAI (Leaf Area Index): Ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows.
- LSB: Island-wide simulation using Land Study Bureau Classification.
- N_RAIN (Net Rain): The volume of rainfall that reaches the soil and comprises throughfall and stemflow.
- NIR (Net Irrigation Requirements): Irrigation requirements estimated by model without accounting for irrigation losses.
- PE: Open pan evaporation
- RO (Runoff): Portion of incoming water that runs off to the low level areas.
- SCS CN (Soil Conservation Services Curve Number): It is related to the imperviousness of a surface; for impervious and water surfaces CN=100, for natural surfaces CN < 100.

1. INTRODUCTION

This report gives an overview of the update of the Irrigation Water Requirement Estimation Decision Support System (IWREDSS, V 2.0) for the determination of reasonable water use quantities for selected crops across the major Hawaiian islands. IWREDSS estimates net and gross irrigation requirements (NIR and GIR, respectively) for different crops grown on specific soils, irrigated with a given irrigation system, grown during a specific time of the year, and under defined climate conditions. The irrigation requirement (IRR) of a crop is the amount of water, in addition to precipitation, that a crop needs to meet its evapotranspiration (ET) demand. The

irrigation requirements do not account for leaching, freeze protection, or crop cooling requirements, even though water for these purposes may be applied through an irrigation system.

IWREDSS is an ArcGIS based software, and its interface enables users to choose input data and display results. The user selects the area of interest based on its TaxID, or included in a digitized may as a GIS layer. Then the user chooses various options from drop down menus of the interface to select the crop to be grown/irrigated, crop leaf area index (LAI), the growing season, irrigation system to be used, and the curve number for the soil type / land use. The program accesses the weather and soil physical database library and interpolates rainfall and ET data based on location of the nearest weather station with respect to the area of interest. These interpolated data are then used for the IRR calculation. Up on the successful execution of the program, the users are given the option to retrieve the results in the form of a text (ASCII) file or displayed as a GIS map.

Recent developments in GIS systems present the opportunity to apply physically based soil water balance and simulation models at a regional scale (Satti et al, 2004). Satti and Jacobs (2004) developed GWRAPPS (GIS-based Water Resources and Agricultural Permitting and Planning System) model by coupling AFSIRS model (Smajstrla and Zazueta, 1988) with GIS. CropSyst (Stockle et al., 1994), AEGIS/WIN (Engel et al., 1997), and GWRAPPS are models that simulate the soil water budget components (WBC) by coupling crop parameters with soil and long-term climate databases. The estimation of IRR using IWREDSS requires databases of soils, crops, rainfall, ET, and other information. Geographical Information System has been employed to integrate these databases. These databases can be used repeatedly and can also be updated when new information becomes available.

This report covers the following deliverables.

- Databases of the IWREDSS elements and parameters
- GIS island maps showing NOAA climate stations used to develop the rainfall and ET databases.
- A DVD containing tested version of IWREDSS
- Results of IWREDSS calibration and validation
- Results of IWREDSS sensitivity analysis
- Testing of IWREDSS using energy crops
- IWREDSS user manual
- IWREDSS technical guide

The user's manual and the technical guide for IWREDSS are two separate documents; they are in appendices 1 and 2, respectively.

2. REVIEW OF LITERATURE

Numerical models for water management track the water budget of the soil-plant-atmosphere system; however, such models require large amounts of computation, time and data storage. Most importantly, data required for such detailed models are not available for all of the production systems of interest. The use of a real-time simulation model to increase accuracy is not justified. Thus, IWREDSS uses a daily soil water budget to calculate crop IRRs.

Technical Release 21, and empirical method developed by the Soil Conservation Service (SCS, 1970), estimates monthly IRR based on monthly average rainfall and ET, and on soil water-holding capacity. However, IWREDSS model integrates the effects of day-to-day distributions of rainfall, ET, and soil water-holding capacity to calculate IRRs.

Since the 1980's, the regional water management districts of Florida have been using this daily water budget approach. Melaika and Bottcher (1988) applied this approach to model nutrient movement from a South Florida watershed in the Everglades Agricultural Area. Villalobos and Fereres (1989) developed a water budget model based on long-term average potential ET and actual rainfall data. In their model, potential ET was assumed to be constant each year because long-term data were not available. Samani et al. (1987) used a water budget approach to develop a crop yield model. They simulated weather data because long-term climate data were not available.

Agricultural engineers recommend the water budget approach for the development of a basic irrigation scheduling model for Florida conditions (Smajstrla et al., 1988a). This approach was also used to develop a Florida citrus micro irrigation scheduling model (Smajstrla et al., 1987). Smajstrla and Zazueta (1987) demonstrated data requirements and sensitivity of the water budget approach to determine irrigation requirements of Florida nursery and agronomic crops.

Some water budget models were developed for specific crops, e.g., Brown et al. (1978), Odhiambo and Murty (1996), and Mishra (1999) worked on rice water balance. Pereira (1989) developed the rice water balance model IRRICEP and tested its performance against field data.

Paulo et al. (1995) validated the IRRICEP model using historical data on water use for selected sectors of Sorraia irrigation system in Brazil. Shah and Edling (2000) used the water balance approach to calculate daily ET from a flooded rice field using measured values of water level, rain, irrigation, seepage, and tail water runoff. Khepar et al. (2000) developed a water balance model applicable to intermittent irrigation practice in rice fields by incorporating saturated and unsaturated water flow concepts to predict deep percolation loss during wet and dry periods.

Many of water budget models lack user-friendly interfaces except few of them; these models offer limited flexibility in selecting a suitable method for estimating potential evapotranspiration. George et al. (2000) developed a user-friendly model (ISM) for field crops. Efforts have been exerted to couple user-friendly interfaces with Geographical Information Systems for efficient and quick data handling. Knox et al. (1996, 1997) developed a procedure for mapping the spatial distribution of crop irrigation water requirements based on crop parameters, climate and soil data in UK. Weatherhead and Knox (2000) developed a methodology for predicting future growth in irrigation water demand in countries with supplemental irrigation such as England and Wales using GIS. The GIS based water- and salt-balance studies at irrigation district level have also been attempted (Young and Wallender, 2002). George et al. (2004) used GIS to include spatial and extensive input information for their irrigation scheduling model.

These models compute the water budget for a specific field, one crop, and a complete growing season (monthly basis). In addition to simulation for an enhanced period of time, estimating IRRs on daily and weekly basis is needed. IWREDSS is based on the same approach used in the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988). IWREDSS calculates IRRs on weekly, bi-weekly, monthly and year bases; more output options are also available with the non-GIS version of the model IManSys (Fares and Fares, 2012). IWREDSS needs spatially distributed historical input data. Databases were developed encompassing the information required by IWREDSS for Hawaii conditions.

3. DATABASES

IWREDSS databases include historical daily potential evapotranspiration and rainfall for different locations across the major five Hawaiian Islands. The range of these two databases is

variable across the different locations. In addition, the model uses the crop database that includes all crop coefficients and root development parameters. Databases of crop factors, climate stations, soil and GIS data were updated in version 2.0 of the software. Brief description of each database is discussed here.

3.1 Crop factors

Crop parameters including effective rooting depths, crop coefficients (K_c), duration of cropping season, allowable water depletion for 29 major annual (Table 1) and 28 perennial (Table 2) crops grown on Hawaii are provided along with common irrigation systems and their corresponding irrigation efficiencies. Nine perennial crops and four annual crops were added to the dataset in IWREDSS 2.0.

3.2 Climate stations

Databases of daily rainfall, minimum and maximum temperature of 67 locations across the Hawaiian Islands were collected from the National Oceanic and Atmospheric Administration, National Climatic Data Center, NOAA, NCDC, (http://www.ncdc.noaa.gov/cdo-web/#t=firstTabLink). The major criterion used to select climate stations is the length of the period of their recorded data. We selected the stations with at least 19 years long data record. Twenty nine stations have more than 50 year data; whereas, 38 stations have data record between 19 and 50 years.

Table 1. Annual crop effective root depth, K_c values and stage lengths as a fraction of growing period

Crop	Root depth (in)		$Kc_{initial}$	Kc_{mid}	Kc_{late}	Duration (fraction of crop cycle)				Allowable water depletion (fraction of total)				Irrigation type	Irrigation efficiency (%)
	Initial	Final				Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4		
Alfalfa, initial	8	24	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	Sprinkler	70
Alfalfa, ratoon	24	24	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	Sprinkler	70
Bana Grass (Sudan), 1st cut	18	36	0.5	0.9	0.85	0.33	0.33	0.2	0.14	0.5	0.5	0.5	0.5	Sprinkler	70
Bana Grass (Sudan), 2nd cut	36	36	0.5	1.15	1.1	0.08	0.4	0.32	0.19	0.5	0.5	0.5	0.5	Sprinkler	70
Banana, initial	24	48	0.5	1.1	1	0.31	0.23	0.31	0.15	0.35	0.35	0.35	0.35	Micro-spray	80
Banana, ratoon	48	48	1	1.05	1.05	0.33	0.16	0.49	0.01	0.35	0.35	0.35	0.35	Micro-spray	80
Cabbage	8	12	0.7	1.05	0.95	0.24	0.36	0.3	0.09	0.45	0.45	0.45	0.45	Drip	85
Cantaloupe	8	12	0.5	0.85	0.6	0.08	0.5	0.21	0.21	0.35	0.35	0.35	0.35	Drip	85
Dry Onion	8	12	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.9	Drip	85
Eggplant	8	12	0.7	1.05	0.9	0.21	0.32	0.29	0.18	0.4	0.4	0.4	0.4	Drip	85
Ginger (AWD potatoes)	8	12	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.25	Drip	85
Lettuce	8	12	0.7	1	0.95	0.2.7	0.4	0.2	0.13	0.3	0.3	0.3	0.3	Sprinkler	70
Other melon	8	12	0.5	1.05	0.75	0.21	0.29	0.33	0.17	0.35	0.35	0.35	0.35	Drip	85
Peanuts	12	18	0.4	1	0.55	0.25	0.32	0.25	0.18	0.5	0.4	0.5	0.5	Drip	85
Peppers	8	12	0.4	0.95	0.8	0.24	0.28	0.32	0.16	0.35	0.35	0.35	0.35	Drip	85
Pineapple, year 1	12	12	0.5	0.3	0.3	0.16	0.33	0.26	0.25	0.6	0.6	0.6	0.6	Drip	85
Pineapple, year 2	24	24	0.3	0.3	0.3	0.38	0.32	0.27	0.03	0.6	0.6	0.6	0.6	Drip	85
Pumpkin	8	12	0.5	1	0.8	0.2	0.3	0.3	0.2	0.35	0.35	0.35	0.5	Drip	85
Seed Corn	12	18	0.4	1.2	0.5	0.16	0.28	0.32	0.24	0.6	0.6	0.6	0.8	Drip	85
Soybean	12	18	0.4	1.05	0.45	0.14	0.25	0.43	0.18	0.5	0.5	0.5	0.67	Drip	85
Sugarcane, ratoon	36	36	0.4	1.25	0.75	0.1	0.15	0.46	0.29	0.65	0.65	0.65	0.65	Drip	85
Sugarcane, New- year 1	18	36	0.4	1.25	1.25	0.21	0.29	0.25	0.25	0.65	0.65	0.65	0.65	Drip	85
Sugarcane, New- year 2	36	36	1.25	1.25	0.75	0.14	0.14	0.14	0.59	0.65	0.65	0.65	0.65	Drip	85
Sunflowers	12	18	0.4	1.05	0.4	0.16	0.28	0.36	0.2	0.45	0.45	0.45	0.67	Drip	85
Sweet potato	8	12	0.5	1.15	0.65	0.12	0.24	0.4	0.24	0.65	0.65	0.65	0.65	Drip	85
Taro (Dry)	12	18	1.05	1.15	1.1	0.2	0.13	0.4	0.27	0.3	0.3	0.3	0.3	Drip	85
Taro (Wet)	12	18	1.25	1.25	1.25	0.2	0.13	0.4	0.27	0	0	0	0	Flood	50
Tomato	8	12	0.6	1.15	0.8	0.2	0.27	0.34	0.19	0.4	0.4	0.4	0.65	Drip	85
Watermelon	8	12	0.4	1	0.75	0.15	0.26	0.26	0.32	0.26	0.32	0.26	0.32	Drip	85

Table 2. Perennial crop effective root depth and K_C values by month of the year

Crop	Rootzone depth, in		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Irrigation type	Irrigation efficiency (%)
	Irrigated	Total														
Avocado	30	60	0.9	0.9	0.9	0.9	0.95	1	1	1	1	1	1	1	Drip	85
Bermuda grass	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Breadfruit	30	60	0.9	0.9	0.9	0.9	0.95	1	1	1	1	1	1	1	Drip	85
Citrus	30	40	0.56	0.62	0.71	0.78	0.82	0.86	0.88	0.87	0.85	0.81	0.75	0.67	Drip	85
Coconut, Palms	30	60	1	1	1	1	1	1	1	1	1	1	1	1	Drip	85
Coffee	24	48	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	Micro spray (MS)	0.8
Dendrobium, pot	8	8	1	1	1	1	1	1	1	1	1	1	1	1	MS; nursery sprinkler	0.80, 0.20
Dillisgrass	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Domestic Garden	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Draceana, pot	8	8	1	1	1	1	1	1	1	1	1	1	1	1	MS; nursery sprinkler	0.80, 0.20
Eucalyptus closed canopy	72	72	1	1	1	1	1	1	1	1	1	1	1	1	Micro spray	0.8
Eucalyptus young	48	72	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	Micro spray	0.8
Garden Herbs	12	24	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Guava	30	60	8	0.9	1	1	9	0.8	0.8	0.9	1	1	9	8.5	Micro spray	0.8
Heliconia	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Micro spray	0.8
Kikuyu grass	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Koa	72	72	1	1	1	1	1	1	1	1	1	1	1	1	Micro spray	0.8
Leuceana (Old)	72	72	1	1	1	1	1	1	1	1	1	1	1	1	Micro spray	0.8
Leuceana (Young	48	72	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	Micro spray	0.8
Lychee	30	60	0.95	1	1	1	0.95	0.9	0.9	0.85	0.8	0.8	0.9	0.9	Micro spray	0.8
Macadamia nut	30	60	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	Micro spray	0.8
Mango	30	60	0.9	0.9	0.9	0.9	0.95	1	1	1	1	1	1	1	Drip	85
Papaya	25	37	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	Drip	85
St. Augustine	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Ti	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Micro spray	0.8
Turf, Golf	9	24	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Turf, Landscape	12	24	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75
Zoysia grass	24	48	1	1	1	1	1	1	1	1	1	1	1	1	Sprinkler	0.75

Table 3. Detailed information of the climate stations used in the database.

S. No.	Climate Station	COOP ID	Island	Latitude (°N)	Longitude (°W)	Elevation (m)	From	To	Annual mean rain (in)	Annual mean ET₀ (in)	Remarks
1	EWA PLANTATION 741	510507	Oahu	21.37472	157.99167	6.1	1950	2005	25.147	70.162	Data gap from 1997 to 2001.
2	HAINA 214	510840	Hawaii	20.10000	155.46667	140.5	1950	1993	75.109	68.234	
3	HALEAKALA EXP FARM	510995	Maui	20.85000	156.30000	640.1	1950	1991	84.655	51.044	
4	HALEAKALA RS 338	511004	Maui	20.76030	156.24700	2122.0	1950	2011	52.137	48.528	
5	HANA AP 355	511125	Maui	20.79470	156.01540	22.9	1951	2011	80.292	52.644	
6	HAWAII VOL NP	511303	Hawaii	19.42970	155.25620	1210.4	1950	2011	106.429	45.387	
7	HILO INTL AP	511492	Hawaii	19.71910	155.05300	11.6	1950	2011	127.086	50.240	
8	HONOLULU OBSERV. 702.2	511918	Oahu	21.31520	157.99920	0.9	1963	2011	19.671	68.159	
9	HONOLULU INTL AP	511919	Oahu	21.32389	157.92944	2.1	1950	2011	20.363	68.442	
10	HONOLULU SUBSTN 407	511924	Oahu	21.31667	157.86667	4.0	1950	1976	26.601	71.849	
11	HONOMU MAUKA 138	511960	Hawaii	19.85000	155.15000	335.3	1950	1977	216.367	37.415	
12	KAHUKU 912	512570	Oahu	21.69500	157.98111	4.0	1950	1972	50.530	65.616	
13	KAHULUI AP	512572	Maui	20.89972	156.42861	15.5	1954	2011	18.293	75.474	
14	KAILUA 446	512679	Maui	20.89050	156.21270	213.4	1950	2011	137.747	53.234	
15	KAINALIU 73.2	512751	Hawaii	19.53360	155.92580	457.2	1950	2011	64.526	34.890	
16	KAMUELA 192.2	513077	Hawaii	20.01667	155.66667	814.1	1951	1979	33.437	36.923	
17	KANALOHULUHULU 1075	513099	Kauai	22.12972	159.65861	1097.3	1955	2011	66.733	33.841	
18	KANEOHE MAUKA 781	513113	Oahu	21.41667	157.81667	57.9	1950	1997	77.365	35.581	
19	KAPALUA W MAUI	513317	Maui	20.96250	156.67530	73.2	1987	2011	28.955	72.312	
20	KAPOHO BEACH 93.11	513368	Hawaii	19.50140	154.82220	6.1	1977	2011	82.909	62.144	
21	KEAAU 92	513872	Hawaii	19.63290	155.03390	67.1	1963	2011	164.000	51.735	
22	KEKAHA 944	514272	Kauai	21.96944	159.71100	2.7	1950	2000	21.861	68.962	
23	KII-KAHUKU 911	514500	Oahu	21.67930	157.94530	7.6	1980	2011	38.208	64.772	
24	KILAUEA 1134	514561	Kauai	22.21389	159.40444	118.9	1950	2011	77.016	61.341	
25	KILAUEA POINT 1133	514568	Kauai	22.23333	159.40000	54.9	1950	1985	58.808	72.148	
26	KOHALA MISSION 175.1	514680	Hawaii	20.22500	155.79330	164.6	1950	2011	74.833	73.553	
27	KONA AP 68.3	514764	Hawaii	19.65000	156.01667	9.1	1950	1979	25.340	52.735	

Contd...

S. No.	Climate Station	COOP ID	Island	Latitude (°N)	Longitude (°W)	Elevation (m)	From	To	Annual mean rain (in)	Annual mean ET$_o$ (in)	Remarks
28	KULA BRANCH STN	515000	Maui	20.75840	156.32120	944.9	1979	2011	23.928	50.010	
29	KULA HOSPITAL 267	515004	Maui	20.70090	156.35620	923.5	1981	2011	31.156	50.418	
30	KULA SANATORIUM 267	515006	Maui	20.70090	156.36700	915.0	1950	1980	34.903	51.059	
31	KULANI CAMP 79	515011	Hawaii	19.54940	155.30110	1575.8	1950	2011	107.146	34.025	
32	LAHAINA 361	515177	Maui	20.87880	156.67410	11.6	1950	2001	16.377	68.239	
33	LANAI AP 656	515275	Maui	20.78950	156.94850	396.2	1950	2011	21.292	62.404	Data gap from 1957 to 1977.
34	LANAI CITY 672	515286	Maui	20.82910	156.92020	493.8	1950	2011	41.112	62.681	
35	LIHUE WSO AP	515580	Kauai	21.98389	159.34056	30.5	1950	2011	40.928	76.480	
36	MAKAHUENA POINT 940.1	515785	Kauai	21.86667	159.45000	15.8	1958	1976	36.171	71.762	
37	HAWAII KAI GC	515800	Oahu	21.29889	157.66444	8.5	1950	1973	31.945	63.148	
38	MAKENA GOLF CRS	515842	Maui	20.64190	156.44000	26.8	1982	2011	16.237	54.468	
39	MAKAWELI 965	515864	Kauai	21.91889	159.62778	42.7	1950	2011	24.524	67.999	
40	MANA 1026	516082	Kauai	22.03000	159.76278	6.1	1950	2001	23.781	63.440	
41	MANOA LYON ARBO	516128	Oahu	21.33310	157.80250	152.4	1975	2011	153.321	43.633	
42	MAUNA LOA SLOPE	516198	Hawaii	19.53620	155.57670	3398.5	1955	2011	21.631	61.383	
43	MOLOKAI AP	516534	Molokai	21.15450	157.09610	135.0	1957	2011	25.682	63.080	
44	MTN VIEW 91	516552	Hawaii	19.54870	155.11010	466.3	1950	1985	193.957	31.493	
45	NAALEHU 14	516588	Hawaii	19.06140	155.58420	201.2	1950	2011	52.957	62.641	
46	OHE'O 258.6	517000	Maui	20.66160	156.04430	26.2	1982	2011	84.703	53.086	
47	OOKALA 223	517131	Hawaii	20.01667	155.28333	131.1	1950	1993	118.574	67.945	
48	OPAEULA 870	517150	Oahu	21.57380	158.03790	288.0	1950	2011	66.205	49.282	
49	OPIHIHALE 2 24.1	517166	Hawaii	19.27050	155.87460	414.5	1956	2011	40.756	40.099	
50	PAHALA 21	517421	Hawaii	19.19870	155.47780	256.0	1950	1984	52.960	50.640	
51	PEPEEKEO MAKAI 144	518000	Hawaii	19.85000	155.08333	31.1	1950	1971	136.458	52.003	
52	PRINCEVILLE RCH 1117	518165	Kauai	22.21806	159.48278	66.1	1950	2011	87.160	59.687	
53	PUUKOHOLA HEIAU 98.1	518422	Hawaii	20.02560	155.82200	40.5	1977	2011	10.388	74.017	
54	PUU MANAWAHUA 725.6	518500	Oahu	21.38139	158.11972	509.9	1977	2008	29.856	66.164	

Contd...

S. No.	Climate Station	COOP ID	Island	Latitude (°N)	Longitude (°W)	Elevation (m)	From	To	Annual mean rain (in)	Annual mean ET_o (in)	Remarks
55	SEA MTN 12.15	518600	Hawaii	19.13350	155.51130	24.4	1982	2011	38.940	56.327	
56	SOUTH KONA 2	518652	Hawaii	19.08260	155.75320	646.5	1989	2011	22.122	62.390	
57	UPOLU POINT USCG	518830	Hawaii	20.25000	155.88333	18.6	1956	1992	32.570	68.147	
58	UPPER WAHIAWA 874.3	518838	Oahu	21.49930	158.01090	306.9	1971	2011	70.133	48.443	
59	WAIAHI LOWER 1054	518958	Kauai	22.01667	159.45000	172.2	1950	1986	122.778	53.031	
60	WAIALUA 847	519195	Oahu	21.57500	158.12028	3.0	1950	2000	34.759	57.520	
61	WAIKIKI 717.2	519397	Oahu	21.27160	157.81680	3.0	1965	2011	23.901	70.887	
62	WAILUKU 386	519484	Maui	20.89972	156.51556	164.6	1950	2002	34.707	55.087	
63	WAIMANALO EXP FARM	519523	Oahu	21.33556	157.71139	19.5	1970	2011	43.392	50.961	
64	WAIMEA ARBORETUM 892.2	519603	Oahu	21.63690	158.05360	12.5	1984	2011	55.335	57.020	
65	WAIMEA 947	519629	Kauai	21.95910	159.67590	6.1	1950	2011	22.432	72.109	
66	BARKING SANDS	22501	Kauai	22.03333	159.78333	4.0	1969	2011	20.143	69.988	Data gap from 1976 to 1981.
67	EWA KALAELOA APT	022514/ 022551	Oahu	21.31667	158.06667	16.5	1950	2011	17.764	71.937	Station ID is changed to 022551 from 1998.

3.2.1 Rainfall

The rainfall databases available to IWREDSS across Hawaii's islands are of different periods of record (Table 3). The minimum period of record of the selected stations is of 19years, several stations have records of more than 50 years.

Short-duration missing rainfall data for a give station were estimated following the normal ratio method that uses three index gauges which have the highest correlation with the station in question. The analysis was carried out for each island individually and all islands combined. There were minimal differences between general statistics of complete data (mean, max, min, standard deviation) generated based on each island individually and data of all islands combined; thus, data based on island wide analysis was used to fill in the missing data.

Fig. 1 shows the comparison of annual average rainfall based on the observed data of each station in the database and the value of rainfall grid of the corresponding station derived from the Rainfall Atlas of Hawaii (Giambelluca et al., 2012).
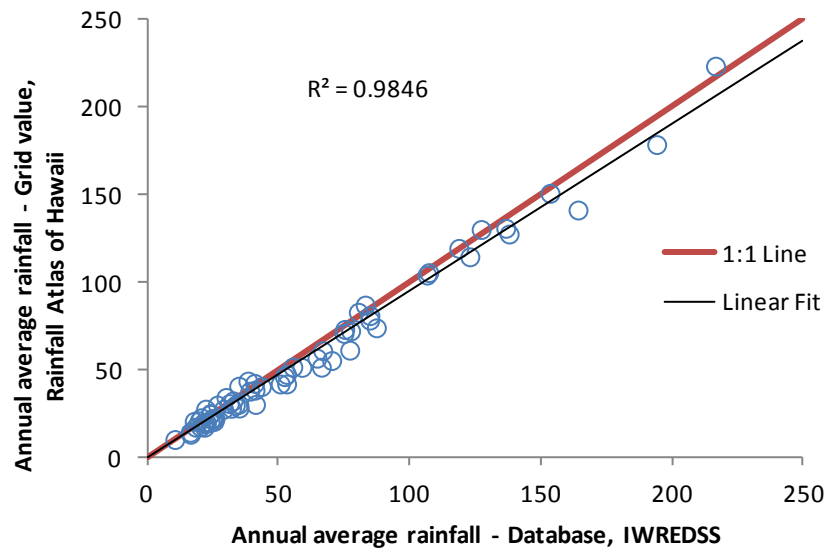

Figure 1: Comparison of annual average rainfall (database, IWREDSS vs. grid value derived from Rainfall Atlas of Hawaii, 2011).

3.2.2 Potential Evapotranspiration (ET$_o$)

Reference evapotranspiration was calculated using Hargreaves-Samani (1982) equation

as detailed in Appendix 3. Minimum and Maximum temperature were used in Hargreaves-Samani equation to calculate reference evapotranspiration. Missing evapotranspiration data for any day was replaced with its daily average of all the other years where there is data.

3.2.2.1 Adjustment of ET_o

Daily ET_o data generated with H-S equation were adjusted so that its average annual value matches the average Pan Evaporation (PE) of the station as reported in Ekren and Cheng (1985). Figure 2 shows a comparison of the annual average potential evapotranspiration, ET_o, of all stations calculated with H-S equation (adjusted) and derived from (PE) data as reported by Ekren and Cheng (1985).
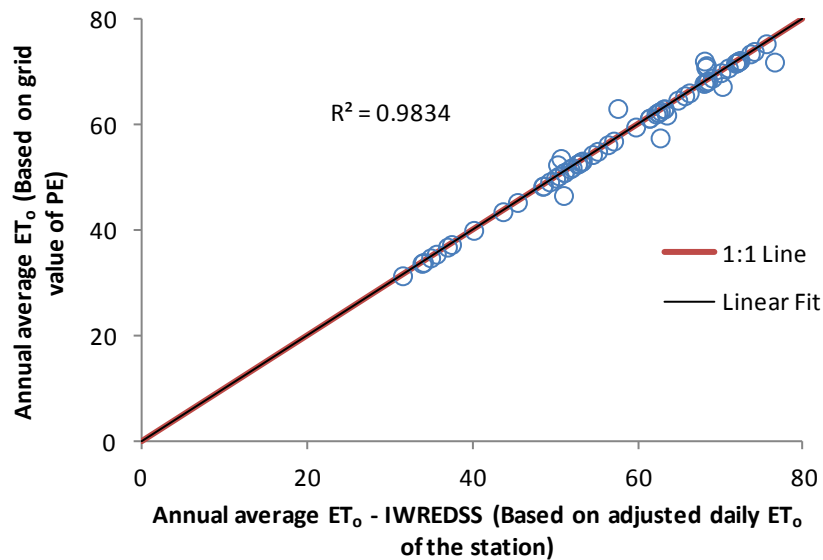

Figure 2: Scatter plot of annual average ET_o after adjustment of 56 stations based on PE grid and 11 stations based on annual average PE of the station

3.3 Soil data

The updated soil survey dataset of the Island of Hawaii become available to the public in September 2012 at the soil datamart (http://soildatamart.nrcs.usda.gov/). Soil data for IWREDSS were updated incorporating updated soil data of the Island of Hawaii. Spatial (Projected Coordinate System – NAD_1983_Zone_4N) and tabular data of the Island of

Hawaii and Hawaii Volcanoes National Park were collected from the webpage of the Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA) (http://soildatamart.nrcs.usda.gov/Survey.aspx?State=HI).

Soil hydrologic group database of the Island of Hawaii was created using updated soil data of Hawaii (i.e. HAWAII.csv). Similar database of all islands were combined to create updated SOIL_HYDROGROUP.dbf.

3.4 GIS data

Details of all GIS layers included in IWREDSS are described in Appendix 1. Brief description of updated GIS data is discussed here.

3.4.1 Soil data

The updated soil data of the Island of Hawaii was released to the public in September 2012 at the soil datamart (http://soildatamart.nrcs.usda.gov/); these soil data were used to update IWREDSS 2.0 database. The spatial GIS data of the Island of Hawaii and Hawaii Volcanoes National Park were downloaded from webpage of Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA).

3.4.2 TaxID

The updated TMK Parcels of all islands as of February 8, 2013 were downloaded from the webpage of the Office of Planning, Department of Business, Economic Development & Tourism, State of Hawaii (http://hawaii.gov/dbedt/gis/tmk.htm). The TMK Parcels of all Islands were merged to create a new "TaxID" layer.

3.4.3 Soil Statistic dataset

The GIS layer of Soil statistics dataset, "TaxID_Soil" and dbf file, "TaxID_Soil_Statistics.dbf" were updated using new data of soil and TaxID as explained in Appendix 2 (Procedure for preparing Statistics dataset).

3.4.4 Rainfall grid

The updated Rainfall Atlas of Hawaii in Grid format (Giambelluca, 2012), was downloaded from the web page of Geography Department, University of Hawaii at

Manoa (http://rainfall.geography.hawaii.edu/downloads.html). The updated rainfall grids are based on the 30-year (1978-2007) mean. The size of grid is 250 × 250m.

3.4.5 Potential evaporation grid

The potential evaporation grid implement in IWREDSS is that produced by Ekren and Cheng (1985). Their raster layer is used to scale evapotranspiration data of the nearest weather station to the TMK of interest.

3.4.6 Climate stations

GIS data of climate stations were updated using coordinates and climate file name of all the updated climate stations. Geographic Coordinates with 5 significant digits were used for all stations in the database.

3.4.7 Aquifers

GIS data of the major Islands aquifers were downloaded from the webpage of Hawaii Statewide Planning and Geographic Information System Program (http://planning.hawaii.gov/gis/download-gis-data/). Aquifer boundaries of DLNR and DOH were added to IWREDSS GIS data set library.

4. CALIBRATION AND VALIDATION

IWREDSS was calibrated and validated with data from the USDA-NRCS Handbook Notice 38 that comprises net annual irrigation requirement maps for various crops grown on the major islands of Hawaii. Several truck crops were selected (i. g., Egg Plant, Tomato, Cabbage, Ginger, Dry Onion, Sweet Potato, and Watermelon). Irrigation requirements were calculated for truck crops and banana at different islands assuming under a drip irrigation system since it is the irrigation system of choice in Hawaii. Table 4 presents the calculated irrigation requirements by IWREDSS and a summary of their corresponding estimates from the USDA-NRCS Handbook 38 (USDA-NRCS, 1996).

Percent differences between the two calculations were as low as 5% and varied as a result of the crop type and location. The differences in the estimates were expected since NRCS technique is more general and does not use specific crop parameters e.g., LAI, and SCS curve number information for different soil hydrological groups.

A regression analysis between the results of IWREDSS and the NRCS Handbook 38 was conducted (Fig. 3). Results show that there was a good agreement between the two data sets ($R^2 = 0.83$).

Table 4. Calibration and validation

| Scenario	Annual NIR (in)		Variation
Location, Crop, Irrigation System	IWREDSS	USDA-NRCS maps	%
Waimanalo (OA), Egg Plant, Trickle-Drip	23.1	17.0	36.1
Waimanalo (OA), Tomato, Trickle-Drip	24.2	17.0	42.3
Waimanalo (OA), Lettuce, Trickle-Drip	16.2	17.0	4.7
Waimanalo (OA), Cabbage, Trickle-Drip	19.1	17.0	12.6
Waianae (OA), Tomato, Trickle-Drip	49.1	59.0	16.8
Waianae (OA), Ginger, Trickle-Drip	55.6	59.0	5.7
Waianae (OA), Cabbage, Trickle-Drip	44.8	59.0	24.1
Waianae (OA), Egg Plant, Trickle-Drip	43.0	56.0	23.1
Waianae (OA), Dry Onion, Trickle-Drip	44.2	56.0	21.1
Kula (MA), Watermelon, Trickle-Drip	46.3	37.0	25.1
Kula (MA), Cabbage, Trickle-Drip	46.2	37.0	24.8
Kula (MA), Lettuce, Trickle-Drip	41.6	37.0	12.4
Haiku (MA), Banana (init), Trickle-Drip	31.2	42.5	26.7
Haiku (MA), Banana (init), Trickle-Drip	28.2	33.0	14.5
Haiku (MA), Banana (init), Trickle-Drip	25.5	30.0	15.1
Hoolehua (ML), Ginger, Trickle-Drip	50.8	55.0	7.6
Kaunakakai (ML), Ginger, Trickle-Drip	50.0	45.0	11.1
Kaunakakai (ML), Cabbage, Trickle-Drip	40.1	45.0	10.9
Kaunakakai (ML), Egg Plant, Trickle-Drip	42.2	45.0	6.3
Kilauea (KA), Egg Plant, Trickle-Drip	16.1	11.0	46.3
Kilauea (KA), Lettuce, Trickle-Drip	10.2	11.0	7.3
Kilauea (KA), Cabbage, Trickle-Drip	13.8	11.0	25.8
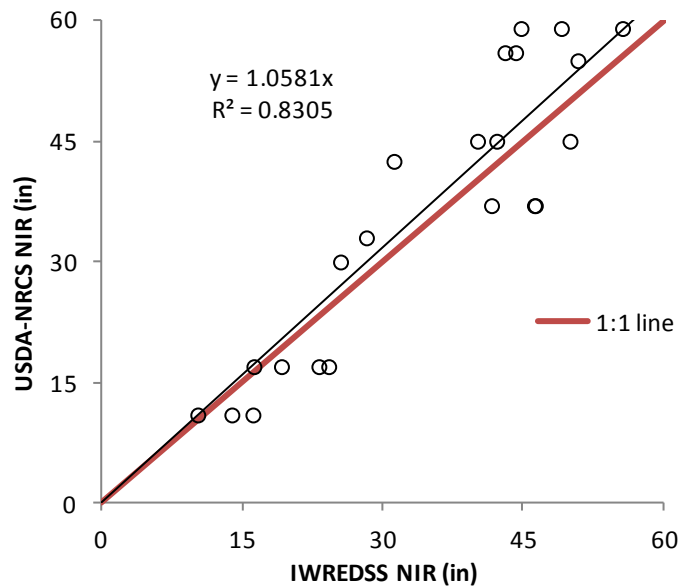
Figure 3: Validation of IWREDSS with USDA-NRCS results

5. PLOTTING THE MODEL RESULTS

The simulation results for all water budget components could be displayed with ArcGIS software where all ArcGIS functions could be used on these output layers i.e., labeling, classifying the parameters into various categories, merging or clipping more than one layer, and/or application of field calculator to generate further data from the attribute tables of the layers.

6. SENSITIVITY ANALYSIS

Sensitivity analysis is used to determine which input parameter has the greatest impact on the model's results/output. If a small change in a particular input parameter results in relatively large changes in the output, the value of the input parameter is considered very important and care should be given to accurately determine its values.

A Seed corn crop was selected for the sensitivity analysis because it became a popular and an economically important crop in Hawaii. Table 5 shows some information about seed corn, the average acreage of seed corn is 492 in the period between1999-2008 (National Agricultural Statistics Service, 2005, 2010) in Hawaii. The Trickle/drip

irrigation system was chosen due to its common use in Hawaii irrigated agriculture. The water requirements/allocations were simulated for a four-month-growing season with twelve different planting dates (from January to December). Since leaf area index (LAI) is a function of the plant growth stage, an average LAI value of 2.0 was used for the entire growing season. Water table depth was selected at 50 ft to consider deep water table conditions. The values of these parameters were kept constant for all the simulations; there were 12 simulations for windward (Waimanalo) and 12 simulations for leeward (Kunia) sides of Oahu. Efforts were made to conduct simulations for a similar soil type with the exact hydrological group (SCS curve number) to avoid soil type effect. Hydrological groups of the soils at both locations were "B" and SCS curve numbers were 81. Annual average rainfall at Kunia was 27.2 in; whereas at Waimanalo it was 44.7 in.

Table 5. Sweet corn: Acreage, yield, production, price, and value, in Hawaii, 1999-2008.

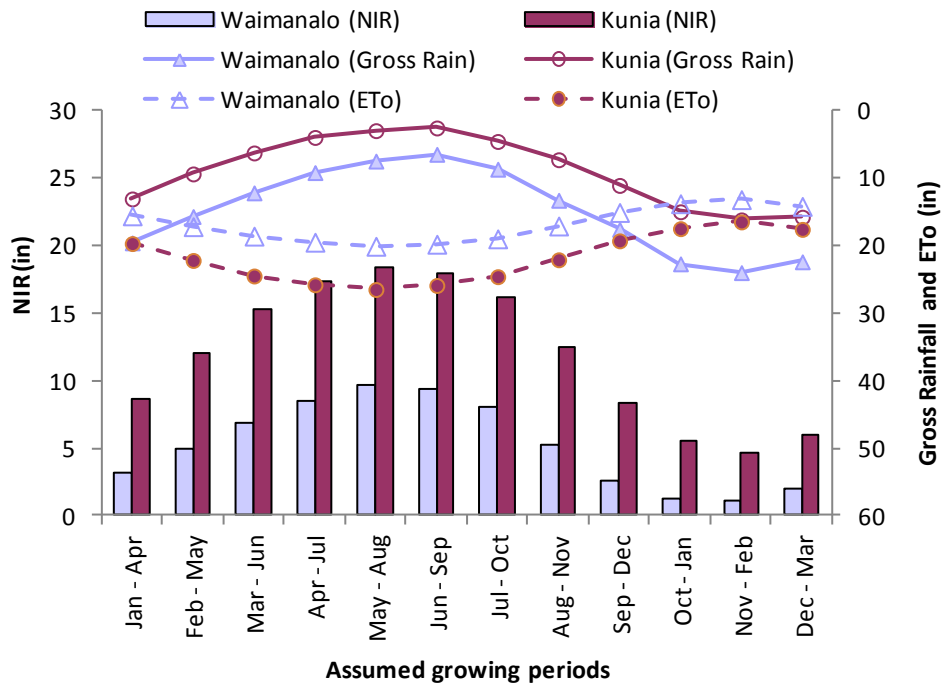| Year	Acres	Yield per acre	Production	Farm price
		1,000 pounds		*Cents per pound*
1999	450	3.8	1,700	58
2000	440	5.5	2,400	55
2001	440	4.3	1,900	64
2002	610	3.9	2,400	54
2003	830	3.0	2,500	51
2004	540	3.3	1,800	58
2005	410	4.1	1,700	55
2006	350	5.1	1,800	66
2007	450	5.3	2,400	62
2008	400	5.5	2,200	56

Figure 4. Changes in NIR based on changes in growing periods for seed corn grown on windward (Waimanalo) and leeward (Kunia) sides of Oahu.

The results of the sensitivity analysis of growing periods and locations comprise water budget components (Appendix 5a) and their corresponding statistics (Appendix 5b). The net irrigation requirements for the assumed growing periods are plotted in Figure 4, which clearly depicts a significant difference in NIR for windward and leeward sides of the island. The NIR were less during the wet period of the year (November to April) and more during the dry months (May to October) regardless of the location on the island.

6.1 Effect of crop leaf area index on irrigation allocations

For seed corn (growing season: April 15 to August 15), the NIR correlated positively with effective rain (ER) and correlated negatively with leaf area index (Fig. 5. NIR increased and ER decreased by almost 4% and 2%, respectively for every unit increase in the average LAI (Fig.9).
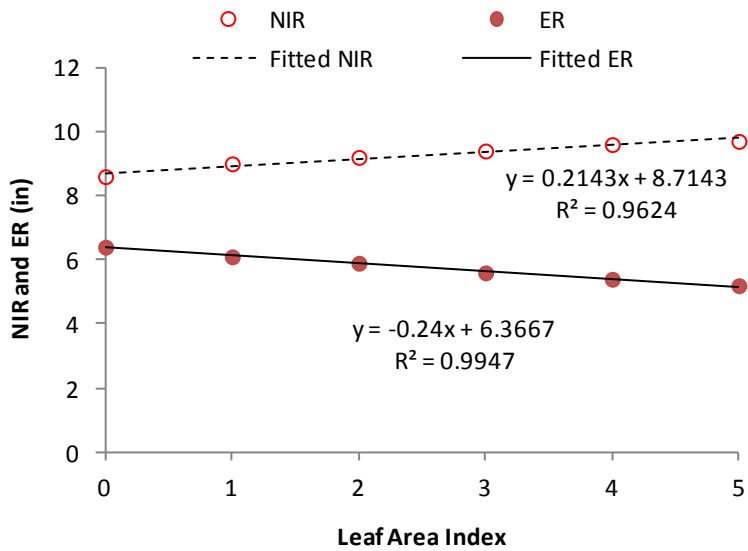
Figure 5: Net irrigation requirements (NIR) and effective rain (ER) versus leaf area index (LAI)
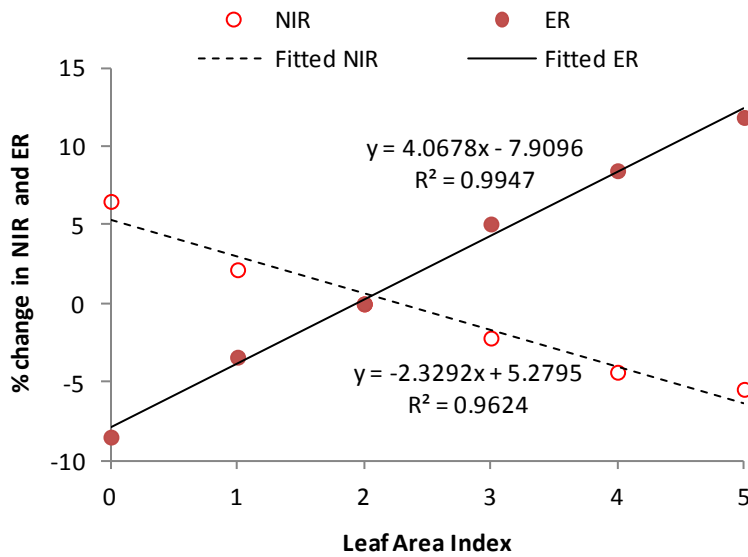

Figure 6. Percent change in Net irrigation requirements (NIR, open symbol) and effective rain (ER, closed symbol) with leaf area index (LAI).

7. SIMULATION USING ENERGY CROPS

Energy crops included the family of crops that could be used to produce energy in forms of heat or liquid fuel. Bioenergy crops often include food crops such as corn (starch for ethanol production) and sugarcane (sugar for ethanol production). The water budget components for the above energy crops were simulated for the dry and the wet growing

seasons for wind- and leeward sides of the island of Hawaii, Oahu, Maui and Kauai.

Growing seasons and their lengths for the selected energy crops are given in Table 6. Sugar cane has one year length irrigation seasons starting in May and October referred to as dry and wet seasons, respectively. For corn, the dry and wet seasons start in April and October, respectively. Since the irrigation seasons for sugarcane prolong to one full year, this crop experiences dry (April to November) and wet (October to March) months during its growth. One should expect approximately the same IRRs for both wet and dry seasons. Whereas, for corn the dry and wet seasons comprise only dry and wet months of the year, respectively, the irrigation requirement estimates would be significantly different for the two seasons.

Table 6. Energy crops and growing seasons selected for simulating irrigation requirements.

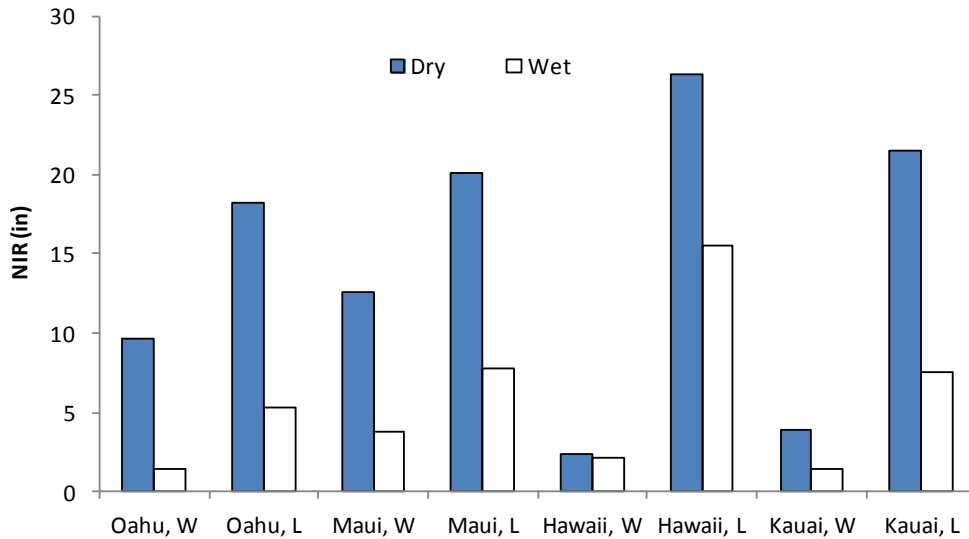| Crop	Season	Sowing	Harvesting	Length of season
Corn	Dry	April 15	August 15	123
Corn	Wet	October 15	February 15	124
Sugar cane Y-2	Dry	May 1	April 30	365
Sugar cane Y-2	Wet	October 1	September 30	365

The results of the simulation are given in Table 7 and plotted in Fig.7. As anticipated, there is a minimal (2.3 to 20.2%) difference (Table 8) in the NIR calculations for sugarcane, but the difference in corn NIR (12.5 to 85.6%) was significant. These variations can be attributed to the start and the end of a growing season for these crops and the plant water needs at different stages of growth. The pattern of rainfall and other weather conditions during these months in windward and leeward sides of the islands is also responsible for such variation.

Table 7: Net irrigation requirements (in) for energy crops grown on windward and leeward sides of the islands in dry and wet seasons
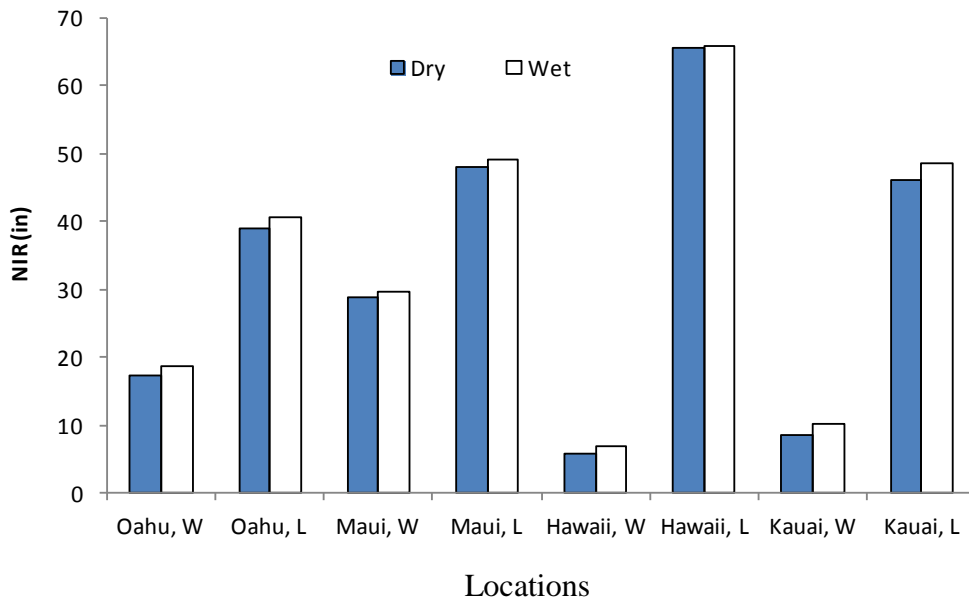
Crops	Irrigation season	Waimanalo Oahu windward	Kunia Oahu leeward	Kula Maui windward	W. Maui Maui leeward	Hilo Hawaii windward	Waikoloa Hawaii leeward	Lihue Kauai windward	Kekaha Kauai leeward
Corn	Dry	9.7	18.2	12.6	20.1	2.4	26.4	3.9	21.5
Corn	Wet	1.4	5.3	3.8	7.8	2.1	15.5	1.4	7.5
SugarC/Y2	Dry	17.2	38.9	28.8	47.9	5.9	65.5	8.4	46
SugarC/Y2	Wet	18.8	40.6	29.6	49	6.9	65.9	10.1	48.7

Table 8: Percent difference in the NIR calculated for energy crops during dry and wet seasons

Crops	Waimanalo Oahu windward	Kunia Oahu leeward	Kula Maui windward	W. Maui Maui leeward	Hilo Hawaii windward	Waikoloa Hawaii leeward	Lihue Kauai windward	Kekaha Kauai leeward
Corn	85.6	70.9	69.8	61.2	12.5	41.3	64.1	65.1
Sugarcane	9.3	4.4	2.8	2.3	16.9	0.6	20.2	5.9

(a) Corn

(b) Sugarcane

Figure 7: Irrigation requirements for (a) corn and (b) sugarcane.

8. SUMMARY AND CONCLUSION

This is the final report for the project: "Water Management Software to Estimate Crop Irrigation Requirements for Consumptive Use Permitting in Hawaii". ArcGIS based IWREDSS 2.0 was updated, calibrated, validated, and tested by conducting a sensitivity analysis. The report presents and discusses results from calibration, validation and sensitivity analysis. Hardware and software requirements are given in the IWREDSS 2.0 user manual (Appendix 1). Details on processes, governing equations, and methodologies are given in the IWREDSS technical guide (Appendix 2).

IWREDSS was calibrated and validated for truck and energy crops based on the data of the USDA-NRCS Handbook 38. A close agreement was observed between the estimates of the two techniques. The sensitivity analysis revealed that IWREDSS results are sensitive to the growing seasons due to variations in rainfall and ET. The LAI had positive effect on NIR.

The new version of IWREDSS 2.0 is capable of calculating water budget components for different crops grown on Hawaii. The current version, 2.0, comes with the following features:

- It estimates irrigation requirements for multiple crops/land uses, i.e., vegetable and fruit crops, lawn and golf courses for different time intervals: daily, weekly, bi-weekly, monthly, seasonally, and annually.
- It uses long-term historical climate databases of daily ET and rain to calculate the corresponding daily water budgets of the crop root zone. These calculations use a long-term historical daily reference ET and rainfall for the locations of interest.
- It estimates IRRs for different irrigation systems, including sprinkler, surface, micro and seepage systems.
- It uses specific inputs parameters for the crops, soils, irrigation systems, and management factors. The user selects the values of these parameters; however, default values are also included.
- The model is flexible enough to allow the users to add more crops and/or update data for a specific crop.

- Data output of the model can be plotted by ArcGIS and corresponding maps will be produced.

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10. APPENDICES

Appendix 1.

USER MANUAL

ArcGIS based graphical user interface of the Irrigation Water Requirement Estimation Decision Support System (IWREDSS) enables users to calculate irrigation requirements for given areas of their interest. Irrigation requirements can be calculated using either a Tax-ID GIS layer or a geo-referenced map of the area. This manual includes the details on how to digitize a hard copy of the area of interest. The user inputs include crop to be grown/irrigated, crop leaf area index (LAI), the growing season, irrigation system to be used, appropriate curve number, and water table depth. In addition to these inputs, IWREDSS uses the corresponding weather and soil data from its Geo-databases. IWREDSS results can be retrieved and visualized in the form of a text (ASCII) file and a GIS map upon successful execution.

System Requirement

Hardware
The system is recommended to have at least 2GB of memory (RAM).

Software
IWREDSS was developed and tested on Windows XP, Windows 7 and 8 with installed applications of ArcGIS 10.0 (ESRI product) and Java package - JRE (Java Runtime Environment). JRE can be downloaded at http://www.oracle.com/technetwork/java/javase/downloads/index.html. The following steps need to be completed to successfully operate the program.

Installation of IWREDSS
1. Copy the parent folder entitled "IWREDSS" and all its contents to preferred location on your computer (to your Desktop is fine). Do not alter the IWREDSS folder structure in any way. The IWREDSS.mxd initiates ArcMap application of ArcGIS and the data folder contains geo-databases of soil, climate, taxID, ALISH, LSB and an executable file of IWREDSS engine IWREDSS.

2. Set system variable "IWREDSS_HOME" to be the location of IWREDSS (Figure 1). To do this, click Start Menu > right-click Computer > click Properties > Advanced Settings > Environment Variables. Under User Variables, click New. In the New

User Variable form, for Variable Name put IWREDSS_HOME. For Variable Value put the path to where you placed the IWREDSS folder, e.g. C:\Documents and Settings\Awal\Desktop\IWREDSS\. Make sure to include the IWREDSS folder in the path name and to have a backslash at the end.
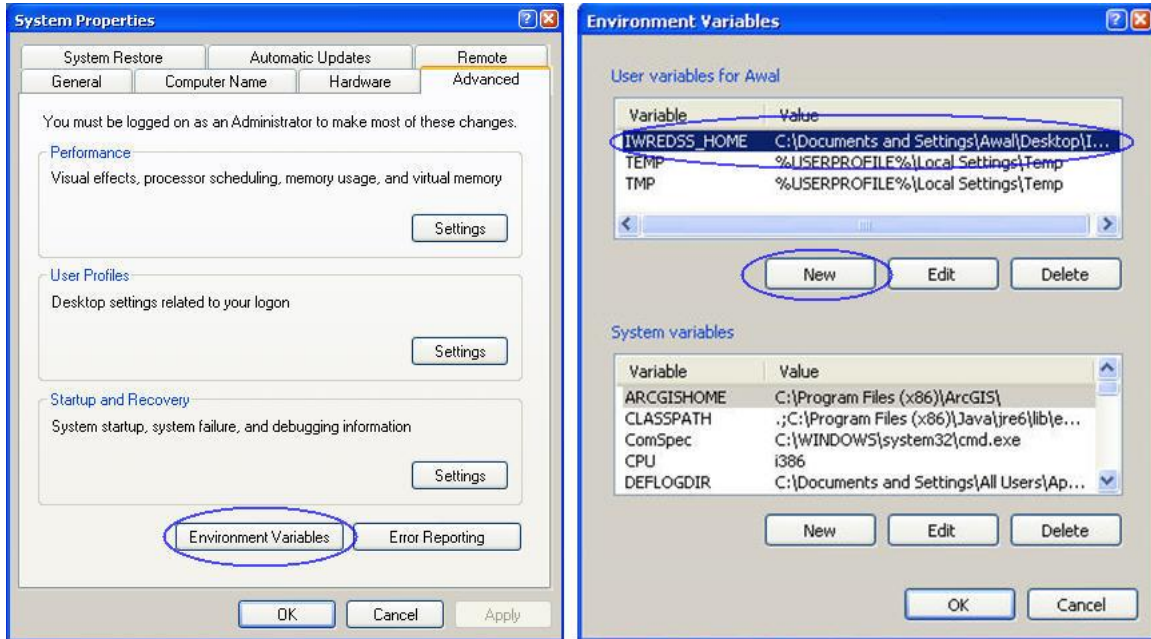

Figure 1

3. Install the IWREDSS ESRI Add-In and add the two IWREDSS buttons to ArcMap. Open the IWREDSS folder and double-click IWREDSS.ESRIADDIN. When the prompt window appears, click Install Add-In. This lets ArcGIS know that the add-in exists. Now double-click IWREDSS.mxd. This will open ArcMap. When it opens, click Customize > Customize Mode > Commands tab. In the Categories list, click .NET Commands. You'll see the two IWREDSS buttons in the Commands list. Drag and drop both buttons onto a toolbar at the top of the ArcMap window.

Simulation using IWREDSS

Water budget components are simulated using various ways. IWREDSS provides an option for Island wide and specific area simulation. Area simulation can be conducted by selecting a TaxID area on any of the islands or by providing a user geo-referenced GIS layer.

Area simulation using TaxID

Step 1: Open the ArcMap document
Open the file "IWREDSS.mxd" by double- or by right-clicking. An alternative way is to launch ArcMap first, then open the document "IWREDSS.mxd" from the File->Open menu or from ArcMap dialog, click the option to start using ArcMap with an existing map, then click OK to browse for IWREDSS.mxd file. The document opens displaying a map of Hawaii with polygons of different Tax ID areas (Figure 2).
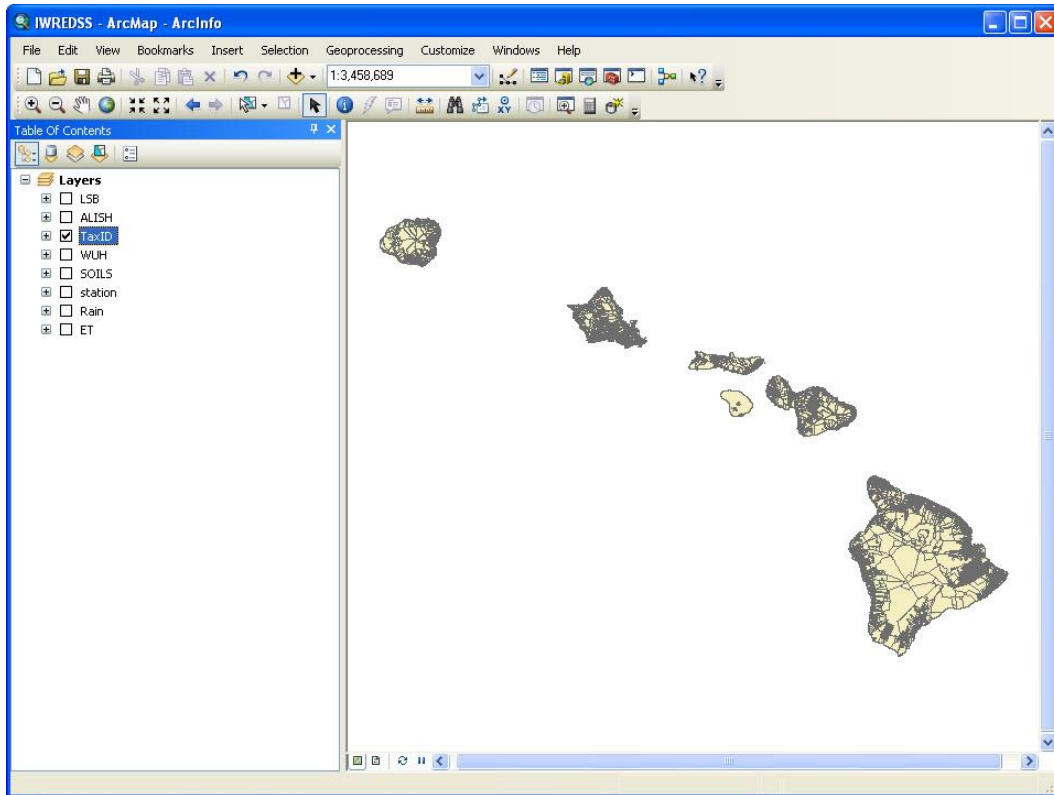
Figure 2

The table of content (TOC) of ArcMap (a list on the left side of the window) includes the following visible layers:

LSB: Land Study Bureau. (not active)

ALISH: Agricultural Lands of Importance to the State of Hawaii. (not active)

TaxID: The TaxID areas of all the islands
Station: The climate stations whose historical daily rainfall and ET_o data are used by IWREDSS.
Rain: Raster layer of rainfall. It contains annual average precipitation of every pixel on the map. The values are calculated from the rainfall isohyets (Giambelluca, et al.,

2012). This layer is unselected by default.

ET: Raster layer of pan evaporation which contains annual average Pan Evaporation of every pixel on the map. The values are calculated from the PE contours (Ekren and Cheng, 1985). This layer is unselected by default.

SOILS: A soil layer presenting soils of Hawaii used in simulation.

The above layers may be at different order in TOC.

Step 2: Select a TaxID area

Locate the area of interest on one of the Hawaiian Islands. It is suggested to zoom in the island of interest and click on TaxtID (irregular shaped polygons, sections on the map) specific to the area of interest. There are two ways to select a TaxID area as follows:

1. Directly select on the map.

    a) Using Zoom-in tool 🔍 find the area to be irrigated/simulated.

    b) Using Feature-selection tool ▣ select an area as shown in Figure 3. Note that you can choose 1 area (TaxID) for simulation at a time.
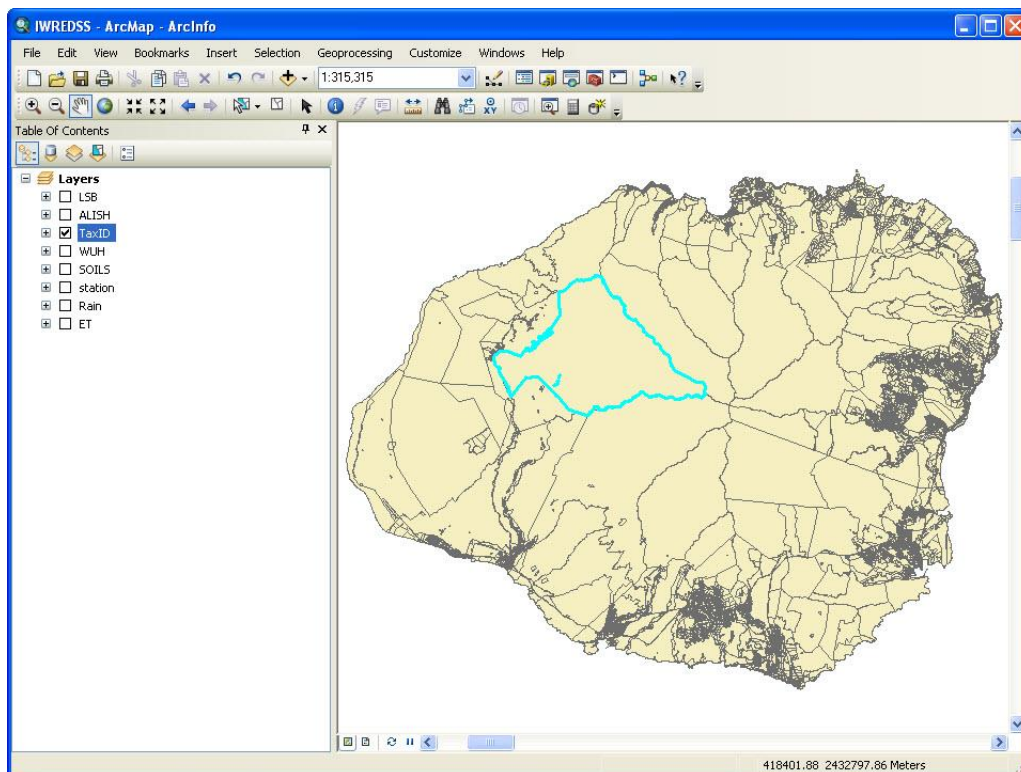
Figure 3

2. Select by area from the attribute table (Figure 4).

    a) In TOC, right click on TaxID and choose "Open Attribute Table" from the pop-up menu.

    b) In the attribute table, select Options->Select by Attribute, and then you can search by TMK or other features (like all areas larger than 300,000 acres)

    c) After clicking "apply", the matched record(s) and area(s) will be highlighted. If there are more than one records matched, you need to select only one from them.

    d) Select TMK number chosen for simulation.
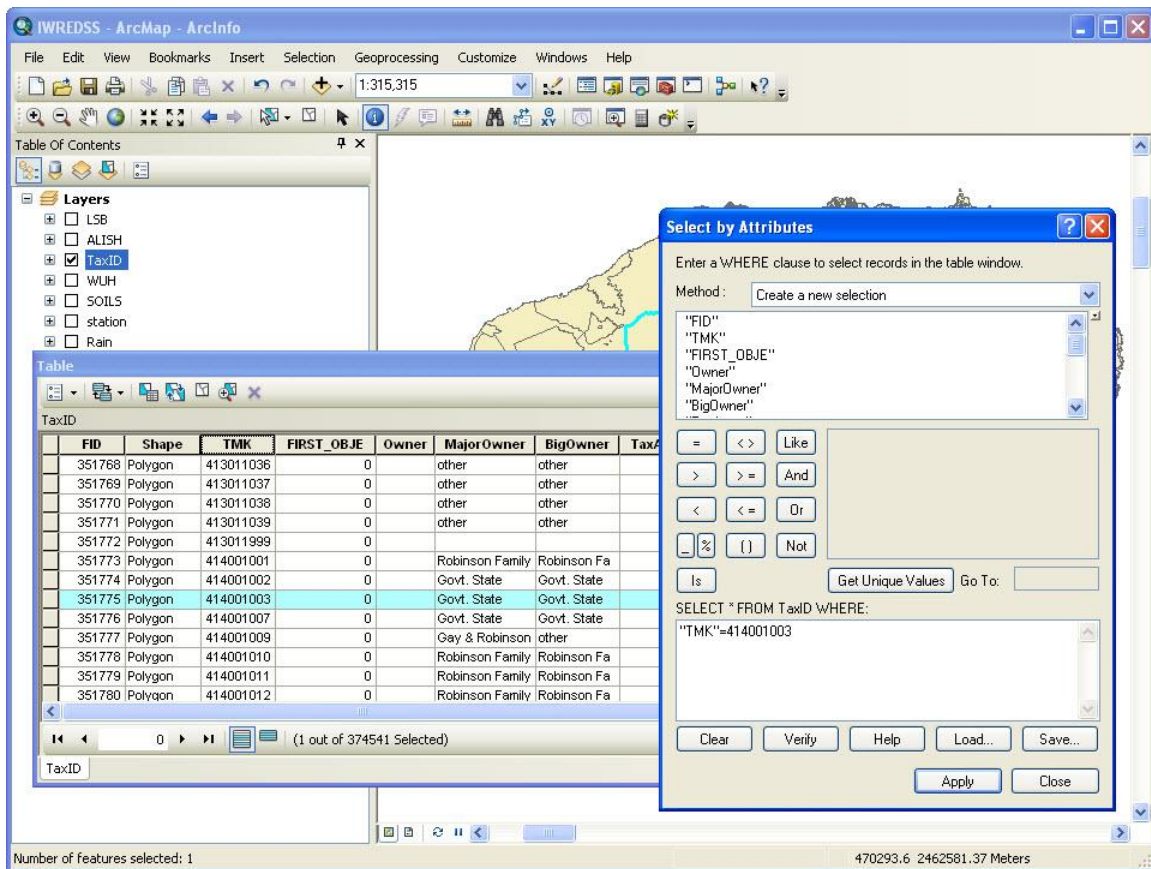
Figure 4

Step 3: Set other input parameters

After selecting an area, the user will need to input other required parameters by clicking the IWREDSS tool button ▦. The following window (Figure 5) will pop up.

User will need to input/select the following parameters:

Crop: User can select from the predefined list of crops given below:

27 PERENNIAL CROPS
GENERIC CROP

AVOCADO
BERMUDA GRASS
BREADFRUIT
CITRUS
COCONUT,PALMS
COFFEE
DENDROB.,POT
DILLIS GRASS
DOMEST.GARDEN
DRACEANE,POT
EUCALYP.,OLD
EUCALYP.,YNG
GARDEN HERBS
GUAVA
HELICONIA
KIKUYU GRASS
KOA
LYCHEE
MACADAMIA
MANGO
PAPAYA
ST.AUGUSTINA
TI
TURF, GOLF
TURF, LANDSCP
ZOYSIA GRASS

28 ANNUAL CROPS
GENERIC CROP
ALFALFA,INIT
ALFALFA,RATN
BANANA,INIT
BANANA,RATN
CABBAGE
CANTALOUPE
DRY ONION
EGG PLANT
GINGER,(AWD)
LETTUCE
OTHER MELON
PEANUTS
PEPPERS
PINEAPP.YR-1
PINEAPP.YR-2
PUMPKIN
SEED CORN
SOYBEAN
SUGAR C.RATN
SUGAR C.YR-1
SUGAR C.YR-2
SUNFLOWERS
SWEET POTATO
TARO (Dry)
TARO (Wet)
TOMATO

Figure 5: Interface of IWREDSS

WATER MELON

For each crop type, different root zone depths and water use coefficient data are defined: for perennial crops, the parameters include irrigate crop zone depth, total zone depth, monthly crop water use coefficient (K_C), and monthly allowable water depletion (AWD). For annual crops, the parameters include initial crop zone depth, maximum crop zone depth, fraction of growth of 4 stages, crop water use coefficient (K_C) of 4 stages, and allowable water depletion (AWD) of 4 stages.

For simplicity, the utility of customize crop is not provided in IWREDSS.

Max LAI: Maximum Leaf Area Index; The parameter used to calculate interception.

Irrigation period: User can specify this period that can be up to 1 year long; it can start at any month of the year and go around to the next year, i.e. starting date October of year one and ending date November of the following year. Note that if the irrigation period is too short (less than 45 days) for some annual crops, the simulation results would not be accurate.

Irrigation system: The users can select from the predefined list of irrigation systems given below:

> USER-SPECIFIED SYSTEM
> TRICKLE, DRIP
> TRICKLE, SPRAY
> MULTIPLE SPRINKLERS
> SPRINKLER, CONTAINER NURSERY
> SPRINKLER, LARGE GUNS
> SEEPAGE, SUBIRRIGATION
> CROWN FLOOD
> FLOOD (TARO)

For an irrigation system different from those mentioned above, the predefined parameters are different. The parameters include: system application efficiency, fraction of soil surface irrigated, and fraction of evapotranspiration.

Option for no irrigation: A provision is given to calculate water budget components without supplying additional irrigation. This option could be used for research purpose as to consider a natural hydrologic cycle where only rainfall is the input parameter and calculations are needed regarding effective rainfall, evapotranspiration, canopy interception, runoff, and drainage of the conservation

lands or other areas of interest.

Irrigation practice: The users are given options to select irrigation practice. A dropdown menu provides options for irrigation practices including a) Irrigate to field capacity (normal practice); b) Apply a fixed depth per irrigation, and c) Deficit irrigation. In case option "b" is selected, the users are asked to enter the depth of irrigation in inches. Percentage of deficit irrigation is required to enter in case option "c" is selected.

Additional Parameters: For the following list of the irrigation systems, additional parameters are needed.

IR System	Extra parameters
Crown Flood System	Crown flood System bed height
Seepage System	Depth to water table
Flood System	Rice flood storage depth

The additional parameters (in inches) can be entered in a box provided next to the Irrigation System box. When extra parameters are not needed, this box is grayed out.

Soil Hydrological Groups and SCS Curve Numbers: All soil types in the selected TaxID area are grouped into four hydrologic groups (A, B, C, and D). The portion of each group of the soils in the selected area is given (for example, a selected area may have 11.3% of group B, 22.8% of group C, and 64.8% of group D). For each group, user has to specify the corresponding SCS curve number (CN) for all the soil types in that group. The curve number is used in the calculation of runoff. For details of the calculation, please refer to IWREDSS User Guide.

By default, a CN value of 78 is given for each hydrologic group to remind users that they need to change these values to their correct values. Moreover, CN value of 78 is representative of most grass covers. A list of CN values for different cover and soil types is provided in Figure 6. User can refer to this list by clicking the "?" button next to the CN input box.

FormCN

Urban Area | Cultivated Agricultural Lands | Other Agricultural Lands | Arid and Semiarid Rangelands

Table 2-2a   Runoff curve numbers for urban areas (1)

Cover description — Cover type and hydrologic condition	Average percent impervious area (2)	— hydrologic soil group — A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) (3):					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc.					
(excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding					
right-of-way)	98	98	98	98	
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) (4)		63	77	85	88
Artificial desert landscaping (impervious weed barrier,					
desert shrub with 1- to 2-inch sand or gravel mulch					
and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre 38	61	75	83	87	
1/3 acre 30	57	72	81	86	
1/2 acre 25	54	70	80	85	
1 acre 20	51	68	79	84	

Figure 6: CN numbers

Depth to water table: This site-specific information is optional as the model considers 50 ft of water table depth. It is recommended to use the default depth unless the precise value of water table depth is known. Note that the units of water table depth are in feet.

Location: This is the name of location or area of interest. The name appears in the beginning of the IWREDSS text output file.

Step 4: Execute IWREDSS
After completing the required inputs, the user can trigger IWREDSS by clicking the "Run" button to start simulation. A text box message will be prompted to the user about the state of simulation (fails or succeeds).

Step 5: Reading the result
After successful execution, a message (Figure 7) pops up giving user an option to view the results. A notepad text file opens by clicking the "Yes" button on the option message box. By default, the output file is saved in the subfolder "data" of the installation folder of IWREDSS with the default name as "IWREDSS_out.txt" and is automatically overwritten by successive execution. Therefore, the user is advised to save the results after every simulation with a different name by using File>Save as option in notepad.
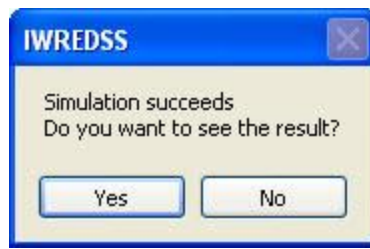
Figure 7

The output text file contains three major sections: a legend table, simulation parameters and simulation results. The legend table defines the abbreviations of parameters used in the output and their corresponding units. These parameters include the inputs parameters described in step 3 and the predefined parameters for crop type, irrigation system, soil type, etc. The simulation results include the simulation result of yearly average, monthly average, bi-weekly average and weekly average.

At the end of the output file, there is a summary of the results. Actually, the simulation of IWREDSS is based on one soil type. Thus, if there is more than one soil type for a particular area (or TaxID), IWREDSS would calculate irrigation requirements for each of these soils independently. The total irrigation requirements for the area of interest will be the weighted average of all the soils available in that area using the following formula:

$$IRR = IRR_1 * A_1 / A_T + IRR_2 A_2 / A_T + \ldots + IRR_n * A_n / A_T$$

where IRR_i , A_i are the calculated irrigation requirements and the area occupied by i-th soil respectively; A_T is the total area of the different soils available in the total area of the TaxID of interest. Note that IWREDSS will not simulate irrigation requirements for the non-arable parts of the area of the TaxID; thus, the sum of the sums of all A's will not be equal if there are non-arable part of the area of interest. In these cases, the proportion will be normalized so as to add up to 1. The list of all the simulated soil types and corresponding proportion of each of them are given in the beginning of the summary section of the report.

Summary of IWREDSS results are available at the end of the output file (Figure 8). IWREDSS uses calculated long-term daily record of irrigation water requirements to calculate statistical parameters and probabilities of occurrence of IRRs for various time periods (i.e., weekly, bi-weekly, monthly and yearly). Summary of IWREDSS results

provides IRRs for different probability levels, e.g. 50% (2 year return period), 80% (5 year return period), 90% (10 year return period) and 95% (20 year return period) probability of GIRs. The 80% probability level (1 in 5 year return period) is recommended by USDA-NRCS and is also used by the irrigation industry when designing irrigation systems; thus, it was adopted for crop water allocation. The summary table also provides information about irrigation season, irrigation system, climate database, TMK, soil data and other parameters used.

```
*******************************************************************
*    Commission on Water Resources Management IWREDSS Summary    *
*******************************************************************

IWREDSS estimates that irrigation needs for the application is:
-----------------------------------------------------------------
UNIT            /      *DROUGHT FREQUENCY      /        OTHER STATISTICS
                / 1 in 2   1 in 5   1 in 10  1 in 20 /
                / year     year     year     year  /   Mean    Median    Max      Min
inch/acre          3.130    6.104    8.108    9.988    3.735    3.626    9.749    0.000
Thou. gpd/acre     0.708    1.381    1.835    2.260    0.845    0.821    2.206    0.000
Total thou. gpd   21.155   41.251   54.794   67.503   25.244   24.505   65.889    0.000
-----------------------------------------------------------------
     *Drought frequency of 2, 5, 10 and 20 year return periods are GIR values of 50%, 80%, 90% and 95%
      probabilities, respectively.
     *GIR of 1 in 5 year return period is recommended by CTAHR for design or water use allocation purposes.

where:
Irrigation season              = 1-1 TO 4-30
Irrigation total days          = 120 days


Irrigation system:
TYPE                           = TRICKLE, DRIP
Design Application Efficiency   =  85 %
Fraction of Soil Surface Irrigated =  50 %
Fraction extracted from irigated zone =  40 %


Climate Data Base:
Location                       = WAIMANALO EXP FARM Latitude  21.3333
Length of Record               = 42 YEARS (1970~2011)
No. of missing rainfall days   = 0
No. of missing ET days         = 0


TMK                            = 41026002
TMK Area (Acre)                = 59.732
Soil Series                    = Haleiwa(0.125), Waialua(0.875)
SCS Curve Number               = 81
Net Irrigated Area (Acre)      = 29.866
Depth to water table (feet)    = 50.00


Crop type                      = SEED CORN
Max Leaf Area Index            = 2.000

-----------------------------------------------------------------
```

Figure 8

Step 6: Plotting the result

Switching from the text output file to ArcMap .The user is prompted to plot the results (Figure 9). The results are plotted on the map based on the yearly irrigation requirements for different soil type in the TaxID area.
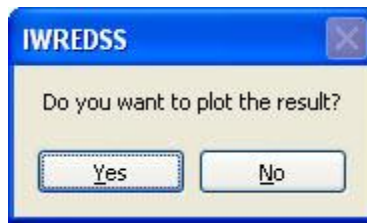
Figure 9

An example of color plotting is given in Figure 10. The user can visualize the results on an enhanced option (Figure 11) by clicking the ⬚ button to zoom to the whole TaxID Area.
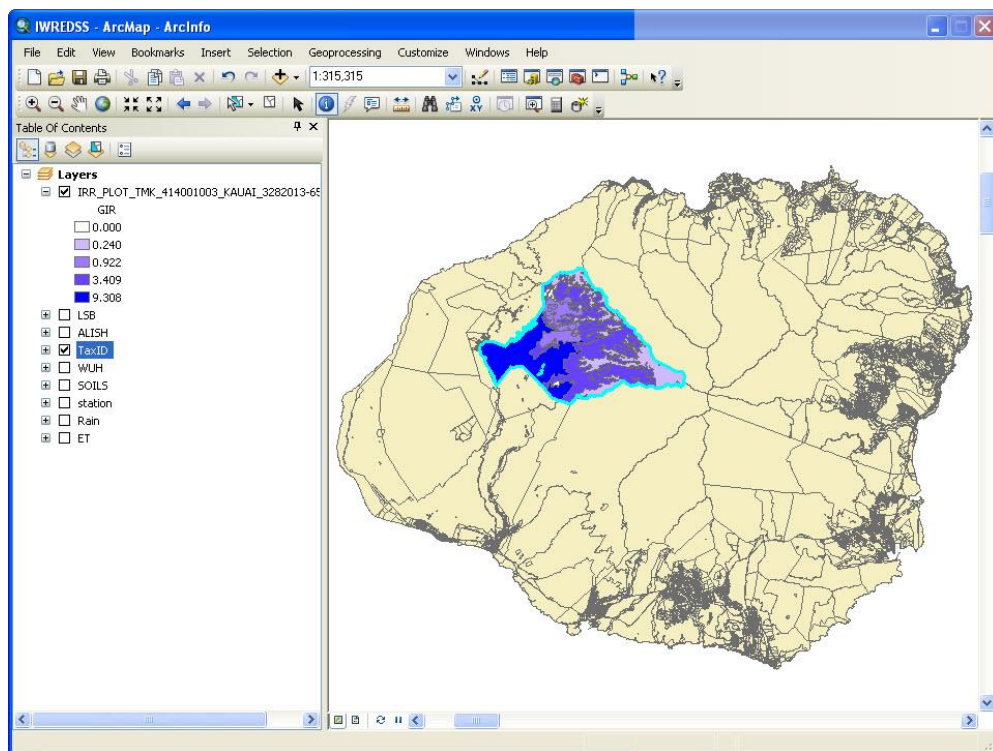
Figure 10
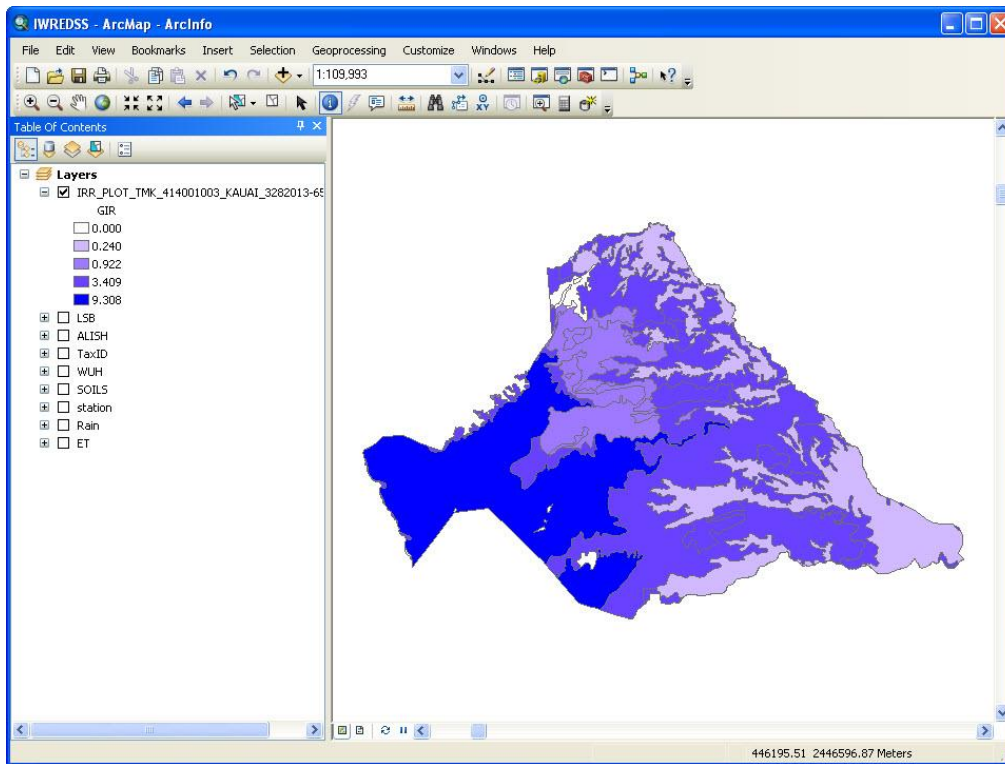
Figure 11

Simulation of user's provided layer

Simulation of an actual location and net acres on a parcel can be conducted by using a layer provided by the user. Ideally user's layer should be a geo-referenced GIS layer. In case user's layer is in the shape of a parcel or a farm map, it needs to be digitized, geo-referenced, saved as a polygon shapefile and have attribute table containing fields including FID, SHAPE, ID, ISLAND. Stepwise procedure on how to digitize from a parcel map is referred in the Technical Guide of IWREDSS.

The irrigation requirements for a user's specified GIS layer can be simulated using two methods. The user needs to provide a Geo-referenced GIS boundary layer of the area of interest e.g. an agricultural field or a golf course. Method 1 is used to simulate user defined layer when the area of interest is different from the combination of multiple TMKs. Method 2 is used to simulate user defined layer when the area of interest is the combination of multiple TMKs as a single polygon.

Method 1.

1. Add the folder containing supporting files of Geo-referenced GIS user's layer in

"IWREDSS\data\GIS"

2.   Create a folder "XXX_Soil (e.g. UserL_Soil)" in IWREDSS\data\GIS, where XXX is the name of user's layer (e.g. UserL). The name of the folder is case sensitive.

3.   Add user's layer in ArcMap TOC from "IWREDSS\data\GIS\folder containing layer" (e.g. UserL).
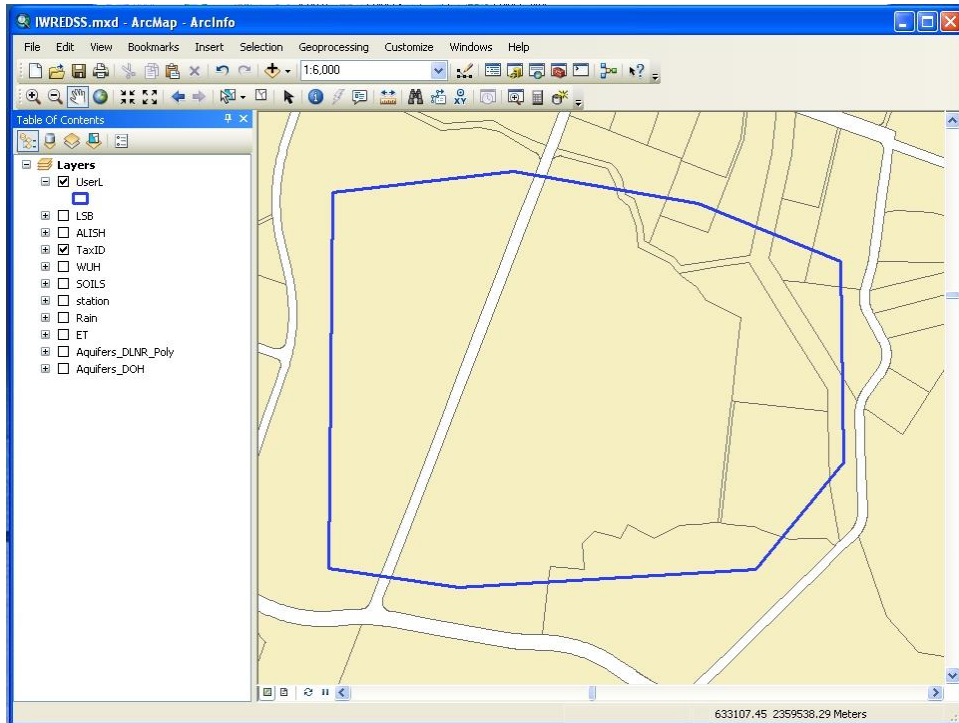
4.   The attribute table of the layer must contain fields including FID, Shape, Id, ISLAND, and AREA. The AREA field should have data "Type" as "double". The ISLAND filed should have data "Type" as "Text" and "Length" equivalent to 10.

5.   Values for the AREA field can be calculated using either VBScript or Python in

the **Field Calculator**. Alternatively, AREA can be calculated using **Calculate Geometry** (Right-click the field heading for which you want to make a calculation and click Calculate Geometry) as follows.
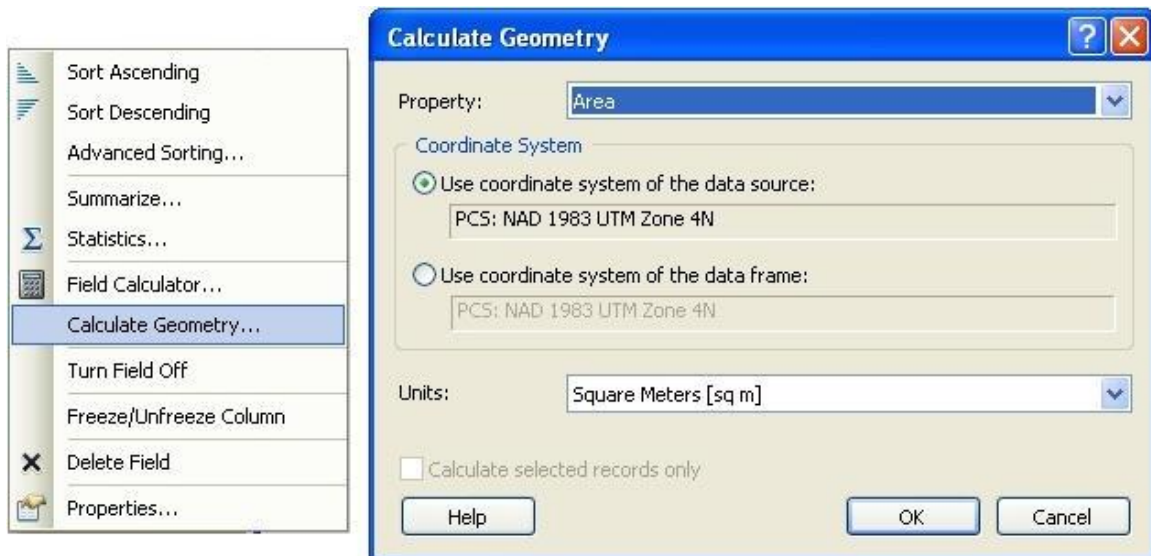
6.   Input file for IWREDSS can be prepared by clicking the database button besides IWREDSS button . (Buttons for IWREDSS execution and input file preparation are both located in the Tools toolbar).

7.   Clicking prompts a message box asking user to type in the name of user's layer (CASE SENSITIVE). Enter the layer name and click OK button. This executes a code to prepare input files (database).

8.   After a successful execution, a statistics table with the name "XXX_Soil_Statistics (e.g. UserL_Soil_Statistics)" will automatically be added to the TOC of ArcMap (You can view the statistics tables in the "List By Source" of the TOC).

Following message box will inform you after completion of data preparation:

9.   Selecting user's layer (e.g. UserL) and clicking IWREDSS button ▤ brings an interface that requires input parameter selections (Don't select other polygons in other layers, just select polygon of user's layer).
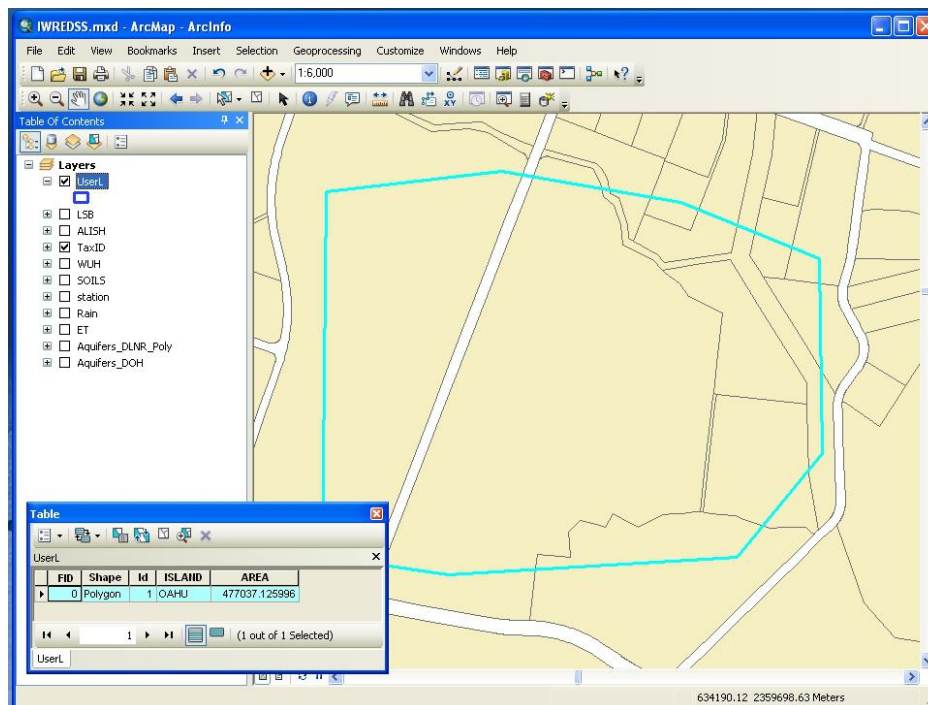
10.   From dropdown menus select the name of Island and the name of the user's layer (case sensitive). (Complete Steps 3 through 6 i.e., complete the other input parameter selections. Hit "Run" to start simulation, "Yes" to continue, "Yes" to see text simulation results, and "Yes" to plot the simulation results.
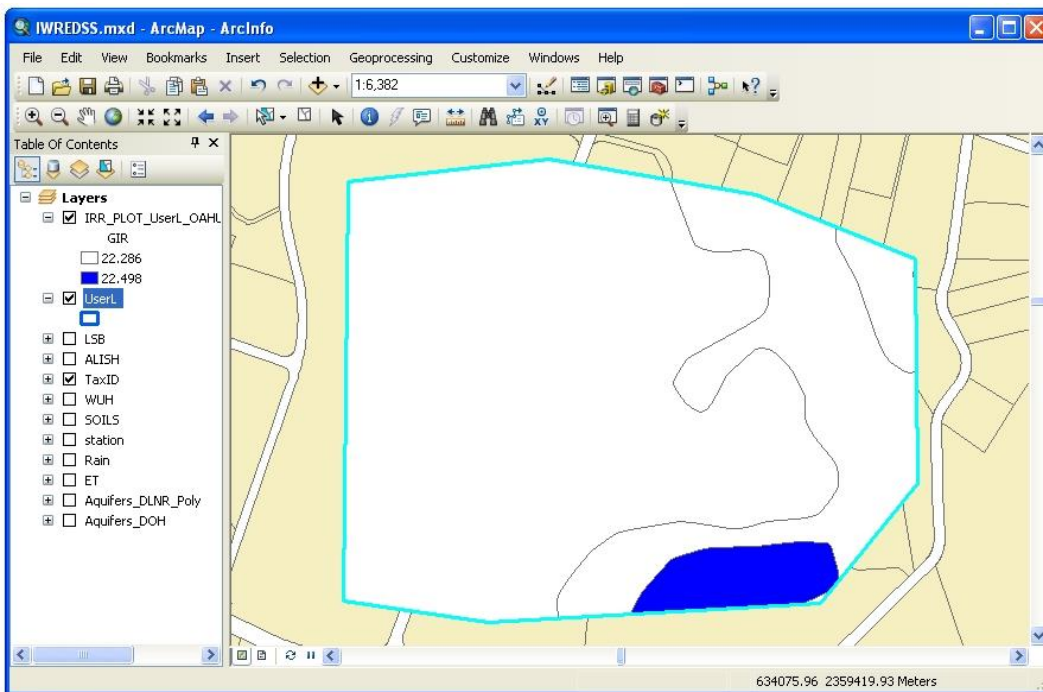
Method 2.

1.   Select TMKs of TaxID which you want to make a single polygon (In this example, TMKs 41026001, 41026002, 41026004 and 4126021 were selected).

2.   Create new shape file (e.g. WUH1) from selected TMKs (Select TaxID at TOC > Right click > Data > Export data)
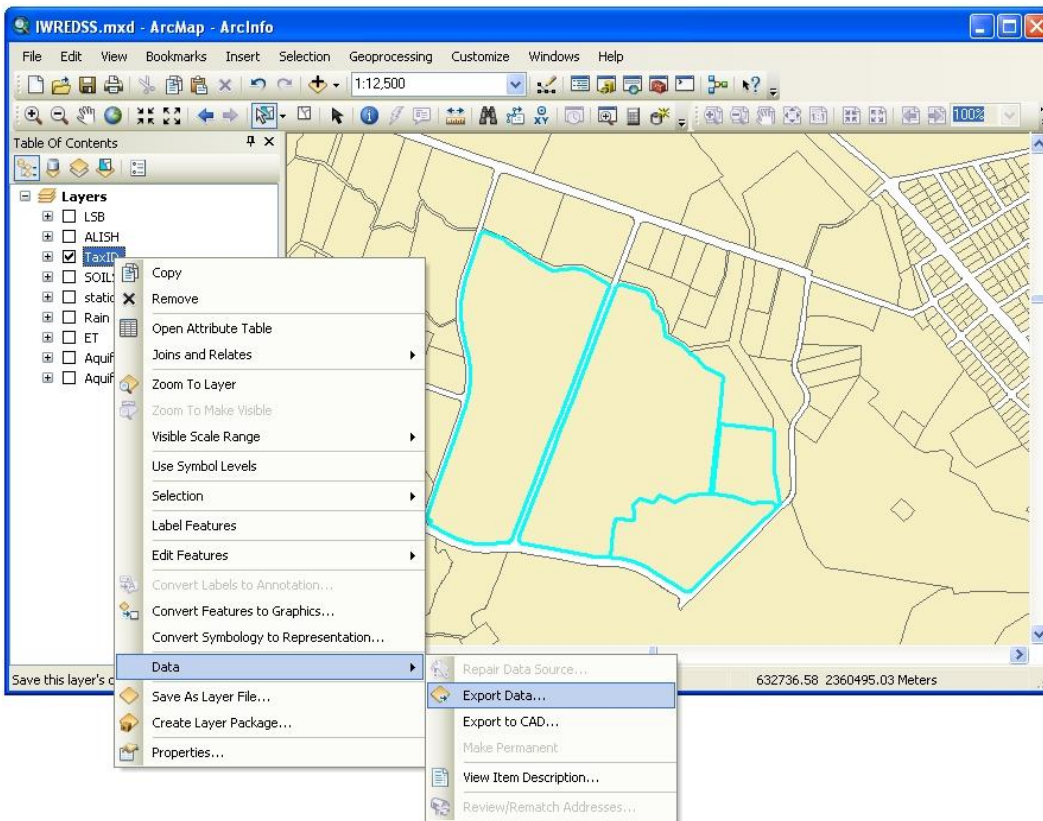
3.	Delete all fields in the attribute table of the new shape file (e.g. WUH1) except FID, Shape, Area and ISLAND.
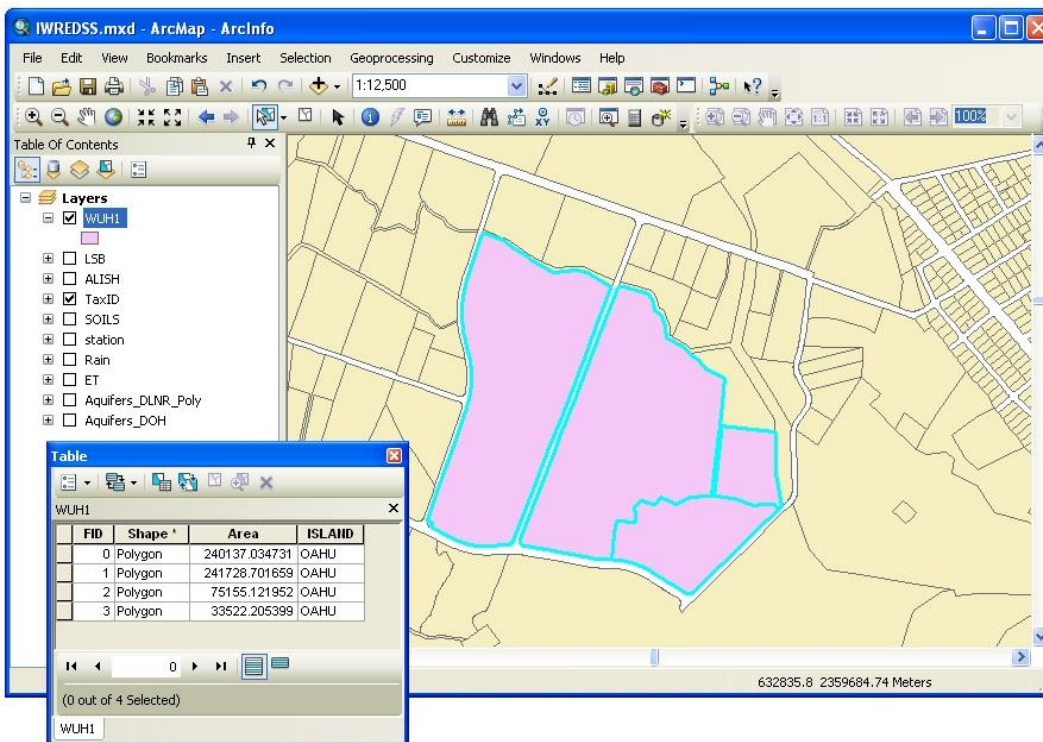
4.	Create a new shape file (e.g. WUH) of a single polygon using Dissolve tool (Geoprocessing > Dissolve) as shown in the following figure.
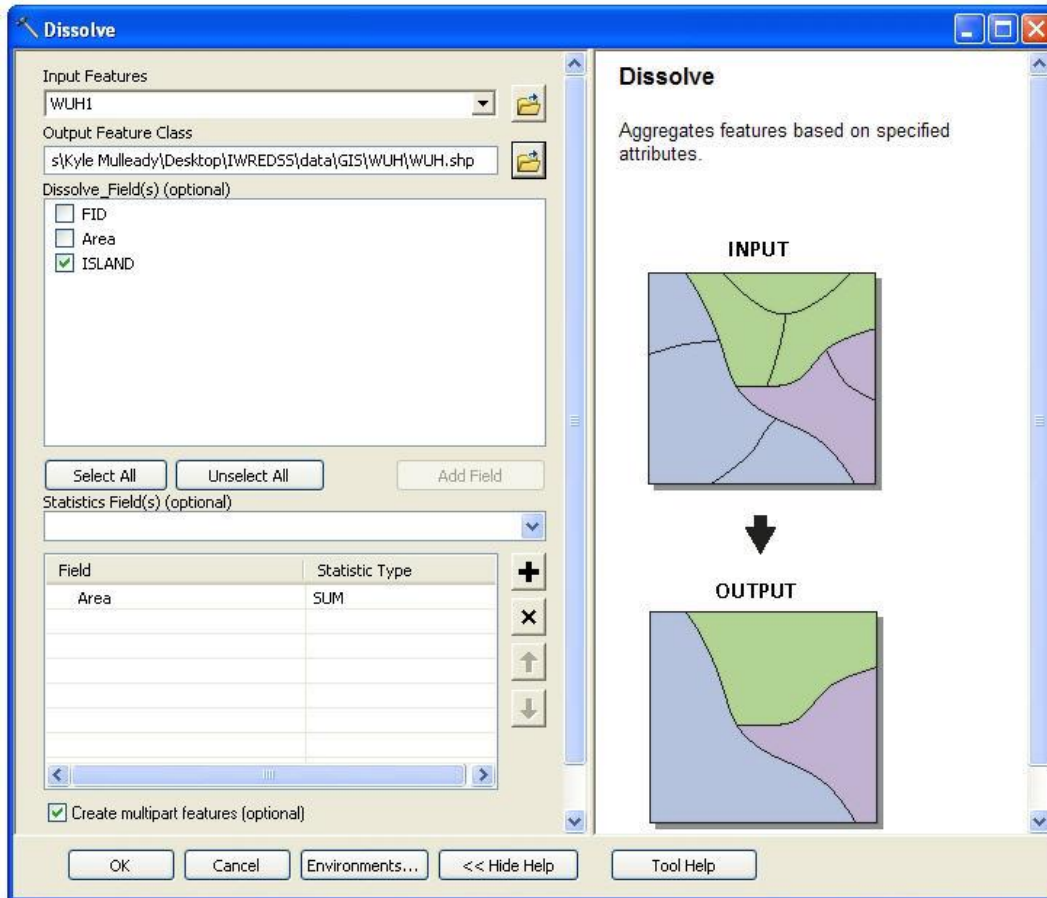
5.	Add field ID in the attribute table of the dissolved new shape file (e.g. WUH). ID should have data "Type" as "Integer" and "Precision" equal to 0.

6.	Update AREA field in the attribute table of the new shape file.

7.	Repeat steps 7 – 10 of the Method 1 to generate soil statistics table and to simulate the area of interest (single polygon dissolved from multiple TMKs) as shown in the following figure (The name of the folder (e.g. WUH) and the shape file (e.g. WUH) should be the same. The shape file should be located at C:../IWREDSS/Data/GIS/WUH/WUH).
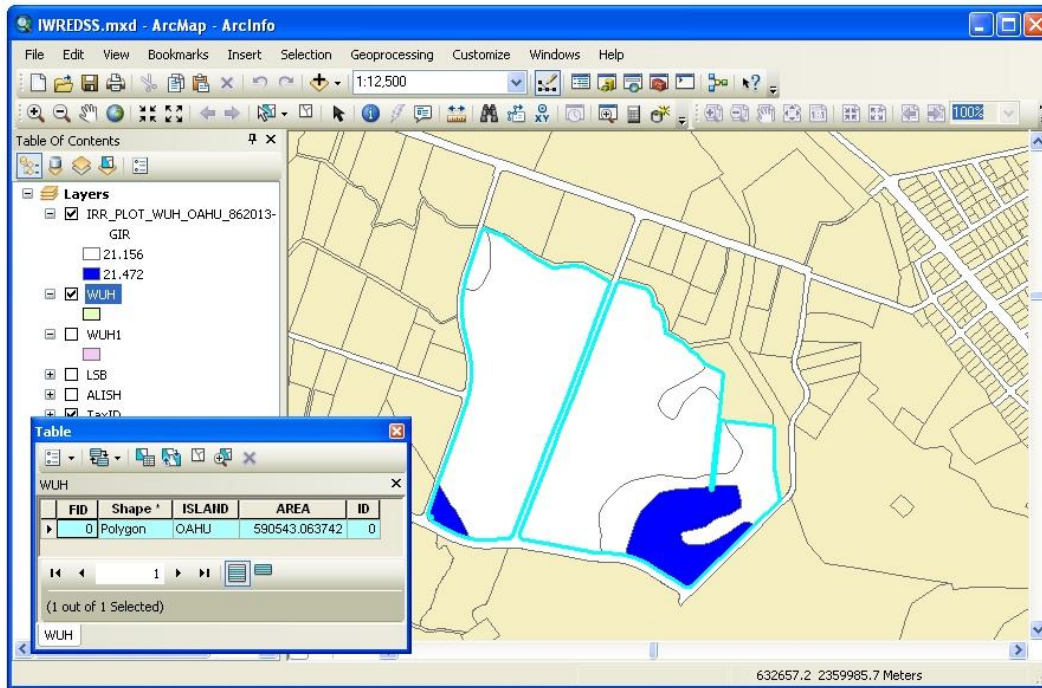
TECHNICAL GUIDE

GeoDatabases, datasets and layers

Beside the visible layers in the table of contents of ArcMAP, following datasets are also included in the IWREDSS package:

TaxID_Soil_Statistics: The dBase dataset which have the intersection results of TaxID layer and Soil Layer. Note in order to calculate efficiently, the original intersection is summed by TaxID polygon and soil type so that there will be only one record for each soil type in one TaxID area. .

Alish_Soil_Statistics: The dBase dataset which have the intersection results of Alish layer and Soil Layer. Note in order to calculate efficiently, the original intersection is summed by Alish polygon and soil type so that there will be only one record for each soil type in one Alish area. .

LSB_Soil_Statistics: The dBase dataset which have the intersection results of LSB layer and Soil Layer. Only type A, B, C, and D in LSB areas are included (type E is conservation lands). Note in order to calculate efficiently, the original intersection is summed by LSB polygon and soil type so that there will be only one record for each soil type in one LSB area. .

User's provided layer: There could be other layers for simulation and the corresponding intersection layer (with soil) and statistic dataset should also be named as XXX_Soil and XXX_Soil_Statistics. (XXX is the layer name).

IWREDSS Mechanism
Area simulation

Upon user's clicking on the IWREDSS tools button ▦, the following data collection process is launched:

1) Get the user's selection; make sure there is one and only one area (of all layers) selected; get the name of the layer the selection belongs to.

2) Query the statistic dataset described above (the datasets of the layer the selected area belongs to) to get all the soil types and corresponding proportions and hydrologic groups inside the selected area; note that non-arable soil types such as water, quarry

and so on will be filtered out before sending to IWREDSS for simulation, and soil types that are of less than 1% of the whole area will not be simulated; get the summation of each hydrologic group for user's reference of CN specification later.

3) Find the geographically closest climate station (from the station layer) to the centroid of the selected area; use the raster layers Rain and ET to get the annual average rainfall and evapotranspiration of the closest station and those of the centroid of the selected area so as to get the approximate ratios of rain and ET between the station and the area. These ratios will be applied to the historic daily climate records of the climate station during the simulation:

   Rain_of_the_area = Rain_Ratio * Rain_of_Station

   ET_of_the_area = ET_Ratio * ET_of_Station

   The ratios are also shown on the parameter window.

4) Open the dialog to accept user's input; assign the CN of each hydrologic group to all the soil types of that group; launch IWREDSS; get results summary from IWREDSS log; prompt error if fails, or confirmation if succeeds.

Data Plotting

After a successful execution, plotting is done upon request. The followings explain how it is done by the VBA code.

1. Area simulation (XXX is the name of layer the selected area belongs to)

1) Add the intersection layer of the simulated area to the map, i.e. data/GIS/XXX_Soil/XXX _Soil;

2) Select all the features (polygons) within the simulated area (the records with FID_XXX = FID of the simulated area).

3) Output the selected features to IRR_PLOT_NNN_TT, where NNN is the island name and TT is the current time of the plotting;

4) Add fields to the attribute table of the output layer, one for each of the water components, and set the values to the IWREDSS results

5) Plot based on GIR field using natural breaks.

6) Remove the added and unused intersection layer.

2. Island simulation (XXX is the name of layer for the simulation)

Similar to area simulation, with the following differences:

1) The plotting is for the whole island, and the unit is area instead of soil polygons within each area

2) The plotting is based on the summarized GIR (Gross Irrigation Requirement) values of each area and the user can manually plot on any other water component.

3) The exported layer includes all areas of the selected island, while some of the areas are not simulated because of non-arability. These un-simulated areas will have value 0 for all water component fields (displayed as white in the plotting).

Procedure for preparing Statistics dataset

This procedure works behind the input files preparation button ⚙ provided besides IWREDSS simulation button ▥. The following description is for TaxID-related simulations. The procedure for the other layers (ALISH, LSB, etc.) is mostly the same.

The TaxID layers are obtained from Hawaii State GIS Program (http://www.hawaii.gov/dbedt/gis) and the soil layers are provided by USDA. In case there are changes in the TaxID area division or soil type coverage, the statistics dataset may need to be reproduced. The following procedure can be followed:

1) Merge the layers to be one big layer: TaxID. The *Merge* tool in ArcToolBox (Data Management > Tools > General > Merge) provided by ArcMap is suitable for this task.

2) Rename the TaxID layer as *TaxID*. Put it in the data/GIS/TaxID folder. Add ISLAND field and set values. Add area field in the TaxID layer and use the Calculate Geometry dialog box to calculate area.
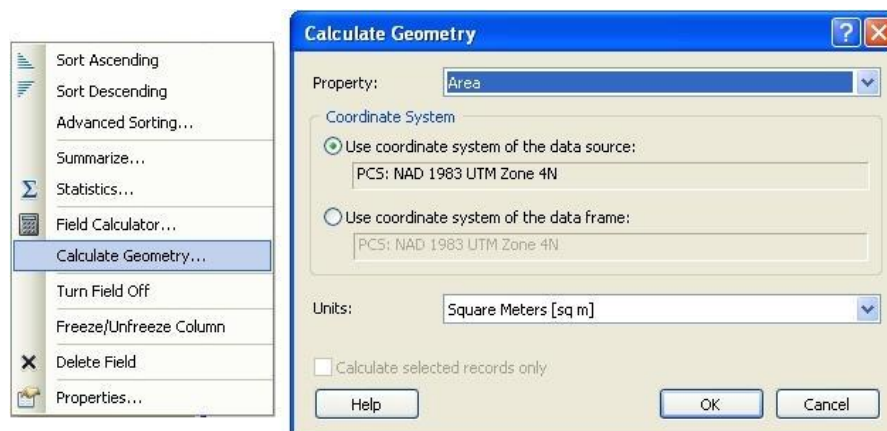
4) 3) Use the ArcTool Intersect (ArcToolbox > Analysis Tools > Overlay > Intersect) to intersect the TaxID layer and the soil layer. Output the intersection layer as data/GIS/TaxID_Soil/TaxID_Soil. Add field *NewArea* (Double, length 19) to be the area of the intersected polygon and field *Portion* (Double, length 19) to be the proportion of *NewArea* to *Area* (the field from TaxID layer): NewArea/Area. Add to the TaxID layer field *FID_TaxID* (Long integer, length 9) and set its value to be same as field *FID*.
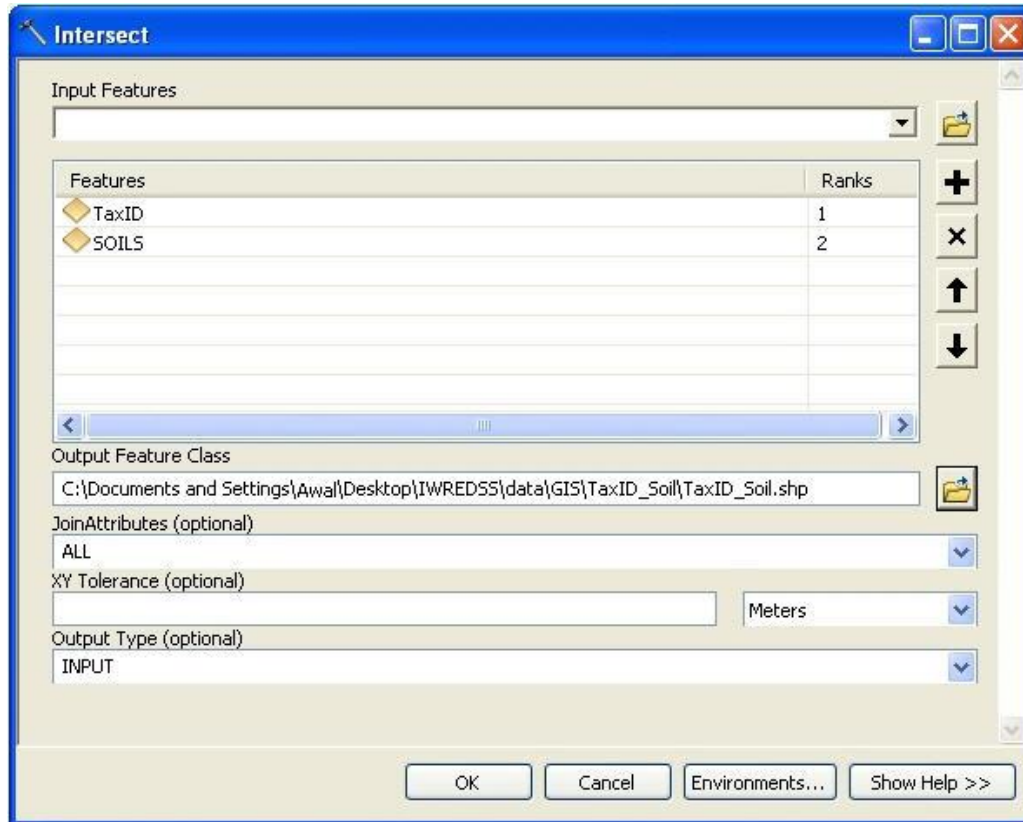
5) Add the field *TaxID_SOIL* (Text, length 20) in the intersect layer. Calculate the field value as:

   "" & [FID_TaxID] & "_" & [SOIL_CODE]

The field *FID_TaxID* is the *FID* field from TaxID layer which is automatically renamed so during the intersection.

6) Use the ArcTool Summary Statistics (Analysis Tools > Statistics > Summary Statistics) to generate the statistic dataset. The summary should be based on

TaxID_SOIL and output *FID_TaxID*, *TMK*, *ISLAND*, *SOIL_CODE*, *NewArea*, and *Portion*. The first four fields can be summarized by first or last while the last two fields must be summed. Output the statistic layer as data/GIS/TaxID_Soil/ TaxID_Soil_Statistics. Note if for layer of other names, not only the layer name should be changed to XXX_Soil_Statistics, but also the path should be changed: data/GIS/**XXX_**Soil/ XXX_Soil_Statistics
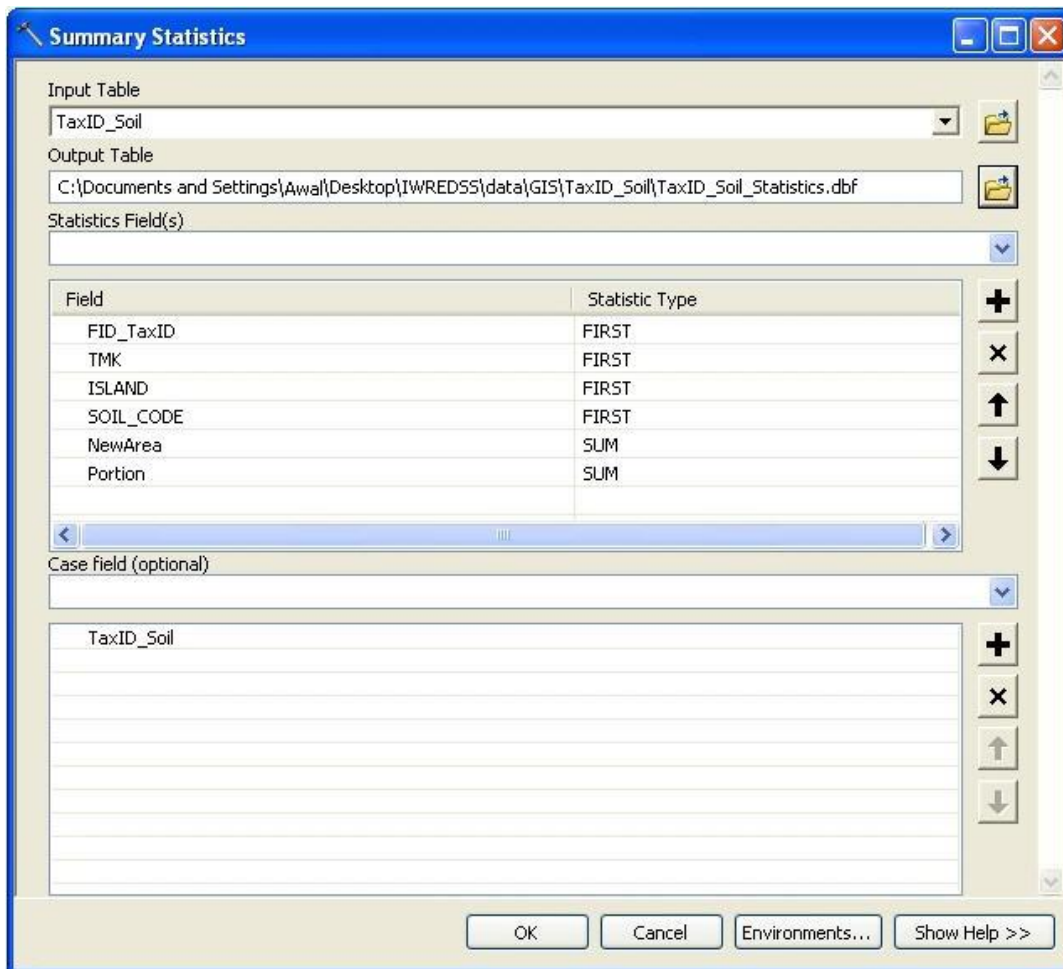
7) Rename the field names of the summary dataset:

first_fid_tax -> FID_TaxID (Double)

first_tmk -> TMK (Double)

first_island -> ISLAND (Text, 10)

first_soil_code -> SOIL_CODE (Text, 20)

sum_newarea -> AREA (Double)

sum_portion -> PORTION (Double)

The renaming process can be done by first add a new field with the desired name and then calculate that field value by assigning it with the old field, and finally delete the old field.

8) Add a field *IL_Soil* (Text, length 20) in the statistic dataset with the following value:

[ISLAND] & "_" & [SOIL_CODE]
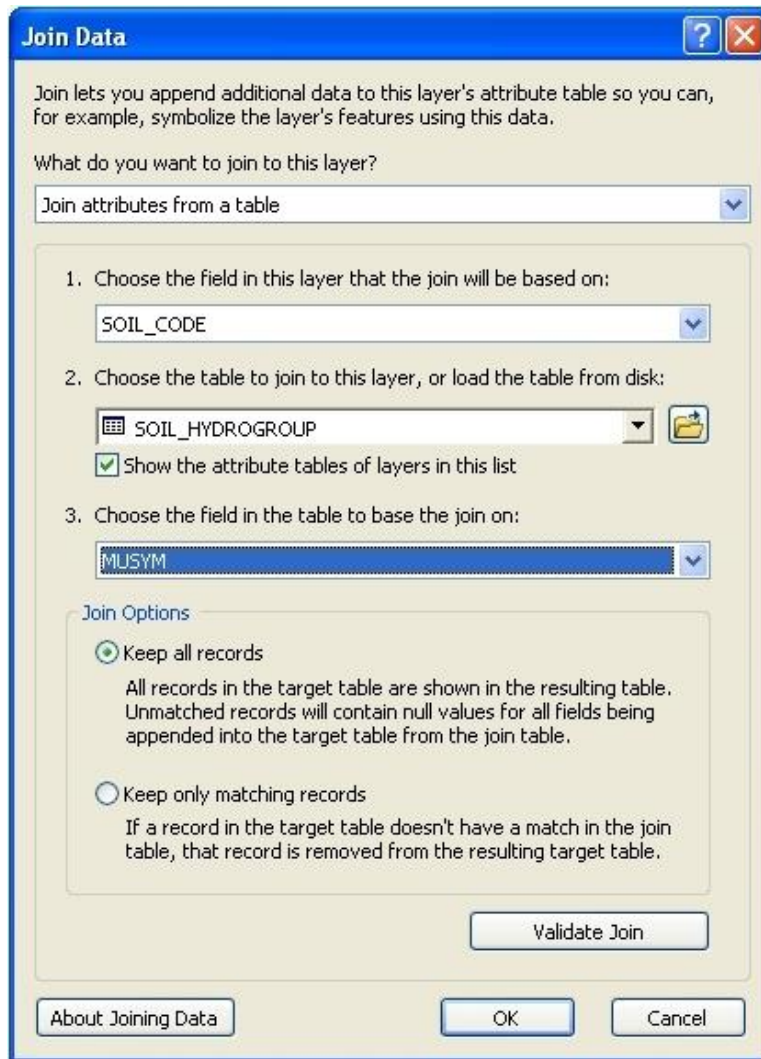
9) Add the data/GIS/Soil/SOIL_HYDROGROUP.dbf; join it to the statistic dataset using IL_Soil <-> IL_Soil. Add a new field *GROUP* (Text, length 1) in the statistic dataset, assign the field value to be the field HYDROLIC of SOIL_HYDROGROUP, then delete the join and remove SOIL_HYDROGROUP as SOIL_HYDROGROUP.HYDROLIC.

10) Recalculate field *PORTION* to make all portions that are larger than 1 to be 1.as:

- o Open the attribute table
- o "Search by Attribute": "Portion" > 1
- o Switch from all records to selected records
- o Right click on the portion field and choose "field calculator"
- o In the input box, type in 1 and click ok.

11) Check and make sure the records with empty value of field *GROUP* are fine.

12) Remove the intersection layer (XXX_SOIL) because it will be added and removed automatically to the ArcMap document by code.

Procedure for preparing Statistics dataset (for user's layers)

This program is designed to be able to handle new layers for simulation. To do that, the corresponding layer and dataset need to be prepared as described above. The most important things to be careful about are: field names, path and layer names. After all datasets are prepared with the correct name in the correct path, the user will be able to do exactly the same simulating job as when using the existing three layers. Area simulation is also doable by choosing the desired area and run. Currently, the database button performs this task for a user's layer.

IWREDSS-related data

All the other data files that haven't been described are of IWREDSS' use. For more details, please refer to IWREDSS User Manual.

How to Digitize in ArcGIS 10.0

1.   Scan the image (rainfall isohyets or pan evaporation (PE) isolines) and save it with extension .img or .jpeg

2.   Open ArcCatalog, right click in your project folder (where your files are located) and click, go to "New", and click "Shapefile". In "Create New Shapefile" window name the new shapefile and select "polyline" as feature type. Select a projection through the "Edit" button under "Description box". You are in Spatial Reference Properties dialog box. Click "Select" button, double click "Geographic coordinate systems", double click "North America", double click "NAD 1983.prj, click "Add" button, and Click "Ok" at

the end.

3.   Open a new ArcMap session and add the scanned image (.img or .jpeg extensions) and the newly created polyline shape file, (You will find this file in the folder you created from ArcCatalog. You can also drag it from ArcCatalog and drop it in TOC of ArcMap). Add an already coordinated/Geo-referenced layer (It could be the coast line layer of the islands or any other layer which have at least three bench marks or proper boundary resembling the scanned image). This layer will be named "reference layer" in the rest of the document.

4.   Select Toolbars from the "Customize" menu in ArcMap and click "Editor" to turn on the Editor toolbar if it is not already opened.

5.   From the "Customize" menu go to "Toolbars" and click "Geo-referencing" if it is not already opened.

6.   Click the image layer to initiate it. Click the dropdown button of "Geo-referencing" and click "Fit to Display". You will see the scanned image on screen.

7.   Right click the reference layer (e.g. island coast layer) and select "Zoom to Layer". You should see both the layers (the scanned image and the reference layer) on screen.

8.   From "Geo-referencing" toolbar click on 'Add Control Points", the line with red and green x as endpoints.

9.   Click a bench mark (any corner of a park, building or boundary) on the image first followed by another click on the reference layer.

10.   Repeat step 9 at least three or preferably four times to obtain different bench marks or until you see the two layers overlaid.

11.   Right click the new shape file and open attribute table. Add a new field ("Add Field") from the "Table Options" button on the top left corner. While creating a new field, select proper features of the filed i.e. string for "text" data and integer or double (depending on the size of the data) "number" data. Text may be the name of Island and number may be the amount of rainfall or PE.

12.   Click the new shapefile to initiate it, and from the "Editor" toolbar select "Start

Editing"

13.   Zoom to the feature to be digitized, and select appropriate "Construction Tools" to digitize desired shape.

14.   Choose from the following options to create and modify the new feature:

- To create a polygon feature, left-click once in the Data Frame to start a new polygon. Successive single left-clicks will create vertices. Double-click at the last vertex to create a closed polygon.

- If you are editing a point feature class, left-click to add a single point location.

- If you are editing a line feature, left-click to start a new line and add vertices with successive single left-clicks. End the line with a double left-click.

- If you are in the middle of editing a line and realize that you want to make a correction to a part of that line you have already completed, double-click to finish the line segment. Then select the "Edit Tool" (the black arrow just to the right of "Editor"). Use this tool to select a feature by double-clicking it, and move the vertices individually.

- Use the "Esc" key to get out of a particular step.

- The Undo option can be quite helpful. To use it, press Ctrl-z; alternatively, from the Edit menu, select Undo. If your polygon gets too complicated to fix, you can use the Edit Tool to select it, and then delete it by pressing the Del key.

Note: You can pan and zoom while in the middle of digitizing a feature. Another handy feature is the magnifier window. To open this, from the main ArcMap menu bar, from the "Window" menu, select "Magnifier". This allows you to have a separate window zoomed into a portion of the main Data Frame. You can pan and zoom this window around your Data Frame, which is a convenient way to follow the path of a long feature.

15.   After the digitizing is complete, enter the information to the attribute table of the shapefile. Right click shapefile; click "Open Attribute Table"

16.   Once you have digitized all the features, to save your edits, from the Editor toolbar, select "Save Edits" from Editor.

17.   To stop editing, from the Editor toolbar, select "Stop Editing' from Editor.

18.   Save the shapefile and use it with its supporting files.

How to add new crops in the existing crop list

The IWREDSS model gives the option to add a new crop in the existing list of crops. Users need to figure out if the crop to be added is annual or perennial. There are two sets of crops in the existing list of 27 perennial and 28 annual crops. Detail on crop parameters including effective rooting depths, crop coefficients (K_C), duration of crop cycle and their fractions, and allowable water depletion (AWD) for major annual and perennial crops are given in Tables 1 and 2 of the project report.

To update the existing list of crops:

- Open **croplist.dat** with Notepad from IWREDSS\data. The first line in the text gives the number of perennial crops followed by the names of the crops in the sequence these appear in the interface of the IWREDSS model as demonstrated in the following figure.

- Update the crop list with the exact number and the names of the crops to be added.

- Save the **croplist.dat** file before closing it

- Open IWREDSS\data**crop.dat** in Notepad. The first two lines in the text give the number of perennial crops and root zone and water use coefficient data i.e., crop name, crop depth (inches), K_C, Fraction, and AWD. The list of crops and the related coefficients should be updated following the example of the existing information as shown in the following figure.

```
crop - Notepad
File  Edit  Format  View  Help

 27 PERENNIAL CROPS : ROOT ZONE AND WATER USE COEFFICIENT DATA
  CROP   DEPTH(IN) .............. KC  / AWD ..........................
GENERIC CROP ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
AVOCADO      ;0.90;0.90;0.90;0.90;0.95;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
BERMUDA GRASS;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
BREADFRUIT   ;0.90;0.90;0.90;0.90;0.95;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
CITRUS       ;0.56;0.62;0.71;0.78;0.82;0.86;0.88;0.87;0.85;0.81;0.75;0.67
             30;40;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
COCONUT,PALMS;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
COFFEE       ;0.85;0.85;0.85;0.90;0.95;0.95;0.95;0.95;0.95;0.95;0.90;0.90
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
DENDROB.,POT ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
              8; 8;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
DILLIS GRASS ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
DOMEST.GARDEN;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             12;24;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
DRACEANE,POT ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
              8; 8;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
EUCALYP.,OLD ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             72;72;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
EUCALYP.,YNG ;0.60;0.60;0.60;0.60;0.60;0.60;0.60;0.60;0.60;0.60;0.60;0.60
             48;72;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
GARDEN HERBS ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             12;24;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
GUAVA        ;0.80;0.90;1.00;1.00;0.90;0.80;0.80;0.90;1.00;1.00;0.90;0.85
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
HELICONIA    ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
KIKUYU GRASS ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
KOA          ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             72;72;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
LYCHEE       ;0.95;1.00;1.00;1.00;0.95;0.90;0.90;0.85;0.80;0.80;0.90;0.90
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
MACADAMIA    ;0.85;0.85;0.85;0.90;0.95;0.95;0.95;0.95;0.95;0.95;0.90;0.90
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
MANGO        ;0.90;0.90;0.90;0.90;0.95;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             30;60;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
PAPAYA       ;0.90;0.90;0.90;0.90;0.95;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             25;37;0.40;0.40;0.40;0.40;0.40;0.40;0.40;0.40;0.40;0.40;0.40;0.40
ST.AUGUSTINA ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
TI           ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
TURF,GOLF    ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
              9;24;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
TURF,LANDSCP.;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             12;24;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50
ZOYSIA GRASS ;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00;1.00
             24;48;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50;0.50

 28  ANNUAL CROPS  : ROOT ZONE AND WATER USE COEFFICIENT DATA
  CROP    DEPTH(IN) .....KC.....  .....FRACTION ..... ALLOWABLE DEPLETION
GENERIC CROP; 8;12;0.40;1.00;0.90;0.25;0.33;0.25;0.17;0.50;0.50;0.50;0.50
ALFALFA,INIT; 8;24;0.40;0.95;0.90;0.14;0.38;0.31;0.17;0.50;0.50;0.50;0.50
ALFALFA,RATN;24;24;0.40;0.95;0.90;0.14;0.38;0.31;0.17;0.50;0.50;0.50;0.50
BANANA,INIT ;24;48;0.50;1.10;1.00;0.31;0.23;0.31;0.15;0.35;0.35;0.35;0.35
BANANA,RATN ;48;48;1.00;1.05;1.05;0.33;0.16;0.49;0.01;0.35;0.35;0.35;0.35
CABBAGE     ; 8;12;0.70;1.05;0.95;0.24;0.36;0.30;0.09;0.45;0.45;0.45;0.45
CANTALOUPE  ; 8;12;0.50;0.85;0.60;0.08;0.50;0.21;0.21;0.35;0.35;0.35;0.35
DRY ONION   ; 8;12;0.70;1.05;0.75;0.10;0.17;0.50;0.23;0.25;0.25;0.25;0.90
EGG PLANT   ; 8;12;0.70;1.05;0.90;0.21;0.32;0.29;0.18;0.40;0.40;0.40;0.40
GINGER,(AWD); 8;12;0.70;1.05;0.75;0.10;0.17;0.50;0.23;0.25;0.25;0.25;0.25
LETTUCE     ; 8;12;0.70;1.00;0.95;0.27;0.40;0.20;0.13;0.30;0.30;0.30;0.30
OTHER MELON ; 8;12;0.50;1.05;0.75;0.21;0.29;0.33;0.17;0.35;0.35;0.35;0.35
PEANUTS     ;12;18;0.40;1.00;0.55;0.25;0.32;0.25;0.18;0.50;0.40;0.50;0.50
PEPPERS     ; 8;12;0.40;0.95;0.80;0.24;0.28;0.32;0.16;0.35;0.35;0.35;0.35
PINEAPP.YR-1;12;24;0.40;0.30;0.30;0.16;0.33;0.26;0.25;0.60;0.60;0.60;0.60
PINEAPP.YR-2;24;24;0.30;0.30;0.30;0.38;0.32;0.27;0.03;0.60;0.60;0.60;0.60
PUMPKIN     ; 8;12;0.50;1.00;0.80;0.20;0.30;0.30;0.20;0.35;0.35;0.35;0.50
SEED CORN   ;12;18;0.40;1.20;0.50;0.16;0.28;0.32;0.24;0.60;0.60;0.60;0.80
SOYBEAN     ;12;18;0.40;1.05;0.45;0.14;0.25;0.43;0.18;0.50;0.50;0.50;0.67
SUGAR C.RATN;36;36;0.40;1.25;0.75;0.10;0.15;0.46;0.29;0.65;0.65;0.65;0.65
SUGAR C.YR-1;18;36;0.40;1.25;1.25;0.21;0.29;0.25;0.25;0.65;0.65;0.65;0.65
SUGAR C.YR-2;36;36;1.25;1.25;0.75;0.14;0.14;0.59;0.65;0.65;0.65;0.65;0.65
SUNFLOWERS  ;12;18;0.40;1.05;0.40;0.16;0.28;0.36;0.20;0.45;0.45;0.45;0.67
SWEET POTATO; 8;12;0.50;1.15;0.65;0.12;0.24;0.40;0.24;0.65;0.65;0.65;0.65
TARO (Dry)  ;12;18;1.05;1.15;1.10;0.20;0.13;0.40;0.27;0.30;0.30;0.30;0.30
TARO (Wet)  ;12;18;1.25;1.25;1.25;0.20;0.13;0.40;0.27;0.00;0.00;0.00;0.00
TOMATO      ; 8;12;0.60;1.15;0.80;0.20;0.27;0.34;0.19;0.40;0.40;0.40;0.65
WATER MELON ; 8;12;0.40;1.00;0.75;0.15;0.26;0.26;0.32;0.26;0.32;0.26;0.32

                                                   Ln 82, Col 13
```

- For perennial crops, the crop data occupy the two rows for a single crop. The two root zone depths in the second line of the crop data are irrigated and total root zone depth i.e., 24 and 48 inches for Generic Crop, respectively. The values of K_C and AWD for different months of the year are given in the first line after crop name and second line after irrigated and total root zone depth, respectively. The root depth data are considered as average data for Hawaii conditions. Details of the data for perennial crops are given in Table 2 of the project report.

- Leave one line space between perennial and the annual crop information.

- Details on the data for annual crops can be found in Table 1 of the project report. The entries in Table 1 and in the above screen shot are explained in the following table:

Column entries	Description
1st	Minimum annual crop irrigated root zone depth. This depth is usually irrigated in the beginning of crop season
2nd	Maximum crop irrigated root zone depth. Crops obtain and maintain this maximum depth during their growth stages. Patterns of crop root zone development are shown in the following figure (Case of Seed Corn).
3rd through 6th	The values of K_C at initial, mid, and late stages of crop.
7th through 10th	These are fraction of crop growing season under the heading of FRACTION. The data represent duration of crop growth stage that varies for various crops.
11th through 14th	The fraction of total AWD during the four stages of crop.

Seed Corn Root Depth Stages and Development Function

Root Depth (Inches) vs Relative Crop Growing Season

Final Depth = 18 Inches

Initial Depth = 12 Inches

Growth Stage 1	Growth Stage 2	Growth Stage 3	Growth Stage 4
F = 0.16	F = 0.28	F = 0.32	F = 0.24

0.0 (Planting) ... 1.0 (Harvest)

Relative Crop Growing Season
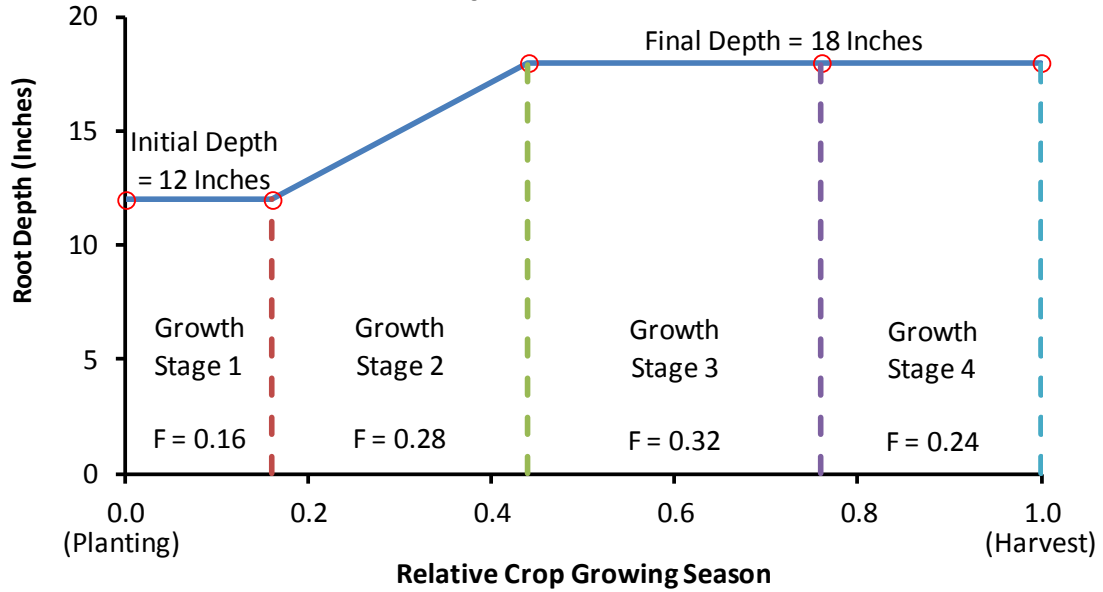
- Save the file **crop.dat** before closing it.

- Open IWREDSS, the interface should include the newly added crops.

Appendix 3. Calculation of daily ET_o using temperature data.

STEP 1: Extraterrestrial radiation (R_a) is calculated for each day using the following equations from Duffie and Beckman (1980) (reproduced from Snyder and Eching, 2002).

G_{SC} = solar constant in MJ m^{-2} min^{-1}
$$G_{SC} = 0.082$$
σ = Steffan-Boltzman constant in MJ m^{-2} d^{-1} K^{-4}
$$\sigma = 4.90 \times 10^{-9}$$
ϕ = latitude in radians converted from latitude (L) in degrees
$$\phi = \frac{\pi L}{180}$$
d_r = correction for eccentricity of Earth's orbit around the sun on day i of the year
$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} i\right)$$
δ = declination of the sun above the celestial equator in radians on day i of the year
$$\delta = 0.409 \sin\left(\frac{2\pi}{365} i - 1.39\right)$$
ω_s = sunrise hour angle in radians
$$\omega_s = \cos^{-1}\left[-\tan\phi\tan\delta\right]$$
R_a = extraterrestrial radiation (MJ m^{-2} d^{-1})
$$R_a = \left(\frac{24 \cdot 60}{\pi}\right) G_{SC} d_r \left[\omega_s \sin\delta\sin\phi + \cos\phi\cos\delta\sin\omega_s\right]$$

STEP 2: Calculate ET using Hargreaves-Samani equation (Hargreaves and Samani, 1982) (reproduced from Snyder and Eching, 2002).

Hargreaves-Samani equation for ET of a short, 0.12 m tall reference surface
$$ET_h = 0.408\left(0.0023 R_a [T_m + 17.8]\sqrt{T_x - T_n}\right)$$
where the 0.408 = $1/\lambda$ factor converts from MJ m^{-2}d^{-1} to mm d^{-1}.

where: T_m = mean daily temperature in ^{o}C, T_X = the maximum daily air temperature in ^{o}C,

and T_n = the minimum daily air temperature in ^{o}C.

References:
Duffie, J.A. and Beckman, W.A. 1980. Solar engineering of thermal processes. John Wiley and Sons, New York. pp. 1-109.
Hargreaves, G.H., and Samani, Z.A. 1982. Estimating potential evapotranspiration, Tech. Note, J. Irrig. and drain. Eng., ASCE, 108(3):225-230.
Snyder, R.L, Eching, S. 2002. Penman-Monteith daily (24-hour) Reference Evapotranspiration Equations for Estimating ET_o, ET_r and HS ET_o with Daily Data. Regents of the University of California.

Appendix 4a. Climate data stations for the island of Kauai. Stations information is in Table 3. The isohyets (dark) indicate gradients in rainfall, while the contours (light) indicate the elevation.
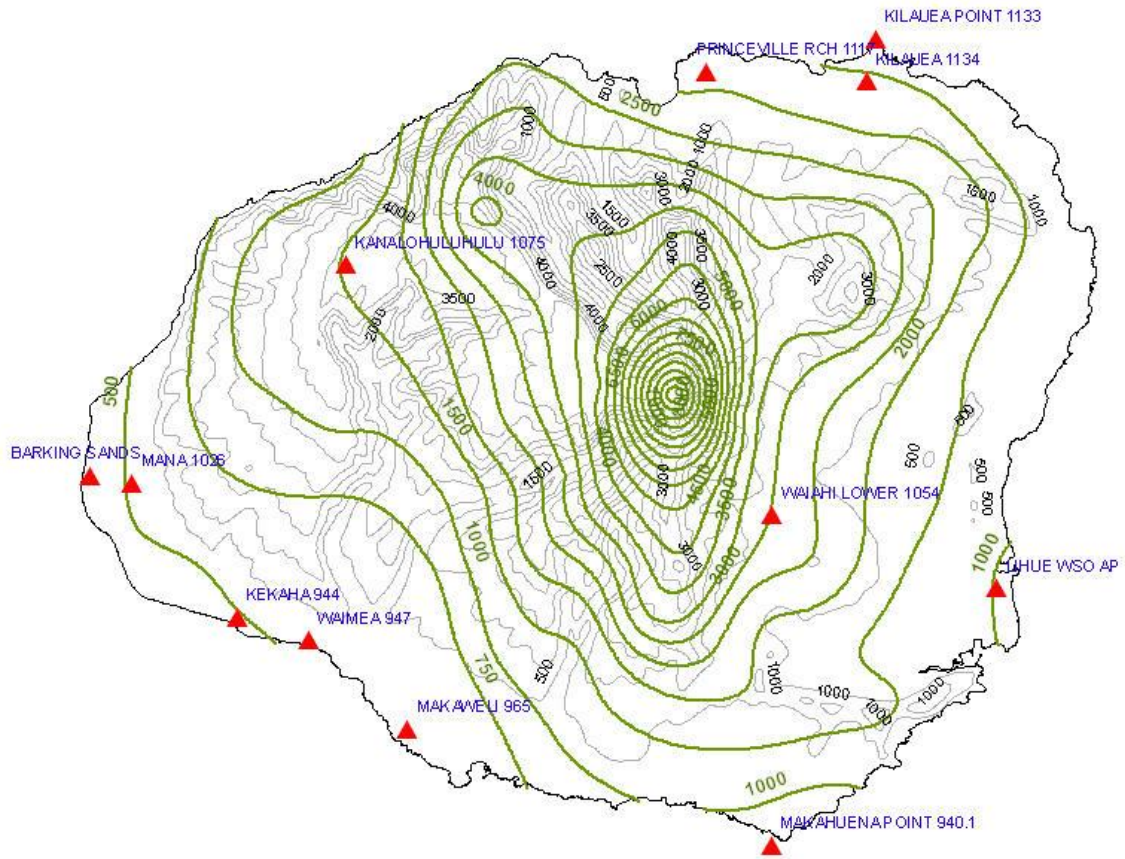
Kauai

Appendix 4b. Climate data stations for the island of Oahu and Molokai. Stations information is in Table 3. Isohyets (dark) indicate gradients in rainfall (dark). The contours (light) indicate the elevation.
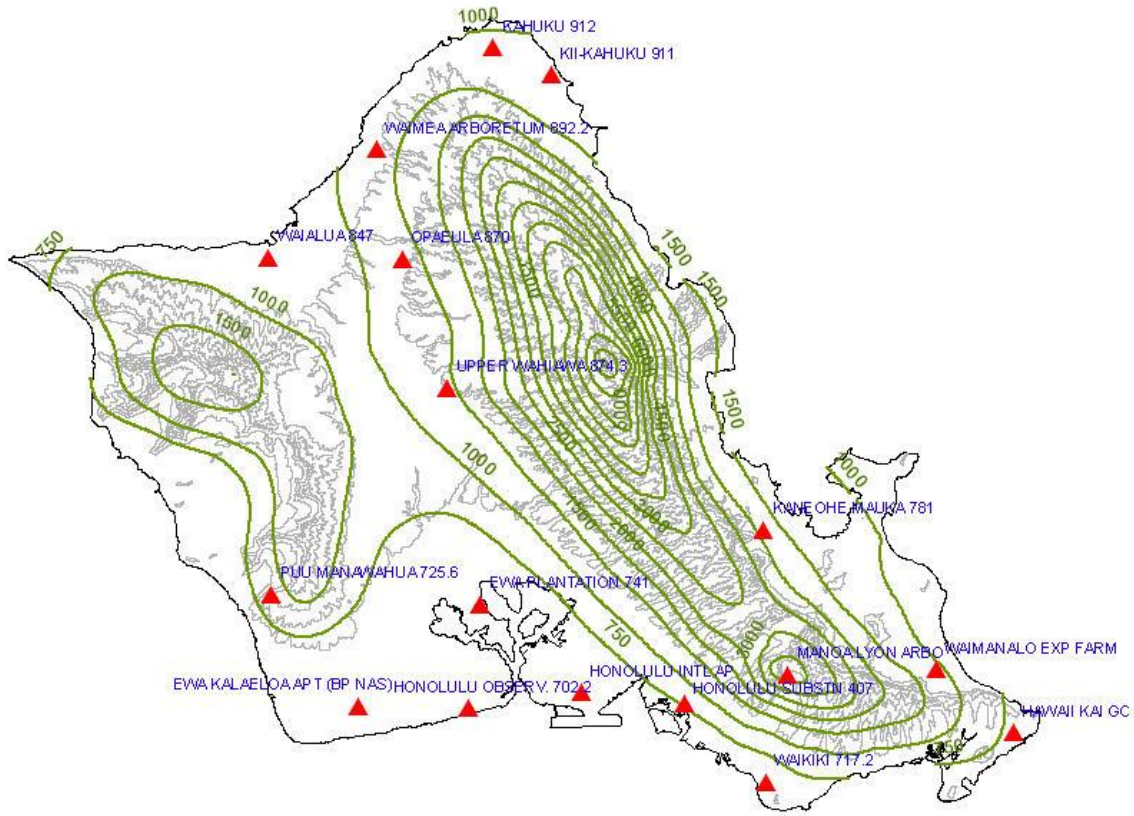
Oahu
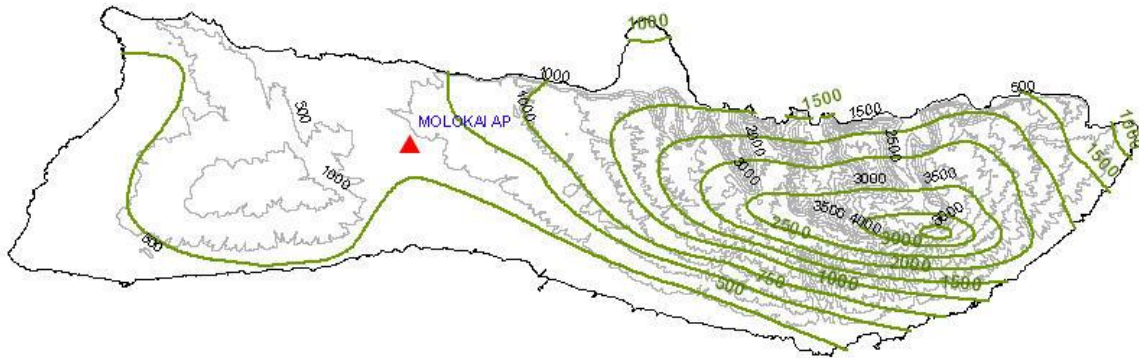
Molokai

Appendix 4c. Climate data stations for the island of Maui and Lanai. Station information is in Table 3. Isohyets (dark) indicate gradients in rainfall. Elevation is indicated by the contours (light).
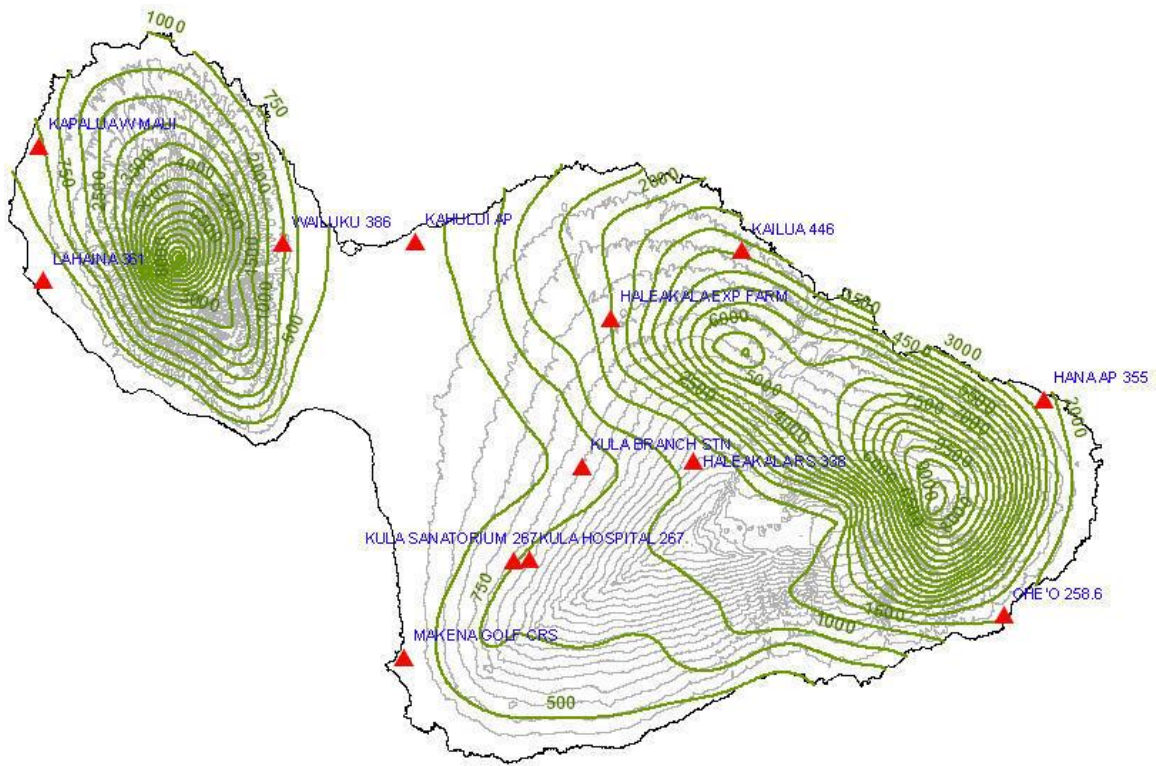
Maui
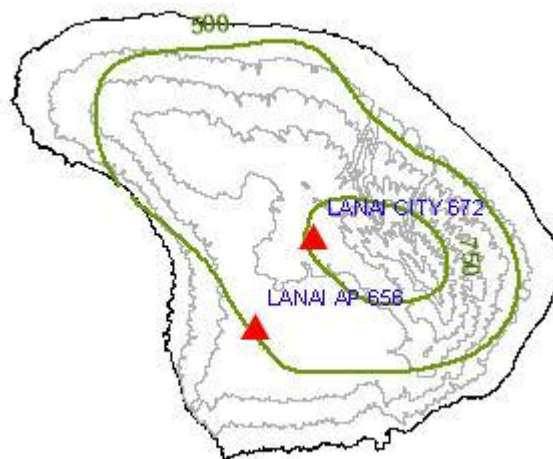
Lanai

Appendix 4d. Climate data stations for the island of Hawaii. Stations information is in Table 3. Isohyets (dark) indicate gradients in rainfall. Elevation is indicated by the contours (light).
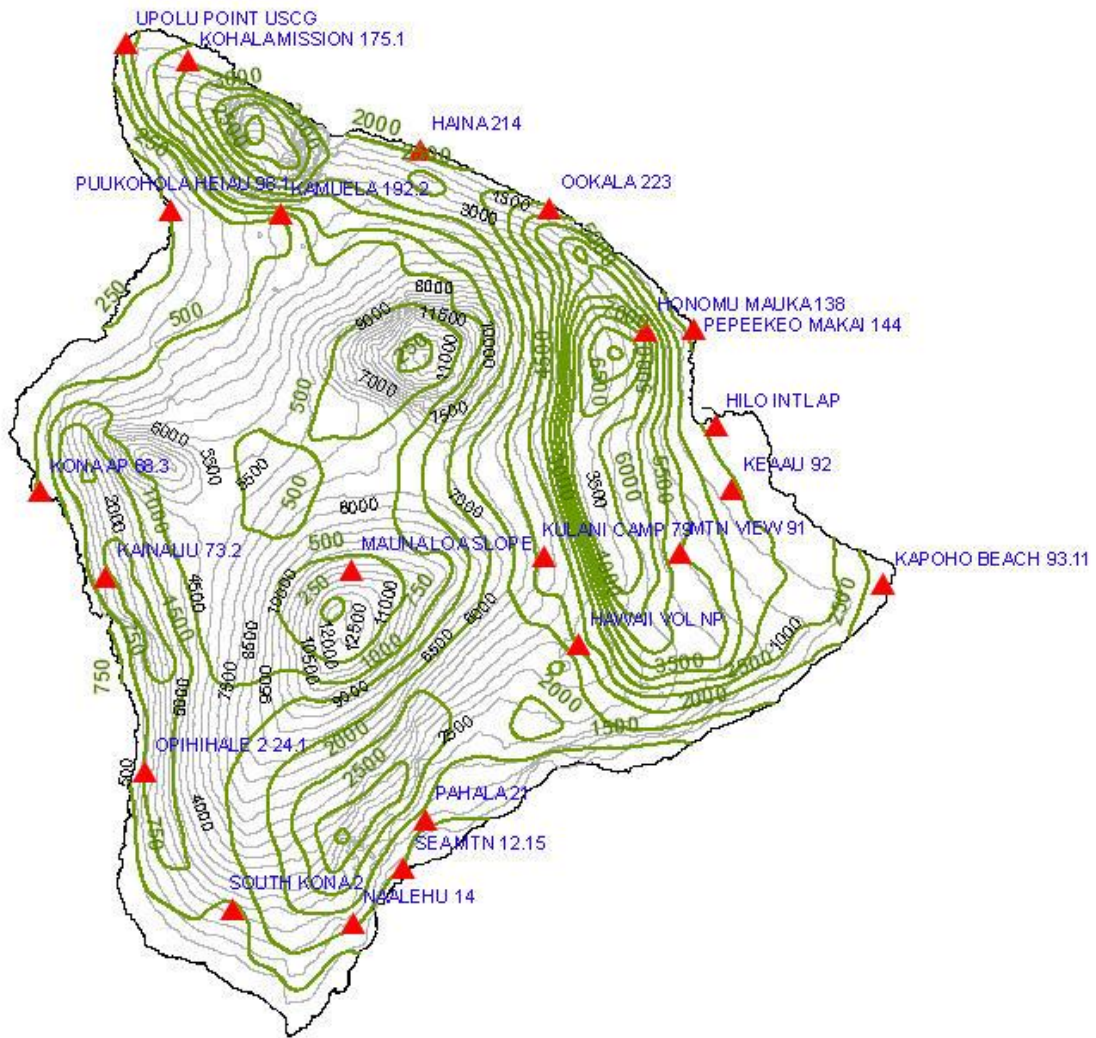
Hawaii

Appendix: 5a: Seasonal water budget components

Seasonal (Jan - Apr) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Jan	0	0	0	6.8	4.9	2.4	3.3	1.9	0	3.4	2.3	2.5
Feb	0.4	0.5	13.1	4.8	3.5	2.3	2.6	1.2	0.2	3.5	3.6	1.2
Mar	1.6	1.9	50.8	4.6	3.4	2.6	2.9	1	0.2	4.2	5.1	0.8
Apr	1.2	1.4	37.5	3.3	2.5	2.3	2.1	0.6	0.2	4.5	3.9	0.2
Jan - Apr	3.2	3.7	101.4	19.6	14.3	9.6	10.9	4.6	0.6	15.6	14.9	4.8

Seasonal (Feb - May) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Feb	0	0	1.3	4.8	3.6	2	2.2	1.2	0	3.5	2.2	1.6
Mar	0.8	1	26.3	4.6	3.5	2.3	2.7	1	0.2	4.2	4.3	1.2
Apr	2	2.3	63.7	3.3	2.5	2.3	2.3	0.6	0.2	4.5	5.4	0.2
May	2	2.4	64.2	2.9	2.2	2.1	1.8	0.5	0.2	5	4.4	0.1
Feb - May	4.9	5.7	155.5	15.7	11.8	8.7	9.1	3.2	0.6	17.2	16.2	3.1

Seasonal (Mar - Jun) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Mar	0.1	0.2	4.2	4.6	3.6	2.1	2.3	1	0	4.2	2.7	1.5
Apr	1.1	1.3	36.1	3.3	2.6	2.2	2.2	0.6	0.2	4.5	4.6	0.4
May	3	3.5	94.7	2.9	2.2	2	2	0.5	0.2	5	6	0.1
Jun	2.6	3.1	83.2	1.4	1	1	1	0.1	0.2	4.9	4.2	0
Mar - Jun	6.8	8	218.3	12.2	9.4	7.3	7.4	2.2	0.6	18.6	17.5	2.1

Seasonal (Apr - Jul) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Apr	0.2	0.2	6	3.3	2.7	2	1.8	0.6	0	4.5	2.8	0.7
May	1.7	2	53.4	2.9	2.2	1.9	1.9	0.5	0.2	5	5.1	0.4
Jun	3.7	4.3	117.8	1.4	1	1	1	0.1	0.2	4.9	5.9	0
Jul	3	3.5	94.3	1.6	1.4	1.4	1.2	0	0.2	5.1	4.4	0
Apr - Jul	8.5	10	271.5	9.2	7.4	6.3	5.9	1.3	0.6	19.5	18.2	1.1

Seasonal (May - Aug) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
May	0.3	0.4	11	2.9	2.4	1.7	1.5	0.5	0	5	3	0.6
Jun	2.4	2.8	75.9	1.4	1.1	1.1	1	0.1	0.1	4.9	5	0
Jul	4	4.7	126.9	1.6	1.4	1.4	1.3	0	0.2	5.1	6.1	0
Aug	3	3.5	95.2	1.6	1.3	1.3	1.1	0.1	0.2	5.1	4.4	0
May - Aug	9.7	11.4	309	7.5	6.1	5.4	4.9	0.8	0.6	20.1	18.5	0.6

Seasonal (Jun - Sep) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Jun	0.4	0.4	11.9	1.4	1.2	1.1	0.8	0.1	0	4.9	2.7	0.1
Jul	2.5	2.9	80	1.6	1.4	1.4	1.2	0	0.2	5.1	5.2	0
Aug	4	4.7	127.9	1.6	1.3	1.3	1.2	0.1	0.2	5.1	6.1	0
Sep	2.5	3	81.3	1.9	1.6	1.6	1.3	0.1	0.2	4.7	4.1	0
Jun - Sep	9.4	11.1	301	6.5	5.5	5.5	4.5	0.4	0.6	19.8	18.1	0.1

Seasonal (Jul - Oct) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Jul	0.4	0.4	11.9	1.6	1.6	1.5	1	0	0	5.1	3	0
Aug	2.5	3	80.4	1.6	1.3	1.3	1.1	0.1	0.2	5.1	5.2	0
Sep	3.4	4	109.3	1.9	1.6	1.6	1.4	0.1	0.2	4.7	5.6	0
Oct	1.7	2.1	55.8	3.6	2.6	2.6	2.1	0.7	0.2	4.1	3.7	0.1
Jul - Oct	8.1	9.5	257.4	8.7	7.2	7	5.6	1	0.6	19	17.5	0.1

Seasonal (Aug - Nov) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Aug	0.5	0.6	15.8	1.6	1.5	1.3	0.9	0.1	0	5.1	2.9	0.1
Sep	2.1	2.4	66.1	1.9	1.7	1.7	1.3	0.1	0.1	4.7	4.8	0
Oct	2.2	2.6	70.5	3.6	2.6	2.5	2.2	0.7	0.2	4.1	4.9	0.1
Nov	0.6	0.7	18.2	6.2	4.4	3.5	3.4	1.6	0.3	3.2	2.9	0.9
Aug - Nov	5.3	6.3	170.6	13.3	10.2	9.1	7.9	2.5	0.6	17.1	15.6	1.1

Seasonal (Sep - Dec) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Sep	0.3	0.3	9	1.9	1.8	1.7	1.1	0.1	0	4.7	2.8	0.1
Oct	1.2	1.4	36.8	3.6	2.7	2.3	2.1	0.7	0.2	4.1	4.1	0.3
Nov	0.9	1	28.1	6.2	4.4	3.4	3.6	1.6	0.3	3.2	3.9	1
Dec	0.3	0.3	9.4	5.9	4.3	2.9	3.1	1.4	0.3	3.1	2.8	1.3
Sep - Dec	2.6	3.1	83.3	17.6	13.2	10.4	9.9	3.8	0.7	15.1	13.6	2.8

Seasonal (Oct - Jan) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Oct	0.1	0.1	2.5	3.6	2.9	2.1	0.9	0.7	0	4.1	2.5	0.7
Nov	0.3	0.3	9.3	6.3	4.5	2.8	1.5	1.6	0.2	3.2	3.3	1.7
Dec	0.6	0.7	18.1	6	4.3	3	1.4	1.4	0.3	3.1	3.7	1.3
Jan	0.3	0.3	8.7	6.6	4.5	2.8	3	1.9	0.2	3.3	2.9	1.6
Oct - Jan	1.2	1.4	38	22.7	16.3	10.9	6.8	5.7	0.7	13.8	12.6	5.4

Seasonal (Nov - Feb) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Nov	0	0	0	6.3	4.7	2.3	1.5	1.6	0	3.2	2.2	2.5
Dec	0.2	0.2	6.3	6	4.4	2.6	1.4	1.4	0.2	3.1	3.2	1.8
Jan	0.5	0.6	16.7	6.8	4.6	3.2	3	1.9	0.3	3.4	4.1	1.4
Feb	0.3	0.4	10.6	4.5	3.3	2.4	2.2	1	0.2	3.4	2.9	0.9
Nov - Feb	1.1	1.2	33.6	24	17.2	10.5	8.1	6.1	0.7	13.2	12.5	6.7

Seasonal (Dec - Mar) water budget components

MO	NIR	GIR	GAL_A	G_RAIN	N_RAIN	ER	ER21	RO	INT	ETo	ET	DR
Dec	0	0	0.9	6	4.5	2.1	1.4	1.4	0	3.1	2.1	2.4
Jan	0.2	0.3	7.6	6.8	4.7	2.8	3	1.9	0.2	3.4	3.6	1.9
Feb	0.9	1.1	29.9	4.9	3.5	2.6	2.2	1.2	0.2	3.5	4.2	0.8
Mar	0.9	1	27.2	4.5	3.4	2.4	2.3	1	0.2	4.1	3.7	0.9
Dec - Mar	2	2.4	65.1	22.4	16.2	10	8.9	5.5	0.7	14.2	13.6	6.2

Appendix 5b: Statistics for seasonal gross and net irrigation requirements

Statistics for seasonal gross and net irrigation requirements (Jan - Apr)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Jan	0	0	0	0	0	0	1	0	0	0	0
Feb	0.5	0	1.35	2.7	0	0	0.73	0.6	1	1.4	1.7
Mar	1.9	1	0.83	4.9	0	0	0.89	1.5	3.1	4.3	5.3
Apr	1.4	1.2	0.78	3.8	0	0	0.81	1.5	2.3	2.8	3.2
NIR (Jan - Apr)	3.2	3.1	0.69	8.3	0	0	0.96	2.7	5.2	6.9	8.5

Statistics for seasonal gross and net irrigation requirements (Feb - May)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Feb	0	0	3.65	0.7	0	0	0	0	0	0	0
Mar	1	0.9	0.98	3.4	0	0	0.91	0.9	1.7	2.3	2.9
Apr	2.3	1.9	0.56	4.9	0	0	0.94	2.2	3.5	4.3	4.9
May	2.4	2.5	0.52	4.7	0	0	0.91	2.3	3.4	4.1	4.6
NIR (Feb - May)	4.9	4.8	0.46	9	0.8	0	0.97	4.6	7.1	8.5	9.7

Statistics for seasonal gross and net irrigation requirements (Mar - Jun)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Mar	0.2	0	1.81	0.7	0	0	0.95	0.6	0.6	0.7	0.7
Apr	1.3	0.9	0.78	3.5	0	0	0.87	1.2	2.1	2.7	3.3
May	3.5	3.8	0.4	5.8	0	0	0.93	3.4	4.8	5.5	6.1
Jun	3.1	3.1	0.39	5.1	0	0	0.89	3	4.1	4.7	4.9
NIR (Mar - Jun)	6.8	7	0.35	11.1	1.9	0	0.98	6.8	9.1	10.2	11.2

Statistics for seasonal gross and net irrigation requirements (Apr - Jul)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Apr	0.2	0	1.43	0.7	0	0	0.75	0.6	0.7	0.7	0.7
May	2	1.9	0.55	3.7	0	0	0.94	1.9	2.9	3.6	4.1
Jun	4.3	4.4	0.27	6.3	0.9	0	0.94	4.4	5.4	5.8	6.2
Jul	3.5	3.7	0.26	5.2	1.2	0	0.87	3.5	4.3	4.7	5
NIR (Apr - Jul)	8.5	9	0.25	12.8	3.4	0	0.99	8.6	10.5	11.4	12.2

Statistics for seasonal gross and net irrigation requirements (May - Aug)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
May	0.4	0.6	0.94	1.3	0	0	0.64	0.6	0.7	0.8	0.9
Jun	2.8	2.8	0.38	4.6	0.8	0	0.93	2.7	3.8	4.4	4.9
Jul	4.7	4.9	0.21	6.1	2.8	0	0.95	4.7	5.6	6	6.3
Aug	3.5	3.7	0.27	5.1	1.3	0	0.85	3.5	4.4	4.8	5.2
NIR (May - Aug)	9.7	9.6	0.2	13.6	4.4	0	0.99	9.8	11.4	12.2	12.7

Statistics for seasonal gross and net irrigation requirements (Jun - Sep)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Jun	0.4	0.6	0.68	0.7	0	0	0.95	0.6	0.7	0.7	0.7
Jul	2.9	3.1	0.3	4.4	0.8	0	0.94	2.9	3.8	4.2	4.6
Aug	4.7	4.9	0.24	6.7	2.8	0	0.94	4.7	5.7	6.2	6.6
Sep	3	2.6	0.27	4	1.2	0	0.81	3	3.7	4	4.3
NIR (Jun - Sep)	9.4	9.4	0.21	13.3	4.9	0	0.99	9.5	11.2	12	12.6

Statistics for seasonal gross and net irrigation requirements (Jul - Oct)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Jul	0.4	0.6	0.93	1.4	0	0	0.63	0.6	0.8	0.9	1
Aug	3	3.1	0.35	4.5	0.8	0	0.91	2.9	4	4.6	5.1
Sep	4	3.9	0.24	6	2	0	0.92	4.1	4.8	5.2	5.5
Oct	2.1	2.3	0.56	4.7	0	0	0.9	2	3	3.6	4.1
NIR (Jul - Oct)	8.1	8.1	0.27	13.5	4	0	0.99	8.1	10	10.9	11.7

Statistics for seasonal gross and net irrigation requirements (Aug - Nov)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Aug	0.5	0.6	15.8	1.6	1.5	1.3	0.9	0.1	0	5.1	2.9
Sep	2.1	2.4	66.1	1.9	1.7	1.7	1.3	0.1	0.1	4.7	4.8
Oct	2.2	2.6	70.5	3.6	2.6	2.5	2.2	0.7	0.2	4.1	4.9
Nov	0.6	0.7	18.2	6.2	4.4	3.5	3.4	1.6	0.3	3.2	2.9
NIR (Aug - Nov)	5.3	5.6	0.36	9.3	1.5	0	0.99	5.3	7.1	8.1	8.9

Statistics for seasonal gross and net irrigation requirements (Sep - Dec)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Sep	0.3	0	1.15	1.4	0	0	0.53	0.5	0.7	0.8	0.9
Oct	1.4	1.3	0.74	3.5	0	0	0.92	1.3	2.2	2.8	3.4
Nov	1	0.9	0.99	2.9	0	0	0.88	1	1.9	2.5	3.1
Dec	0.3	0	1.6	1.3	0	0	0.87	1.1	1.2	1.2	1.2
NIR (Sep - Dec)	2.6	2.3	0.59	5.4	0	0	0.96	2.3	4.1	5.1	6.1

Statistics for seasonal gross and net irrigation requirements (Oct - Jan)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Oct	0.1	0	2.45	0.7	0	0	0.92	0.5	0.6	0.6	0.7
Nov	0.3	0	1.62	1.8	0	0	0.78	0.4	0.9	1.2	1.5
Dec	0.7	0.9	1.07	2	0	0	0.78	0.8	1.3	1.6	1.9
Jan	0.3	0	1.68	1.3	0	0	0.94	1.1	1.2	1.2	1.2
NIR (Oct - Jan)	1.2	0.8	0.94	4.2	0	0	0.92	1	2	2.7	3.4

Statistics for seasonal gross and net irrigation requirements (Nov - Feb)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Nov	0	0	0	0	0	0	1	0	0	0	0
Dec	0.2	0	1.68	0.9	0	0	0.61	0.7	0.8	0.9	0.9
Jan	0.6	0	1.21	2.8	0	0	0.78	0.7	1.2	1.6	2
Feb	0.4	0	1.94	2.5	0	0	0.78	0.4	1.1	1.6	2.1
NIR (Nov - Feb)	1.1	0.8	1.02	3.5	0	0	0.93	0.9	2	2.7	3.5

Statistics for seasonal gross and net irrigation requirements (Dec - Mar)

MO	MEAN	MED.	CV	XMAX	XMIN	ZERO	RSQ	50%	80%	90%	95%
Dec	0	0	4.47	0.7	0	0	0	0	0	0	0
Jan	0.3	0	1.5	1	0	0	0.68	0.7	0.9	0.9	1
Feb	1.1	0.9	0.95	3.8	0	0	0.87	1	1.9	2.5	3.1
Mar	1	1	1.12	3.8	0	0	0.82	1.1	2	2.6	3.2
NIR (Dec - Mar)	2	1.6	0.87	6.2	0	0	0.94	1.5	3.4	4.8	6.1