CROP CONSUMPTIVE USE SIMULATION USING A WATER HARVESTING MODEL

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ABSTRACT

A Compartmented Reservoir Operation Program, CROP84, is a computer program developed, by C. B. Cluff (1977), as a tool for optimizing the design dimensions of water harvesting agriculture systems. This model is used in conjunction with a rainfall/runoff model called RAMOD. The objective of the research was to compare the actual and the simulated values of seasonal irrigation and consumptive use of four crops: wheat, sorghum, cotton, and grapes. After repeated simulations structural improvements were made in the soil moisture accounting routine of CROP84. These improvements were in the equations that calculated the rate of root growth, the soil moisture depletion fraction and actual evapotranspiration. In the final simulation, the percentage difference for crop consumptive use calculated from the actual data and the simulation was +2.6 % for sorghum, -2.4 % for grapes, +2.0 % for wheat, and -8.8 % for cotton.

INTRODUCTION

Water harvesting is the ancient practice of collecting and storing rainfall. Usually practiced in arid and semi-arid regions of the world, its use establishes more reliable water supplies for agricultural, livestock, industrial, domestic, or recreation activities. Water harvesting systems utilize a catchment area, which vary in size from as small as a square meter to thousands of hectares. To increase runoff, the catchment area surface is often made impervious by a physical or chemical treatment. Many water harvesting agrisystems use a storage tank or an open reservoir to provide supplemental irrigation during dry periods, thus making the system more reliable. Water harvesting agrisystems may be built without storage where water is channeled directly to the crop or particular use. In recent years, water balance models, such as the Compartmented Reservoir Opera-

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tion Program (CROP84), have served as practical tools for engineers designing water harvesting agrisystems. Through modeling, optimal dimensions for a catchment area and a reservoir may be determined to adequately meet the water requirements for a particular cropping patern on a given area of land.

MODEL DESCRIPTION

CROP84 consists of three main routines, which are: 1) a compartmented reservoir routine which calculates the design dimensions of the reservoir component; 2) a reservoir storage routine which accounts for the water gains and losses in the reservoir due to evaporation, seepage, irrigation use, runoff, and rainfall; and 3) a soil moisture routine which accounts for the water gains and losses in the crop area due to rainfall, irrigation, consumptive use, and deep percolation. The simulation testing and subsequent model structure adjustments performed in this research were concentrated in the latter routine. A complete system may be broken into three main components as shown in Figure 1. CROP84 allows the user the option of not using a reservoir storage facility.

Cropped Areas

Compartmented
Reservoir

Watershed
Catchment

Figure 1. A schematic diagram of a water harvesting system with storage

CROP84 outputs a weekly schedule for each year of simulation showing the rainfall, runoff, evaporation rates, the quantity of water in soil and reservoir storage, the quantity of water used in crop evapotranspiration and lost through deep percolation. Optimization of the system design and dimensions requires repetitive simulations. For example, if the reservoir runs dry during a cropping period in one simulation, the user may enlarge the catchment area if the amount of runoff is not sufficient. Or, if the storage is not sufficient, it may be necessary to increase the size of the reservoir. It is recommended that simulations be made over a ten or twenty year period. The user is then able to take wet and dry cycles in the rainfall record into consideration. CROP84 is capable of operating on a water calendar using October 1 as the beginning day of the year.

The conversion of daily rainfall events to runoff in the watershed catchment is computed in a separate model called RAMOD. RAMOD allows the user the option of computing runoff using the U.S. Soil Conservation Service curve number equation approach or an empirical approach developed by Cluff. RAMOD creates an output record of weekly rainfall and runoff, which is accessed during the operation of CROP84. A full description of the RAMOD and CROP84 models is provided in Risley (1984).

CROP84 allows the operation of either a compartmented or uncompartmented reservoir. Compartmentalizing a reservoir is a method of reducing evaporation losses and in some cases seepage losses by dividing a reservoir into separate compartments. As the water in the reservoir is diminished during the dry season, it is consolidated into fewer compartments thus decreasing the surface area exposure. A discussion of the concept of compartmented reservoirs is provided in Cluff (1977).

The second major routine of CROP84 computes the water gains and losses for each compartment used in the reservoir for each week. Gains include weekly rainfall on the water surface, and weekly runoff from the catchment. Any overflow of the reservoir is considered lost from the system. An additional reservoir gain is the option of adding surface flow and base flow from the cropped areas into the reservoir. Surface and base flow rates would be computed as a percentage of the weekly runoff rate. This option would be used when the cropped area is contained within the watershed and is of significant size in comparison to the watershed size.

Reservoir losses are due to evaporation and seepage. In computing the evaporation loss, the model allows the use of either weekly pan or pond evaporation rates. A reduction coefficient may be used with the pan evaporation data. The rate of seepage loss is assumed to be a linear function of the hydraulic head in the reservoir as shown in the following.

$$SV = (MA - MI) / CD \quad (1)$$

$$SR = (SV * WD) + MI \quad (2)$$

where
SV = slope value

MA = maximum seepage rate determined by the user
MI = minimum seepage rate determined by the user
CD = maximum compartment depth
SR = calculated seepage rate for a given week
WD = current weekly water depth of compartment

The third major routine, soil moisture accounting, calculates the amount of water in storage in the cropped area. CROP84 allows the simulation of up to five different types of crops. Water gains to the crop area soil zones are rainfall on the crop surface areas, and irrigation applications. A decimal fraction may be entered for irrigation efficiency to account for all water losses from the system as water is transported from the reservoir to the crop. Water losses from the crop area soil zones are from plant consumptive use and deep percolation.

To account for consumptive use Crop84 computes total weekly amounts of potential and actual evapotranspiration loss from all the crop areas. For each crop, a record is entered containing 52 consumptive use values representing each week of the year. Consumptive use values may be depth or coefficient values. The coefficients are multiplied times the evaporation rate for the corresponding week to get a value of depth.

For plants having established root systems (such as perennials), a constant average root depth is used for the entire simulation. However, for most annual field crops simulated by the model a root growth function is used to allow the root depth to increase throughout the growing plant period. The function is based on the assumption that by the time a crop has reached the peak of its consumptive use curve, root growth will have stabilized. Since the first week of cropping will most often be the time of most rapid root growth, the program designates 0.2 meters as the rate of growth for that week. The root begins growing at a linear rate on the second week. The rate is based on the designated maximum root depth and the number of weeks between the second week and the peak of the consumptive use curve.

The activation time of the root growth function in CROP84 is controlled by a "floating" planting date. For each crop that is simulated, the user enters the earliest and latest possible weeks of the year during which the crop will be planted. This defines the time of the year that planting is allowed. The user also enters a percent of the total reservoir volume that must be filled with water before the crop may be planted. If sufficient water is available during the time of planting, cropping will begin the following week.

When the root growth function is used, the available moisture for a particular week IVM is computed by multiplying the available soil moisture decimal fraction SMC by the crop area and by the current root depth for that week. When the root depth has reached its maximum, IVM equals the available soil moisture storage capacity, SVM. When the root growth function is not used IVM is a constant value and equal to SVM. VS is the volumetric quantity of water that is held within IVM from week and to week. As IVM increases during the cropping due to an increase in root depth, the quantity of water in the zone of soil accumulated into IVM will be added to VS.

The routine for the Crop program used to calculate the water stress of the plant is based on research published by Doorenbos and Kassam (1979). For each week of cropping, the program calculates a soil water depletion fraction P which is the fraction of available water in the zone that must be depleted before the plant is stressed. Doorenbos and Kassam base the depletion fraction as a function of the type of crop and the daily potential evapotranspiration.

Table 1. Crop Groups According to Soil Water Depletion.

Group	Crops
1	onion, pepper, potato
2	banana, cabbage, grape, pea, tomato
3	alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
4	cotton, maize, olive, safflower, sorghum, soybean, sugarbeet, sugarcane, tobacco

$$\text{Group 1} \quad P = 0.6 * e^{-.13 * EMAX} \tag{3}$$

$$\text{Group 2} \quad P = 0.84 * e^{-.14 * EMAX} \tag{4}$$

$$\text{Group 3} \quad P = 0.97 * e^{-.12 * EMAX} \tag{5}$$

$$\text{Group 4} \quad P = 1.05 * e^{-.10 * EMAX} \tag{6}$$

where
EMAX = daily potential evapotranspiration rate (mm)

If a plant stress occurs, the program will call for an irrgation. The quantity of water requested will be the difference between the soil moisture capacity volume IVM and the current soil moisture level VS, divided by the user entered irrigation efficiency. The amount of requested irrigation water would then be taken directly out of the reservoir and added to the soil moisture level VS. If the requested irrigation quantity is greater than the quantity of water remaining in the reservoir, then the difference is multiplied by the irrigation efficiency and subtracted from the soil moisture level VS. If there is no remaining water in the reservoir, the requested irrigation amount is multiplied by the irrigation efficiency, and subtracted from the soil moisture level VS. If the water stress is not eliminated by an irrigation, the gap between the current soil moisture level VS and the level at which a stress begins is defined as a deficit. During a deficit period the actual evapotranspiration becomes less than the potential evapotranspiration. AET is computed based on the following equation developed by Doorenbos and Kassam (1979).

$$AET = (DSA/T)*[1-(1-P)*\exp(X)] \qquad (7)$$
$$X = -((EMAX*T)/(1-P)*DSA) + P/(1-P) \qquad (8)$$

where
AET = actual evapotranspiration (mm)
DSA = depth of available water (mm)
T = number of days since any water was applied to the crop area

$$T = YMIN + (WX*7 - 3) \qquad (9)$$

where
YMIN = number of days between last irrigation and the start of the deficit
WX = number of weeks since deficit began

$$YMIN = (P*DSA)/EMAX \qquad (10)$$

If the soil moisture level, due to a rainfall event, is greater than the field capacity level, the difference would become percolation. If the root growth function was not being used, this percolation would be either lost from the system or returned to the reservoir for reuse on the crops if the user activated a percolation recovery function. This function would be used in shallow soils with a hard pan or soils with a high water table. However, if the root growth function was being used, percolated water would go into the lower soil zone between the current root depth and the maximum root depth. It would then be lost from the system or returned to the reservoir (as explained above) when that zone was filled to field capacity.

SIMULATION

The objective of the research was to test the performance of the soil moisture accounting routine of the model and if necessary make structural improvements. Using water budget data of actual field crops, a comparison was made with the water budget simulated by the program. It was necessary to address two questions: 1) Would the program call for irrigations similar in quantity and timing to irrigations actually applied to the selected crops, and 2) would the amount of seasonal consumptive use calculated from the simulation be similar to an amount calculated from the actual data?

In the past thirty years, the U.S. Department of Agriculture Water Conservation Laboratory in Phoenix, Arizona has done considerable research in investigating the consumptive use requirements of major field crops commonly grown in the Southwestern United States. The results of much of the research were published by Erie et al. (1981). The publication contains empirically derived consumptive use curves for numerous crops grown in the Salt River Valley of Arizona. To calculate consumptive use, the researchers used the soil moisture depletion method. Changes in the soil water content, using soil sampling and gravimetric analysis, were measured over a period of time under actual field conditions. Soil samples were taken at 1-foot interval depths throughout the root zone and at locations that could be expected to evaluate the average soil moisture distribution and depletion by the plants. The samples were weighed, dried in forced air ovens, and the amount of moisture was calculated. Soil moisture samples were taken at planting and harvesting dates, before and after (3 to 4 days) irrigations, and at intermediate dates as necessary. Consumptive use was then calculated from knowledge of the soil moisture changes. The consumptive use curves used in the publication were developed from the averages for several years.

Table 2. Test plot information of crops used in the model calibration.

	Wheat	Sorghum	Cotton	Grapes
Growing season:	11/68 - 5/68	6/58 - 10/58	4/58 - 11/58	3/64 - 7/64

(Continued on following page)

	Wheat	Sorghum	Cotton	Grapes
Size of plots:	270' X 33'	270' X 33'	2 acres	-
Soil field capacity by weight:	18.5%	18.5	19.5%	15%
Soil wilting point by weight:	8%	8%	8%	7%
Specific gravity:	1.46	1.45	1.45	1.47
Maximum root depth (inches):	60	60	72	72

The wheat and sorghum were grown at the Mesa Experimental Station, Mesa, Arizona. The cotton was grown at the University of Arizona Cotton Research Farm, Tempe, Arizona. The grapes were grown at the Drake Ranch, Litchfield Park, Arizona. It was necessary to calculate the total quantity of irrigation water applied to each of the crops during the growing season, and the remaining quantity of water at the end of the season. The soil moisture depletion data contained gravimetric soil moisture readings before and after each irrigation application for the crop. Since the CROP84 model only accounts for available soil moisture, it was necessary to subtract the percent wilting point value from each of the soil moisture readings in the data. It was also necessary to convert gravimetric soil moisture values into metric volumetric values. This is shown in the following equation:

$$DP = [SP * DS * 25.4 * PW] / 100 \qquad (11)$$

where
DP = depth of water in the soil (mm)
SP = average specific gravity of the soil
DS = depth of soil profile (inches)
PW = average gravimetric percent soil moisture (minus the percent wilting point)
25.4 was used as a metric conversion

The depth of soil profile in inches DS was calculated by using the same method that is used to calculate the root depth in the program. This is shown in the following equation:

$$DS = [(RD * CW) / NGW] + 7.87'' \qquad (12)$$

where
RD = maximum root depth (inches)
CW = current week of the growing season counting

from the beginning of the season
NGW = number of root growing weeks in the season

7.87 is a constant value in inches to account for more rapid root growth that usually occurs in the beginning of the season. NGW was calculated by using the consumptive use curve developed by the researchers Erie et al. (1981). It is defined as the number of weeks from the beginning of the season to the week in which the curve has peaked.

For each irrigation, DP was calculated before and after the irrigation. The depth of irrigation was found from the following equation:

$$ID = [(DPA - DPB) + CU] / IE \qquad (13)$$

where
ID = depth of irrigation (mm)
DPA = DP after irrigation (mm)
DPB = DP before irrigation (mm)
CU = water consumed by the crop during the period between the two measurements (mm)
IE = irrigation efficiency (0.75)

The quantity of water consumed by the crop during the period before and after each irrigation CU was calculated by using the consumptive use curve developed by the researchers Erie et al. (1981).

The seasonal crop consumptive use was calculated from a water budget equation. This is shown in the following equation (all values are in mm):

$$SCU = BSM + R + I - DP - FSM \qquad (14)$$

where
SCU = seasonal crop consumptive use
BSM = depth of water in soil profile in the beginning of the season
R = total precipitation during season
DP = total deep percolation durring season
I = total irrigation applied at the crop (ID*IE)
FSM = depth of water in soil profile at the end of the season

Table 3. Total irrigation and seasonal crop consumptive use calculated from the crop data (all values in mm)

	Wheat	Cotton	Sorghum	Grapes
Total Irrigation:	548	1031	471	704
Consumptive Use:	716	1132	651	709

The available soil moisture capacity of the soils of the four crops was calculated from the given data by the following equation:

$$AC = (FC-WP) * SG \tag{15}$$

where
AC = available soil moisture capacity by volume
SG = specific gravity of soil
FC = percent field capacity by weight
WP = wilting point by weight

A value for soil root depth was used for each crop. For wheat, cotton, and sorghum, the chosen value was the maximum expected depth of the crop's roots during the growing season. Since grapes are a perennial plant, an average root depth was used. The values used for each crop are shown in Table 2.

A water year calendar was used for wheat and sorghum. However, a regular calendar was used for cotton and grapes since they have growing seasons during the months of September and October. The historical daily rainfall data, from Climatological Data-Arizona Section (1958, 1964, 1968, and 1969), were used in each of the four simulations to account for rainfall on the crop areas. Weekly crop consumptive use values for the growing season of the crops were computed from the consumptive use curves developed by Erie et al. (1981). Since wheat, cotton, and sorghum were preirrigated at the beginning of the growing season, the soil zone was set to field capacity at the start of the growing season for these crops. Grapes were not given a preirrigation. Thus, the soil moisture level was not artificially adjusted for the first week of the growing season in the simulation.

The first set of simulations showed that for the crops wheat, grapes, and sorghum the values for total simulated irrigation were higher than the actual values. The program was calling for irrigations near the end of the growing season. Although some crops will require irrigations until the end of the season, this was not the case with the crops being used for the simulations. Doorenbos and Kassam (1979) do mention that for each of the four crops, that the depletion fraction P value must be raised towards the end of the season. However, the equations used for calculating P do not use the date during the season as a variable. As a structural improvement for the soil moisture accounting routine, an option was given to the user to indicate the number of weeks prior to the end of the season at which time irrigations would then be suppressed. When this was taken into account in new simulation trials, the total calculated and total simulated irrigation quantities for each of the crops (with the exception of wheat) were much closer. A summary of each simulation is shown in Table 5.

After rechecking the accuracy of the weekly consumptive use values used in the wheat simulation, it was concluded the soil depletion fraction P equation recommended for wheat by Doorenbos and Kassam (1979) was not appropriate for the variety of wheat grown by the researchers Erie et al. (1981). The P values were too low, and were thus calling for too much irrigation. The wheat was again simulated using the same inputs as previously, however this time equation (6) of the soil depletion fraction equations was used. This equation computed higher P values. The results showed an improvement in the timing of the irrigations. The simulated irrigations occurred during the same weeks as the actual irrigations. A comparison of the simulations using both equation (5) and (6) for wheat are shown in Table 4. The right most column shows the simulation results of wheat when the final irrigation in the growing season was suppressed.

Table 4. Total Irrigation Depths for Wheat (all values in mm)

Crop	Actual Data:	Simulation Data: No Suppression	Suppression
Wheat5	548	808	668
Wheat6	548	747	583

Table 5 shows a percentage comparison between the actual and simulated total irrigation depths for each crop. The difference between the simulated and the actual was divided by the actual, and expressed as a percentage.

Table 5. A Comparison of Total Irrigation

Crop	Actual Data:	Simulation Data: No Suppression		Suppression	
	(mm)	(mm)	%Diff.	(mm)	%Diff.
Sorghum	471	723	+54.0	516	+10.0
Grapes	704	907	+29.0	693	-1.6
Wheat6	548	747	+36.0	583	-6.4
Cotton	1031	798	-23.0	-	-

Seasonal crop consumptive use was calculated from the simulations by using the water budget equation (14). Total applied irrigation was taken from the sum of the irrigation column in the simulation output and multiplied by an irrigation efficiency of 0.75. The beginning soil moisture BSM was assumed to be at field capacity in both the simulation and actual measurements. Since it takes into account the entire soil profile, its value was the same as the maximum soil moisture capacity SVM. Table 6 shows a comparison between the simulated and the actual seasonal consumptive use for each crop and their percentage difference.

Table 6. Seasonal Crop Consumptive Use Comparison

Crop	Actual Data: (mm)	Simulation Data: (mm)	Difference:
Sorghum	651	668	+2.6 %
Grapes	709	692	-2.4 %
Wheat6	716	730	+2.0 %
Cotton	1132	1032	-8.8 %

SUMMARY

The study showed that the soil moisture accounting routine of CROP84 may be used to adequately simulate seasonal crop consumptive and seasonal irrigation depth for four crops: sorghum, wheat, grapes, and cotton. The routine also called for irrigations at dates within a week of the actual irrigation date. As a structural improvement for the soil moisture accounting routine, an option was given to the user to indicate the number of weeks prior to the end of the season at which time irrigations would then be suppressed. When irrigations were not suppressed the simulated seasonal irrigation depth for wheat, sorghum, and grapes were higher than the actual seasonal irrigation depth. The simulated values for seasonal consumptive use and irrigation for cotton were lower even without any irrigation suppression than the actual values. When these actual values for cotton were compared with other consumptive use values for cotton grown in the Salt River Valley, there was reason to suspect that the cotton grown for this particular test case was over irrigated. Erie et al.(1981) estimate a value for seasonal cotton consumptive use of 1042 mm which is lower than the value of 1132 mm shown in the table above.

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