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Presentation of an Irrigation Management Model for a Multi-cropping and –pattern Setting

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Abstract The variation in crop water demand during the growth cycle is significant, and the cumulative effect of a multi-crop setting has the potential of having a more distorted variation. Multi-cropping on small holdings with undulating topography is characteristic of many developing countries. The irrigation systems for these settings are designed for average conditions, which represent various parameters – crop, climatic condition, and soil- and a known, and generally limited, amount of water. Increased degrees of management and operational challenges are faced by irrigation systems that serve fields which are comprised of multi-tenureship, and cropping patterns. This paper presents a spreadsheet model, that not only provides water budgeting and forecasting for a multi-plot fields; but also optimizes the acreage of each plot ensuring that all the crops can be irrigated daily to meet current ET_c demands utilizing all the available water and time during an extended simulation (365 days), and the prioritization of plots to be irrigated based on RAW deficit and net revenue. The ‘micro-management’ model is universal in its application, transformation and interpretation; that facilitates the generation of additional information with alteration of the requisite parameter values and or algorithms.

Keywords: *Cropwat*, crop water demand, daily time step, evapotranspiration, irrigation, irrigation scheduling, *Kansched*, optimize, and prioritize and WISE.

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Introduction

The design of an irrigation system in relation to crop water demand is accomplished with the consideration of several parameters that are captured in algorithms as presented by authors such as Doorenbos et al. (1977), James (1993) and Pair et al. (1983). One of the driving forces for plant growth is the movement of water which occurs both within and exterior to the plant. The movement of water on our planet is illustrated by the hydrologic cycle, which includes evaporation as one of the processes. Water loss from crop-soil interface is known as evapotranspiration. Quantifying both evaporation and evapotranspiration has been the focus of intense research for several decades. The loss of water either by evaporation or evapotranspiration is important in the development of irrigation systems, and is pivotal both in the representation of open surfaces such as dams and ponds which are used as storage and in cultivated areas, respectively. ASCE (1990) presented an examination of over twenty approaches that can be used for the estimation of evapotranspiration, which also included a ranking of the approaches from different perspectives. The paper presents several of the “members of the Penman’s family” of methods/approaches/equations, as the most consistent in estimating evapotranspiration directly or indirectly. Penman (1948) acknowledges the contribution of several previous works which include that of Dalton, Rohwer (1931), Sutton (1934), Brunt (1939) and, Sutton and Pasquill (1943). The work presented by Penman (1948) was later used by many to estimate evapotranspiration with consideration given to several factors, such as site specific differences, and the lack of data sets.

Crop water demand is calculated as the product of the estimated reference evapotranspiration (ET_0) and the crop factor (k_c). The crop water demand varies both spatially and temporally. The variation of crop factor throughout the crop’s growth stages – initial, vegetative, and maturity- has been presented in the literature by various researchers including Doorenbos et al. (1977) along with the ratio of consumptive use to evaporation over the crop’s relative growth period (Hansen et al., 1980) as shown in Figure 1.

Several models are available to derive crop water demand for both design and irrigation scheduling purposes, including Cropwat, Kanschd and WISE. The checkbook format has also been presented by Werner (2002) and is similar to the reconciliation process that is done with a checking/saving account. This approach can be utilized with water budgeting and forecasting activities. The design of an irrigation system can be enhanced with the utilization of software such as Cropwat, which has crop water demand as an output (Smith, 1992). Design activities are generally done with the best representation of the parameters which are often weighted to their variability, cost implication and expected benefits and/or revenue.

According to James (1983), irrigation systems are not implemented solely for replacement of soil-water deficit. However, the emphasis of this paper will be on the provision of water to ensure readily available water (RAW) conditions to the plant. The depth of RAW is a function of the soil water holding capacity, root depth and the maximum allowable depletion (MAD) value or factor.

Background

As previously mentioned, irrigation schemes/systems are designed for average conditions, which is efficient and suitable for the purposes, but does not adequately address the needs of 'micro-management'. The term 'micro-management' addresses the operation and maintenance of the areas within the system that are smaller than those considered in the average conditions. The issue is magnified when the areas of concern are like those described in Ricketts and Rudra (2004), which comprise small fragment land holdings with arithmetic mean of 1.1 ha and geometric mean of 0.74 ha.

Lands in settings with undulating topography and/or growing a wide cultivar of crops throughout the year have additional management concerns. Often the needs are not adequately met by the irrigation system design, and therefore a reduced acreage has to be considered with the limited water supply. In some cultures the normative practice is to have multi-cropping patterns on a field. The farmer's field is usually cultivated with several crops, noting that the area covered by a particular crop is referred to as a plot. Thus it should be easily recognized that a plot can be a small fraction of a hectare, and it often represents a significant percentage of the farmer's holding. To a farmer with a field size of 0.7 ha, a 0.1 ha plot is a significant percentage of the total holding, and thus has to be viewed and managed with the same diligence that a farmer of field of much larger acreage would give to 13 % of the field or farm.

The situation and economic calculations related to the systems are even more complicated when the capital and operation and maintenance costs are the farmer's responsibility. Additional factors that influence the need for this approach of micro-management are the following (Ricketts and Rudra, 2004):

- ✓ Localized micro-climates or the occurrence of rain within a section of the project area
- ✓ Selection of crop and cropping patterns
- ✓ Localized differences in soil type on farm plots
- ✓ Poor house-keeping by farmers with hydrants left on or off at the scheduled
- ✓ time for closure or opening, respectively. The application of water without specific guides, leaving farmers to choose to irrigate according to their way of thinking. This situation has the potential of both oversupplying- more is better- or undersupplying, as a cost-saving measure
- ✓ The need to offset or stagger production so as to meet market obligations
- ✓ Loss of field production due to unforeseen situations such as disease
- ✓ The accommodation of cultural practices
- ✓ The reduction of pumping during peak hours to control electrical cost

The above factors contribute to what is referred to as outliers, which all have the potential of generating unsuitable operational concerns. According to Ricketts et al. (2004) the following has to be noted: *"Therefore, the concern is how to operate both the farms and the irrigation system efficiently, with the possibility that deviation from design specifications will occur."* Zero risk would be ideal, but according to McBean et al. (1998) such is not the norm and the management of the systems has to be done with the presence of outliers.

Although an investigation was conducted to identify a model or software that would assist with the abovementioned scenario(s), no suitable models were identified since the models did not have the desired outputs, had formats that were extremely labour intensive to utilize, required tedious operation to conduct daily operations, and had inaccessible source codes.

An additional concern was to establish a model that can assist with the daily management of irrigation scheduling activities within the outlined scenario, including the incorporation of the element of social concerns, which according to Heathcote (1998) should be incorporated in the process.

Model Description

The model is presented in a spreadsheet environment that has all the required data in one file on several worksheets. Calculations within the model are done on a daily time step basis for greater sensitivity. The execution of the model requires entry of several prerequisite data sets, which are placed in individual worksheets, and include the following: climate – ET_0 and rainfall; crop (for the three primary growth stages) – k_c , root depth, MAD, duration of crop including each of the primary growth stages, and net revenue per unit area; irrigation system – field's supply discharge rate, application rate (must be less than the maximum infiltration rate), application coverage area (spacing), available time for application each day, available number of days per week and irrigation efficiencies. Farmer/field specific data include (as shown in Table 1): field - size, desired plot size for each of the eight plots; climatic conditions – meteorological zone (rainfall and ET_0); soil – field capacity and wilting point (water holding capacity, the initial moisture content at beginning of planting); crop cycle composition – a maximum of four crops for each of the of seven cycles, and date of planting and termination of crops.

One of the advantages of the spreadsheet environment is the reduction of entry of parameters, as the entry in the database worksheet is required once since entries are instantaneously routed to their linked cells. The crop library currently facilitates 25 crop types but is expandable. The entry of a particular crop type in the field specific database worksheet will automatically retrieve the corresponding associated parameters for that crop from the crop database worksheet. The spelling of the entered crop has to match that of the database, otherwise the data for the closest alphabetic crop name will be returned.

The number of plots for which the model performs individual water budgeting and forecasting operation is not limited to the seven plots as presented but can be expanded. Climatic data is required for the period being simulated. This can be entered in zones which offer flexibility and a better representation of that which is being experienced in each plot. Currently four meteorological zones are within the model but this is expandable as model source the data on a name reference basis. The meteorological zoning facilitates the appropriate factoring or correlating of the 'meteorological database' data to the specific plot conditions.

Along with the meteorological zones additional flexibility can be incorporated within the model by altering the daily value of each parameter as daily calculations are conducted. The effectiveness of precipitation and applied irrigation, and efficiency of the irrigation system can be accessed daily. Similarly the effectiveness of ET_0 throughout the field can be altered within the characterized meteorological zones.

Once the required data are entered in the field database worksheet, then plot acreages can be optimized. The optimization process is initiated with the program's calculator within each plot worksheet. The "solver" option returns the plot size that would be adequately irrigated daily by replacing the current ET_c value within the available daily irrigation duration. This process ensures that the entire plot can be irrigated on any day throughout the simulation period by

replacing the ET_c with the field's total available discharge rate, noting that the plot is a fraction of the field, since a field can be comprised of up to eight plots, one of which is dedicated to being in fallow. The fallow plot is considered as having no water demand on the system as the assumption is made that the ground is covered with mulch thus eliminating evapotranspiration. The duration between the termination of a crop and the planting of the consecutive crop within the cropping cycle is referred to as fallow crop or condition. The alteration of any of the parameters should be followed by repeating the optimization process to ensure that a good representation is achieved. The current plot-size optimization process is not sensitive to the rainfall nor MAD, as the objective is to replace the current daily water demand, which is a function of ET_c and the specifications of the irrigation system. The number of days with non-RAW conditions is a function of the following: the crops in the proposed cycle system – crop factor, root depth, crop duration for the stages and MAD; the specification of the irrigation system – the available irrigation hours, the maximum available discharge rate, the infiltration rate, application rate and irrigation efficiencies; climatic conditions – ET_0 and effective rainfall; and soil – water holding capacity and initial moisture content at planting.

All seven cycles are optimized individually, followed by the optimization of the field. The optimization of the all field's plot sizes is done with the objective of optimizing field's net revenue. The model optimizes the net revenue that can be generated from each field, by establishing acreage for each plot. The chosen plot acreages are less than that which was optimized earlier but are influenced by the initial value that was used to commence the process. The model also ranks the plots that are to be irrigated, either by the net revenue or actual depleted depth, with reference to RAW conditions based on the suggested acreages that were derived from the field-revenue optimization process. The model duplicates all the previously mentioned calculations for each plot with the field-revenue optimization acreage in a separate worksheet. This facilitates comparison of the plot calculation using the two optimized acreages. The ranking process facilitates the prioritization of the plots to be irrigated with the limited water supply.

Output Description and Discussion

The model currently conducts simulation of water budgeting and forecasting for a 365 day duration but it is expandable. The time and volume that are required to meet several objectives, such as replacing the entire RAW or the current daily water demand, is calculated and presented by the model. The number of days with non-RAW conditions is tracked by the model for the entire cropping cycle, as is the number of occurrences for each of the primary growth stages for all the crops within the cycle.

The optimization process ensures that all the crops of a cycle are adequately irrigated throughout the simulation duration for a particular acreage, by having the daily ET_0 being replaced with the daily available irrigation hours. This optimized acreage is less than that which has been suggested or arrived at with the use of the control volume or discharge when only considering lumped parameters. The process is illustrated with data from Ricketts (2005), where a control discharge per hectare was considered. It can be seen from Figure 2 that not all the plot is being irrigated by the discharge rate which is restricted by a plot size constraint, but all of the optimized plot size can be irrigated throughout the duration utilizing the entire field volume as shown in Figure 3. It should be noted that the periods where the acreage is zero are identical for Figure 2 and Figure 3, which correspond to durations without crops that are referred to as fallow.

It must be noted that although the optimized area can be adequately irrigated by replacing the current daily ET_c value, the status of the soil could be that of non-RAW conditions. This

approach allows for the modeling of periods with limited precipitation and thus facilitates the appropriate drought control to be implemented if the need arises, as in periods of agricultural drought. The system is not only required to supply the net ET_c value but additional water due to irrigation efficiencies. The “gross” time and volume required to replace current ET_c values, depleted RAW depths, along with the depths required to ensure one-day within RAW conditions are generated by the model.

The assumption is made within the model that there is a linear relationship between crop yield and net revenue with the acreage cultivated. The optimization of the field revenue is based on the hypothesis that the farmer aims at yielding the optimized net revenue based on limited water and thus dedicates the field’s water to a plot(s) that has the greatest potential of ensuring the realization of this objective.

Results & Concluding Remarks

The model is universal with its application as a budgeting and forecasting tool along with optimizing and prioritizing functions. The forecasting potential of the model is limited by the user’s resourcefulness or intuition. Being in a spreadsheet environment, the model is highly flexible. Using the proposed cropping cycle (as shown in Figure 4) for an irrigation system in Jamaica as presented by Hydroplan (2002), examples of some of the information that can be displayed graphically are shown in Figure 5 to Figure 10. The model can also be utilized as an educational tool, allowing for investigation of several scenarios as seen relevant by the user which can be saved as different files. The storage and retrieval options of the stored files can be readily appreciated. The perspective of the system that is viewed by an individual can be altered within the model, thus enhancing the comprehension of the system and its functionality. The potential of the model to be expandable is limited by portability and availability of computing resources.

The flexibility that is allowed by the model contributes to the limited incorporation of a graphical user interface (GUI). The development and establishment of a GUI is being slated for future developments with the view maintaining the model’s flexibility while creating a friendly interface for users who are not particularly interested in seeing the algorithms and also who fear unintentionally modifying the model. Although the model incorporates the MAD value, which offers some indication of when water stress is likely to occur, it does not give a good representation of relative crop yield with water stress. There are two primary factors which influence crop yield (Kuo et al., 2000) – insufficient water which leads to water stress commonly referred to as drought; and low aeration or water logging. According to Kuo et al. (2000), Neale (1994) presented work that indicates that water stress results in yield reduction. The model currently lacks an input for the daily variability of root depth but this can be easily incorporated once a suitable mathematical expression is identified by the user.

The model allows for greater insight to be gained into the irrigation process and into the supplying of a wide range of information. The model allows for the adaptation of particular interest(s) of any of the system’s stakeholder to be examined. Several scenarios can be investigated by the model, presenting answers to some of the commonly asked questions in a ‘non-ideal’ environment. The occurrence of non-ideal situations is often the challenge of well designed systems which are implemented with some limiting parameter(s).

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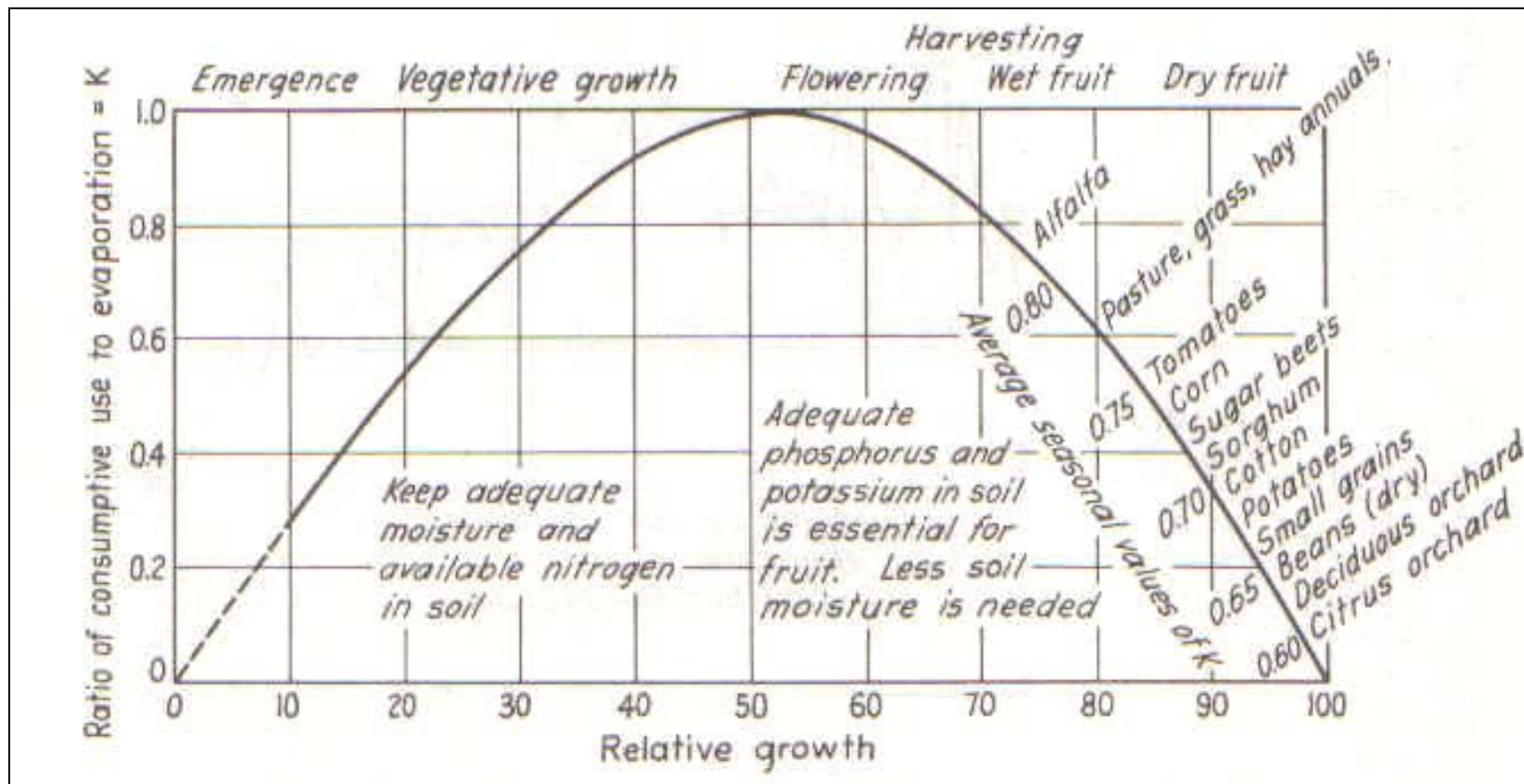


Figure 1 Generalized Curve Comparing Consumptive Use-Evaporation Ratio to Relative Growth of Crop (adapted from Hansen et al., 1980).

Table 1 Description of irrigation system data sheet

Name of Field	Lot 300							
Name of Farmer	Mr. John Brown							
Location or Address of Field	4 Burnside Road,							
Area of all Irrigable Plots (ha)	3							
Name of Hydrant that serves field	Node 03							
Designed Flow rate (l/s/ha)	1.18							
Initial Date of year being considered	01-Jan-03							
Proposed Cropping Cycle	Cycle A	Cycle B	Cycle C	Cycle D	Cycle E	Cycle F	Cycle G	Fallow/Check (Ref.)
Met Zone	Zone A	Zone A	Zone A	Zone A	Zone A	Zone A	Zone A	Zone A
Selection of Plot Area (ha)	0.428	0.428	0.428	0.428	0.428	0.428	0.428	0.0
Selection of Plot Area (%)	0.142666667	0.142666667	0.142666667	0.142666667	0.142666667	0.142666667	0.142666667	0.00
Allowed Flow rate (l/s)	0.168346667	0.168346667	0.168346667	0.168346667	0.168346667	0.168346667	0.168346667	1.18
Total Potential Annual Returns	J\$385,610.93	J\$788,990.84	J\$527,194.39	J\$565,317.00	J\$342,272.88	J\$155,857.91	J\$274,988.87	J\$3,040,232.82
Total Potential Annual Returns/ha	J\$900,960.12	J\$1,843,436.54	J\$1,231,762.59	J\$1,320,834.12	J\$799,703.00	J\$364,154.00	J\$642,497.35	J\$1,013,410.94
Irrigation Efficiency	72%	72%	72%	72%	72%	72%	72%	72%
1st Crop	Beet	Water Melon	Hot Pepper	Cucumber	Escallion	Thyme	Cabbage	Fallow
Enter date of Planting	03-Jan-03	21-Jan-03	06-Jan-03	08-Jan-03	01-Jan-03	01-Jan-03	06-Jan-03	01-Jan-03
Initial Soil Moisture: (% of WHC)	10.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	65.71%
Date of Veget (70% to 80%)	02-Feb-03	20-Feb-03	05-Feb-03	23-Jan-03	31-Jan-03	31-Jan-03	05-Feb-03	01-Jan-03
Date of Maturity	04-Mar-03	21-Apr-03	07-Mar-03	07-Feb-03	02-Mar-03	02-Mar-03	06-Apr-03	01-Jan-03
Date of end of crop	09-Apr-03	21-May-03	21-Apr-03	28-Feb-03	01-Jan-04	01-Jan-04	08-Apr-03	01-Jan-03
Potential Crop Returns	J\$118,493.48	J\$129,032.20	J\$120,417.71	J\$111,556.66	J\$342,272.88	J\$155,857.91	J\$146,699.74	
2nd Crop	Hot Pepper	Sweet Pepper	Water Melon	Carrots	Fallow	Fallow	Sweet Corn	Fallow
Enter date of Planting	21-Apr-03	06-Jun-03	01-May-03	18-Mar-03	31-Dec-03	31-Dec-03	24-Apr-03	01-Jan-03
Initial Soil Moisture: (% of WHC)	20.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	67.14%
Date of Veget (70% to 80%)	21-May-03	06-Jul-03	31-May-03	10-Apr-03	31-Dec-03	31-Dec-03	24-May-03	01-Jan-03
Date of Maturity	20-Jun-03	05-Aug-03	30-Jul-03	03-May-03	31-Dec-03	31-Dec-03	23-Jul-03	01-Jan-03
Date of end of crop	19-Aug-03	21-Aug-03	22-Aug-03	03-Jun-03	31-Dec-03	31-Dec-03	12-Aug-03	01-Jan-03
Potential Crop Returns	J\$120,417.71	J\$265,622.35	J\$129,032.20	J\$214,849.15	J\$0.00	J\$0.00	J\$743.07	
3rd Crop	Cabbage	Cauliflower	Tomato	Beet	Fallow	Fallow	Water Melon	Fallow
Enter date of Planting	06-Sep-03	01-Sep-03	06-Sep-03	21-Jun-03	31-Dec-03	31-Dec-03	24-Aug-03	01-Jan-03
Initial Soil Moisture: (% of WHC)	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%
Date of Veget (70% to 80%)	06-Oct-03	01-Oct-03	06-Oct-03	21-Jul-03	31-Dec-03	31-Dec-03	23-Sep-03	01-Jan-03
Date of Maturity	05-Dec-03	30-Nov-03	05-Dec-03	20-Aug-03	31-Dec-03	31-Dec-03	22-Nov-03	01-Jan-03
Date of end of crop	31-Dec-03	30-Dec-03	31-Dec-03	03-Sep-03	31-Dec-03	31-Dec-03	31-Dec-03	01-Jan-03
Potential Crop Returns	J\$146,699.74	J\$394,336.29	J\$277,744.48	J\$118,493.48	J\$0.00	J\$0.00	J\$129,032.20	
4th Crop	Fallow	Fallow	Fallow	Hot Pepper	Fallow	Fallow	Fallow	Fallow
Enter date of Planting	31-Dec-03	31-Dec-03	31-Dec-03	16-Sep-03	31-Dec-03	31-Dec-03	31-Dec-03	01-Jan-03
Initial Soil Moisture: (% of WHC)	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%
Date of Veget (70% to 80%)	31-Dec-03	31-Dec-03	31-Dec-03	16-Oct-03	31-Dec-03	31-Dec-03	31-Dec-03	01-Jan-03
Date of Maturity	31-Dec-03	31-Dec-03	31-Dec-03	15-Nov-03	31-Dec-03	31-Dec-03	31-Dec-03	01-Jan-03
Date of end of crop	31-Dec-03	31-Dec-03	31-Dec-03	31-Dec-03	31-Dec-03	31-Dec-03	31-Dec-03	01-Jan-03
Potential Crop Returns	J\$0.00	J\$0.00	J\$0.00	J\$120,417.71	J\$0.00	J\$0.00	J\$0.00	
Note: Fallow used for areas not irrigated								
Crop length is not constant for a specific in the different cycles and have adjusted according. Shortern days - <i>Crop is Italics</i>								

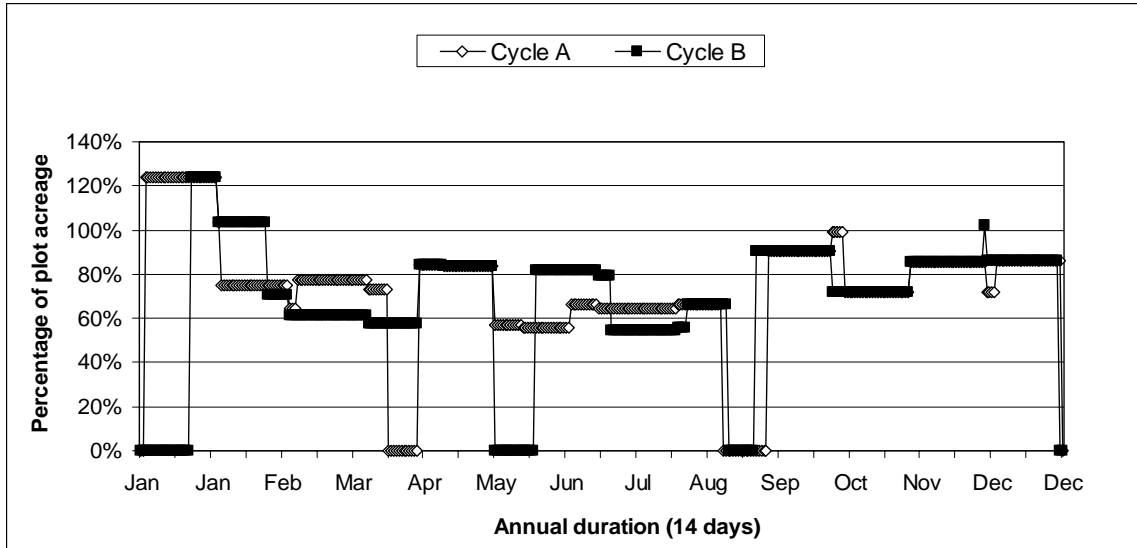


Figure 2 Variation of plot area to be irrigated using plot allotment discharge throughout a year with average annual evapotranspiration (adapted from Ricketts, 2005).

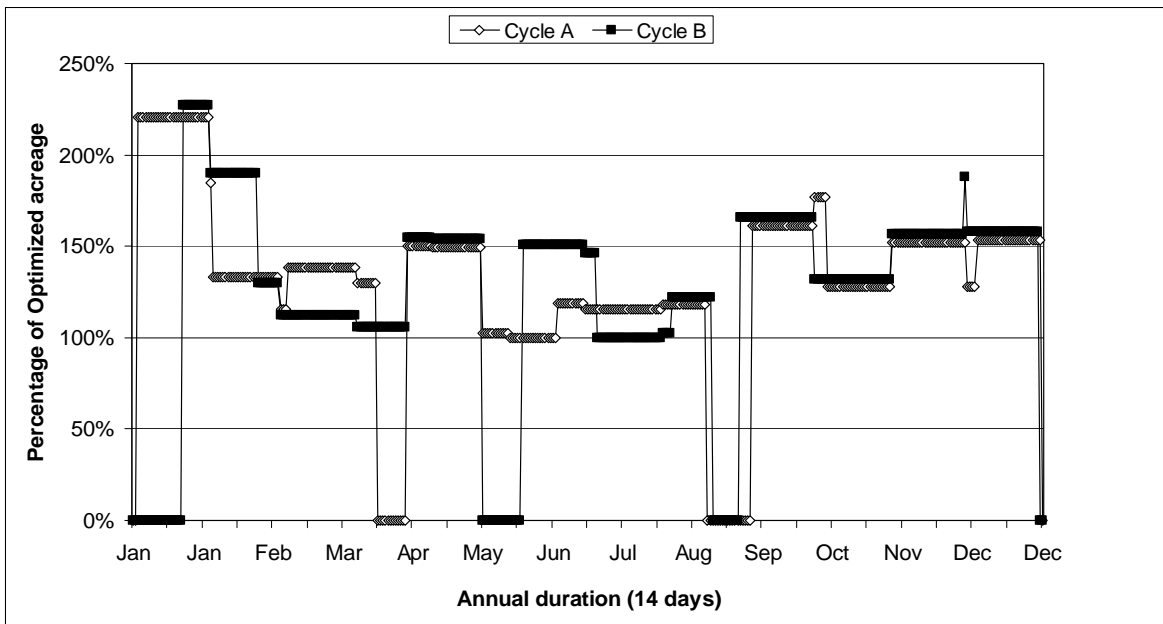


Figure 3 Variation of optimized plot area to be irrigated with field allotment discharge throughout a year with average annual evapotranspiration utilizing the field's discharge allotment (adapted from Ricketts, 2005).

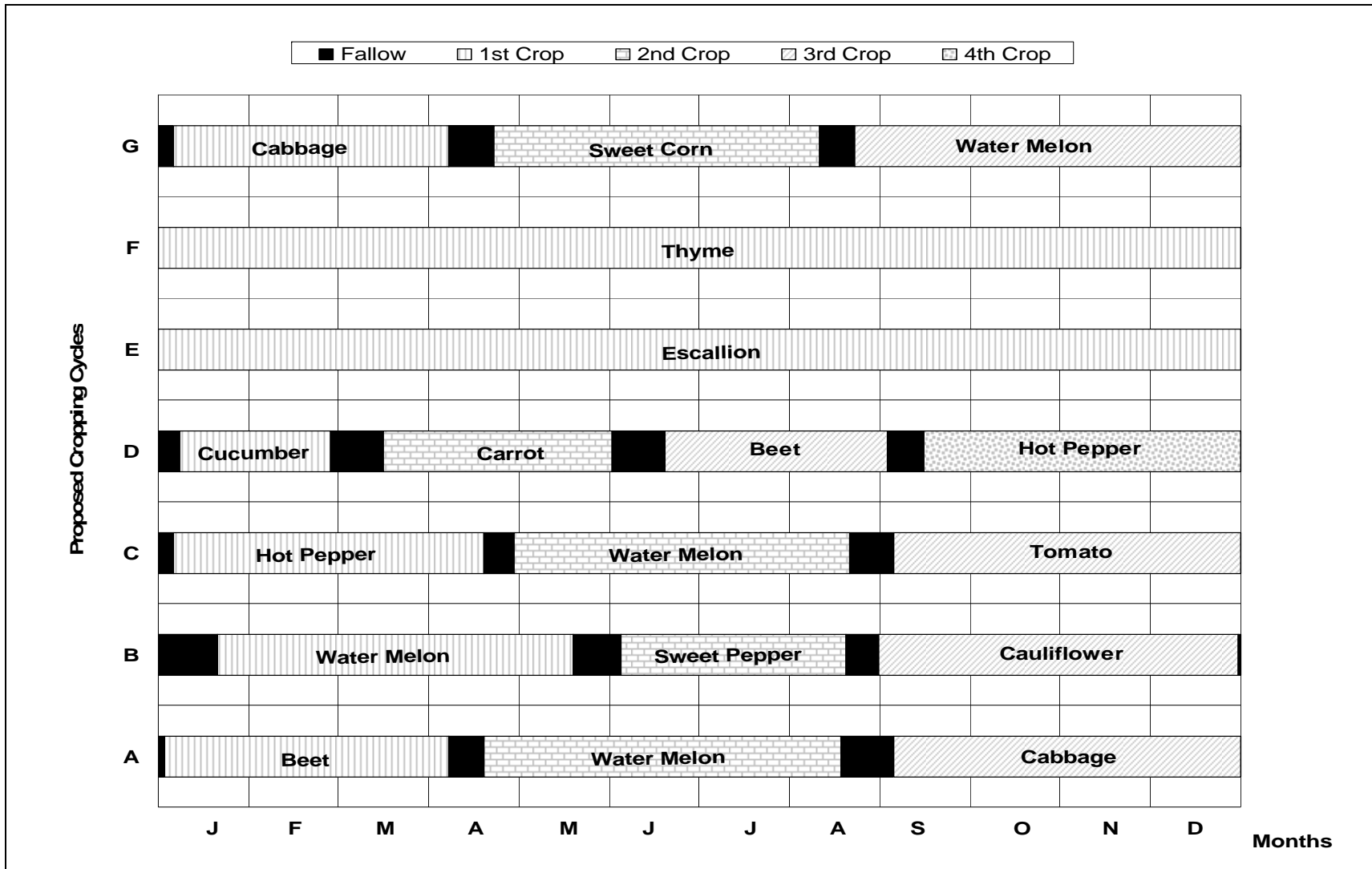


Figure 4 Proposed cropping pattern for Beacon irrigation scheme (adapted from Hydroplan, 2002).

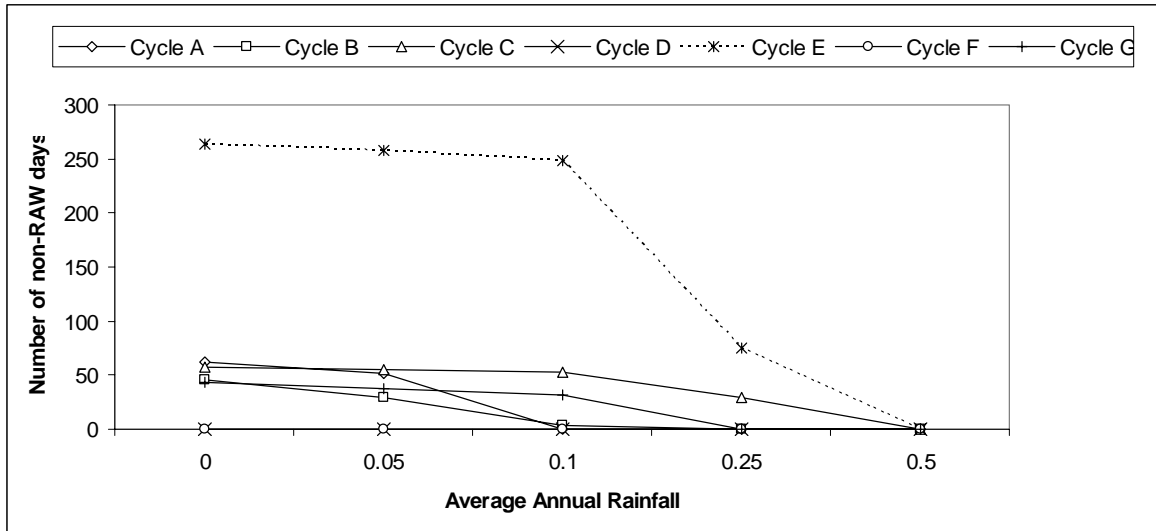


Figure 5 Variation of number of days experiencing non-RAW conditions with average annual rainfall (adapted from Ricketts, 2005).

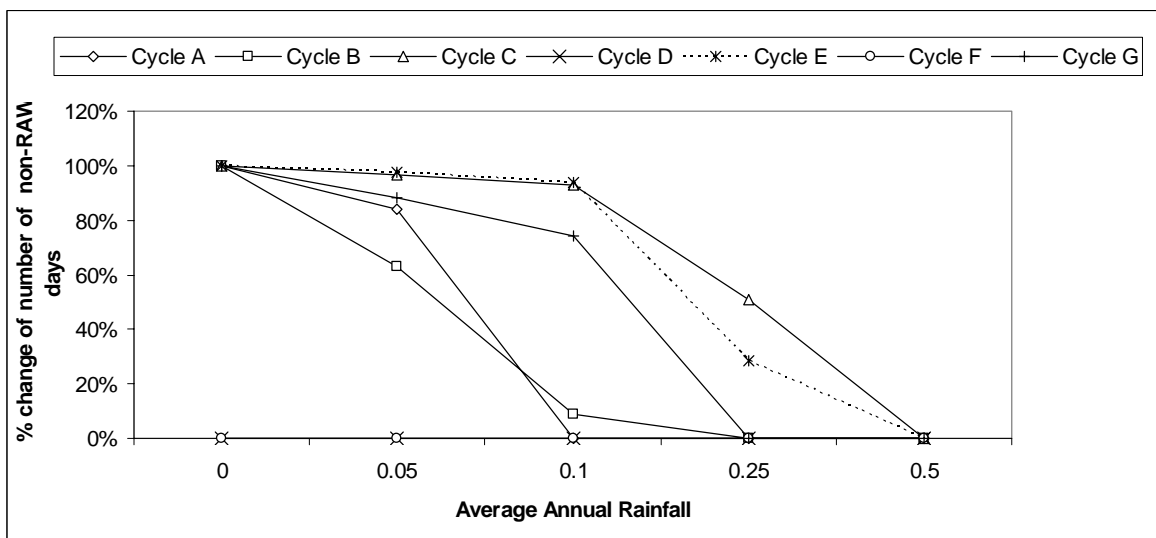


Figure 6 Variation of percent change of days experiencing non-RAW conditions with average annual rainfall (adapted from Ricketts, 2005).

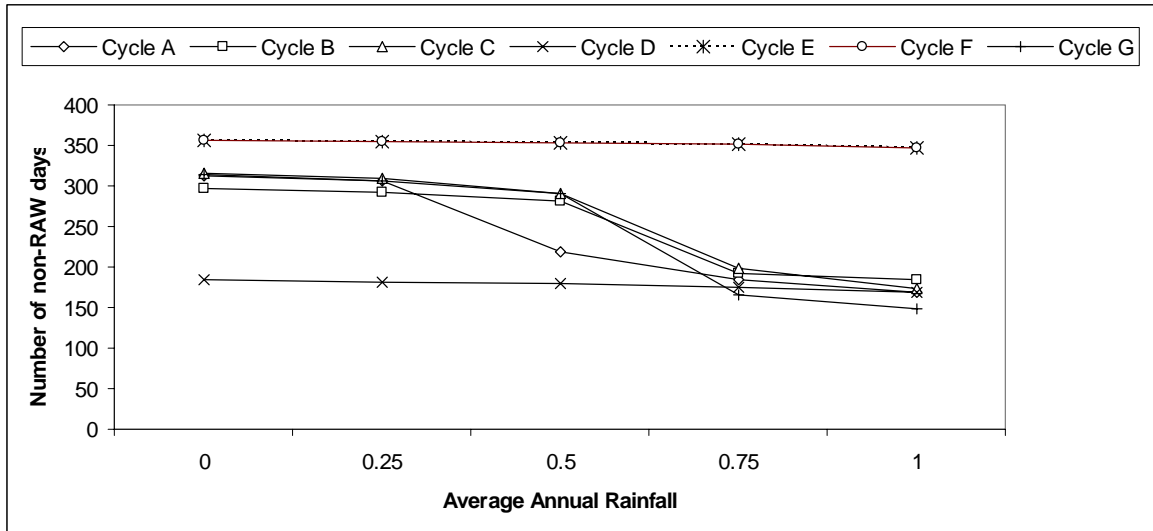


Figure 7 Variation of number of days experiencing non-RAW conditions with average annual rainfall, having no daily irrigation application (adapted from Ricketts, 2005).

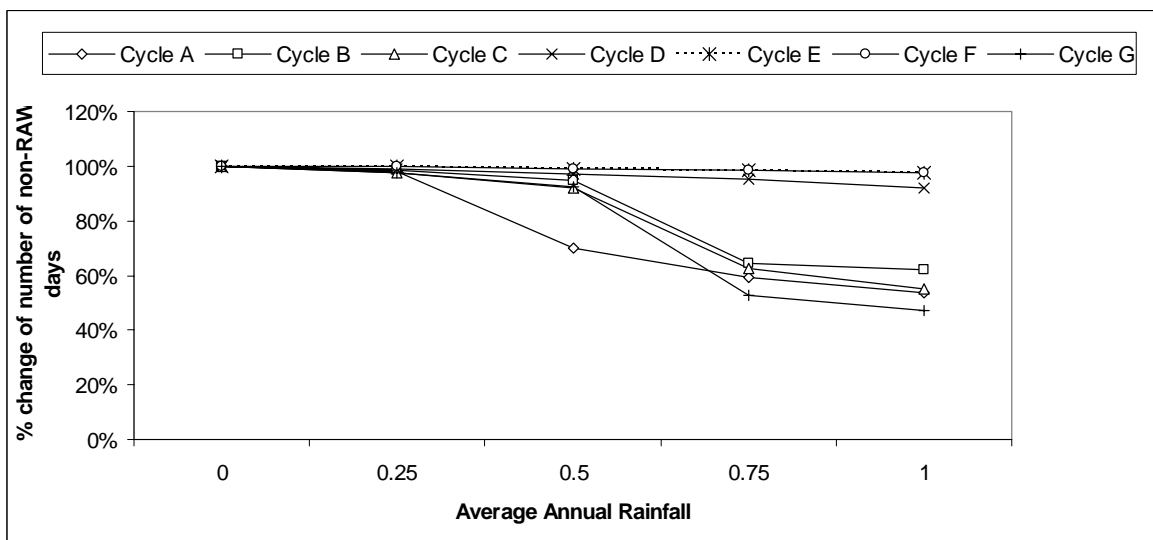


Figure 8 Variation of percent change of days experiencing non-RAW conditions with average annual rainfall, having no daily irrigation application (adapted from Ricketts, 2005).

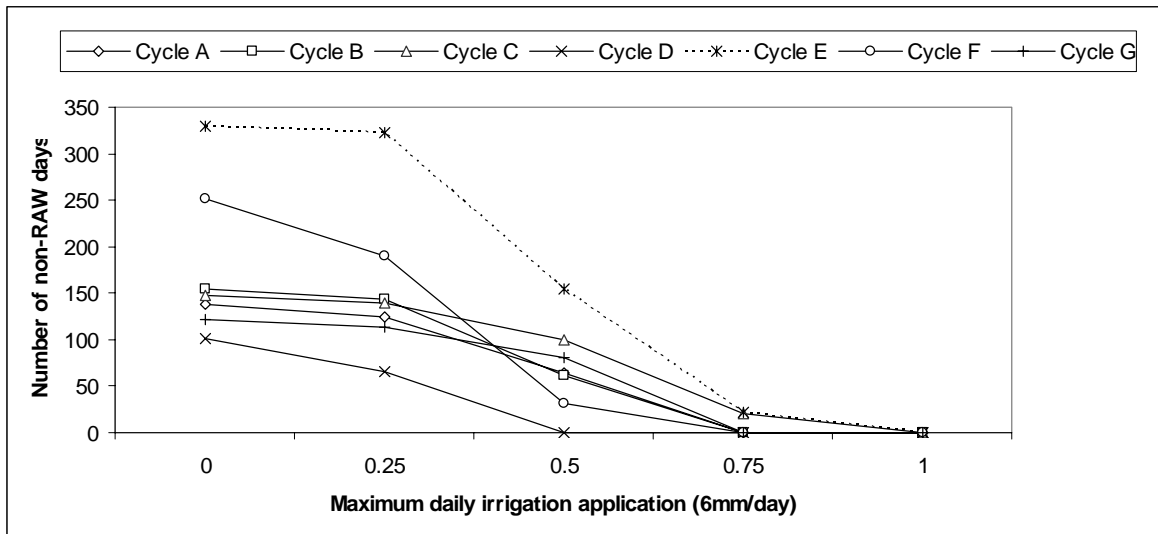


Figure 9 Variation of number of days experiencing non-RAW conditions with maximum daily irrigation application (6mm/day), having average rainfall (adapted from Ricketts, 2005).

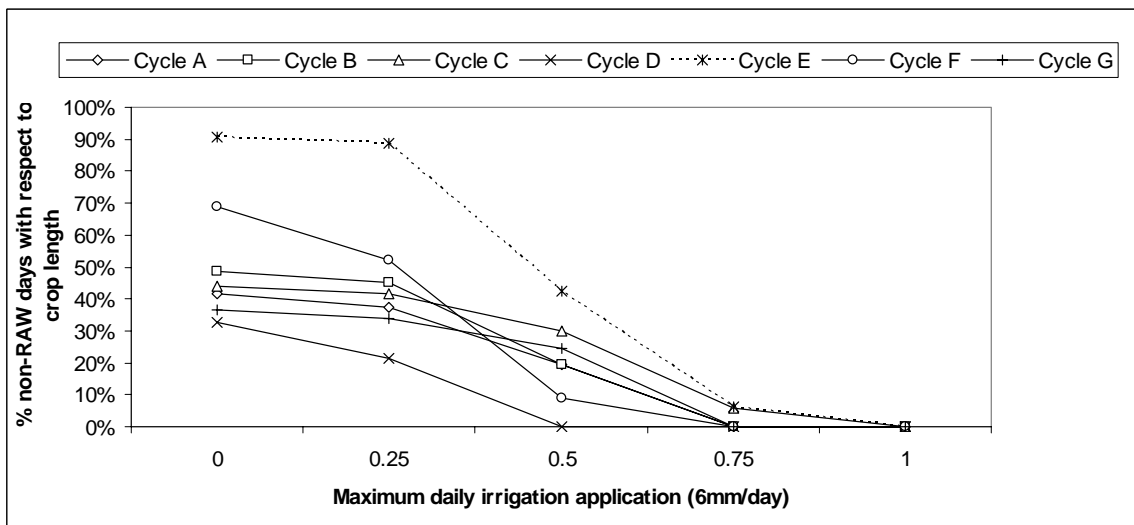


Figure 10 Variation of percent change of days experiencing non-RAW conditions with maximum daily irrigation application (6mm/day), having average rainfall (adapted from Ricketts, 2005).