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

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: Refer to 200 Annual Report

APPROACH AND RESEARCH PROCEDURES: Refer to 2002 Annual Report

PHYSICAL AND HUMAN RESOURCES: Refer to 2002 Annual Report

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

PROGRESS:

IRRIGATION SYSTEM EVALUATION

The fiber-optic advance and opportunity time sensor, developed in prior years has been upgraded with a sensor to turn off the display to save battery life. We have also discussed commercialization of this device with a CRADA partner. In addition, we have extended this concept of detecting the presence of water to produce a digital depth sensor. A prototype has been constructed for testing in the lab. We are in the process of producing a field prototype version that we can test in the field. The CRADA partner has expressed more interest in this device and may cooperate with us on setting this device up for field testing. Durability and ease of construction are the factors that might limit commercialization and thus will be the focus of the field tests.

FERTIGATION

Efficient injection of fertilizer into irrigation water in surface systems depends on predicting post-irrigation chemical distribution. Fertigation experiments were conducted in the Coachella Valley Irrigation District in California. Testing of samples from FY02 are complete and data analysis begun. Analyses of water and soil samples from FY03 are under way. Data from FY02 show that application uniformity of the water was 0.7 to 0.8. Application uniformity of bromide tracer ranged from 0.15 to 0.6. Injection over the entire irrigation gave the best application uniformity. Timing refinements are needed to improve performance.

MODELING SOIL MOISTURE AND CHEMICAL TRANSPORT WITH SURFACE IRRIGATION

Predicting chemical transport under surface irrigation requires linking soil-water flow, chemistry, and surface-flow models. A first step in linking the soil moisture and chemistry model, HYDRUS (ARS, Riverside, CA), to SRFR (ARS, Phoenix, AZ) was made by using a time dependent hydraulic head from a border strip water-depth hydrograph calculated by SRFR for input to HYDRUS. It proved necessary to modify HYDRUS to account for the cutoff of water supply to the soil as the surface water recedes, while allowing access of soil pores to the atmosphere as moisture is redistributed in the soil following recession.

MODELING UNSTEADY INFILTRATION FROM FURROWS

A simple and fast alternative to formally linking soil-moisture models (HYDRUS) with furrow-hydraulics models (SRFR) is an algorithm in SRFR designed to approximate infiltration with a variable wetted perimeter. HYDRUS-2D was used to simulate furrow infiltration at various wetted perimeters and furrow spacings through accurate solution of the Richards equation for unsaturated flow in a homogeneous, isotropic soil medium. The results were compared with the SRFR algorithm and also a well known NRCS approximation. In the limited range of cases tested, the SRFR algorithm was found to consistently underpredict infiltration, while the NRCS formula consistently overpredicted it.

MODELING SOIL EROSION AND PHOSPHORUS TRANSPORT

Coding the sediment transport module in SRFR continues. The anomalous negative transport capacities calculated for very small particles by the Laursen formula have been eliminated by the correction of an inconsistency in its derivation, but, still, the calculated transport capacities are suspiciously low. The problem of extrapolation beyond the range of empirical data remains. The hope is that there is sufficient physical basis for the formula to allow limited extrapolation. Experimental corroboration with the field studies at ARS, Kimberly, ID, will either confirm or condemn this approach.

MEASURING SOIL EROSION AND PHOSPHORUS TRANSPORT

Laboratory tests at ARS, Kimberly, ID, cooperating with USWCL, showed phosphorus (P) quickly released from suspended sediment to the water. Field tests showed most sediment was transported as small aggregates (<0.05 mm for a silt loam soil); the P concentrations associated with each sediment size were similar. Diffusion of phosphorus, P, from furrow soil did not appear to be the main mechanism adding dissolved P to furrow flow. Desorption of P from transported sediment seems to contribute the largest portion of dissolved P to furrow water. Most of the P in the tailwater is associated with sediment which may or may not settle out, but any P dissolved in the water typically remains with the tailwater, to flow to the receiving river.

PHOSPHORUS DESORPTION IN SURFACE IRRIGATION

Two sets of experiments have been performed in a flume with various water depths and velocities over a phosphorus-enriched soil surface and with neither infiltration nor erosion. Analysis of the differing entrainment results in the two sets is under way, with the difference in ambient temperatures (summer and late fall) as a likely cause. Infiltration, controlled by a porous drain at constant negative pressure, will be studied next. Partially complete design for the drain is based on simulations of soil moisture flow from the bulk water on the soil surface to the bulk water in the porous pipe, via solution of the Richards equation (HYDRUS-2D, ARS, Riverside, CA).

GRID-SUPPLIED AND DRAINED LEVEL BASINS

A study was initiated in collaboration with Louisiana State University to develop design and management recommendations for grid supplied and drained level basin systems. Such systems are being adopted in Louisiana and Arkansas, even though they are not sanctioned in state NRCS guidelines, due to concern over drainage of excess rainfall. Data is being collected on a farm on which many traditional graded furrow systems have been converted to level basins. Such data will help document claims made by the farmers about the production and cost advantages of level basins as compared to graded furrows.

SURFACE IRRIGATION PARAMETER ESTIMATION SOFTWARE (SIPES)

We have continued the development of software for estimation of surface irrigation field parameters. The software will assist action agencies, such as NRCS, with their parameter-estimation needs and will provide a vehicle for comparing alternative methods. Progress has been made in the development of screens and data-file structures needed to capture the inputs required by the various methods. Only simple volume-balance methods have been programmed so far, and initial studies have been conducted to contrast the effectiveness of those methods and to assess their limitations.

ERRORS INHERENT IN SIMPLIFIED INFILTRATION-PARAMETER ESTIMATION METHODS

Simple methods for estimating infiltration in surface irrigation from measured stream parameters require estimates of average cross-sectional area of the surface water flows. A simulation study was conducted to determine the degree of error in estimated time to infiltrate a target depth as a consequence of errors in assumed average cross section or measured advance times. For soils well characterized by the Merriam and Clemmens Time Rated Infiltration Families, the errors generated in the corresponding One-Point method proved moderate and well behaved even for infiltration times well in excess of the advance time. And as expected, the larger the field slope, the smaller the error.

IMPLICATIONS OF UNCERTAIN FIELD PARAMETERS FOR BORDER IRRIGATION MANAGEMENT

A study was performed on the effect of variations in infiltration characteristics (relative to the values assumed in design) on border irrigation performance. The study is part of a broader effort aimed at developing design and management recommendations given uncertain design information. Current results suggest that border systems, if properly designed, have some tolerance for erroneous design information. However, compensating for the effect of such uncertainties requires an in-depth understanding of the hydraulic characteristics of the particular system.

MEASURING FURROW FLOW AND EROSION

In prior studies of furrow erosion, the flumes used to measure water flow in the furrow restricted flow, so that sediment deposited upstream from the flume. Placing the flume lower caused difficulties in getting downstream water and sediment samples, in addition to causing flume submergence: placing them higher resulted in deposition of sediment upstream. A new flume was designed for furrow erosion studies by engineers at the U.S. Water Conservation Lab, Phoenix, AZ and the Northwest Irrigation and Soils Research Lab, Kimberly, ID, such that changes in upstream depth and velocity are minimized throughout the range of flows. Prototypes were constructed with sheet steel and a commercial version was manufactured in fiberglass by a local manufacturer of flumes. Studies on the performance of these flumes is ongoing.

Alfalfa is a profitable crop for farmers throughout the U.S., widely used in dairy production and as feed for horses, but in arid and semiarid areas the water use by alfalfa is high. A study, aimed at improved water management was conducted in Arizona by the U.S. Water Conservation Laboratory (USWCL). Results show that irrigation water applications to alfalfa can be reduced by as much as 10% from the current irrigation scheduling-software-generated recommendations without significant loss of yield and resulting, also, in less contamination and irrigation water leached below the root zone. These results will be useful to producers, consultants, other researchers, and policy makers.

Natural Resources Conservation Service (NRCS) engineers applying USWCL border-irrigation design-aid software have occasionally been frustrated by hardwired limits on trial values of design variables, intended to steer inexperienced users away from potentially troublesome combinations of values. USWCL engineers have re-examined these limits and the penalties for selecting inappropriate values. A two-tiered system was introduced into the software allowing experienced designers to select their own limits on input variables, while guiding the less experienced toward Asafer@ values. The adjustments make application of the design aid software more attractive to action agencies and thus help to put more science into the design and management of surface irrigation systems aimed at increasing uniformity and efficiency.

Field evaluations of surface-irrigation performance depend upon measurements of advance and recession, which are often difficult to obtain under field conditions. USWCL engineers designed a remotely operated device for measuring when the water arrived (advance) and when it disappeared from the surface (recession), which would make it unnecessary to enter the wet field. Development has been completed on a new fiber-optic advance and opportunity time sensor with no moving parts. The device can be used by action agencies and state-funded mobile irrigation laboratories for irrigation evaluations and infiltration parameter estimates, with the ultimate goal of improving irrigation management in surface systems.

In general, in future years, increased coordination between the modeling and field studies is planned.

In FY2004 simulations of post-irrigation fertigation-chemical distributions will be extended to basins with no runoff, and compared with field results to discern the role of mixing or diffusion of the fractions, ignored in the present model. A new grower cooperator has allowed progress to accelerate. Analysis of samples from the field studies should be completed by the middle of FY04 and the data used to develop guidelines for producers to use when applying fertilizer in the irrigation water. The development of complete fertigation guidelines will require the addition of a dispersion term to the existing chemical transport model and completion of linkage to a subsurface flow model such as HYDRUS. These tasks will be the focus of the fertigation work in FY04 and FY05.

During FY2004, we plan to continue development of an inexpensive sensor for shallow water depths to provide additional data for estimating field values of infiltration and roughness. We plan to seek assistance from a CRADA partner to commercialize the product.

Calibration models, which account for the effects of soil salinity on the output of an inexpensive, time domain reflectometer (TDR) soil moisture sensor, will be developed by the end of FY2004, subject to time constraints. This will provide the capability of the sensor to measure more accurately soil water content in fields where high soil salinity decreases the reliability of TDR measurements.

During FY2004, programming for an integrated, true Windows version of the surface-irrigation software should be under way, with a conclusion in FY2006. Acquisition of additional IT staff, expected early FY2004, should keep this project on track in accord with the Project Plan.

The major part of the programming for the sediment fate and transport component of SRFR should be completed by the end of calendar 2003, with the phosphorus component following in FY2004; calibration and validation should be completed in FY2004-FY2005.

In FY2004, our cooperators at ARS, Kimberly will continue to analyze field and laboratory data to develop relationships for modeling transfer of phosphorus from sediment to flowing water.

Efforts will be continued during FY 2004 to equip the SRFR program with infiltration models more physically based than the purely empirical formulas now in use. Formal linkage with existing stand-alone software based on solutions of the Richards equations for soil moisture flow is expected in FY2005.

Development of SIPES is planned to occur in phases reflecting the different parameter-estimation methods, with periodic releases to cooperators during FY2004 and beyond. A newly developing cooperative agreement with Oregon State University may provide graduate-student help with programming the different phases. The approaches will be assessed and recommendations made also via informal collaborative agreements stemming from scientists' participation in the ASCE Task Committee on surface-irrigation parameter estimation, to which USWCL scientists contribute substantially. We expect to complete a comprehensive report on this work in 2005.

We will continue the theoretical studies on field-parameter uncertainty in design and management of level basins and borders through FY2004, with the objective of developing graphical tools that can be used for assessing the effect of uncertain infiltration inputs on irrigation performance. In FY2004 we will also expand the work to include furrow irrigation systems. Beginning in FY2004, we will pursue field studies in collaboration with NRCS to assess performance of actual NRCS surface irrigation designs and the contribution of field-wide and seasonal variation.

By the end of FY05, we expect to have sufficient field data on the performance of level basins in Louisiana and Arkansas to provide guidelines for grid-supplied and drained level basins. Field data collection efforts have been hampered by the distance to field sites (>1000 miles). We expect additional data to be collected during FY04 and FY05, with assistance from Louisiana State University, ARS Baton Rouge, and NRCS, Little Rock, AR. These data collections will provide support to efforts to document the performance of these irrigation/drainage systems and help to validate the mathematical models developed.

We expect to produce a mathematical model to describe irrigation and drainage from grid-supplied level basins by the end of FY06, in cooperation with Louisiana State University. We are currently investigating alternative formulations of the governing equations to deal with the complexity of the grid-supplied systems, which our current 1-dimensional models cannot describe and which cannot be adequately handled by our existing 2-dimensional formulations either.

By the end of FY04, we expect to complete the numerical analyses to provide some preliminary guidelines for drain-back level basins. These will be augmented with further analysis through use of the mathematical models under development by the end of FY06.

Conversations with cooperators suggest that farmers continue to convert from traditional graded (furrow and border) to level-basins (including drainback and grid-supplied-and-drained variations) in various parts of the country. Reasons expressed for this conversion include improved water management and reduced irrigation labor costs. Expansion of this technology in humid areas is hampered by local NRCS rules which do not support surface irrigation systems with zero-grade. Hence, farmers are converting their systems in the humid areas exclusively with their own financial resources.

Surface irrigation design and operating guidelines and tools have been transferred to a variety of clients through personal visits (e.g., NRCS, cooperative extension, experiment stations, state mobile irrigation labs), software used world wide (available on USWCL web pages -- with a link from the NRCS Water and Climate Center web page), and through technical presentations at irrigation meetings and conferences.

Publications:

Strelkoff, T.S., Bautista, E., Clemmens, A.J. Errors inherent in the simplified infiltration parameter estimation. Proceedings of 2nd Int. Conference on Irrig. & Drain. 2003. p. 735-745.

Tamimi, A.H., Clemmens, A.J., Bautista, E., Strelkoff, T.S. SIPES - Surface Irrigation Parameter Estimation Software. Proceedings of 2nd Int. Conference on Irrig. & Drain. 2003. p. 615-624.

Abbasi F., Adamsen, F.J., Hunsaker, D.J., Feyen, J., Shouse, P., van Genuchten, M.Th. Effects of flow depth on water flow and solute transport in furrow irrigation: Field data analysis. J. Irrig. and Drain. Engineerimg. 2003. v. 129. p. 237-246.2.

Zerihun, D., Sanchez, C.A., Farrell-Poe, K.L., Adamsen, F.J., Hunsaker, D.J. Performance indices for surface N fertigation. J. Irrig. and Drain. Engineering. 2003. v. 129. p. 173-183.

Bautista, E., Strelkoff, T.S., Clemmens, A.J. Border irrigation management implications of imprecise infiltration parameter estimates. Proceedings of 2nd Int. Conference on Irrig. and Drain. 2003. p. 603-614.

Perea, H., Strelkoff, T.S., Simunek, J., Bautista, E., Clemmens, A.J. Unsteady furrow infiltration in the light of the Richards equation. Proceedings of 2nd Int. Conference on Irrig. and Drain. 2003. p. 625-636.