IRRIGATED FARM MANAGEMENT

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MISSION

To develop irrigation farm management systems for arid zones that integrate year-round crop rotational strategies with best management practices (BMPs) for water, fertilizer, and other agricultural chemicals. These systems will be economically viable and environmentally sustainable, including protection of groundwater quality.

STUDIES ON CONSUMPTIVE USE AND IRRIGATION EFFICIENCY

D.J. Hunsaker, Agricultural Engineer; and A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Effective irrigation management provides the timely and correct amount of water consistent with the crop water demands, soil conditions, crop production goals, and environmental quality goals. Irrigation efficiency (IE) is a term often used to describe the effectiveness of irrigation, where IE is defined as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied. Beneficial uses include crop evapotranspiration (ET_c), salt leaching, frost protection, etc. General measures that can be taken to improve surface irrigation efficiencies include increasing the uniformity of the water applied, reducing deep percolation and surface runoff, and improving the control of application depths. However, proper irrigation management is a vital requirement for attaining the optimum irrigation efficiency of the system. Thus, the ability to predict actual daily crop water consumption, or ET_c, is of major importance.

A practical and widely used method for estimating actual ET_c is the crop coefficient approach, which involves calculating a reference crop evapotranspiration (ET) with climatic data: ET_c can then be determined by multiplying the reference ET with an appropriate crop coefficient (K_c). The Food and Agricultural Organization (FAO) Paper 24 (FAO-24), *Crop Water Requirements*, published in 1977, has been used worldwide as a primary source for crop coefficients and related ET procedures. Recently, the FAO published FAO-56, *Crop Evapotranspiration*, a revision of FAO-24, which presents updated procedures for calculating reference and crop ET from meteorological data and crop coefficients. In addition to the single K_c model developed in FAO-24, FAO-56 also includes a dual, or basal, crop coefficient model. Here, K_c is determined on a daily basis as the summation of two terms: the basal crop coefficient (K_{cb}) and the contribution of evaporation from wet soil surfaces following irrigations or rain (K_e). When the soil surface is dry, K_c is equal to K_{cb}, assuming soil moisture is adequate to sustain full crop water use. The usefulness of the dual crop coefficient model is that it provides better estimates of day-to-day variations in soil surface wetness and the resulting impacts of irrigation frequency on daily crop water use.

FAO-56 also introduced the need to standardize one method to compute reference ET from meteorological data and thus recommended the FAO Penman-Monteith as the sole method for the calculation of grass-reference evapotranspiration (ET_0). Although FAO-56 presents generalized crop coefficient values for use with FAO Penman-Monteith ET_0, derivation of localized values based on the FAO ET_0 is advisable due to the effects of local climatic conditions, cultural practices, and crop varieties on K_c or K_{cb}. In order to calculate daily crop ET by the FAO-56 dual crop coefficient approach, information on the evaporation characteristics of the soil type is also needed in additional to $K_{cb.}$ The FAO-56 procedure requires two soil drying parameters called the readily evaporable water (REW), defined as the maximum depth of cumulative soil water evaporation (E_s) from the soil surface layer at the end of the stage 1 (energy limiting stage) drying cycle, and the total evaporable water (TEW), defined as the total maximum cumulative depth of water that can be evaporated from the soil surface layer. FAO-56 presents typical values of REW and TEW for certain soil types and recommends that the effective depth of the soil evaporation layer (Z_e) used in the procedures be about 0.10 to 0.15 m.

Recently, several different entities have approached the USWCL interested in new information on consumptive use of crops in the area. A particular concern is the realization that many farmers have been unable to meet a target irrigation efficiency of 85%. In addition to obtaining information on basal ET for crops, quantifying the contribution of wet-soil evaporation is particularly important since soil evaporation in excess of basal ET is sometimes included in ET_c as a beneficial use and sometimes it is not. The objective of this project is to determine the consumptive use and attainable irrigation efficiencies for crops presently produced, as well as for several new industrial crops that are being developed in the region.

APPROACH: Research is being conducted through a series of field experiments to determine crop evapotranspiration for current varieties of cotton, wheat, alfalfa, rape, lesquerella, and guayule grown under irrigation and soil conditions common in the region. Crop ET and soil evaporation during different growth stages in the season will be determined primarily with a soil water balance using neutron probes and time-domain-reflectometry (TDR) measurements, although other methods such as sap flow gauges and lysimeters also will be used when possible. Basal crop coefficients will be derived from the ET_c and soil evaporation data using the FAO-56 ET_0 method calculated with local meteorological data. For each crop, K_{cb} values derived from the different experiments will be combined and used to develop crop coefficient models as a function of common time-based indexes; e.g., days past planting and cumulative growing degree days. The crop coefficient curves will then be tested to determine their effectiveness in predicting ET_c for different field conditions and years.

The FAO-56 soil evaporation parameters, REW and TEW, were derived for a clay loam soil using data collected during lysimeter studies by USWCL personnel in March-April of 1971. The experimental site was a 72- by 90-m field in Phoenix, Arizona. The flat, bare field was divided into three plots, each plot surrounding one weighing lysimeter. On March 2, 1971, two of the lysimeters and surrounding plots were irrigated with 100 mm of water. After irrigation, the lysimeter weight loss, and hence soil evaporation, as well as meteorological data, were monitored at 0.5-hour intervals for 16 continuous days and also for the 23rd and 37th days after the irrigation. In the surrounding plots, soil water contents were determined from gravimetric soil samples for the 0- to 0.10-m surface layer and from neutron probe measurements for deeper soil layers at 0.5-hour intervals starting two days after irrigation through 16 days after irrigation and also for the 23rd and 37th days after irrigation. Soil water contents for the clay loam at field capacity (FC) and wilting point (WP) are 0.34 and 0.16 $m^3\ m^{-3}$, respectively.

FINDINGS: Figure 1 shows the average daily E_s for the clay loam soil determined from two lysimeters during March 1971 for 16 continuous days after irrigation and for the 23rd day after irrigation. Also shown in the figure are estimates of daily E_s based on the average change in soil water contents ($\Delta\theta$), between the 00:00- and 24:00-hour measurements of a day, calculated over the 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers. The data of Figure 1 suggest that the total daily soil water evaporation that was measured in the lysimeters occurred from a soil layer deeper than 0.10 m. From the 4th through the 10th day after irrigation, the daily change in soil water contents within the 0-0.15-m layer matched the daily measured E_s particularly well, whereas the daily change within

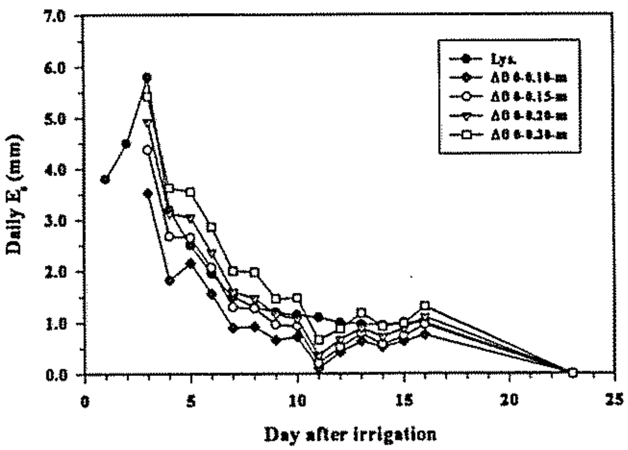

Figure 1. Average daily soil evaporation (E_s) as determined by lysimeters and the change in soil water content ($\Delta\theta$) calculated over 0-0.10-, 0-0.15-, 0-0.20-, and 0-0.30-m soil layers during March 1971.

the 0-0.20-m and 0-0.30-m layers was often greater than the measured E_s. From the 11th through the 16th day after irrigation, the data suggest that the soil water change within the 0-0.30-m layer was often a better reflection of the measured E_s than were the changes calculated over shallower soil layers. However, the determinations of minute daily changes in soil water contents for days occurring 11 days after irrigation and beyond (which typically were on the order of less than 1 mm) were probably subject to error arising from diurnal water loss and recovery characteristics of the surface layer, measurement inaccuracy, spatial variability, etc. Therefore, in the following evaluation of the REW and TEW parameters, it was assumed that the effective depth of surface evaporation layer (Z_e) for the clay loam soil was best represented by the 0.15-m layer.

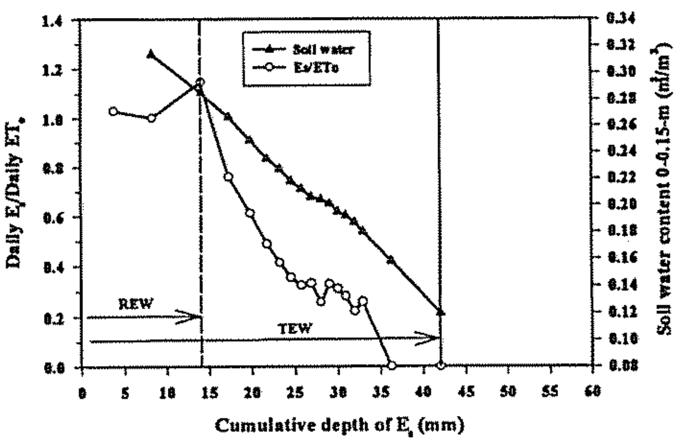

Figure 2. Ratio of daily E_s to ET_0 and the soil water content within the 0-0.15-m layer with cumulative depth of E_s during March-April 1971.

Figure 2 shows the ratio of the daily E_s to daily ET_0 for each of the 16 days following irrigation, plus those for the 23rd and 37th days after irrigation, plotted as a function of cumulative depth of E_s. The figure also shows the decline in soil water contents within the 0-0.15-m layer from the 2nd through the 37th day after irrigation. Note that cumulative evaporation between the 16th and 23rd day and between the 23rd and 37th day after irrigation was estimated from the change in soil water contents within the 0-0.15-m depth. Early in the drying cycle, when the surface layer was moist, water evaporation occurred at a rate close to the potential rate, as reflected by the near 1:1 ratio of E_s to ET_0. This stage of evaporation, referred to as the stage 1 drying cycle, occurred during the first three days after the irrigation. Therefore, it can be inferred that REW for this soil is about equal to the 14 mm of cumulative E_s during the first three days of drying. As the soil layer dried further, the rate of evaporation decreased relative to the evaporative demand until it reached a very low rate ($\approx$0 mm on the 23rd day after irrigation). Although there was no soil evaporation on the 23rd day after irrigation, the soil layer had dried from 0.18 $m^3\ m^{-3}$ on the 16th day to 0.16 $m^3\ m^{-3}$, the wilting point, on the 23rd day. At that point, the estimated total cumulative evaporation was 36 mm. On the 37th day, the soil water content of the surface layer had declined to 0.12 $m^3\ m^{-3}$ and the TEW, 42 mm, had essentially been reached. In most soils, evaporation can continue to dry the surface layer to a water content below wilting point. An approximate estimate of TEW is obtained by multiplying the depth of the soil layer by the difference between the field capacity soil water content and the water content halfway between the wilting point and the oven-dry point. For example, the calculation based on the FC and WP of our clay loam soil for a 0.15-m soil layer would result in an estimated TEW of 39 mm, close to the TEW derived in the analysis.

FAO-56 procedures were used to derive and partition the seasonal water consumption for a commercial cotton grown on a sandy loam in central Arizona during 1994. Using the FAO-56 approximations, the values determined for REW and TEW for this soil type were only 9 mm and 19 mm, respectively. As shown in Table 1, soil evaporation represented about 7% of the total crop ET contributed solely from irrigation water. An additional 88 mm of ET were contributed from in-season and pre-season precipitation. About one-third of the seasonal precipitation, which occurred primarily during the early portion of the season before full crop cover, evaporated from the soil surface. Of the total 1162 mm of ET consumed by the crop, 9% was evaporation from wet soil conditions.

Table 1. Water consumption for a grower's cotton field in 1994.

	Irrigation water	In-season precip.	Pre-season precip.	Total
Basal ET	996	48	13	1057
Soil E_s	78	27	n/a	105
Total crop ET	1074	75	13	1162

INTERPRETATION: Findings from our evaluations of a grower's field indicated that evaporative water losses from the soil need to be considered in determining crop water use and irrigation efficiencies. This was further illustrated by the 1971 lysimeter data presented above, which showed that over 40% of the 100 mm of water applied to a bare clay loam soil was evaporated from the surface layer. In arid or semi-arid conditions, soil water evaporation, particularly following pre-plant and early season irrigations, can therefore represent a significant amount of water loss above the basal crop water requirement. Information to quantify crop ET and soil evaporation more accurately will continue to be developed in this project.

FUTURE PLANS: Once appropriate basal crop coefficient curves and soil drying parameters have been developed, they will be incorporated into the FAO-56 dual crop coefficient model, which can then be used as an effective irrigation scheduling tool for determining ET_c and soil evaporation on a daily basis. The FAO model for ET also will provide a means to estimate on-farm irrigation efficiencies on a single irrigation basis, as well as for the entire season.

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DEVELOPING GUIDELINES FOR "FERTIGATION" IN SURFACE-IRRIGATED SYSTEMS

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PROBLEM: Applying fertilizer through irrigation water, when properly done, can be a highly effective fertilizer management practice. This method of fertilizer application, "fertigation," offers certain advantages compared to conventional field spreading or soil injection techniques, such as reduced energy, labor, and machinery costs. Moreover, it allows growers to apply nutrients in small amounts throughout the season in response to crop needs without the potential crop damage or soil compaction caused by machinery-based application methods. Although fertigation is more commonly associated with microirrigation and sprinkler irrigation systems, injecting nitrogen (N) into irrigation water has become increasingly frequent and widespread among surface irrigation growers in the western United States. However, unlike pressurized irrigation systems, which are designed to apply controlled and precise amounts of water to the field, application of water by many surface irrigation systems can be highly nonuniform and is often subject to excessive deep percolation and surface water runoff. Consequently, N-fertigation through surface irrigation systems may result in fertilizer distributed unevenly throughout the field and potential nitrate-nitrogen (NO_3-N) contamination of groundwater through deep percolation and of surface water through tail water runoff. Because the environmental fate and distribution of nitrogen applied in surface irrigation water has not been studied extensively in the field, adequate N-fertigation management guidelines have not been developed.

APPROACH: The primary objective of the research is to develop information that will lead to best management practices (BMPs) for N-fertigation through surface irrigation systems. The project will derive this information through a series of extensive farm-scale field experiments conducted on representative surface irrigation systems commonly used in the western U.S. The measurement objectives include the determination of the spatial distribution and seasonal variation of N within the field, and the relative potential of groundwater and surface water contamination as a function of the timing and duration of N injection during the irrigation event. Irrigation water application distribution also will be determined for each irrigation. Ultimately, the data derived from this project will be used to incorporate chemical fate and transport components into existing soil water and surface irrigation simulation models, which once validated, will allow more comprehensive evaluation of fertigation practices and an expansion of BMPs for conditions and irrigation systems other than those encountered in this project.

In 1999, two simulated fertigation events were conducted on cotton grown in furrowed level basins at the Maricopa Agricultural Center (MAC). The first fertigation was conducted following cultivation which provided a rapid infiltration rate and a high degree of surface roughness. The second event was carried out during the third irrigation following cultivation which provided lower infiltration rates and less surface roughness than the first fertigation. During both events, potassium bromide (KBr) was injected into the water stream. The treatments for the experiments were injection during 100%, first 50%, and last 50% of the irrigation. Water was applied to five furrows in a 185 m long field. Soil samples were taken before and after the event to a depth of 1.2 m in the turn around area at the head of the field and every 30 m along the run. In the turn around area, two samples were taken and at the sampling locations along the length of run samples were taken from two adjacent cotton beds and from the furrow bottom of a wheel and non-wheel furrow. Samples were analyzed for bromide concentration. Irrigation parameters measured were advance and recession times, flow rate, and surface water depth.

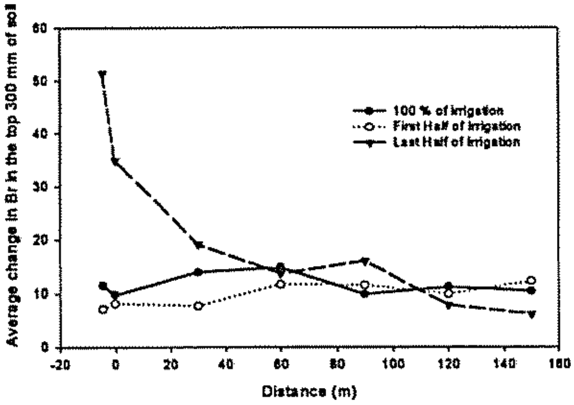

Figure 1. Distribution of the change in bromide concentration in the top 300 mm of soil with distance after application of bromide during 100%, the first 50%, and the last 50% of the irrigation of a level basin.

FINDINGS: Figure 1 shows the average field distribution of the change in bromide concentration within the 0-300 mm soil depth for each of the three fertigation treatments following the first irrigation. The bromide concentration for our 100% fertigation treatment was depressed at the head end of the basin (reflecting possible deep percolation losses), peaked at a distance of 60 m, and then decreased slightly with distance towards the end of the basin. The distribution of bromide that was applied during only the first 50% of the irrigation followed a trend quite similar to the bromide distribution for the 100% fertigation treatment. There was not an apparent increase in bromide level at the far end of our level basin. In contrast, the bromide pattern that resulted when fertilizer was injected during just the last 50% of the irrigation showed strong downward trends with distance.

In level basins, a controlled volume of water is applied from one end or one corner of a basin, completely enclosed with perimeter dikes to prevent runoff. Figure 2 shows a relatively uniform infiltrated depth distribution for a level basin irrigation, estimated by a simple advection (volume balance) model. This example illustrates a situation in which applying fertilizer during 100% of the irrigation event may be the best fertigation option. Injecting fertilizer during just the first 50% of the irrigation may result in poor fertilizer distribution uniformity throughout the basin, as suggested by the rather large differences between the infiltrated depths at the far end versus other areas of the basin after 50% of the irrigation had been applied. Also, deep percolation losses would be proportionately high with this fertigation application, since all deep percolation water is contributed just from water applied during the first 25% of the irrigation. In contrast, adding fertilizer during just the last half of the irrigation would result in too much N at the front end of the basin and too little at the far end, although there would be no N lost due to deep percolation. Applying fertilizer during 100% of the irrigation would result in a relatively even distribution of N in the root zone with a small portion of the total N leached with deep percolation (as represented by the area underneath the deep percolation curve).

INTERPRETATION: The example of Figure 2 suggests that if irrigation uniformity is relatively good, adjustment of the timing and duration of fertigation, as opposed to continuous injection during the entire irrigation, may not be warranted. However, it is important to point out that fertigation recommendations derived using modeling techniques, e.g., the simple advection model used above, are highly speculative, since dispersion, adsorption, and desorption processes are either ignored entirely in the models or models have not been validated based on actual field conditions. In practice, fertigation recommendations are expected to vary widely, subject to the myriad of combinations of irrigation specifics; e.g., the split between the deep percolation and runoff, relation between advance and opportunity time, soil texture, changing infiltration and surface roughness characteristics, cultural practices, etc. In order to develop models which adequately describe and predict solute transport processes during fertigation of surface systems, comprehensive field studies must be undertaken to develop data over a wide range of irrigation systems, practices, and field conditions.

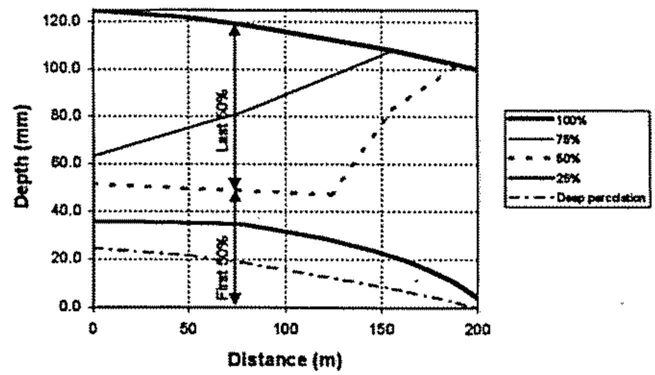

Figure 2. Cumulative infiltrated depth with distance after 25%, 50%, 75%, and 100% completion of the irrigation and deep percolation with distance for a level basin irrigation system.

The lines in Figure 2 represent the infiltrated depth of the first, second third and fourth quarters of an irrigation applied to a 200 m long level basin. It is interesting to note that some similarity exists between the pattern of bromide distribution for a particular fertigation treatment in our level basin experiment (Fig. 1) and the predicted pattern based on the infiltrated depth distribution estimated with different field conditions for the level basin of Figure 2. Our preliminary research results on the timing and duration of fertigation during the irrigation event suggest that significant progress can be made towards defining the best fertigation management strategies for surface irrigation systems. However, technology in this area is underdeveloped and progress has been greatly hindered by a lack of sufficient field data.

FUTURE PLANS: Analysis of remaining soil samples will be completed. Irrigation data will be analyzed using the software package EVALUE to estimate average field infiltration and to estimate Manning n values for surface roughness. Pending additional outside funding, similar data sets will be developed for unfurrowed level basins, furrowed and unfurrowed sloping borders with and without runoff over a variety of soil types and lengths of run in Arizona and California. When completed, the data sets will provide a sufficient range to develop fertigation guidelines for a large portion of the surface irrigated acreage in the western United States.

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USE OF A LOW COST COLOR DIGITAL CAMERA TO MEASURE PLANT PARAMETERS

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PROBLEM: The number and timing of flowers a plant produces is of interest because it can be an important factor in determining yield. The time required manually to count flowers in the field makes it difficult to carry out large studies involving flower numbers. It is possible to detect flowers on plants which are not obscured by leaves and stems in digital images. Documenting plant parameters such as crop senescence rates, fertility levels, insect damage, salinity problems, disease and nematode damage, etc., which result in changes in plant color, is often difficult due to the need for frequent sampling during periods of rapid change and the subjective nature of visual observations. Digitized images of crops should show temporal changes in the greenness of crop plants as well as differences related to treatments. Low cost digital cameras, which are available in the market, provide an easy and inexpensive method of obtaining digital images of plants that can be analyzed for a number of plant parameters. The objectives of this work are (1) to develop the methodology needed to use digital color images for documenting crop senescence rate, flowering, and other plant parameters, and (2) to apply the methodology to improve nitrogen and water management practices.

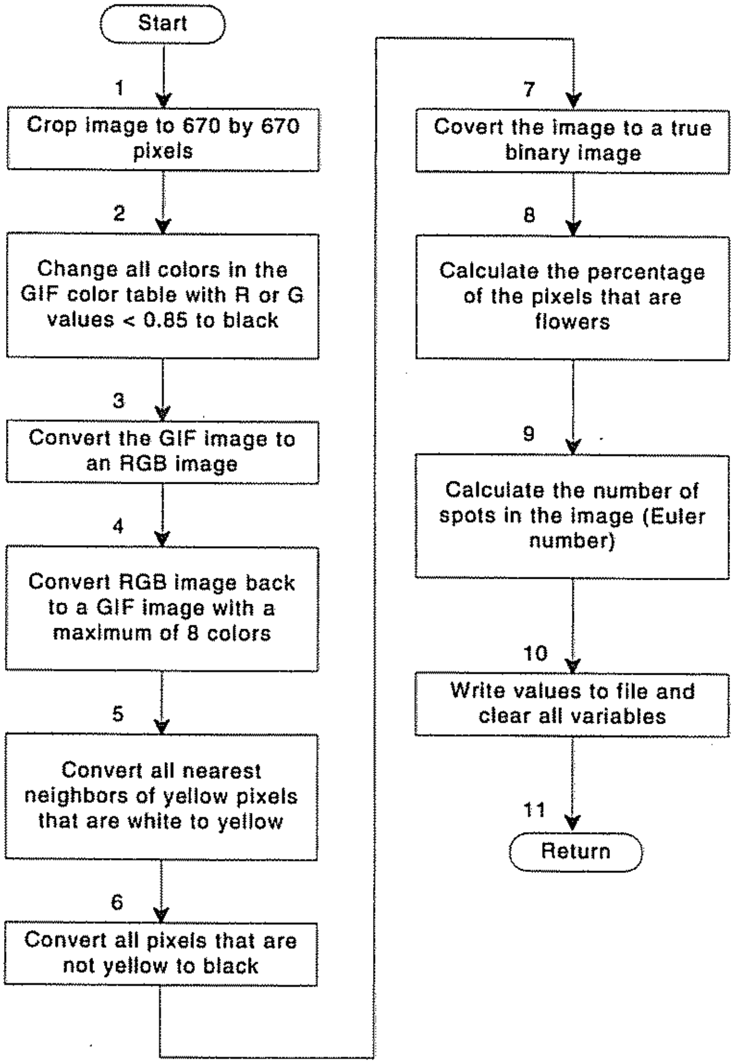

Figure 1. Flow diagram of main automated image processing loop for flower counting.

APPROACH: A digital camera which costs less than $1000 was used to obtain images of lesquerella (*Lesquerella fendleri*) in a field experiment of fertility and seeding rate at the University of Arizona's Maricopa Agricultural Center (MAC), near Phoenix, Arizona. The experimental design was a complete factorial of three fertilizer rates and four seeding rates. Fertilizer as ammonium sulfate at rates of 0, 60, and 120 kg ha^{-1} was applied at flowering. Digital images of the plots were taken periodically from mid-March to early-June using a color digital camera. Images were acquired between 1030 and 1300 h MST. The camera had a 1024 by 768 pixel resolution and twenty-four bit color resolution. The method described in Fig. 1 was used to count the number of flowers in the images. The first step in processing the images was to crop the image so that it showed an area of 1m by 1m. All pixels with yellow color were identified, and spots of yellow color were then counted (Fig. 2). Two indices were developed. The simplest was the number of pixels in the image identified as flowers and the second was a count of the number of spots. Thus far, the number of flower pixels has been the most useful.

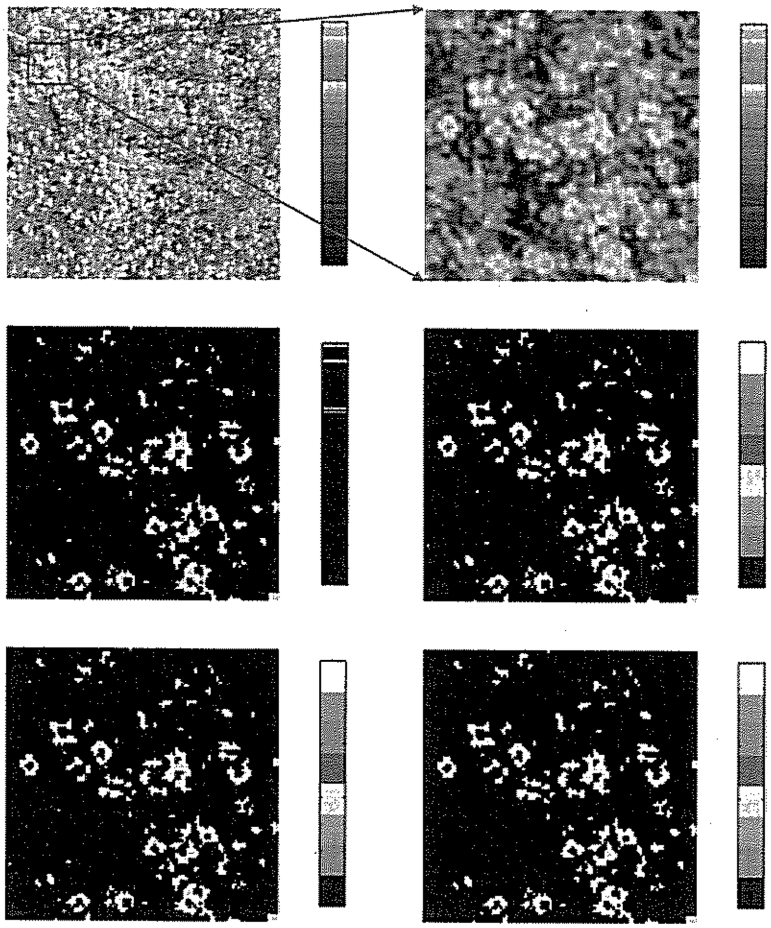

Figure 2. Results of image processing on the image from Plot A on April 15, 1997; (a) cropped image; (b) area of cropped image outlined in red; (c) after color depletion; (d) after color remapping; (e) after search for yellow spots; (f) after elimination of non-yellow pixels.

FINDINGS: Flowering responded to the amount of fertilizer applied but not to seeding rate (Fig. 3). Peaks in flowering occurred following irrigations through March and April (Fig. 3). In May as the crop approached maturity, flowering responded to irrigation only at the lowest nitrogen level (Fig. 3a). In plots where fertilizer was applied at flowering, flower production continued at a higher rate than in the unfertilized plots which received only preplant fertilizer (Fig. 3). Peak flowering occurred on March 26, 1998, for the 0 N treatment but not until April 16, 1998, for both the 60 and 120 kg N ha^{-1} treatments. Peaks in flowering were less pronounced and the decline in flowering was more abrupt in the 60 and 120 kg N treatments than in the 0 N treatment. By June 4, 1998, the last date that images were acquired, all of the treatments ha essentially stopped flowering. Treatment means of % flower pixels for each date and the sum of % flower pixels from March 19, 1998, through each date were regressed against the treatment means of yield. The coefficient of determination for the regression was then plotted against date (Fig. 4). Flowers formed in March and early April appear to have little impact on yield. The r^2 values for this period are less than 0.30 while the r^2 values from the first three weeks in May were all 0.85 or higher. The largest r^2 for a single date was 0.95 for May 14. For sums of % flower pixels, the regression with yield never provided as good a fit as the single dates from the first three weeks in May. The drop off in r^2 values for single date regressions after May 14, 1998, occurs because there is no difference between treatments in flowers after mid-May while there are differences in yields between treatments. Daily high temperatures in late May typically approach 40° C and may reduce flowering.

INTERPRETATION: The flowering data show that while flowering lasts for twelve weeks, there is a four to six week period beginning 180 d after planting that has the greatest influence on yield. The number of flowers present at the beginning of flowering reflect the emergence and survival of seedlings, but the early flowers do not reflect yield. Substantial growth occurs after fertilization at the start of flowering thus much of the seed is formed later in the growing season.

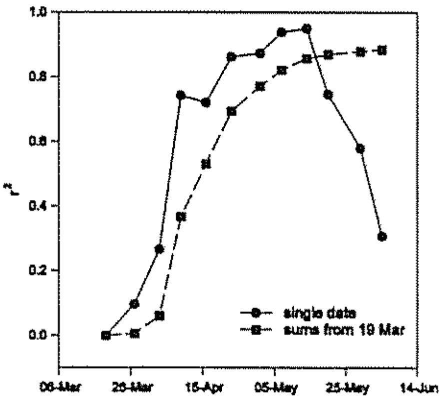

Figure 4. Change in coefficients of determination for regressions of treatment means of percent flower pixels against treatment means of yield for single dates and for the sums of percent flower pixels across dates beginning on March 19, 1998.

The data suggest that fertilizer application at flowering may not be the best nitrogen management strategy. Applying fertilizer to achieve growth prior to flowering should shorten the flowering period and take better advantage of the first flush of flowers formed by having a larger healthier plant. However, an impediment to early fertilizer application is the slow emergence and early growth of lesquerella. Because of slow emergence, it was necessary to make four irrigations for stand establishment. When the crop is grown with surface irrigation, as in this case, minimum water applications were 50 mm. In this case, that means at least 200 mm of water was applied when the crop was not able to use it. Applying 200 mm of water to a fertilized crop often results in leaching of nitrate from preplant applications below the root zone.

While not shown directly by this study, the flowering data suggest that the reason lesquerella responds to planting date is related to growth of the plant before flowering begins. Earlier planting dates allow for more vegetative growth, resulting in larger plants when flowering begins in the spring.

Results from this study validate the method proposed by Adamsen et al. (in press) for using a digital camera to monitor flowering in a crop. They also show that by monitoring flowering, critical flowering times can be identified. This can lead to altering production practices, such as earlier application of fertilizer, to maximize yield and smaller more frequent irrigations to reduce the effects of short term water stress. The cessation of flowering in conjunction with weather data should be useful in determining precise harvest dates.

FUTURE PLANS: Flowering data will be developed for rape, crambe, alfalfa, and vernonia. Rape flowers are similar to lesquerella flowers in color and crambe flowers are white. Vernonia and alfalfa flowers are purple to pink in color but appear blue in digital images. These crops should test the applicability of the general methodologies developed for lesquerella. If this effort is successful, the feasibility of counting flowers on other crops such as cotton will be evaluated. Greenness indices will be developed for sorghum and alfalfa. The use of greenness indices with forage crops can help assess the effects of various treatments on regrowth and harvest date. The relationships of greenness indices and flower number with fertility and water management will be developed. Once these relationships are developed the will be used to develop improved water and fertilizer management practices.

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SURFACE IRRIGATION MODELING

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PROBLEM: Throughout the irrigated world, water is applied to fields unevenly and excessively, leading to wastage, soil loss, and pollution of surface and groundwaters. Computer modeling would allow rapid evaluation of physical layouts and operation in a search for an optimum. But most models are limited to single furrows or border strips and basins with zero cross-slope and a uniformly distributed inflow at the upstream end. Yet large basins are usually irrigated from a single inlet. The flow spreads out in all possible directions, and any one-dimensional simulation must be viewed as a very coarse approximation. A non-planar basin surface influences the flow as well. An irrigation stream concentrated in the lower-lying areas can significantly affect infiltration uniformity. Only a two-dimensional model can simulate these factors.

While a one-dimensional approach is suitable for furrows, in real fields, flows in neighboring furrows of a set are often coupled through common head and tail-water ditches. Tailwater from a fast furrow can enter a slower furrow from its tail end and modify its ultimate infiltration profile. To appreciate the effects of such coupling fully, simulation of interconnected furrows is necessary.

Irrigation management can influence the quality of both surface and ground waters as well as of the field soils. Irrigation streams can be of sufficient power that soil boundaries erode, with the material entrained into the stream and transported downfield, reducing soil fertility upstream. Farther downstream, as infiltration reduces the discharge or as the result of slope reduction, part of the load, perhaps only the coarse fractions, might deposit back onto the bed. Or else, entrained material can run off the field, introducing turbidity into drainage water or deposit in quiescent areas, to the detriment of aquatic life.

Chemigation introduces agricultural chemicals into the irrigation water. Alternately, initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, phosphorus, and heavy metals, for example, brought to farm fields in agricultural operations and naturally occurring chemicals, such as selenium, can be transported to surface or subsurface water supplies by irrigation water, to the detriment of both human consumers of the water resource and wildlife dependent on the receiving water bodies. Nutrients or pesticides adsorbed to eroded soil in irrigation tailwater is an important example.

APPROACH: The objective of current work is validated computer simulation models for providing quick responses to a wide variety of "what-if" situations. For example, the trade-offs between irrigation efficiency and uniformity, on the one hand, and soil loss, on the other, could be explored. Recommendations could then be made on the basis of environmental considerations as well as water conservation and crop yield. Funding for this effort is provided in part by the Natural Resources Conservation Service.

For one-dimensional single-furrow, border, or basin simulation, user-friendly, menu-driven data input and output graphs and text are linked to a simulation engine based on the universal laws of hydraulics

MEASUREMENT AND CONTROL OF WATER FLOW UNDER DIFFICULT CONDITIONS

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PROBLEM: There are many flow conditions that are not amenable to the use of simple flumes and weirs. Many other measurement devices and methods are more expensive, more difficult to use, or less accurate than flumes and weirs. Improvements in these other methods are needed to complement the advances with flumes and weirs. Problems of continuing interest related to pipe flows include flow profile conditioning in pipes, field applications of several flow meters to irrigation wells, and automatic regulation of flow through large irrigation outlet pipes from main canals to lateral canals.

Most delivery canal systems use pipes through the canal banks to deliver flows to farm canals. Propeller meters, end-cap orifices, Pitot systems, and ultrasonic meters placed in these pipes frequently are subjected to poorly conditioned flow profiles that compromise the meters' operation. All of these are affected by upstream pipe bends and valves. Propeller meters readily clog in debris-laden flows and usually can be inserted into trashy flows for only a few minutes. End-cap orifice meters do not work well on rusted pipe ends. Pitot systems are considered difficult to apply to discharges from wells without special wall taps and insertion ports. Inserting a standard combination Pitot-static tube, such as the Prandtl tube, into the outflow end of a pipe has been used. However, these tubes are expensive, requiring specialized manufacturing techniques not available in most machine shops. Methods to condition flows and improve the flow profiles are needed, particularly when short lengths of straight pipe precede the meter.

Fluctuating flow-rate deliveries from a main canal to a secondary canal increase the difficulty of effective irrigation and may require expensive means to monitor total delivered water volume. The same type of pipe outlets described above are being considered for retrofitting with mechanical-hydraulic mechanisms that would stabilize the discharge rate through them regardless of changes in the level of the source canal. Steady flows can use simple time clocks for total volume.

Several ongoing objectives associated with pipe system flows are: (a) to complete papers and technical notes regarding the design and calibration of the modified Pitot system for irrigation wells that can be constructed in ordinary shop settings, the back pressure effects of flap gates at pipe outlets, and the suggestions for simplifying the use of portable end-cap orifices (see previous Annual Reports); (b) to develop practical methods to achieve effective flow conditioning for flow meters installed in difficult short-pipe situations, and (c) to evaluate prototypes of clog-resistant propeller meters that have been manufactured to our suggestions.

APPROACH: Standard calibration procedures were previously completed on the end-cap orifice system. An alternate pressure tapping system was studied. This involved using a small static pressure tube (with holes drilled through its walls), similar to that used for the Pitot system described last year, to detect the pressure in the approach pipe upstream from the orifice. The tube was inserted through a grommet-sealed hole in the face of the orifice plate near the pipe wall so that the pressure sensed was that for one pipe diameter upstream from the face of the orifice. No further lab data were gathered.

applied implicitly in fully nonlinear form. Constants in commonly accepted empirical equations for infiltration, roughness, and soil erosion are entered as input. The computer model, SRFR, is based on this approach.

Two-dimensional simulation is also based on hydraulic principles. Under the assumption of flow velocities small enough to neglect accelerations, force components in each of two mutually perpendicular directions on the field are in equilibrium. The resulting parabolic partial differential equations, solved implicitly by locally linearized finite differences in the two directions and time, yield a wave-like solution encompassing both wet and dry areas of the field. A similar but one-dimensional approach, treating wet and dry cells uniformly, is applied to multiple coupled furrows.

Erosion, transport, and deposition of irrigated soil is too complex to simulate on the basis of general physical principles alone. Currently, it is *fundamentally* an empirical science, in which the trend in recent years has been towards ever more general relationships, containing as much general physics as possible. Many conceptual models of parts of the total process have been proposed in order to avoid pure empiricism, but these are only partially convincing, with researchers intuitively leaning toward one or another. The measures of a good predictive relationship or procedure are its generality with respect to different soils and different irrigation conditions, and ability to predict soil transport at different locations in a furrow, especially in the tailwater runoff, at all times during the irrigation.

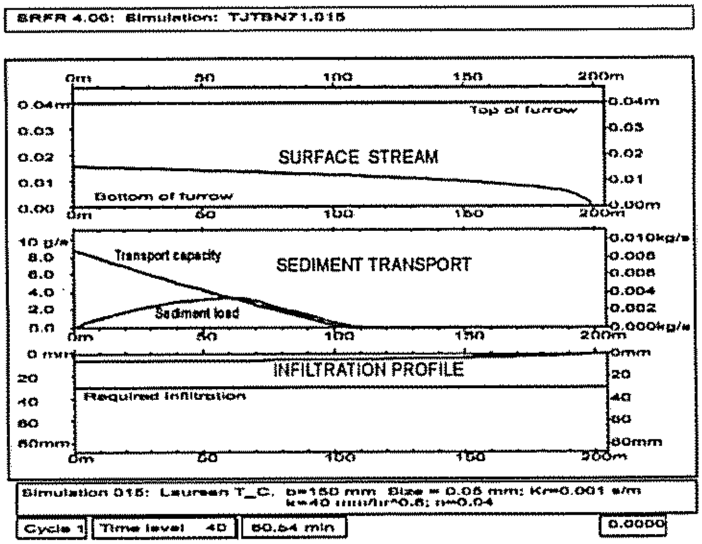

Figure 1. Frame of animated output of SRFR simulation – profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths; time=61 min

FINDINGS: The SRFR 4.00-series surface-irrigation simulation model has been released for downloading through the U.S . Water Conservation Laboratory (USWCL) web site (also newly available at this site are the earlier programs, BASIN and BORDER, design and management aids for level-basin and border-strip irrigation). In addition to the wide variety of surface-irrigation techniques and scenarios that can be simulated with this menu-driven graphics-oriented program, a preliminary erosion component is available to cooperating researchers. Figure 1, drawn from the animation displayed by SRFR during a simulation, illustrates typical behavior of the transport-capacity function and resultant sediment loads at one instant of time (61 minutes into the irrigation). Note the lengthy region behind the stream front in which the transport capacity and detachment are zero. Because of upstream infiltration, the flow rate is so small there that the boundary shear is below the threshold for entrainment. Far upstream, the sediment load grows the fastest at the clear-water inflow, where the transport capacity is a maximum

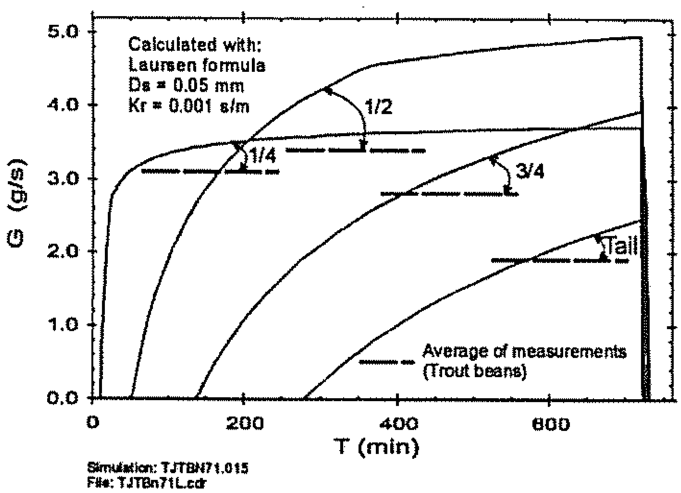

Figure 2. Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data of July 1, 1994. Site-specific Kr=0.001s/m, τ_c=1.2 Pa. Laursen (1958) transport-capacity formula in effect. (Strelkoff and Bjorneberg, 1999)

and the existing sediment load zero. With distance downstream, the transport capacity decreases due to infiltration, and the sediment load increases due to upstream entrainment; both factors lead to reductions in further growth in the load. Eventually, though, transport capacity *is* exceeded, and some of the load starts to deposit back onto the bed. Finite fall velocities are seen in the "super-saturated" concentration of sediment evident in the figure.

Strelkoff and Bjorneberg (1999), utilizing in SRFR's erosion module the Laursen (1958) formula with a representative particle size midrange in the field-measured mix, got a reasonable match between results of the simulation and Idaho field data, as in Figure 2. They also found that the Yang (1973) and Yalin (1963) formulas (WEPP) greatly overestimated the capacity of furrow flow to carry sediment, with consequent under-prediction of deposition back to the lower reaches of the furrow.

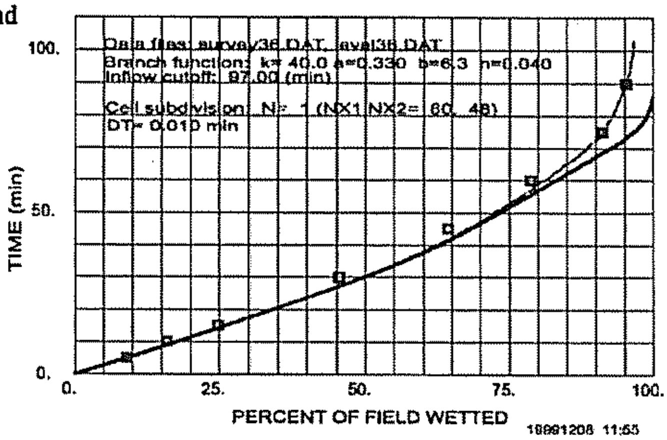

Figure 3. Advance curves –
Squares: measured;
Dotted: computed, with surveyed field elevations;
Solid line: computed, for a plane, level field.

The two-dimensional simulation model was tested against field measurements obtained in a 3 ha (7 acre) basin at the Gila River Farms, irrigated from the center of one side. Monitoring of water levels in 26 locations and a land-level survey allowed estimation of the soil infiltration characteristics, represented by a power law of time in the early stages, branching to a constant infiltration rate after 4 hours of wetting. Assumption of the reasonable Manning n=0.04 yielded the results shown in Figure 3. Predictably, the irregular field surface requires additional time to wet the high spots; in fact, it is apparent that some 4% of the field area is so high that with the given cutoff, at 97 minutes, it is never wetted. The computations appear to agree with field data to within measurement errors.

INTERPRETATION: The growing body of simulation software is finding users in the national and international irrigation community for design, management, and evaluation of surface irrigation. It is likely that studies of the interrelationship among distribution uniformity, standard deviation of surface elevations, and inflow rate will provide a useful adjunct to current design software. Predictions of soil erosion, transport, and deposition are significantly less accurate than predictions of hydraulic performance, but the influence of design and management is easy to see, so that these aspects also can be taken into account.

FUTURE PLANS: In order to get a more accurate simulation of sediment transport and, in particular, for subsequent simulation of chemical adsorption to the surface areas of that sediment, the distribution of particle sizes in the sediment mix should be accounted for. For example, the extensive field work ofFernandez (1997) shows consistent decreases in sediment concentrations with irrigation time at various locations along the furrow. This suggests a supply-limited erosion event, which is, in the absence of scour-hole formation, a concept possible only in a graded mix. This is because in a cross section essentially constant with time, a homogeneous soil provided with a constant supply of, say, clean water continues to churn out sediment at a constant rate. The reductions with time noted most likely stem from the fact that gradually all of the particles which *can* be detached *are*. What remains on the bed are particles too large or heavy to be entrained, with finer ones underneath, protected from scour by the coarse layer at the soil-water interface.

Deficiencies in SRFR noted by users will be addressed, including coalescing of successive surges. As funding becomes available, the two-dimensional pilot model will be reoriented towards routine application. Increasing the allowable time step, currently very small in basins with a fine grid of soil and water surfaces, will be explored. A multiple-furrow model will be completed, and additional field verification for both the two-dimensional and the coupled-furrows programs will be sought, pending outside financial support. Long-term plans include incorporation of relationships for cohesive soils, a relatively poorly understood area in the field of sediment transport. Incorporation of soil-chemistry components is contemplated; water and soil salinities play a great role in erosion, especially in clays. Estimates should be made of the pre-wetting effect for surge irrigation. Pre-wetting phenomena have been shown to have a significant effect on detachment; but virtually all of the WEPP erosion database is for pre-wetted (rained-on) soils, which do not exhibit the violent fine-scale commotion observed at the front of a wave of irrigation water in a dry, powdery bed. Also, soil and water temperature effects on infiltration and erosion require quantification.

As funding becomes available, chemical transport and fate will be included in SRFR.

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