AGRICULTURAL WATER USE MODELING

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INTRODUCTION

Economic and social development of a country is entirely dependent upon the achievement of increased agricultural production. This often requires the opening of additional lands to agriculture through new irrigation projects. For irrigation of land, one needs water.

In the past, proper management and control of water was not always emphasized, as it was thought that there was plenty of water for various kinds of development; however, water supplies available for human use through agricultural production processes are limited in quantity. The amount of fresh water available on the earth's surface has not changed measurably in the past and will not change significantly in the future. On the other hand, irrigation has become increasingly essential and will continue to be so for purposes of feeding the rapidly expanding population of the world.

Planners and managers need information on water demands for the management and operation of presently irrigated lands, and also for planning the future water needs of anticipated new irrigated lands.

The overall purpose of this report is to highlight types of approaches in estimating present agricultural water use and in estimating future water requirements that can be utilized by engineers and planners to increase food and fiber production for the benefit of the ever-increasing population. The more specific objectives are: (a) to identify some of the major types of agricultural water demand projection models which have been developed, (b) to highlight the major features of these currently available models (including data requirements and types of output), and (c) to present detailed discussions of some of these models which reflect the current state-of-the-art of agricultural water demand projection techniques.

It is hoped that by the end of this session, you, as participants, will be able to choose one model among those presented here which will apply to your line of work.

AGRICULTURAL WATER DEMAND MODELS

Basically, the function of all agricultural water demand models is to estimate the inches of supplemental water needed per acre of irrigated land. The literature on this subject is vast. There are, for example, at least eleven different methods for estimating potential evapotranspiration; at least forty different and significant journal articles published (in the United States) on items quantifying the crop yield-water relationship. Thus, a good deal of judgment is necessary to select representative articles and models. All of the models, however, try in some form or other to incorporate part or all of the following functional relationship:

$$\text{Inches of supplemental water required/acre of land} = f\,(\text{soil - water - plant relationships, socio-economic - institutional - political environment [human interaction]}) \quad (1)$$

All the agricultural water demand models can be classified on the basis of whether they are at the (a) plant-field, (b) farm-firm, (c) multi farm-county-state, or (d) river basin-regional-national level. Needless to say, the field level model can be aggregated to the farm-firm level and possibly even to larger aggregates, given appropriate multiplier and aggregation techniques.

The spatial dimension (area) is a key property of agricultural water demand models; however, consideration in the model has to be given also to temporal (time), socio-economic, statistical properties and the climatic/soil/crop factors.

Temporal Characteristics

The time features of each model can be separated as (a) short run, (b) long run, (c) static, (d) dynamic, etc.

Socio-Economic Factors

These factors reflect involvement of the human element in (a) prices and/or costs of water, (b) fertilizer costs, (c) prices of products, (d) technological changes - new type of crop or new water control measures reducing water demand, etc., (e) behavioral features - farm managers trying to maximize their yield, and (f) institutional features - District encourages water conservation through such modes as irrigating during low evaporative demand periods (as at night).

Statistical Properties

This feature relates to the degree to which random events have been incorporated in the modeling process as (a) stochastic - uncertainty and random events influencing the effect of demand. Given a particular water demand projection there will be an associated variance of that estimate; and (b) deterministic - no random error and demand projection exhibit no variance properties and particular levels are known with certainty.

Climatic-Soil-Crop Features

This category includes all those physical features of the environment that affect the amount of water used in an agricultural field situation. These variables are essentially proxies for the complex phenomena that are involved in an actual field, as follows:

Temperature or Heat Budget - The mean daily (or monthly) temperatures are used in several models. The heat budget notion depends on an understanding of the relationships among radiation, actual duration of sunshine, maximum possible duration of sunshine, vapor pressure in the air, vapor pressure at mean air temperature, and several other variables (Israelsen & Hansen, p. 241).

Length of Growing Season - This variable will, for various reasons, affect the consumptive use of the crops.

Precipitation - This is a stochastic variable which is difficult to predict, but most assuredly affects the water demand from ground and/or surface sources. This effect is through influence on the air/environment surrounding plants, as well as having an effect on soil water availability.

Soil Character or Moisture Holding Capacity - The water holding capacity of the soil is a key variable in determining consumptive use. Soil texture and structure are especially important as these forces give rise to "capillary phenomena". These affect the flow or movement of water in soils and the availability of water on plant growth.

Humidity and/or Wind Conditions - This is simply another weather factor which affects evaporation and general conditions of the crop.

Sunlight, Solar Radiation - An energy source, of course, is necessary to drive the entire plant growth process. The amount of solar radiation will vary across latitudes of the planet and will affect the amount of water used.

Specific Crop Features - The root system and leaf area of the plant in question will affect the amount of water used. Also, different crops are at different stages of growth at different times of the year. In addition, plants will use varying amounts of water through their growth process, with the highest consumptive use relative to the potential occurring somewhere during the flowering stage (Israelsen and Hansen, p. 257).

Evaporation or Potential Evapotranspiration - This factor is a function of many of the soil/climatic/crop factors mentioned above.

It really measures, as a proxy variable, the overall influence of these elements. It is included here because many of the yield models rely on measurements of relative evapotranspiration, where either evaporation or potential evapotranspiration serves as the denominator of the ratio.

A listing of the models by major categories, using the foregoing classification system, is presented in Table 1. Tables 2-6 are used to detail the specifics of some of the models.

Overall and Major Features of a Few Selected Agricultural Water Demand Models

Nearly all models reviewed are short run, static models with deterministic statistical properties (Table 1). Another overall feature applicable to the entire set of models is that some tend to emphasize the socio-economic factors and others, not usually the same ones, emphasize the climatic-soil-crop factors (Table 1). If, in fact, water demand is affected by behavioral, social, political, and/or institutional elements as well as temperature, precipitation, soil factors, and crop features, then the "best" models from the set shown in Table 1 are probably the ones having the most of these features included. On this ground, it appears that the Mapp-Eidman model is probably the most appropriate over the entire set, followed very closely by the Utah, North Carolina, and CARD models (Table 1).

The plant-growth type of model, if modified to include socio-economic factors as well, probably shows the most promise for the future with respect to incorporating all different factors into the demand projection process. The Mapp-Eidman model does incorporate many features of the plant-growth simulation approach. These types of detailed models are also the most expensive and difficult to develop.

Table 1. Major Features of Agricultural Water Demand Models[a]

	Temporal Characteristics				Socio-Economic Factors							Statistical Properties		Climatic-Soil-Crop Factors							
Spatial Properties and Model Names	Short run	Long run	Static	Dynamic	Prices and/or costs of water	Other input prices or costs	Prices of products	Technological changes	Production process changes[d]	Behavioral features	Institutional features	Stochastic	Deterministic	Temperature or heat budget	Length of growing season	Precipitation	Soil features	Humidity and/or wind	Sunlight, solar radiation	Specific crop features	Evaporation or potential evapo-transpiration
Plant-field level models:																					
Blaney-Criddle	X		X										X	X	X				X	X	X
Hargreaves	X		X										X	X	X			X	X	X	X
Hexem-Heady	X	X	X		X	X	X		X	X			X			X	X				
Hogg, et al.	X		X		X		X			X			X			X	X				X
Minhas, et al.	X		X		X		X			X			X				X				X
Energy Balance	X		X										X	X	X			X	X		X
Plant Growth	X			X					X				X	X[b]	X[b]	X[b]	X[b]	X[b]	X[b]	X[b]	X[b]
Thorntwaite	X		X										X	X	X				X		X
Farm-firm level models:																					
Mapp-Eidman	X	X		X	X	X	X			X	X		X	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]	X[c]
Moore-Hedges		X	X		X	X	X			X	X		X				X				
County-multi-county-river (or sub) basin-state models																					
Input-output	X		X		X	X	X			X			X								
Kansas	X	X	X					X					X	X	X				X	X	X
Lowry-Johnson	X		X										X	X	X						
New Mexico	X		X							X			X	X	X	X	X		X	X	X
North Carolina	X		X		X	X	X			X			X			X	X			X	X
Pecos Basin	X		X		X	X	X			X	X		X				X				
Pennsylvania	X		X		X	X	X			X		X	X		X		X				X
Sonnen-Evensen-Morgan	X		X		X					X			X			X					
Texas High Plains	X	X	X		X	X	X			X	X		X								
Utah	X		X		X	X	X			X	X		X	X	X	X	X		X	X	X
River basin-regional-national models																					
CARD	X	X	X		X	X	X			X			X	X	X	X	X		X	X	X
Ruttan		X	X			X	X						X								

[a] Blanks sometimes mean the information was not available. See the text for elaboration. An "X" means these elements, factors were considered explicitly in the model.

[b] The plant growth models require detailed information on how the photosynthetic-respiration rate is affected by climate, soil, and plant features.

[c] The yield simulation portion of this model is really a plant growth model, although not as detailed as the models discussed briefly under the "Plant Growth" category. See footnote 'a'.

[d] Also includes interactions among the various inputs of production (e.g., the fertilizer-water interaction effects).

Table 2. Modified Blaney-Criddle Model

CHARACTERISTIC	SUMMARY DATA
Mathematical Description	$U = K(\Sigma pt) = KF$ where U = consumptive use of crop, inches for a given time period; F = sum of the consumptive use factors for the period (sum of the products of mean temperature and percent of annual daytime hours) $\Sigma(t \times p)/100$. K = empirical coefficient (annual, irrigation season, or growing season). t = mean temperature in degrees Fahrenheit; p = percentage of daytime hours of the year occuring during the period, f = monthly consumptive use factor, $(txp)/100$; k = monthly coefficient, u/f; $u = kxf$ = monthly consumptive use, inches. $K = K_t x K_c$; K_t = a climatic coefficient related to mean air temperature (t) $K_t = .0173t - .314$ K_c = a coefficient reflecting the growth stage of the crop.
Type of Output	Total water demand as measured by U, on a monthly basis.
Temporal Properties	Can be used for varying time periods. Generally, a season or one year. It is dynamic only in the sense that climatic factors throughout the year are used; it is essentially a static model.
Spatial Properties	Generally, estimates are made on a per acre basis.
Input data required	Data are needed on temperature, rainfall, the percent of annual daytime hours, empirical crop coefficient, and crop growth stage. These data are available from the Soil Conservation Services Tech. Bulletin No. 21.
Technological/Production Process Changes	Irrigation and/or crop technology are not considered in this projection model. Also, the crop is considered to have optimal quantities of other input, commensurate with maximum yields.
Behavioral Assumptions and Institutional Settings	Neither of these are made explicit; however, use of this approach assumes implicitly that farm/firm managers wish to maximize yields and that the institutional environment does not affect use.
Stochastic/Deterministic Features	The model is deterministic.

Table 2. Modified Blaney-Criddle Model - Continued

Climatic/Soil/Crop Factors	The Blaney Criddle model explicitly considers temperature and daytime hours. Basically, the term f represents a proxy for the potential evaporation and/or potential evapotranspiration. The sunlight or solar radiation factor is brought in via the length of the growing season and the percentage of daytime hours for the period of concern (as a percent of the total for the year). A specific crop coefficient is developed relating to the amount of water that a non-stressed crop will use during a particular period of time.
Documented Computer Program	A user's manual is available through the Soil Conservation Service of the United States Department of Agriculture. A computer program has been developed by the District. This computer program is used to calculate irrigation water needs under the behavioral assumption that producers wish to maximize yields. A detailed documentation of the program is available from the District upon request.
Data Base	Input data are readily available from national/state data bases for all input parameters except the empirical crop coefficient. Even for this need, however, there are estimates in the SCS publication, Technical Report No. 21. Also, agricultural experiment stations in the respective states have some information on this coefficient.
References:	Soil Conservation Service, 1970. Irrigation Requirements. Technical Report No. 21, Wash., D.C., U. S. Dept. of Agr.

Table 3. Hargreaves Model

CHARACTERISTIC	SUMMARY DATA
Mathematical Description	(After Criddle, 1958, pp. 1507-12). $e = m\ (t-32)$ where e = monthly evaporation in inches, m = an empirical factor; t = mean monthly temperature in °F. When corrected for the time element, it becomes $e = cd(t - 32)$ where e = climatic factor; d = monthly daytime coefficient. Also, disregarding wind movement, $c = 0.38 - 0.0038\ h$ where h = mean monthly humidity at noon. Then $U = KE = \Sigma ke$ where U = annual or seasonal consumptive use (actual ET) of the crop; K = crop coefficient; E = sum of monthly evaporation for the period; and k,e = monthly values of K,E.
Type of Output	The physical requirement or actual ET (total water demand) is estimated with the model, as shown by U above.
Temporal Properties	The model is suitable for seasonal predictions and/or shorter periods (like one month intervals).
Spatial Properties	The equation is suitable over larger areas or at the acre, field level.
Input Data Required	Mainly climatic data as shown in the above mathematical description.
Technological/Production Process Changes	It is assumed that all other input levels and technology are invariant. Further it is assumed the plant is not being stressed by any other factors. Of course, alternative levels of K could be selected.
Behavioral Assumptions and Institutional Settings	No explicit statement of the role of the human element.
Stochastic/Deterministic Features	The model is deterministic.
Climatic/Soil/Crop Factors	This model basically uses a relationship between evaporation, temperature, and length of day. Wind movement and the influence of water vapor is also considered via relative humidity included as a variable. A crop coefficient is also necessary for the model which varies with the season of the year.

Table 3. Hargreaves Model - Continued

Documented Computer Program	None available.
Data Base	Climatic data available from the U. S. Weather Bureau.
Reference	Criddle, W.D., 1958. Methods of Computing Consumptive use of Water. Journal of Irrigation & Drainage, Proc. ASCE, Vol. 84, No.IR1

Table 4. Hexem and Heady Models

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	$y = b_0 + B_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2$ Profit = $\pi = P\ Y - r_1x_1 - r_2x_2$ with X_2 = constant ("short run") $\frac{\partial\pi}{\partial x_1} = P_y \frac{\partial Y}{\partial x_1} - r = 0$ or $P_y\ (b_1 + 2b_3x_1 + b_5x_2) = r_1$ or $X_1 = \frac{r_1 - P_y(b_1 - b_5X_2)}{2p_yb_3}$ This is the "short run" demand function. The "long run" (fertilizer also varying) demand function would be given by the simultaneous solution of both $(\partial\pi/\partial x_1) = 0$ and $(\partial\pi/\partial x_2)_2 = 0$. The general form will be $X = f(r_1,r_2,p_y)$ where x_1 = total water available, in acre inches, x_2 = fertilizer applied; p_y = product price; r_1 = water price and/or irrigation cost for that portion applied through the irrigation system; r_2 = fertilizer price.
Type of Output	The production function as exemplified by these models allows the derivation of short run and long run demand functions as illustrated in the mathematical description. Thus, the quantity of total water demanded can be shown to be a function of changes in various physical phenomena as reflected in the production function but also will be affected by changes in the prices of the water and fertilizer and the product price.
Temporal Properties	These models are usually annual in their term. Also, they are static models and can be used for comparative static analyses.
Spatial Properties	These models are on a per acre basis.
Input Data Required	Detailed experimental station types of data are needed - showing the relationship between yield response and fertilizer and water applied. Also, input and product prices are needed.
Technological/Production Process Changes	These water fertilizer models allow the fertilization program to vary; however, all other cultural practices and technological features are assumed invariant.

Table 4. Hexem and Heady Models - Continued

Behavioral Assumptions and Institutional Settings	The farm/firm manager is assumed to be a profit maximizer. The institutional setting is assumed invariant.
Stochastic/Deterministic Features	A deterministic model.
Climatic/Soil/Crop Factors	The water variable in these regression models is generally the sum of water available in the soil plus precipitation plus irrigation water applied.
Documented Computer Program	None available.
Data Base	Experimental data on the yield-water relationship are available from agricultural experiment stations on a limited basis, with some states having much *more than others.* Product price data are available from the Crop and Livestock Reporting Service, a cooperative effort between state and federal entities in each state. Irrigation cost information will also be available from the agricultural experiment stations.
Reference	Hexem, R.W. and E.O. Heady, 1978. Water Production Functions for Irrigated Agriculture. *Ames, Iowa: The Iowa State University Press.*

Table 5. Energy Balance Model

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	$E_T = \frac{\Delta H + 0.27Ea}{\Delta - 0.27}$ $H = R_A(1-r)\ (0.18 + 0.55n/N) - \partial T_a^4\ (0.56 - 0.092 \sqrt{e_d})\ (0.10 + 0.90n/N)$ $Ea = 0.35\ (e_a - e_d)\ (1 + 0.0098n_2)$ where H = daily heat budget at surface in mm H_2O/day; R_A = mean monthly extra terrestrial radiation in mm H_2O/day; r = reflection coefficients of surface; n = actual duration of bright sunshine; N = maximum possible duration of bright sunshine; ∂ = Boltzman constant; ∂Ta^4 = mm H_2O/day; e_d = saturation vapor pressure at mean dew point (i.e., actual vapor pressure in air) mm Hg; Ea = evaporation in mm H_2O/day; e_a = saturation vapor pressure at mean air temperature in mm Hg; u_2 = mean wind speed at 2 meters above the ground (miles/day)^3; E_T = evapotranspiration in mm H_2O/day; u_1 = measured wind speed in miles/day at height h in feet; Δ = slope of saturated vapor pressure curve of air at absolute temperature T_a in 0°F (mm/Hg/0°F).
Type of Output	Consumptive total water demand measured in mm of water per day. The level of aggregation is simply a matter of multiplying the estimates times the acreage figure. This equation estimates the potential evapotranspiration which is not related to crop type.
Temporal Properties	Generally used for intra seasonal predictions. It is a time dynamic model to the extent that predictions will vary through the years and are only limited by the extent of the weather information to the user.
Spatial Properties	Crop or field level; although results can be generalized at the larger areas.
Input Data Required	All of the climatic variables illustrated above in the mathematical description.
Technological/Production Process Changes	No changes are considered in the agricultural production process or in technology. This model assumes the crop is not being stressed for any cultural or technological reasons.

Table 5. Energy Blance Model - Continued

Behavioral Assumptions and Institutional Settings	Both of these variables are assumed invariant. The implicit behavioral assumption is that farm/firm managers wish to maximize yields.
Stochastic/Deterministic Features	The model is deterministic in nature, with no statistical reliability coefficients having been estimated.
Climatic/Soil/Crop Factors	The Energy Balance Model is theoretical in nature and uses basic structural relationships from physics and other basic services to relate several climatic variables. That is, this model utilizes several climatic variables - most of which are defined in the foregoing mathematical section. There are no crop factors involved, however. The basic feature is that consumptive use is assumed to be ". . . inseparably connected to incoming solar energy" (Israelsen and Hansen).
Documented Computer Program	Availability unknown.
Data Base	Climatic variables from the U.S. Weather Bureau.
Reference:	Penman, H.C., 1948. Natural Evaporation from Open Water, Bare Soil and Grass. Proc. of the Royal Society, Series A.

Table 6. Plant Growth Models

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	As noted by Jones (1979) crop growth is usually related to the difference between photosynthesis and respiration multiplied by a conversion coefficient between biomass and CO_2 as follows: $\frac{1}{\emptyset}\frac{dW}{dt} = (Pg - RoW)/(1 + \emptyset G_R)$ where $\frac{dW}{dt}$ = biomass growth rate ($kgha^{-1}day^{-1}$) $\emptyset$ = biomass: CO_2 conversion factor (kg^{-1} CO_2) Pg = gross photosynthesis (kg CO_2 ha^{-1} day^{-1}) Ro = maintenance respiration factor (kg CO_2 kg^{-1} biomass day^{-1}) W = biomass (kg ha^{-1}) G_R = growth respiration factor (kg CO_2 kg^{-1} biomass). Production is then represented by: $\frac{dWi}{dt} = \alpha_i \frac{dW}{dt}$ where $\frac{dWi}{dt}$ = biomass growth rate of leaves (i=1), stems (i=2), roots (i=3), and fruit (i=4). α_i = partioning coefficient for leaves, stems, roots, and fruit. Jones notes that "crop growth models vary in detail and complexity . . . generalities are used to describe this overall approach because of a lack of a universally accepted framework for representing crop growth processes and their interrelationships". Water stress will reduce photosynthesis; thus, there is a relationship between water availability and yield. Water balance equations are included in these models, when water demand is of concern.
Type of Output	The yield associated with various levels of total water being made available are the direct output of these kinds of models.
Temporal Properties	Usually these are daily models with seasonal yield projections. These models usually have the capability of telling the state of the plant-soil-water conditions at any given day in the season. They are also dynamic in nature with today's impacts influencing the state conditions tomorrow and on future days.

Table 6. Plant Growth Model - Continued

Spatial Properties	These are usually developed on a per plant and/or per acre basis.
Input Data Required	Climatic data is needed to estimate evapotranspiration and to calculate a soil water balance. Detailed information is also needed on air temperature, soil data (including soil water retention curves), root zone depth, and unsaturated hydraulic, conductivity relationships (Jones, 1979). Crop parameters must be specified as well. Of course the detailed structural relationships, some of which are described above, must also be input.
Technological/Production	Generally, these models allowed that other inputs of production (for example fertilizers, pest control programs, other cultural practices) can be varied, and can also affect yield. Thus the interaction between water and other inputs can be isolated. Technology is generally assumed invariant, although different varieties can usually be evaluated for any given crop model.
Behavioral Assumptions and Institutional Settings	The human element is not explicitly included in these models; however, it is recognized implicitly that the manager may wish to vary the various input and thus, this flexibility is built into these models. The institutional setting is not a consideration for these models.
Stochastic/Deterministic Features	These models are generally deterministic in nature. It would be possible to consider stochastic processes.
Climatic/Soil/Crop Factors	These models build from knowledge of the structural relationships involved in soil physics, plant physiology, climatic forces, as well as the relationships among climatic/soil/plant factors. Of all the modeling approaches, this particular method utilizes the most theory and concept as well as empirical measures, with respect to this particular characteristic.
Documented Computer Programs	Extent of documentation unknown.
Data Base	Much of this information is available from agricultural experiment stations. Basic climatic data is available from U. S. Weather Bureau.
References	Jones, J.W., R.F. Colwick and E.D. Threadhill, 1972. A Simulated Environmental Model of Temperature, Evaporation, Rainfall & Soil Moisture. Trac. ASAE Vol. 15, No. 2

Several models did include other input prices and/or the costs of other inputs in the modeling effort. Only in the case of the Hexem-Heady model, however, did the other input prices affect the water use. That is, it can be hypothesized the demand for water may be affected by the prices of substitutes for water including such things as fertilizer and other inputs of production to the crop process. The Hexem-Heady study isolated the effects of fertilizer in order to facilitate the direct consideration of changing fertilizer prices. The other studies tended to include the costs of all other inputs under one category and not deal explicitly with the substitutability problem.[1] It appears modelers have yet to successfully deal with this dimension.

Another basic feature of nearly all the models was that technology was generally assumed constant over the projection interval. The one exception was the Kansas model, which allowed for changes in irrigation efficiency over the longer run. An explanation for this invariance in technology is that most models are short run in nature, in which case it is logical to hold technology constant. Over longer run periods, however, technology could have a significant impact on the quantity of water utilized. This would be exemplified through variety changes and/or changes in the cultural practices and/or changes in the irrigation system.

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[1] This is somewhat misleading with respect to the Texas High Plains Model. The developers of that model did in fact allow energy prices to vary, and they map the effect on water demand from rising energy prices. This is essentially the same thing as raising the price of water and is not necessarily dealing with the substitution phenomena at all. The CARD model also allows for consideration of some input price changes and the effect on water demand and use, but the full range of substitutionality among input factors was not allowed in that modeling process either.

Specific Features of Agricultural Demand Models

Some of the models are now discussed in more detail. Emphasis is on explaining where the models are similar and where large differences exist, using geographic-spatial differences as having a major influence.

Plant-field level models

The mathematical description of each model is the first item in each of the Tables 2 - 6. All of the approaches have a few equations, all of which require estimates of various parameters. Some of the more "physical models" have parameters that have been fairly well established by researchers such as for the Blaney-Criddle model. Others require parameter estimation for the site of concern such as in the Hexem-Heady models. This latter feature is also descriptive for Hogg *et al.*, and Minhas *et al.* models.

The most common feature is that all the models project water demands for some land area, most generally an acre or hectare. Also, all the models are short run and are usually concerned with estimating demand on an annual crop year basis. Some are appropriate for growth stage (intraseasonal) projection such as the Plant Growth type models. The water used during growth stages can also be approximated using the Blaney-Criddle, Hargreaves, Energy Balance, and Thorntwaite models. This is the case as most of these models use a month during the growing season as the appropriate time period. Thus, the various monthly periods can be appropriately aggregated given some assumptions about the length of each stage of growth of the plant.

None of the plant-field level models included technological changes and only two incorporated production process changes. Technological change phenomena is of course not necessarily included when only very short run periods are being examined. The production process changes, however, probably should be included; but again, they are not important over real short time periods. None of the models at this level included institutional features, and about half of them included behavioral features. The institutional setting is also probably relatively fixed within a crop season, and this would be appropriate.

The exclusion of behavioral features tends to reflect a notion that man does not affect water use, an hypothesis that could be tested. In some sense, however, the exclusion of the behavioral element is simply not possible. Said somewhat differently, even the projection models which do not specifically include man assume (implicitly) the goal of maximizing yield per unit of land area. This is the case for the Blaney-Criddle, Hargreaves, Energy Balance, and the Thorntwaite methods. The Plant Growth simulation model could be developed to include the influence of the human beings involved in irrigation processes as well as the features of the plant and the soil-water relationship pertaining to a particular field.[2]

The type of output varies greatly among these plant-field level models. This is the case, primarily due to the role ascribed to, and the objective function assumed for, the human factor. The Hexem-Heady, Hogg et al., and Minhas et al., models, for example, all assumed that producers will choose to maximize profit. As a result, it is likely the projections for a particular area would be different than those from models where maximum yields are assumed. Of course this is an empirical question and it cannot be answered in any general way. In all cases the total water demand is presented for some intraseasonal and/or seasonal period, usually specified as inches or acre inches. Irrigation water requirements then depend

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[2] This type of research is in progress at the University of Florida through an interdisciplinary research group in the Institute of Food and Agricultural Sciences.

on precipitation received. Substantial variation in the degree of sophistication with respect to including climatic/soil/crop factors is the most descriptive for this group of models. The Hexem-Heady models, for example, attempt to quantify all the complexity of these factors by simply adding the sum of available soil water to the precipitation plus the irrigation water (Table 4). The Plant Growth models at the other extreme (Table 6) include detailed structural relationships which explain how waters are moved through the soil and the plant to affect growth. The Energy Balance model, which is useful for estimating potential evapotranspiration, is also very detailed with the theoretical conceptual relationships requiring a large number of parameters as well as input data. The Hogg et al. and the Minhas et al. models do incorporate some agronomic factors and may be a good compromise between the two extremes for certain types of application. Several of the models choose to summarize all of these factors within the relative evapotranspiration ratio (Tables 3 and 4, and sometimes the plant growth models as in Table 6).

Input data requirements vary extensively across these models. At one extreme is the plant growth type of model which requires a high degree of sophistication in the plant-engineering sciences in order for the model to be developed. Also, if these models included socio-economic factors, they would require the same degree of sophistication in the socio-economic sciences. Models at the other extreme, while not necessarily technically less sophisticated, require only secondary data sources. The Blaney-Criddle, Hargreaves, and Thorntwaite models fit in this category. As an example, only three pieces of information are needed for the Blaney-Criddle model including temperature, the percent of annual daytime hours, and the empirical crop coefficient (Table 2).

The models which attempt to relate yield to various proxies for the water variable, such as the Hexem-Heady, Hogg *et al.* and Minhas *et al.*, models, require data from experimental trials. These types of data would generally have to be obtained from agricultural experiment stations and a high degree of technical sophistication would be necessary to arrive at the actual functions. Useful models of this type require successful integration of knowledge from the crop-soil sciences, economics, and statistics.

The major data sources for this category of models are the agricultural experiment stations, state/federal weather services, and the crop and livestock reporting services. Utilization of such models will probably require establishing contact and working relationships with scientists and personnel of these entities. Generally speaking, there has been little effort made to develop computer program documentation and user's manuals. The only known user's manual in this category is that available from the Soil Conservation Service. This manual explains how to use the computer program which implements the procedure in Technical Release 21.

Farm-firm level models

The mathematical description of these kinds of models is characterized by the simulation approach used in the Mapp-Eidman model (Table 7). The Mapp-Eidman model uses a plant growth simulator as its basis. This simulator generates the yield for varying levels of water availability. Various acreage combinations of the crops in this study area are included. Also, a particular type of farm manager is assumed, namely one that is "rational" in the sense of seeking profits and/or minimizing the costs. The model is actually used to examine the short and long term effects of a declining water supply to a farm-firm. The price of water is increased over time and compared with the results when less water is available.

Table 7. Mapp-Eidman Model

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	This is a simulation model with a crop yield simulator as an important and basic component. The basic features of the yield simulator are as follows: $YR_{ij}{}^{k} = O_j^k(SMD_{ij}) + b_j^k\ (P_{ij} = P_A) \quad YR = \sum_j \sum_i YR_{ij}$ where $YR_{ij}{}^{k}$ = yield reduction on day i for stage j and crop k; O_j^k = yield reduction in units per day as a result of adverse soil-water conditions, stage j and crop k; SMD_{ij} = soil-water depletion in inches on day i for stage j; b_j^k = yield reduction coefficient due to severe atmospheric demands, stage j and crop k; P_{ij} = pan evaporation in inches, day i and stage j; P_A = critical pan evaporation level; if at or below this level, get yield reductions due to severe atmospheric conditions. The SMD_{ij} was calculated by $SMD_{ij} = (a = SMT_{ij})/b$ where a,b = parameters associated with the soil type; SMT_{ij} = inches of soil water in the entire profile on day i of stage j. Prices of the products and several of the inputs (nitrogen, seed, labor, capital, irrigation water) are also input variables.
Type of Output	Net farm income for a representative farm-firm is projected under different water availability and institutional change scenarios. The demand for irrigation water is predicted.
Temporal Properties	The model works on an intra-seasonal basis but is used to project farm income over several years of time.
Spatial Characteristics	It is a firm level model for a typical 648 acre firm in Oklahoma, using water from the central Ogallala formation.
Input Data Required	The yield simulator requires certain types of parameters and input on precipitation and climatic conditions, as shown in the above description. In addition, information is needed on resource availability, crop types to be grown and the cost of growing various crops. Such yield simulators must be developed by professionals having knowledge of basic plant-water relationships. Generally, this expertise, as well as other data requirements, is available from agricultural experiment stations.

Table 7. Mapp-Eidman Model - Continued

Technological/Production Process Changes	The simulation model is oriented towards examining the effects of price changes on tax policies on the water input. Or it has the capability to examine the effects of different water availability plans. The yield simulator is not sensitive to changes in other cultural practices such as fertilization programs. Similarly, the current version apparently does not allow for examining alternative technological features that may occur in the future. Of course such simulation can be generally modified to deal with the wide range in types of outside influences on net farm income.
Behavioral Assumptions and Institutional Settings	The farm-firm managers are assumed to be profit maximizers. Several institutional changes relating to the allocation of water to agriculture can be examined with the model.
Stochastic/Deterministic Features	The model is deterministic in nature.
Climatic/Soil/Crop Factors	The underlying yield simulator for this model requires fairly detailed consideration of basic relationships. Rainfall pan evaporation distributions were necessary. Soil water is then estimated given some initial starting value by using the daily rainfall and pan evaporation values which in turn were generated from probability distributions. Potential evapotranspiration is calculated from pan evaporation given some knowledge of the stage of growth. Two layers in the soil's profile are modeled and the amount of water kept in each is monitored. The simulation model makes all of these calculations each day of the growing season (Mapp, Eidman, Stone, and Davidson, pp. 16-17).
Documented Computer Program	None available.
Data Base	Most data available through agricultural experiment stations. Climatic and product price information will be available from state/federal sources.
References	Mapp, Jr., H.P. and V.R. Eidman, 1976. An Economic Analysis of Regulating Water Use in the General Ogallala Formation. Tech. Bull. T-141, Stillwater, Oklahoma, Agricultural Experiment Station. Mapp, Jr., H.P., et al., 1975. Simulating Soil Water and Atmospheric Stress-Crop Yield Relationships for Economic Analysis. Tech. Bull. 140, Stillwater, Oklahoma, Agricultural Experiment Station.

The Moore and Hedges model[3] has the capability of examining demands over longer time horizons (Table 1). This is a linear programming model with the normative influence of the assumption that farm managers maximize profits in dictating the optimal organization of a farm-firm. In this model, not only crop types can vary, but also crop acreages; whereas in the Mapp-Eidman model the crop acreage is an estimate of net farm income as well as demand for irrigation water under different price assumptions.

Technology is not addressed in the model, even though long run projections are provided. This puts the model subject to question. Also, the interaction effects between irrigation water and other inputs of production are not explicitly considered in the model, thus making the production process changes invariant over the time horizons considered. Both models are deterministic. The Mapp-Eidman model is much more explicit with respect to including the climatic-soil-crop factors. All of these factors are implicit in the Moore and Hedges model in that yield for different levels of water are included in the model. In fact, the Mapp-Eidman model is very similar to the plant growth models discussed in the previous group with respect to the inclusion of various structural relationships as regards the climate/soil/crop interaction features.

In terms of input requirements, the Mapp-Eidman model requires more technical expertise in the development of the structure of the model. Also,

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[3] A third type of mathematical model developed at the firm level but not represented here is the regression type of model. A large amount of work was accomplished by agricultural economists in the 1950's in the attempt to develop production functions at the firm level using regression techniques. These efforts were generally not successful, because of high multicollinearity among the independent variables. See Lynne (1977) as an example of this type of approach.

this model requires more actual data, at a detailed level with respect to how farm-firm managers might deal with particular types of changes in the environment.

Data base sources are similar to those at the plant-field level. The only difference lies in the level at which these models are developed to function.

Linear programming models at the firm level require a high level of expertise for development, but generally, they can be considered to be less complicated than the simulation models for farm-firms. Said somewhat differntly, a higher level of abstractions is usually incorporated in linear programming models. Another major difference is that the linear programming model allows for an optimization subroutine to be used. The actual crop mix and water level usage for various price scenarios then are all developed on the assumption that the farm-firm managers pursue some single dimensional goal, such as to maximize profits. The Mapp-Eidman model can examine the level of profitability only after the fact. That is, the results of several "real year" conditions (or postulated conditions) are simulated. The maximum profit level is then selected from all the model results available to the user. None of the computer programs developed for this category are documented. Also, user's manuals are not available.

County-multicounty-river (or sub) basin-state models

The largest share of these are linear programming models with linear objective functions and linear constraints. There are also some single equation and simulation models and input-output models represented in this category. Some have also been developed to predict water demand at this level (See e.g., Howitt, Watson, and Adams, 1980). This model type is identical in nature to the linear programming model except for the provision of the non-linear objective function. This allowance is made to facilitate evaluating the effects of variable farm commodity prices on water demand.

The models in this category are as general as to predict the total amount of water used for major economic sectors, such as in input-output modeling and the Kansas model (Table 8), which has the capability of predicting water requirements for particular crops on particular soil types over 61-day time periods. The Lowry-Johnson model, in turn, considers no economic or socio-political factors, while the Pennsylvania, Texas High Plains, Pecos Basin, and Utah models all incorporate a substantial amount of this kind of influence. This type of output from all these models is more aggregate in nature generally, giving the irrigation water demand over at least the county level of aggregation. The Kansas, New Mexico, North Carolina, Pennsylvania, and Utah (Table 9) models all have the capability of generating estimates of the irrigation water demand for each of the respective states. Input-output models can also be developed at that level of aggregation.

Input data requirements are quite extensive for most of the models. Acreage bounds on the various crops are generally needed; some require detailed soil information. The New Mexico, North Carolina, Pennsylvania, and Sonnen-Evensen-Morgan models all require knowledge of the production function relating yield to water. The other models assume yield is fixed per acre. Nearly all these models would require considerable expertise in their development and an ongoing data collection process to keep them current.

The Lowry-Johnson model requires the least amount of data, followed by the Kansas model. All that is needed for the former is effective heat in thousands-of-day degrees, while the latter model requires dollar value

Table 8. The Kansas Water Model

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	Dollar outputs are projected and water demand is related to the dollar output. It is similar to an input-output model.
Type of Output	Water demand as related to the total value of the product produced over the state.
Temporal Properties	Total annual projection in intervals of 20 years. The model is time dynamic in the sense that it steps (in 20 year intervals) from one static situation to another.
Spatial Properties	Water demand is shown by eleven regions in the state.
Input Data Required	Agricultural projections, in terms of the total dollar value of output, are necessary by regions. Also, unit water requirements by type of crop or activity are needed. This model splits agricultural crops into corn, sorghum, wheat, and others. The factors were developed for the volume of water required to produce the unit value of each crop. The Blaney-Criddle formula was used to estimate consumptive use. Long term precipitation was then subtracted from that estimate. Data is needed on total acres sown, total acres harvested, yield per acre, total production and farm value of crops produced in each county. Similar information is also developed on irrigated land. The irrigation requirement per crop was assumed constant across the state. Crop acreage and production by hydraulic areas were necessary. The proportion of irrigated land relative to total crop land is needed.
Technological/Production Process Changes	Irrigation efficiency was allowed to change over the projection horizon from 1965 to 2020. No other cultural practices were allowed to change.
Behavioral Assumptions and Institutional Settings	None were made explicit. Implicitly, however, all behavioral and institutional arrangements in 1965 were assumed to remain the same.
Stochastic/Deterministic Features	The projection methodology is deterministic in nature.
Climatic/Soil/Crop Factors	These elements were included to the extent they are in the Blaney-Criddle method. That is, the Blaney-Criddle model was utilized to estimate the agricultural water use coefficients.

Table 8. The Kansas Water Model - Continued

Documented Computer Program	None available.
Data Base	Input data sources would include U. S. Weather Service climatic data, county statistics from the agricultural census data, and information from agricultural experiment stations in each state.
References	Kansas Water Resources Board, 1972. Kansas Long-Range Water Requirements, Topeka, Kansas. State Water Plan Studies, Part B.

Table 9. The Utah Model

CHARACTERISTICS	SUMMARY DATA
Mathematical Description	Linear programming model.
Type of Output	Water demand functions for each of ten subregions of the state of Utah, associated with parametrically changed shadow prices on water.
Temporal Properties	A single-year time dimension is assumed. Intra-seasonal variations are not allowed. It is a static model.
Spatial Properties	The model is designed to examine the demand in ten major drainage basins in Utah.
Input Data Required	Data requirements include the potentially irrigable and presently irrigated land. Climatic information was used to adjust acreage data to conform to uniform classes. Rotation requirements had to be specified for crops and restrictions have to be placed on what kind of crops can be grown in what regions. Cost data for the production activities was necessary. Costs and labor hours as well as yields were specified by county and subregions. Also, irrigation water requirements in irrigation hours are specified by county and region. Land development and distribution costs were specified by regions and land class. Yields were also specified by land class. The Blaney-Criddle model, along with climatic information, was used to determine the consumptive irrigation water requirement. Irrigation efficiency estimates are needed. Two water and yield levels were necessary for alfalfa. All of the rest of the crops were inserted with one yield and one water level. The costs of bringing irrigable lands into production were calculated as a necessary input to the model. Both new and currently irrigated lands were considered and acreage estimates were necessary. Past research projects were relied upon greatly for input data.
Technological/Production Process Changes	Technology and cultural practices were assumed invariant.
Behavioral Assumptions and Institutional Settings	The farm-firm manager was assumed to maximize profits and this was exemplified at the regional level. Water rights were assumed to exist, which is part of the institutional setting. This precluded the development of new lands until current lands had been irrigated.

Table 9. The Utah Model - Continued

Stochastic/Deterministic Features	The model is deterministic in nature. No random variables were considered.
Climatic/Soil/Crop Factors	The Blaney-Criddle model was utilized to estimate water requirements. Yield water relationships were invariant in the sense that only one yield was included (except for one of the crops considered).
Documented Computer Program	None available.
Data Base	Most agricultural experiment stations will have data sufficient to develop such a model. Climatic data will be available from the U. S. Weather Bureau.
References	Anderson, M.H., *et al.*, The Demand for Agricultural Water in Utah, Logan, Utah. Utah Water Research Lab., College of Engr.

projections for the various sectors and some notion of the amount of water used per dollar of gross output. Both of these models would be severely limited under changing economic and/or physical conditions. That is, sudden or quick changes in the economy or in the natural climatic system would cause these models to give predictions with a large standard error. Only the Pennsylvania model attempted to deal with stochastic processes. This is a shortcoming of all the models examined in this group.

As with the previous categories, major data base sources again include the agricultural experiment stations, the weather service, Soil Conservation Service, and the Crop and Livestock Reporting Service. Several more aggregate types of data are generally needed at this level of aggregation.

The Utah model was the most all-encompassing in terms of dealing with the socio-economic and climatic/soil/crop factors. Yield-water relationships were not incorporated into the model. The North Carolina model on the other hand, had a great deal of detail incorporated into the soil water balance estimated model, as did the Pennsylvania model. The Sonnen-Evensen-Morgan model included virtually none of these elements. All the crop and climatic features have to enter through the constant term and/or the outdoor conservation factor within the equation. It is not at all clear how these constants are related to the climatic/soil/crop features.

A users manual has been developed only for the Sonnen-Evensen model. The computer program is documented in a general sense, with major features specified.

River basin-regional-national models

A major model represented here is the national linear programming model developed at Iowa State, called the CARD model (Table 10), and the Ruttan model. The latter is an econometric, regression model using county

Table 10. The CARD Model

CHARACTERISTIC	SUMMARY DATA
Mathematical Description	A linear programming least cost model where certain commodity demands are to be met - subject to restrictions on resources available.
Type of Output	Demands for water as associated with economic activity in the agricultural sector, by regions of the U.S. The water demand functions that are provided will vary for the major agricultural crops of the U.S. Water requirements for other crops are simply fixed in the model.
Temporal Properties	The model is essentially a long run model. The agricultural sector assumes some sort of competitive equilibrium position. The model is static in nature.
Spatial Properties	The model encompasses the whole U.S. with 223 land regions, 51 water supply regions, and 27 market regions.
Input Data Required	Cost and budget information are input on a per crop basis and vary across producing regions. Detailed information on crop water use coefficients is needed. Basically, this model utilizes physical consumptive use requirements for estimating water demand.
Technological/Production	Basically, technology is chosen for a base year - in this particular case, 1964. The model has the capability of being modified to examine different farming techniques.
Behavioral Assumptions and Institutional Settings	Basically, the model is developed under the assumption that costs are to be minimized subject to meeting certain demand constraints in terms of amounts of commodity actually provided. The institutional setting is essentially fixed, although some variation is allowed in such things as (1) imposing soil loss limitations on alternative land classes or (2) affecting market prices by controlling supply quotas. Also, export market demands can be modified. Policies regarding land use can also be examined.
Stochastic/Deterministic Features	The model is deterministic in nature.

Table 10. The CARD Model - Continued

Climatic/Soil/Crop Factors	Crop water requirements were determined using various other models, such as the Blaney-Criddle model (Nicol and Heady, p. 119). Yields do not vary with water levels in the model.
Documented Computer Program	General documentation of the programs are available. Use of the model will be through the CARD center at Iowa State.
Data Base	Massive data requirements from state agricultural experiment stations, state agricultural agencies, Crop and Livestock Reporting Service, Soil Conservation Service, U. S. Weather Service, and others.
References	English, Burton C. and Dan Dvoskin, 1977. National and Regional Water Production Functions Reflecting Weather Conditions. CARD Miscellaneous Report, Ames, Iowa Center for Agricultural and Rural Development, Iowa State University.

data and estimating the demand for irrigated land at regional levels. Both models give estimates of the irrigation demand for water at larger aggregates. The models allow some prediction of the effect of change in agricultural output on the amount of irrigation water used. The CARD model is much more extensive than the Ruttan model and requires considerably more input to its operation. Both water supply and market regions are considered explicitly in the CARD model (Table 10). Detailed cost and budget information are developed and necessary for the CARD model. This is also true for the Ruttan model. Overall, the CARD model is more appropriate for examining the national demand by regions. As has been argued elsewhere, the Ruttan model has been fraught with difficulties due to statistical problems which in turn are due to inadequate data (see Lynne, 1978). Input data are much less for the Ruttan model, however, and are considerably easier to generate. As a result, the Ruttan model is much less costly to develop and maintain. Climatic/soil/crop factors are not included in the Ruttan model. Some of these elements are incorporated in the CARD model through the fact that several of the potential evapotranspiration-consumptive use formulas (such as the Blaney-Criddle equation) were used to determine water requirements in different regions of the nation.

The general features of the CARD model are documented (Nicol and Heady, 1975). Any use of this model would have to be coordinated through the Center for Agricultural and Rural Development (CARD) at Iowa State University in Ames, Iowa. The Ruttan model is documented in the early book (Ruttan, 1965).

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