SURFACE IRRIGATION WATER QUALITY AND MANAGEMENT

Theodor S. Strelkoff, Research Hydraulic Engineer
Floyd J. Adamsen, Soil Scientist
Eduardo Bautista, Research Hydraulic Engineer
Douglas J. Hunsaker, Agricultural Engineer
Albert J. Clemmens, Research Hydraulic Engineer
Robert J. Strand, Electrical Engineer
Hadi Tabbara, Soil Scientist

PROJECT SUMMARY

Surface irrigation is the most widely used irrigation method in the world. In the US, over 50% of irrigated land is watered by surface means. It is the most inexpensive method, in terms of capital outlay, power requirements, and maintenance costs. Traditional surface methods are labor intensive. Poor uniformity of application, and excessive runoff and deep percolation, often carrying agricultural chemicals into the environment, are common. The complexity of the hydraulics of surface systems has, until recently, made rational design very difficult. Accordingly, many surface systems are built and operated without the benefit of any technical design. The proliferation of computers has now made numerical solutions of the hydraulic equations easily attainable, and is putting design of surface irrigation systems and their operation on a par with other engineering disciplines -- with reliance on multiple analyses (simulations) with trial values of the design variables in the search for an optimum.

The proposed research is intended ultimately to provide guidance in the design and operation of surface systems, both traditional and innovative. The investigators will collaborate with several ARS sites addressing all four of the NP201 research initiatives. Intermediate goals are (1)simulation of the transport and fate of water, sediments, and nutrients such as phosphorus and nitrogen by irrigation in furrows, border strips, and basins of various types, along with attendant field studies,(2) software for presenting overviews of simulations to aid in the search for an optimum, (3) software to assist in evaluating extant field conditions on which irrigation performance depends.

OBJECTIVES

1. Develop validated software (a) for simulating surface-irrigation hydraulics, (b) for assisting in design and management of such systems, and (c) for estimating the field parameters that bear upon system behavior.
2. Develop guidelines for design and operation of drain-back and other surface-drained level basins to improve water use in surface irrigation, while maintaining farm profitability and sustainability.
3. Develop validated surface-irrigation models incorporating the fate and transport of sediments, phosphorus, and nitrogen, including their ultimate off-site discharge.
4. Develop guidelines for water and nutrient management under surface irrigation for minimizing introduction of nitrogen into surface and ground waters while maintaining soil fertility, crop yields, and farm profitability and sustainability.

NEED FOR RESEARCH

Description of the Problem to be Solved

Surface irrigation accounts for half of the irrigated land area in the U.S. and over 90% worldwide. Many systems are built and operated without adequate technical input, with consequent low uniformity and efficiency of water application. Yet, water supplies for irrigation are limited and likely to decline due to competition from environmental and urban water demands. Improved management and conservation will be required to maintain current levels of crop production; at the same time, demand for food is expected to grow. Science-based criteria for design and management of surface systems can often improve surface irrigation performance to levels commensurate with pressurized systems at substantial savings in capital costs and energy. Irrigated agriculture also contributes to non-point source pollution of groundwater and surface waters with nitrogen and phosphorus. Application of nitrogen fertilizer in the irrigation water is widely practiced but often leads to nonuniform, excessive application and contributes to nitrogen contamination of the groundwater. Tailwater runoff can carry sediments, nitrogen, and phosphorus to surface streams. Improved design and operation of surface irrigation systems and improved nitrogen application practices should improve agriculture's utilization of water and reduce its adverse effects on the environment.

Relevance to ARS National Program Action Plan

The research is part of NP201, Water Quality and Management. The project falls under Component 2, Irrigation and Drainage Management. Objectives 1 and 2 deal with agricultural water conservation, while 3 and 4 deal with the effects of irrigated agricultural on the environment. All fit under Problem Area 2.3 (Water Conservation Management), Goal 2.3.3 (Agricultural Water Conservation and Environmental Quality). Objective 3 concerns also Problem Area 2.6 (Erosion on Irrigated Land), Goal 2.6.2 (Irrigation/Erosion Model).

Potential Benefits

Process-based predictive tools can be effectively used to examine the consequences of various system designs and management practices on the utilization of water and nutrients by the crop and on the contamination of surface water and groundwater by irrigated agriculture. These tools can become the basis for improving practices that conserve water, minimize fertilizer costs, and protect the environment, while maintaining yields of crops under irrigation, particularly with surface methods.

Anticipated Products

1. A process-based model of surface irrigation, including water flow, sediment movement, and the movement over the field surface of chemicals, both dissolved in the water and attached to sediment particles. For studies on fate and transport of nitrogen, the model is to be linked with other models, developed at collaborating laboratories, simulating soil physical and chemical processes.
2. Design and management-aid software, integrated with the simulation model.
3. Guidelines and recommendations, grounded in contemporary scientific and engineering principles, for improving surface irrigation performance and for reducing the impact of irrigation on the environment, while maintaining or improving crop production and quality.

Customers

The NRCS (Natural Resources Conservation Service, particularly through the National Water and Climate Center and Thomas L. Spofford, Irrigation Engineer) has supported our development of surface-irrigation design and management tools and has promoted these for use at its field offices. We thus expect our main customers to be the NRCS, as well as agricultural consultants, mobile field labs, and extension agents, with farmers as the ultimate beneficiaries (particularly in the case of software). We plan to have these groups review the software and predictive tools throughout the development process, as well as the ultimate recommended practices.

SCIENTIFIC BACKGROUND

Objective 1 - Irrigation Software

Simulation models are used to aid system design and management. The most widely disseminated, covering all of the phases of an irrigation and forming a basis for constituent transport, are the one-dimensional SIRMOD (Utah State University, 1989) and SRFR (Strelkoff et al, 1990). An uncounted number of additional, ad-hoc constructions are built for specific applications (e.g., Fernandez, 1997). One-dimensional models are those in which the pertinent variables are considered functions of a primary (longitudinal) direction, such as distance down a furrow or border strip, and time (in contrast, a typical two-dimensional problem might deal with a large basin with a point inlet, the inflow spreading out in all possible directions). SRFR accommodates spatially and temporally varying slopes, cross sections, infiltration and roughness, as well as a variety of inflow-management strategies -- cutback, surges, cablegation, and drainback. A selection of infiltration, roughness, and plant-drag formulations are available. Irrigation-stream responses to field and inflow conditions such as front-end recession and re-advance are accommodated. In 1998, a mouse/menu-driven version with graphical user interface was released (Strelkoff et al, 1998).

For given field conditions (topography, infiltration, roughness) and water availability at the site, performance (which includes efficiency, uniformity, water cost per hectare, etc.) is a function of the design variables. That functionality, which can be imagined for each performance variable as a response surface, can be explored informally, by trial and error. The engineer tries different combinations of the design variables and calculates simulated performance level for each. In a more direct, inverse, procedure (BASIN, Clemmens et al., 1995), the engineer specifies a desired performance level, and the program, interpolating within a database of previously run simulations, quickly calculates the values of the design variables which achieve that level. In another approach, the engineer specifically seeks the maximum point of the response surface. Then, in a formal optimization procedure (e.g., Wallender et al., 1990), a simulation model is called repeatedly in an automated search for the maximum. A more recent development (BORDER -- Strelkoff et al, 1996) provides performance overviews, which present the response surface itself to the viewer, as contours, again, obtained by interpolation within a massive database of simulation results. These are intended to span the practical range of field and design variables of interest, and are “hardwired” into the program. Such a static database is limited by the specifics under which the simulations were run (even with the enormous generality afforded by use of dimensionless representations).

Estimation of Field Parameters

Infiltration and hydraulic drag are essential soil-boundary conditions on the irrigation stream and constitute inputs to simulation and design/management software.

Infiltration: Surface-irrigation modelers and evaluators have mostly relied upon the wholly empirical Kostiakov power law in time, for cumulative infiltration (volume per unit infiltrating area), often modified (Lewis, 1937) by a long-time, *basic* rate, and sometimes a constant, to account for soil cracks. The Kostiakov-Clemmens branch function (Kostiakov, 1932; Clemmens, 1981) is the simple power law at small times, but crosses to a constant final rate at the time the power-law rate matches the long-term rate. It fits some soils better than the Kostiakov-Lewis formula. With these formulas, great flexibility in matching observed infiltration is provided by as many as 3 independent empirical parameters, but selecting 3 values also presents a challenge.

The SCS (now, NRCS – USDA, 1974) proposed a set of infiltration *families* for all soils to fit, each member with a specified coefficient and exponent in the Kostiakov power law. The families proved easy to use, and many engineers learned to associate the soils in their region to specific families. Not surprisingly, many soils fail to fit any of the families, and in response, Merriam and Clemmens (1985) introduced the Time Rated Intake Families for non-cracking soils. These families were based on an empirical correlation (fitted with an algebraic equation) between the time to infiltrate just 100 *mm* and the Kostiakov exponent. A single measurement, of the time required to infiltrate the 100 *mm*, provides a Kostiakov cumulative infiltration function.

In simulating furrow flow, the fundamental infiltration boundary condition required as a function of time is the volume infiltrated per unit length, A_z, rather than volume per unit infiltrating area, z. In a theoretical (Richards, or Green and Ampt) approach to furrow infiltration the obvious direct dependence of A_z upon wetted perimeter comes out as part of the solution (Enciso et al, 1991; Peck and Talsma, 1968; Talsma, 1969; Youngs, 1972; Freyberg, 1983; Philip, 1984; Schmitz, 1993a,b,). In one popular empirical approach (Elliot and Walker, 1982; Walker and Humpherys,1983), A_z is directly determined for a series of time values by dividing the corresponding measured infiltrated volumes V_z in a furrow test section by its length. For a flow depth other than in the test, the necessary modification is not clear. The SCS, on the other hand, identifying a *soil* by its family, *calculates* the effect of furrowing on infiltration by multiplying the family z by an "empirical" wetted perimeter, whose value can be as much as 2 or 3 times the actual furrow wetted perimeter (USDA, 1985; Strelkoff, 1992). In SRFR, infiltration is approximately characterized by empirical z parameters, and in a time step of simulation, the increase in z is multiplied by the extant wetted perimeter to compute the corresponding increase in A_z. The theoretical implications of this practical device are unclear.

Point measurements of infiltration seldom identify representative field values suitable for simulating an entire event. There are two basic approaches to estimating field infiltration and roughness from irrigation-stream observation. In one, inflow and outflow are measured, along with enough time-varying stream geometry to apply mass balances and determine the time rate of infiltration into the soil (Finkel and Nir, 1960; Maheshwari et al, 1988; Gilley, 1968; Roth et al, 1975; Fangmeier and Ramsey, 1978, Strelkoff et al, 1999). In the other, only selected features of stream behavior, e.g., inflow and advance and possibly a stream-flow depth, are measured and compared with simulated stream behavior, to deduce the field parameters (Shepard et al, 1993; Elliott and Walker, 1982; Clemmens, 1991; Walker and Busman, 1990; Bautista and Wallender, 1993; Clemmens and Keats, 1992; Clemmens, 1992, Scaloppi et al, 1995; Clemmens, 1981; Monserrat and Barragan, 1998; Valiantzas, 1994; Yost and Katopodes, 1998; Katopodes et al, 1990, Playan and Garcia-Navarro, 1997). The basic problem with the first method is the intensive field work required. The problem with the second is the uncertainty over whether the deduced field parameter values are at all correct. An error in estimating infiltration from measured advance can be compensated, in a particular event, by adjusting the roughness. With what certainty does an automatic optimization technique lead to a *global* minimum of errors, rather than a local depression (Katopodes, 1990; Katopodes et al, 1990)? How does actual spatial variability influence an assumed spatially uniform deduced value? The ultimate practical question is: what are the most *advantageous* measurements to obtain sufficiently accurate estimates of field properties with minimum effort.

Hydraulic Drag/Roughness: Many of the same considerations apply to estimation of surface roughness and plant drag, with the general understanding that it is not quite as important an issue as infiltration, partly because it does not vary as much as infiltration, and partly because in some cases (sloping border strips) errors in estimation partially cancel (Fangmeier and Strelkoff, 1979).

SRFR Suite: Many of the problems associated with collecting simulation, design/management, and field-parameter estimation into a single Windows-based suite with data crossing easily between components have been anticipated by the U.S. Corps of Engineers' Hydrologic Engineering Center, which is in a program of updating its software (NexGen project) to integrated, multiplatform, object-oriented status. An alternative to recoding hundreds of thousands of lines of Fortran legacy code is *wrapping* sections of such code in, e.g., Java so they can be treated as objects by the integrated shell (Davis, 2000). An amalgamation of soil-erosion models into an integrated package is found in MOSES (Meyer et al, 2001). Interactive data entry permits consideration of small watersheds, larger than the field/farm scales associated with earlier versions of its component modules. An integrated package of hydrologic and erosion models is also described in Ascough II et al, 2001.

Objective 2 - Surface-Drained Level Basins

The advantages of laser-graded level basins in improving water-distribution uniformity, application efficiency, and crop yields are documented (Dedrick, 1984; Clemmens, 2000), and software to aid in their design has been released (Clemmens et al, 1995). The relatively high costs of conversion, the large depths that must sometimes be applied to achieve high uniformity, and the danger of crop damage from undrained precipitation are all mitigated by a modification, *drainback*, which provides both inflow and outflow through a single broad, shallow ditch running down the prevailing slope, alongside a series of benched level basins, each irrigated and drained in turn. In this way, a portion of the applied water is returned to the supply channel before excessive infiltration has occurred (Dedrick, 1983; Dedrick and Clemmens, 1988). Such systems, developed at the USWCL in the 1980s, are expanding rapidly in central Arizona. The flow in a level-basin with drainback is essentially one dimensional, and its simulation has been programmed into SRFR. Some field studies have been conducted, but no general design and operational guidelines are available.

A further modification, developed in northern Louisiana where surface drainage is essential, is characterized by a square grid of shallow *spin ditches,* so called because the excavated material is spun out over the surrounding land to avoid berms on the banks, facilitating both water supply to the interiors of the grids and drainage (Clemmens, 2000). Thus, both supply and drainage occur throughout the basin. The effectiveness of these spin ditches, required spacing, etc., have not been studied. As a result, NRCS is reluctant to endorse them, even though farmers are pleased and acreage is expanding.

The flows in grid-supplied and drained level basins are essentially two-dimensional. A two-dimensional treatment of a dambreak flood on irregular topography was presented by Xanthopoulos and Koutitas (1976). The zero-inertia formulation therein, described by a parabolic partial differential equation, precludes true wave dynamics, but allows theoretically correct inclusion of both wet and dry areas into the calculation. Their work, however, incorrectly treats the vector components of hydraulic resistance. The first two-dimensional fully hydrodynamic model explicitly considering advance on a dry bed was the characteristics-based dam-break-flood model of Katopodes and Strelkoff (1978, 1979). Dam-break models were built by Hromadka and Yen (zero-inertia,1986), Akanbi and Katopodes (finite elements, 1988), and Bellos et al (finite-difference MacCormack scheme applied to irregular quadrilaterals transformed to rectangles, 1991). The full hydrodynamic leapfrog solution of Playan et al (1994), extended to irregular topography (1996), requires postulation of a small depth everywhere initially with the tacit assumption that the surge of irrigation water advances as a hydraulic bore over this small depth. The authors expressed some concern about the theoretical satisfaction of boundary conditions, in view of the neglect of a momentum-conservation relation there.

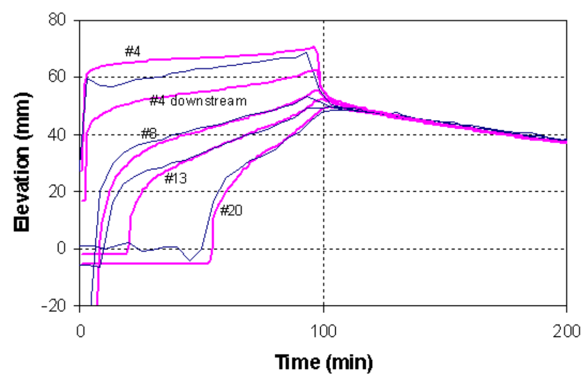

Figure 1. *Simulated (broad line) and measured (fine line) water-surface elevation hydrographs at selected points in basin (Clemmens and Strelkoff, 2001)*

Strelkoff et al (2001) utilized the zero-inertia approximation to avoid both the fictitious initial film of water and characteristics-based equations at the boundary. Furthermore, to permit large time steps, they developed an implicit numerical scheme with an alternating-direction solver for the resulting system of simultaneous linear algebraic equations. However, despite theoretical determinations of unconditional stability, computational experience shows that to avoid growing oscillations, especially in the neighborhood of deep depressions in the soil surface, time steps must be small, especially with fine spatial grids. Nonetheless the scheme provides useful simulations. Figure 1 shows a comparison of simulated and measured depth hydrographs at selected points in a 4 hectare basin (Clemmens et al (2001). Of note, computational points *#4* and *#4downstream* straddle the field depth sensor which supplied the measured hydrograph plotted between them.

Objectives 3 - Fate and transport of sediment, phosphorus, and nitrogen

Sediment: The Water Erosion Prediction Project (WEPP – USDA, 1995) is a process-based model primarily of rainfall-induced soil erosion. It appears not very well suited to surface-irrigation-induced erosion. The NRCS, while planning implementation of the hydrologic-erosion WEPP model in its watershed program, has found WEPP's surface irrigation component unvalidated and unacceptable

(Spofford, NRCS, 1995, 1998). Bjorneberg et al., 1999, and Strelkoff and Bjorneberg, 1999 detail some of the deficiencies of hydrologic – and specifically, WEPP – modeling of the erosion/transport process when applied to furrow irrigation. In contrast to the hydrodynamic components of surface-irrigation models, sediment detachment and transport research is almost fundamentally empirical, and determinations suitable for hydrologic watershed models are sometimes not at all satisfactory in the surface-irrigation context. Typical hydrologic factors which impact on erosion-prediction capabilities, for example, include raindrop energy, flow rates which increase with distance downstream, lateral sediment influx from interrill flow, and, typically, concave landforms. In furrow irrigation, raindrops do not influence either entrainment or transport, flow rates decrease in the downstream direction, encouraging redeposition in downstream portions of a furrow; typically, there is no lateral influx of sediment, and the flow channels are essentially straight. Fernandez (1997), utilizing some of WEPP's basic premises, developed a complex model, tracking several size fractions through the phenomena of entrainment, transport and deposition, and documented satisfactory agreement with several Spanish soils. At USWCL, a simple erosion component was incorporated into SRFR, based on a single particle size representative of the mix in the furrow-bed, and with empirically determined critical shear and erodibility (Laflen et al, 1987; Elliot et al, 1988). Figure 2, drawn from a frame of the animation displayed by SRFR during a simulation (Strelkoff and Bjorneberg, 1999), illustrates a typical profile of the transport-capacity function and resultant sediment loads at one instant of time (61 minutes into the irrigation). The long region downstream, behind the stream front, in which the transport capacity

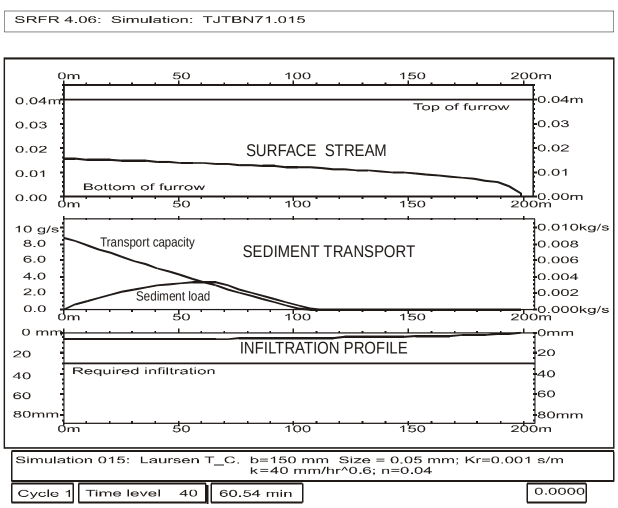

***Figure 2**. Frame of animated output of SRFR simulation – profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths; time=61 min*

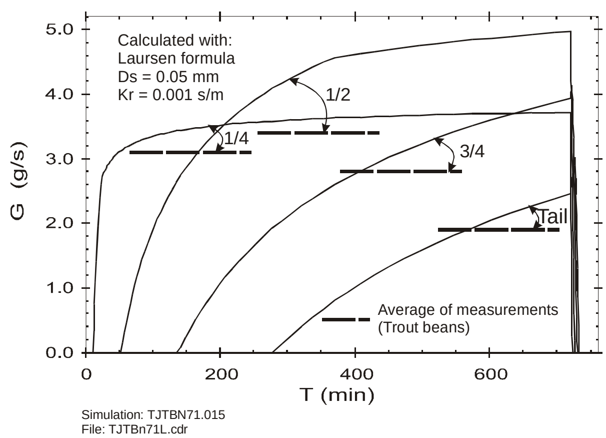

***Figure 3** Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data of Julky 1, 1994. Site specific Kr=0.001 s/m, Jc=1.2 Pa, Laursen (1958) transport formula. (Strelkoff and Bjorneberg, 1999)*

and detachment are zero, testifies to the low flows there; boundary shear lies below the entrainment threshold. Upstream, the sediment load grows the fastest at the clear-water inflow, where transport capacity is a maximum and the existing sediment load zero. In the given instance, transport capacity is eventually exceeded, initiating deposition back onto the bed. Strelkoff and Bjorneberg (1999), utilizing the Laursen (1958) transport-capacity formula, and with the representative particle size midrange in the field-measured mix, compared the simulation with field data obtained by Trout (1996) -- Fig. 3. In comparing several transport formulas, they found that the Yang (1973) and Yalin (1963) formulas greatly overestimated the capacity of furrow flow to carry sediment; consequently, deposition back to the lower reaches of the furrow is under-predicted. The Yalin formula provided the poorer predictions, corroborating the WEPP experiences of Bjorneberg et al. (1999). It is noteworthy that both the Laursen and Yang formulas were recognized by Alonso et al. (1981) as superior to that of Yalin, in predicting transport capacity in long channels, both in flumes and in the field. The Yalin formula, however, was selected for WEPP because it best predicted erosion in the very shallow rain-fed overland flow on concave hillsides (Foster, 1982).

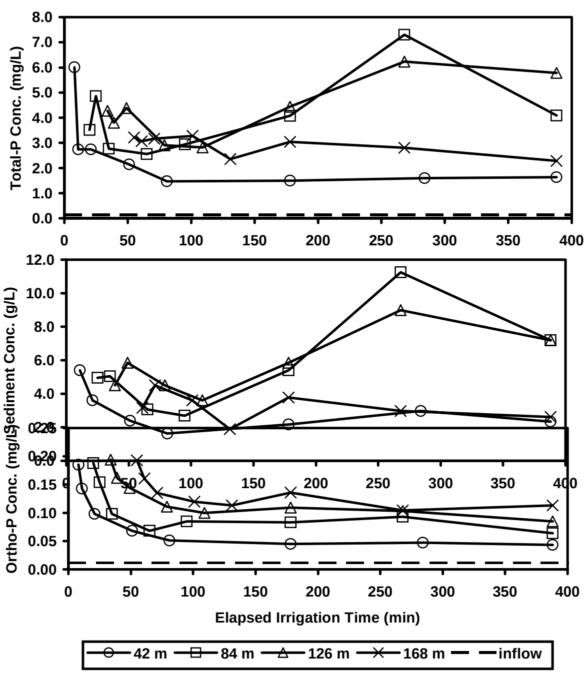

***Figure 4**. Sediment, total-P and ortho-P concentration at four locations in an irrigation furrow (preliminary data – unpublished)*

While the agreement of SRFR simulations with measurements can be satisfactory, preliminary data shows that calculation with a single representative particle size is too sensitive to its selection. Furthermore, the most likely explanation for observed decreases in sediment flux across a section with time is a decrease in the supply from upstream due to armoring -- protection of smaller particles from entrainment by a gradually developing layer of larger ones above (Fernandez, 1997). Suggestions for treating the phenomenon were made by Borah (1982) and Borah and Bordoloi (1989), while Wu and Meyer (1979) suggested a reasonable way of apportioning total transport capacity amongst the size classes.

Phosphorus (P): When furrow erosion is significant, affinity between P and soil-particle/aggregate surfaces ties the fate and transport of P in an irrigation stream to the sediments in transport. Several preliminary data sets on Portneuf silt loam (*Durinodic Xeric Haplocalcid*) have been collected at the NWISRL (ARS, Kimberly) for model development. Sediment, total-P and ortho-P concentrations along with water flow rate were measured with time and distance in a furrow (Fig. 4). Total-P concentrations closely follow sediment concentrations, while ortho-P concentrations are unrelated. Ortho-P concentrations decrease with time at a particular distance, but increase with distance at a given time.

Amongst the existing hydrologic/chemistry models, e.g., CREAMS (USDA, 1980), Opus (Smith, 1992), GLEAMS (Knisel, 1993), two approaches to modeling chemical constituents of runoff, Storm et al. (1988) and Ashraf and Borah (1992), appear the most promising for the purposes of the proposed study. In the first approach, the model of Storm et al. (1988) deals with uniform

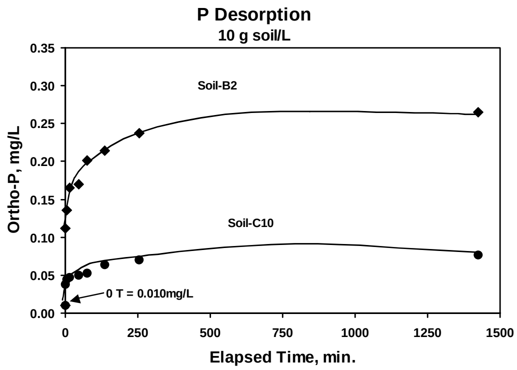

Figure 5. *Phosphorus desorption for two soils (preliminary data from batch studies -- unpublished)*

(lumped) field units and was designed for estimating rain-induced P transport from a field; in this case, the kinetic energy of the falling drops plays a role in P desorption (by influencing the thickness of the soil layer contributing P to solution). Storm et al. recognized a dynamic equilibrium in the runoff between soluble P and soil-bound P. In the transport of sediment-bound P, it is assumed that the distribution of P amongst the size classes of sediment is in proportion to their surface areas (confirming the need for a sediment transport model that tracks particle-size fractions in the flow). An empirical expression (Sharpley et al, 1981a, b, 1983), a power law in time, models the desorption of soluble P by the irrigation stream. The adsorption of P, on the other hand, can in many cases be assumed instantaneous. A common description of the equilibrium conditions of P reactions is the Langmuir isotherm (Tchobanoglous and Shroeder, 1985), which exhibits a limited adsorption capability, unlike, e.g., the Freundlich isotherm. A potentially significant factor in the chemical sub-models is the assumption of equilibrium isotherms in predicting reactions. Preliminary data collected at the NWISR Laboratory on reaction kinetics (Fig 5) may prove useful in judging the significance of those assumptions. NWISRL findings on the influence of soil chemistry on P in irrigation tailwater can be found in Westermann et al (2001).

The second hydrologic approach, the chemical component of the Ashraf and Borah (1992) model, is perhaps the most adaptable to the chemical aspects of furrow-water P modeling. This is a deterministic simulation of the entrainment (by rainwater) of P initially in the soil, partly in solution, and partly adsorbed to flow-entrained sediment, with the consequent P loading of the irrigation stream routed as kinematic waves to the field end and into the runoff. In this model, rainwater mixes with a mixing soil layer at the surface of the soil matrix, the degrees of interaction depending upon depth (*non-uniform* mixing -- Ahuja, 1982; Heathman et al., 1985). Simulation of this interaction is based on the following assumptions: -- (1) the mixing layer can be divided into depth increments, each increment homogeneous; (2) initial water content, porosity, and concentration in each soil increment are known; (3) all rainwater infiltrates into the soil during the early part of the rainfall event; (4) all pores participate, sequentially, in solute and water movement; (5) water entering the soil matrix mixes with soil water initially present in each increment and displaces it to the next increment, below; (6) except for adsorption and desorption, other chemical reactions are negligible; (7) dissolved and adsorbed phases in the furrow stream are in equilibrium, governed by a linear adsorption isotherm, simply a proportionality between concentration of solute and concentration of adsorbate, i.e., an empirical partition coefficient.

Thus, the result is a pair of advection equations in the respective concentrations in the furrow flow, one for dissolved P, and the other for adsorbed P, the two related by the partition coefficient. Source/sink terms for the first are described by the interchange of P between the pore water and the active soil bed layer, and between that layer and an assumed layer of the surface stream that experiences complete mixing with the pore water. The second depends on the net entrainment of each particle-size class and the preference of P to adsorb to that class.

Objectives 3(c) and 4

Nitrogen -- Field work, modeling, and guidelines: Applying fertilizer through irrigation water (fertigation) can be a highly effective fertilizer management practice which offers certain advantages compared to conventional field spreading or soil-injection techniques -- reduced energy, labor, and machinery costs (Beth and Filters, 1981). A nitrogen management scheme of multiple fertigation applications with smaller amounts of N would reduce the need for large preseason or early-season applications, often associated with heavy N losses (Silvertooth et al., 1992; Watts et al., 1993). Fertigation is also more compatible with management tools such as residual soil nitrate assessment and in-season plant-tissue tests (Adamsen and Rice, 1995). In many cases, fertigation may be the only practical and economical method to apply additional nitrogen to surface-irrigated crops once the development of the crop precludes the use of machinery fertilizer applications. However, comprehensive guidelines for surface irrigation systems have not yet been adequately developed (Watts and Schepers, 1995).

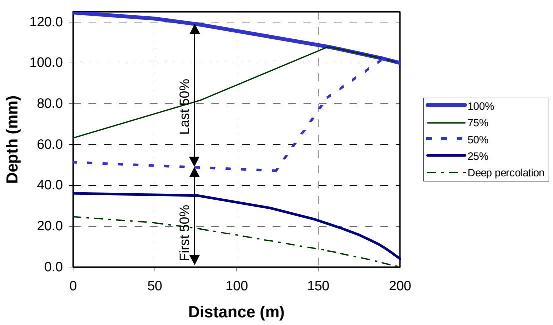

Figure 6. *Cumulative infiltrated depth with distance, as contributed by the first 25%, 50%, 75%, and 100% of the applied water, and deep percolation with distance for a level basin irrigation system (preliminary simulation data -- unpublished).*

Burt et al. (1995) provide a few general guidelines for fertigation in furrow and border-strip systems with tailwater runoff. One suggestion was to inject the fertilizer at a constant rate during the entire irrigation event. This recommendation assumes that the N-laden tailwater runoff will be blended with other water and reused in another field. Preliminary modeling studies have indicated that the timing and duration of fertigation applications during a surface-irrigation event play a critical role in determining the distribution of fertilizer in the field and the potential for nitrate movement to the groundwater (Watts et al., 1993; Playan and Faci, 1997). Deeper leaching of nitrogen can occur when using fertigation because the nitrogen, as NO_3, is already dissolved and moves with the water more readily than soil-applied fertilizer (Jaynes et al., 1992). The most effective fertigation practice appears to be strongly tied to the specific field conditions for the irrigation system, as demonstrated by the models of Playan and Faci (1997), Watts et al. (1993), and Boldt et al. (1994).

Santos et al. (1997), used simulation and field measurements to characterize nitrate movement under level-basin irrigation/fertigation. They established, for a particular sandy loam soil in Southern Portugal, that the transport and fate of NO_3-N was highly dependent on soil water movement, i.e., advection was governing the solute transport processes and dispersion was not important. If the irrigation uniformity is poor and if water freely flows off the end of the field, a large portion of the applied N can be either leached below the root zone in the areas with excessive infiltration or transported in solution with tailwater runoff.

The importance in adjusting the timing and duration of a fertigation application during the irrigation event is illustrated theoretically for a level basin irrigation system (Fig. 6). Three options were considered -- injecting the fertilizer during the first 50% of the irrigation, the last 50%, or over the entire duration of the irrigation. To illustrate the problem, the curves identifying the source of infiltrated water in the basin were generated by a very simple advection model with zero longitudinal mixing. Furthermore, it was assumed that all water which enters the soil first is displaced downward by subsequent infiltration (in fact, some of the early infiltration can remain bound to the soil particles near the surface, while later infiltration flows around it, downward, through the remaining pore space). Consequently, the model shows that any deep percolation must contain the first water infiltrated.

The figure shows a relatively uniform infiltrated depth distribution following an irrigation; but water which enters the field in the early part of the irrigation, if not infiltrated *en route*, is pushed to the end of the field by later inflow and disproportionately infiltrates into the far end of the basin. This example illustrates a situation (closed basin) 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 N 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 the first 50% of the irrigation water has infiltrated. Also, deep percolation N losses would be proportionately high, since all of the water in deep percolation is contributed by just 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). Quite different conclusions emerge with the same kind of simulation applied to sloping-border irrigation with tailwater runoff; in this case the smallest N losses are incurred with fertigation during the middle 50% of the irrigation. All of these conclusions are based on the aforementioned simple advection model, assuming, moreover, no spatial variability in soil properties; field verification is required.

We conducted a few fertigation experiments in level basins cropped to cotton, applying potassium bromide, a mobile tracer, during the whole 100%, the first 50%, and the last 50% of an irrigation event. The data have not yet been completely analyzed, but notable differences that appear in post-irrigation bromide distributions resulting from the different treatments suggest that significant progress can be made towards defining best fertigation management strategies in surface irrigation systems.

Results of CSREES-CRIS Search

A search of current and recent CRIS projects shows no research related to Objectives 1 and 2.

The sediment aspects of Objective 3 are addressed by research in ARS laboratories in West Lafayette, Indiana, (Implementation of Water Erosion Prediction Project, with L.D. Norton and D.C. Flanagan), Oxford, Mississippi (Evaluation of soil erosion and sediment transport processes on support of the DEC project with M.J. Romkens and C.V. Alonso), as well as Kimberly ID, with D.L. Bjorneberg and others. Nutrient constituents of irrigation water are addressed at Utah State University, Logan (Chemical application strategies for surface irrigation systems, with W.R. Walker and G.P. Merkley), and Univ Nebraska, Lincoln (Agrichemical control in irrigation runoff water from surface irrigated fields, with C.D. Yonts, R.G. Wilson).

Objective 4 is supported by three active non-ARS projects, two at Yuma AZ and one at Logan UT that are conducting research on fertigation in surface irrigation systems and one project completed in 1997 at Lincoln NE. We currently cooperate with the projects at Yuma AZ. In addition to the above fertigation projects, we also found two active CRIS projects and two inactive projects dealing with surface irrigation and nitrogen management. Our project is unique in that we are developing guidelines for injecting fertilizer into the water during operation of surface irrigation systems. This work will encompass a wide range of field conditions including a variety of soil types, irrigation inflows, and length of run and other aspects of irrigation system design.

APPROACH AND RESEARCH PROCEDURES

Objective 1 - Irrigation Software

Experimental Design

(a) Our current suite of stand-alone OS-based software products for one-dimensional surface-irrigation simulation (SRFR) and system design and management aids (BORDER, BASIN) will be reconfigured within a single shell, facilitating sharing of information. Bautista, Adamsen and Strelkoff will investigate alternative software development platforms on which to build this new software. Initial development will be Microsoft Windows but maximum portability to new PC operating systems is intended as these develop. Any such software needs to be object oriented. Appropriate ways will be sought for dealing with FORTRAN legacy code comprising the simulation and (interpolation-based) design engines. In addition, we will modify the SRFR simulation engine, as necessary, to allow it to interface with routines for erosion, sedimentation, and chemical transport. Whether the overall software shell development will be done in-house with current programmers or contracted out is yet to be determined.

In addition, Strelkoff and Clemmens will explore the possibility of linking the infiltration routines with a subsurface water and chemical transport model HYDRUS or UNSATCHEM (ARS, Riverside). This would allow use of soil physical data in determining infiltration rather than the current empirical approach. At a minimum, we will investigate SRFR’s current options for treating the effect of furrow wetted perimeter on infiltration by comparing them with the more fundamental approach afforded by the subsurface models which accept time-varying depths in a furrow as a boundary condition. A range of soil textures from sandy loam to clay loam will be used for several representative furrow shapes. Initially, these simulations will be run with a constant water level. Then, we will input varying water surface hydrographs that are representative of different surface irrigation conditions (e.g., different locations along the furrow, different flow rates, etc.). Field tests (Hunsaker, Adamsen) will be run at the Maricopa Agricultural Center to compare model and field results in conjunction with experiments described in Objective 3, below.

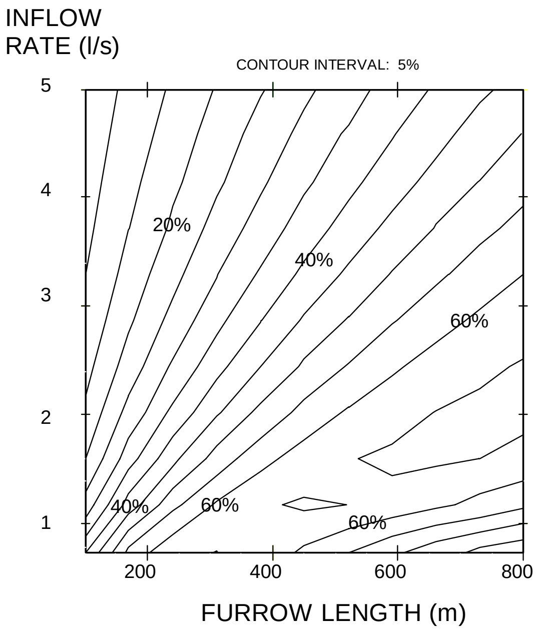

***Figure 7**. Potential Application Efficiency based on minimum depth equal to required depth (k = 30.1 mm/hr^a, a = 0.51, n = 0.05, W = 1 m, S_0 = 0.002, d_{req} = 80 mm)*

(b) Our current design software, based on a static database of previously run simulations, is limited in its range of applicability (even though expressing the results in non-dimensional form requires orders of magnitude less data). Simply extending this range would not be worthwhile because the designs would still be limited by the currently assumed border-strip geometry and two-parameter Kostiakov infiltration equation; and simulation and search procedures have not proven to be robust enough for novice users. So even with the ever increasing speed of personal computers, they still do not provide an adequate design approach. We recently developed a new approach that combines a very simple design approach with a limited number of simulations (Clemmens et al, 1998). This new approach mimics the approach in BORDER, where the performance parameters such as application efficiency are displayed as contours on a two-dimensional graph of two unknown design parameters (e.g., flow rate and field length). Under this approach, a single simulation is run at what we call an anchor point. The simulation results are used to tune the parameters of a simple design procedure which uses continuity, an assumed surface shape factor and a simplified recession relationship (Clemmens et al. 1998). This simplified design approach, with the tuned parameters, is used to calculate the performance parameters of interest (e.g., potential application efficiency) on a grid within the two-dimensional graph – through which the performance contours are drawn. An example is shown in Fig. 7 for furrow irrigation. The accuracy of the results varies with distance from the anchor point. Simulation at another point (perhaps as many as four) will be used to judge the accuracy of extrapolation or to allow interpolation. Further studies will determine the range over which extrapolation is acceptable. Within the software (Clemmens, Strelkoff, Bautista), the user will be able to execute a simulation at any point on the grid to determine the actual conditions there and note how far they deviate from the design solution presented. This new approach should be more robust than simulation-based search procedures and more accurate than the simplified design approach without tuning. It also has the advantage of allowing a wide variety of infiltration and roughness functions in addition to the full range of possible conditions for other input variables.

(c) A difficulty with the current software is selecting appropriate values for field infiltration and roughness coefficients needed as input to both simulation and design programs. A new software component for the SRFR suite will be generated to help users estimate these parameters from measured irrigation data (Bautista, Strelkoff, and Clemmens). It will be geared toward handling spatial and temporal variability. In addition, the measured irrigation data will be used, to the extent possible, to provide an evaluation of the irrigation event (e.g., application efficiency, distribution uniformity) based both on the measured data and on simulation with the estimated parameters.

The difficulty in developing such software comes from the variation in the type and amount of field data available. With research-level data, such parameters can be determined with good accuracy. However, typical surface irrigation evaluations by NRCS, mobile field labs, etc. provide a limited amount of data. Then assumptions have to be made, making the results potentially less accurate. Inaccurate parameter estimates can lead to inaccurate recommendations from the simulation and design programs. The proposed software will include routines for making parameter estimates that use the best available method (or methods) for the available data -- ranging from a minimum of data (inflow rate and advance times) to comprehensive research data (e.g., including water surface hydrographs). We have grouped the methods into four main categories, shown below. We are being assisted in evaluating these methods by the ASCE Task Committee on Soil and Crop Hydraulic Properties (chaired by Strelkoff). This group plans to publish guidelines for selection of methods based on the data-collection requirements of each method and on the expected accuracy.

Methods that measure only advance: • Shepard et al, 1993 (one-point method) • Elliott and Walker, 1982; Smerdon et al, 1988 (two-point method) • Clemmens, 1991 (direct inversion of ZI solution) • Walker and Busman, 1990 (simplex method minimizes differences between measured and simulated advance) • Bautista and Wallender, 1993 (Marquardt method minimizes differences between measured and simulated advance) • Clemmens and Keats, 1992; Clemmens, 1992 (Baysian estimation)	**Methods that measure advance, recession and enough water depths, y(x,t), to estimate the volume of surface water, $V_y(t)$ (volume-balance methods):** • Finkel and Nir (unstable); Maheshwari et al, 1988 (stable) • Gilley, 1968 (underestimates k, a for a complete irrigation) • Roth et al, 1974 (Fangmeier's method); Fangmeier and Ramsey (1978) • Strelkoff et al, 1999 (EVALUE, interactive selection of infiltration parameters; roughness follows)
Methods that measure advance and/or recession: • Clemmens, 1981 • Scaloppi et al, 1995 • Monserrat and Baragan, 1998	**Methods that measure advance and some water depths:** • Katopodes et al. 1990 • Valiantzas, 1994 • Playan and Garcia-Navarro, 1997 • Yost and Katopodes, 1998

Contingencies

The difficulty in filling vacancies for computer programmers is currently a significant problem. Student programmers often do not have the training and experience needed. We are considering contracting out portions of the software development as a necessity, although that can lack the desirable characteristics of long-term association with the project and retention of control by the scientists. If HYDRUS or UNSATCHEM is unable to adequately model soil infiltration or we are unable to link it with SRFR, we will explore other models. If simulation at a single point is not adequate for our design method, we will use more simulations to avoid extrapolation. There are such a wide variety of parameter estimation techniques available that we should be able to find appropriate methods for our software.

Collaborations

Necessary (within ARS) – Don Suarez, Rien van Genuchten, U.S. Salinity Laboratory on USSL soil water/chemistry flow models. Necessary (external to ARS) – Tom Spofford, National Water and Climate Center, NRCS, on relevance of research to NRCS field offices.

Objective 2 - Surface-Drained Level Basins

Experimental Design

Adoption of level basins with surface drainage by farmers is well ahead of our ability to provide design and operating recommendations. We have added the ability to remove applied irrigation water by surface drainage to the one-dimensional SRFR simulation software (Strelkoff et al 1998). A few field studies also have been conducted to provide preliminary data about the drain-back level basin systems, as used in the southwestern U.S. (Arizona, Colorado, Utah). Figure 8 shows a preliminary comparison between simulated and measured hydrographs with drainback for 2.5 ha flat-planted level basin (i.e., no furrows). Evaluation procedures followed the methods of Merriam and Keller (1978). In this example, the gross application depth (volume over field area) was 112 mm, while a volume representing 57 mm over the field surface drained off -- slightly more than half! While the fit of the data in Fig. 8 is good, the difference between the measured and simulated hydrographs represents 13 mm of applied water; 52 mm and 65 mm, respectively, remained on the field as measured and as modeled. We observed channeling of the flow that drained off the field surface, allowing more water

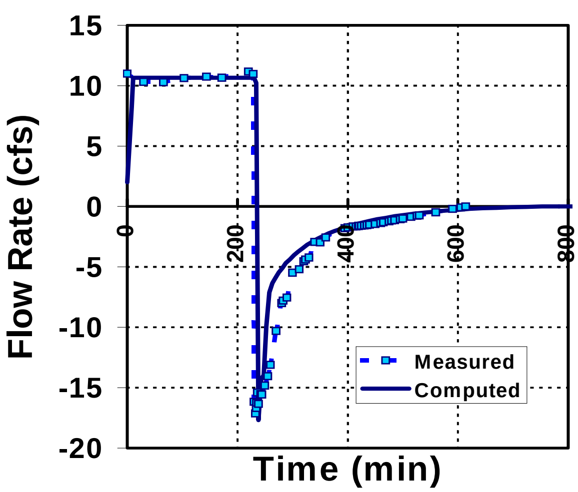

Figure 8. *Measured and computed flow rate into and out of a 2.5 ha level basin with drainback. Eloy, AZ 9/3/98*

to drain off than if flow had remained one-dimensional. Prior research had all been done under furrow irrigation, in which undulations in the furrow bottom elevation can be expected to reduce the predicted surface drainage (Dedrick and Clemmens 1988). We intend to conduct additional field studies on these drain-back level basins to further test our one-dimensional model and to determine its limitations.

Extensive field testing conducted in the late 1980s on drainage from irrigated furrows will be used to test the SRFR model routines for drainback (Clemmens, Strelkoff). Several dozen test furrows were run on two different soil textures; however, this preceded the addition of the drainback routines in SRFR (Strelkoff 1990). If necessary, we will conduct addition field tests on drain-back level basins with furrows (Hunsaker). We have half a dozen potential cooperators and will contact them as the need arises.

Once validated, we will conduct studies with the SRFR model to develop recommendations for (1) design and (2) operations. Initial design recommendations will be based on comparison to designs based on level basins without drainback according to the BASIN software. In particular, we will try to determine how to adjust the input to BASIN to give reasonable recommendations for drainback design, for example, increasing the depth of application entered as design input, since some fraction will drain off. Second, we will examine current operating criteria on when to cut off the water and start drainback or whether to hold water on the basin by allowing only partial drainback for a period of time (i.e, by holding a constant water level in the ditch and letting the inflow pass through to the next basin).

Clearly, even with the drain-back level basins, there is a need to model the two-dimensional nature of the flow to capture the influence of an undulating surface topography on drainage. With the grid of surface drainage channels (spin ditches) used in Louisiana, a two dimensional model is essential for modeling not only the irrigation and its drainage but also the drainage following significant rainfall events. Bautista and Clemmens will conduct field tests of irrigation events on these systems in Louisiana, both to evaluate their performance and to provide field data. Such evaluation will require more extensive data on field and water surface elevations than more traditional irrigation evaluations (Clemmens et al, 2001). In order to model this phenomenon (Strelkoff, Clemmens, Bautista), we will start with our existing two-dimensional model (Strelkoff et al, 2001) and assume that these spin ditches are one cell wide and just give them a lower elevation. This either creates a huge number of uniformly sized cells, or requires us to modify our computational routines to allow a non-uniform grid spacing. Another alternative is to model the spin ditches as a one-dimensional grid with side inflow and outflow. If these methods don't produce useful results, we will consider other models such as developed by Playan (1994) or Khanna (2000). Two-dimensional river flooding models are not adequate since they do not handle advance on a dry-bed, and they ignore flow over and through surface depressions because of computational difficulties (personal communication, Gary Feeman, West Consultants, Inc.).

Once a validated two-dimensional model is developed, Bautista and Clemmens will use it initially to assist farmers with proposed designs. They will conduct studies to provide preliminary design guidance, for example, spin-ditch spacing. For Louisiana and other areas in the humid South, this may be constrained more by the requirement for draining off rainfall than by irrigation concerns. We plan to observe these basins during rainfall events to determine how long it takes for them to drain. The nature of the microtopography is expected to have a significant effect on drainage and thus on the modeling. Understanding the limits of this technology is important for avoiding failures that would slow adoption.

To date, information on the economic advantages of level basins, drainback level basins (Arizona) and grid-drained level basins (Louisiana) is all anecdotal (e.g., Clemmens 2000). Results in Arizona generally suggest conversion to level basins is economical only if water costs are high or yields increase by at least 10%. Such yield increases have been reported in several studies (Bathurst 1988, Galusha 1986). Conversions to drainback level basins are less expensive and have shown payback in one to two years. In Louisiana, yield increases of 20 to 40% have been reported over traditional furrow irrigation perhaps due to land leveling. Data on the systems in Louisiana have been insufficient either to determine the cause of the yield changes or to conduct an economic analysis of the new systems. Bautista will collect sufficient information on the costs and benefits of systems which have been converted so that an economic analysis can be performed. Interviews with growers and irrigators will ensure that the recommendations are compatible with farming practice and will be viewed as leading to effective, safe approaches to farm profitability and sustainability. As these studies unfold, we will contact appropriate extension personnel in Louisiana and neighboring states to assist us in the analyses. We also plan to establish links with the ARS station in Stoneville, Mississippi, which is currently hiring an irrigation engineer.

Contingencies

Development of a useful two-dimensional model could fail due to scale problems (i.e., 0.2 *m*-wide drainage channel versus a 50 *m*-wide field surface). In this case we may explore a multiple furrow model partially developed but on hold. Field evaluations rely on farm cooperators. We have several in Arizona and Louisiana and can find alternates if current cooperation does not continue.

Collaborations

Necessary (ARS) – New hire irrigation engineer, Stoneville MS.
Necessary (external) – Farm owner, manager of test fields; Tom Spofford, NWCC, Mike Sullivan, NRCS National Water Management Center, Little Rock AR on local needs and practical applications; distribution and training.

Objective 3 - Fate and transport of sediment, phosphorus, and nitrogen

Experimental Design:

MODELING

Erosion: Strelkoff will expand the current single particle-size erosion component of our surface irrigation simulation model (SRFR) to accommodate mixes of particle sizes, in the furrow bed and in the flow. These are not the same, with the mix in the flow typically finer than the mix in the bed (hence, phosphorus enrichment in the irrigation tailwater). The mix of particle sizes in the furrow bed will be measured with relatively coarse subdivisions, either three (% sand, silt, and clay) or five, in which fine sands and fine silts are separated out, depending on measurement capabilities of a cooperating project at Kimberly, ID (discussed below, under the *Field Studies* subheading). With mean, standard deviation, and skew of the distributions measured, we can replace the coarse subdivisions by a continuous distribution with the same characteristics to enter into the model. We plan to apply the Borah et al (1982) concept of selective entrainment to each location along a furrow bed of assumed well-mixed particles: the smallest go first, and then larger, and so on, until the transport capacity at that section is filled. The largest particles may well stay behind, shielding smaller ones beneath from detachment. We will apportion the total transport capacity amongst the entrained size fractions in accord with Wu and Meyer (1989). Here, the fraction of total transport capacity allocated to a particular particle size in the mixture is governed by a weighting factor, namely, the transport capacity for a homogeneous soil composed of the given size, relative to the sum of such transport capacities for all the fractions carried by the flow. When transport capacity for any size is exceeded, the deposition rate will be based on the pertinent fall velocities, using the Rubey formula (Simons and Senturk, 1992). From these processes, the sediment loads and concentrations at selected points along the furrow will be output, as tables and graphs, as will the profiles of erosion and depositions along the furrow length. This output can be used to judge the relative merits of one design or management procedure over another.

Phosphorus: Strelkoff and Clemmens will add a component to SRFR to simulate fate and transport of phosphorous (P). P transport is primarily through sorption to soil surfaces with more sorption per unit mass of soil on smaller soil particles. Thus the planned full particle size-distribution erosion component in SRFR is essential. In addition, P desorbs from the soil and can be transported in the liquid phase. Initial studies of this desorption process will be used to develop relationships for modeling the advection and dispersion of ortho-P in the flowing water. Batch studies from a cooperating project at Kimberly ID (*Field Studies* subheading, below) will be used to develop desorption relationships. We plan to fit a first-order reaction formula to the measured data in which the rate of desorption is dependent upon the difference in concentrations, replacing Sharpley’s et al (1981a,b) power law for cumulative desorption with time. This desorption *rate* is required in the simulation algorithm.

When the soil is eroded from the soil surface, we will assume P in equilibrium between the solid and liquid phases, i.e. an equilibrium version of Ashraf and Borah (1992). We will evaluate the suitability of this approach relative to that used for P desorption from the surface so that they are compatible. If necessary we will implement fully non-linear or time-dependent desorption of P from the entrained sediment. Furthermore, the transport in the irrigation stream of dissolved and adsorbed P will be assumed by advection alone in a kinematic wave-like formulation. Longitudinal dispersion arising from the interplay of vertical turbulent diffusion and the mean-velocity distribution in the vertical will be ignored, in keeping with standard practice in modeling sediment transport. To ensure as little numerical dispersion as possible, numerical solution of the advection equations will be undertaken by the piecewise method of characteristics on SRFR’s rectangular net in the x-t plane with cubic-spline interpolation along the known time line (Komatsu et al, 1997). This maintains compatibility with the SRFR grid used for surface hydraulics and avoids dissipative effects that are strictly numerical stemming from use of a rectangular grid as commonly used for kinematic-wave solutions.

The suitability of the above modeling approach will be evaluated with data from the field studies conducted by a cooperating project at Kimberly ID (*Field Studies* subheading below).

The simulations will lead to SRFR output tables and graphs of concentrations and total P-load hydrographs at selected points along the irrigation furrow, in particular the loading in the tailwater. This output is designed to help guide development of design and management practices that take total P loading into account.

Nitrogen: Nitrogen (N) transport will be added to SRFR after sediment and P transport have been verified (Strelkoff, Adamsen, Clemmens). In this case, the N is applied in the irrigation water (fertigation). Initially, N will be considered completely nonreactive with the soil and move only with the water flow. Complete transverse mixing in the irrigation stream will be assumed while longitudinal advection and dispersion will be modeled. Dispersion coefficients will initially be based on values from the literature. We will investigate ARS software (HYDRUS and UNSATCHEM) developed at other locations for modeling the subsurface transport and fate in response to the concentration and water-depth histories at the surface. Field studies of N fertigation practices, described below, will be carried out to develop an understanding of various practices on the fate of applied N under different application regimes and different surface irrigation systems. These studies will provide both a basis for preliminary recommendation and data for model validation. Specifics of the modeling approach will depend on results from the P modeling described above.

FIELD STUDIES

Erosion, Phosphorus: Field measurements of irrigation water flows and sediment and phosphorus concentrations, as well as laboratory batch studies of P/soil/water reactions, will be undertaken by our cooperating institution, ARS, Kimberly, ID., under (old) CRIS Project Numbers, 5368-13000-004-00D (Irrigation Management to Reduce Erosion and Improve Water Use Efficiency) and 5368-12130-007-00D (Water Quality Protection in Irrigated Cropping Practices and Systems).

Nitrogen: A series of field experiments will be conducted by Hunsaker and Adamsen to determine the distribution and potential leaching of nitrogen applied in the irrigation water. Initially, these experiments will be conducted at each of 10 proposed field sites as listed in Table 1, which represent several types of surface irrigation systems and a range of soil types. Each fertigation experiment will include four treatments and three replications for a total of 12 field plots per site. Plots will be at least 6.5 m wide and as long as the length of run of the field. The four fertigation treatments proposed are (1) fertilizer injection over 100% of the irrigation, (2) just the first half, (3) just the middle half, and (4) just the last half of the irrigation.

Table 1. Proposed field sites for fertilizer application studies.

System type	Soil types	Location	Crop
Level basin, unfurrowed	sandy loam	Maricopa, AZ	wheat
	clay loam	Maricopa, AZ	wheat
Level basin, furrowed	sandy loam	Maricopa, AZ	cotton
	clay loam	Maricopa, AZ	cotton
Sloping border without runoff, run less than 275 m	sandy loam	Coachella Valley, CA	small grain
Sloping border without runoff, run greater than 360 m	sandy loam	Coachella Valley, CA	small grain
Sloping border with runoff	silt loam	Coachella Valley, CA	small grain
	cracking clay	Imperial Valley, CA	small grain
Sloping furrows with runoff	sandy loam	Casa Grande, AZ	cotton
	silt loam	Coachella Valley, CA	corn

Preliminary data will be collected at each site to determine field conditions – field geometry, infiltration and roughness, and soil texture. SRFR will be used to determine the application time and flow rate needed for the border width used to achieve the best water application uniformity. These will be used for each irrigation event at the site and adjusted as needed for specific conditions at the time of irrigation.

During experiments, nitrogen fertigation will be simulated by injecting potassium or calcium bromide into the irrigation water stream. Bromide was selected because it simulates nitrate well and is present in low concentrations in the environment, making it detectable as a tracer. In addition, bromide is conserved biologically so that a mass balance can be calculated. While the most common form of fertilizer used for injection is urea ammonium nitrate solution, it is the nitrate dissolved in the irrigation water that poses the greatest immediate threat to the environment.

Prior to each simulated fertigation event, soil samples will be taken from the field. Samples will be taken in the non-cropped turn around area at the head of the field if one exists, at the beginning of the cropped area, and then at five evenly spaced locations between the top of the field and the end of the run, resulting in a maximum of seven sample locations in each plot. When the experimental site is furrowed, a sample will be taken from two adjacent beds and from a wheel and non-wheel furrow bottom at each sampling location. When the site is flat, unfurrowed, two samples will be taken from an area not affected by wheel compaction and two samples from wheel tracks at each sampling location. Soil samples will be taken to a depth of 1.2 m and divided into 5 depths, 0 to 0.15, 0.15 to 0.30, 0.30 to 0.60, 0.60 to 0.90 and 0.90 to 1.2 m. A complimentary set of samples will be taken as soon after the irrigation event as possible. Plant samples also will be taken after the irrigation for analysis of bromine. This data should amply show the spatial variability of fertilizer distribution.

Basic irrigation performance data also will be collected for each event (Merriam and Keller 1978). In addition, water depths will be measured directly with rulers placed in the field at selected locations.

Water samples will be taken every 15 minutes from the input water stream below the injection point and when runoff occurs from the runoff stream.

Soil samples will be analyzed for bromide and gravimetric water content and nitrate. Samples will be kept in a field-moist condition from sampling until gravimetric water content measurements can be made. During transport from the field to the laboratory, samples will be stored on ice to prevent nitrification. Sub-samples will be taken for soil moisture contents. Nitrate and bromide will be extracted from the samples with a 1:1 weight to volume water extraction. Plants will be analyzed for bromine after acid digestion of the plant material. Nitrate determinations of soil extracts and water samples will be made with an autoanalyzer using cadmium reduction (Adamsen et al., 1985) and bromide determinations on soil extracts, water samples, and plant digestions will be made with an autoanalyzer using a fluorescein dye method (Marti and Arozarena, 1981).

Distribution of bromide will be compared to the infiltrated water depth distribution from each fraction of the irrigation to determine the degree of mixing that occurred between fractions and the degree of variability that exists. The estimates of mixing between fractions will be used to help validate the N fate and transport component for SRFR, proposed above. Additional field studies will be conducted as needed to validate this aspect of the model.

Contingencies

In the event the proposed computational algorithms fail to yield satisfactory predictions, the program of field and laboratory measurements of sediment movement and chemical exchanges will provide an empirical basis for alternate algorithms. The proposed project does not deal with the movement of water and chemicals below the soil surface, and the results could be limited by not properly modeling this aspect. However, other scientists, both within and outside ARS, have such capabilities (e.g., as noted at ARS Riverside) that can be used to significantly enhance this project. Field heterogeneity and preferential flow can often cause significant differences in infiltration rates during irrigation, which may produce misleading results of bromide distributions and irrigation uniformity during some of our experiments. Results may be inconclusive due to excessive heterogeneity.

Collaborations

Necessary (within ARS) – Dale Westermann and David Bjorneberg (ARS Kimberly) to collect sediment samples in the field and analyze for physical and chemical-exchange properties. Don Suarez and Rien van Genuchten (ARS Riverside) on modeling water and chemical movement below the soil surface. Necessary (external to ARS) – T. Spofford, NWCC (NRCS).

Objective 4 - Guidelines for water and fertilizer application

Experimental Design

Hypothesis: Timing and duration of fertilizer injection during surface irrigation events affects the fate and uniformity of nitrogen fertilizer. The appropriate timing and duration of fertilizer injection is affected in predictable ways by many factors including irrigation system design, infiltration rates which are in turn affected by soil type, tillage, frequency of irrigations, and sealing of the soil surface as a result of previous irrigations. The investigations will be performed primarily by Hunsaker, Adamsen, and Clemmens.

The results of the field experiments should provide an estimate of the uniformity of fertilizer applications in surface irrigation system when the fertilizer is added to the irrigation water during different periods of the irrigation. The experimental design encompasses a range of soil types and common designs of surface irrigation systems. The preliminary data set will be robust enough to provide basic guidance to farm managers and consultants for BMPs for fertigation with surface irrigation systems. These guidelines will be disseminated to Cooperative Extension and NRCS field offices as they become available as well as published in refereed scientific journal articles.

The simulation model will be used to conduct a more systematic study of the preliminary recommendation developed from the field studies. This will allow us to examine tradeoffs in the design and operation of surface irrigation systems, including chemigation, and to develop recommendations, taking into account prevalent farmer attitudes and practices. The scope of these studies depends on the results of the field studies and the capabilities of the simulation model to reproduce those results.

Contingencies

The development of comprehensive fertigation recommendations relies on our being able to model the movement of nitrogen under surface irrigation. Recommendations can be made without this, but will be less generally applicable.

Collaborations

Necessary (within ARS) – None. Necessary (external to ARS) – T. Spofford, NRCS.

NATIONAL COLLABORATION

All four NP201 Water Quality and Management Policy Initiatives are supported by this research. USWCL's contribution to the Initiatives on TMDL Monitoring and Research and Coastal Water Quality Protection relates to the edge of field and other offsite contributions of surface irrigation to sediment, phosphorus, and nitrogen in the watershed (Problem Areas 2.6, 3.1, 3.4, 3.7). The initiative on Drought and Water Scarcity is addressed in connection with Problem Area 2.3. The Water Resources Models, Decision Support Tools and Information Databases National Initiative, is supported by USWCL's development of surface irrigation software. ARS laboratories outside Phoenix address these initiatives primarily at the watershed scale and in connection with irrigation sprinkling and microirrigation systems. Deliverables stemming primarily from the Phoenix location are validated models, software assisting in design and management of surface irrigation systems, and recommendations on water and nutrient applications in surface irrigation, as detailed in the above sections. Collaborative efforts are currently ongoing with Spofford, NRCS Water and Climate Center, Portland OR to ensure the relevance of our program to NRCS field applications, and with Westermann and Bjorneberg, ARS Kimberly ID on soil erosion and P transport under surface irrigation. We anticipate expanded cooperation with Suarez and van Genuchten, ARS Riverside CA on modeling water and nitrogen movement in soils under surface irrigation. We hope to establish cooperative relationships regarding level basins in humid areas with the irrigation engineer to be hired at ARS Stoneville MS to complement those established with Sullivan and Carman at the NRCS National Water Management Center in Little Rock AR.

PHYSICAL AND HUMAN RESOURCES

The USWCL has full time staff and laboratory facilities to conduct a wide variety of agricultural research. In addition to high speed LAN and Internet connections, the Lab's PCs are well-equipped with current word-processing, spreadsheet, graphics, presentations, and development software. A soils laboratory is available to conduct, e.g., soil particle size analysis. Soil samplers, neutron scattering, and TDR equipment is available for field analyses. An analytic chemistry lab is available for analyses of water and soil samples. An electronics shop, staffed with an electronics engineer, is available for development and repair of electronic instruments as needed. The Maricopa Agricultural Center, The University of Arizona, is available for nitrogen field work. Field and laboratory batch studies on phosphorus will be conducted by a collaborating facility, the ARS NWISRL, at Kimberly ID.

In addition to the named category I scientists, three Physical Science Technicians (2.8 FTE), a temporary Computer Specialist and Computer Assistant will be employed in this research. In addition, a temporary category II (Post-Doctoral Research Scientist, 1.0 FTE, GS-12 term appointment) position is in the process of being filled. Though the position is funded extramurally, much of the incumbent's responsibilities will lie within the purview of this project.

MILESTONES AND EXPECTED OUTCOMES

Expected outcomes include an extended surface-irrigation-simulation model (SRFR) with fate and transport of water, sediment, phosphorus, and nitrogen in the irrigation stream. The simulation model is to be part of an integrated user-friendly suite, SRFRSuite, including design/management aids and field-evaluation components. We expect to publish guidelines for the design and management of surface-drained level basins and for fertigation management in surface irrigation.

Milestone Timeline

Research Component	End of year 1	End of year 2	End of year 3	End of year 4	End of year 5
SRFR Suite: hydraulics	Select platform languages	Complete field-evaluation component	Complete furrow-design component		Complete SRFR Suite
Surface-drained level basins		Complete field studies of GSDLB (grid-supplied & drained level basins)	Guidelines for DBLB (drainback level basins)	Complete modeling of GSDLB	Guidelines for design and management of GSDLB
SRFR constituent simulation	Complete sediment transport component	Complete phosphorus fate and transport	Validate and calibrate sediment and phosphorus models	Complete N transport in the irrigation stream Couple to soil-water/chemistry model	Validate and calibrate nitrogen model
Nitrogen fertigation management		Field studies of nitrogen uniformity and efficiency completed	Preliminary guidelines on fertigation with surface irrigation issued		Final guidelines on N fertigation with surface irrigation

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