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Appendix C

A Hydrologic Balance Approach to Saline Seep Remediation Design

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ABSTRACT. *Concern about saline seeps is increasing in the dryland production regions of Kansas and the North American Great Plains. To reclaim salt-affected seep areas, site hydrologic factors must be modified to reduce seep recharge. A simple method is needed to help design effective remediation treatments. A hydrologic balance model, POTYLDR (Potential Yield Model, Revised), was modified and used to estimate the water balance in a saline seep recharge area and to estimate the effectiveness of various acreages of alfalfa treatments in reducing seep recharge. This model uses readily available data, such as daily rainfall and temperature, NRCS runoff curve numbers, NRCS soil irrigation classes, Penman evapotranspiration parameters and Blaney-Criddle crop coefficients, to determine runoff, evapotranspiration, soil moisture, and percolation from the root zone. According to the assumed seep mechanism, deep percolation from the local recharge area was used to estimate seep recharge. Various percentages of the seep recharge area were shifted from the current wheat cropping to alfalfa to determine the reductions in total recharge and number of months contributing to recharge. A 50% reduction in total recharge required 14 to 32% alfalfa acreage*

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depending upon site-specific factors of five targeted fields. A given alfalfa acreage reduced total recharge volume more effectively than it reduced the number of months contributing to recharge. The major limitation in application of these results is selection of the percentage seepage reduction needed to provide seep control. The modeling approach provides an important indication of a system's responsiveness to changes in vegetation and quantifies this response in a way that is useful for designing bioremediation treatments that require control of seepage or shallow groundwater recharge. **Keywords.** *Bioremediation, Hydrologic balance, Modeling, Alfalfa, Wheat.*

Seeps are intermittent or continuous groundwater discharges fed from upslope recharge areas. After evaporation, transpiration, and runoff losses, excess rainfall percolates through the soil profile. If one layer in the soil profile has a lower or higher permeability than overlying layers, percolating water is transported downgradient on or as lateral flow within that layer. This local groundwater flow emerges downslope as a seep.

Saline seeps occur in response to three factors: hydrogeology, climate, and land management (Doering and Sandoval, 1976; Halvorson, 1988). Water dissolves salts as it percolates through the substrata and transports these salts to the surface via a seep. Over time the water evaporates while the transported salts accumulate until once-productive soils can no longer support crops. It is hypothesized that a common seep type in central Kansas is the slope-change seep with an adjacent, local-recharge area (Figure 1). For various reasons seeps often are tilled, planted, and managed with fertilizers and chemicals even though the salinity hinders or prevents crop production. The reduction in productivity also causes environmental problems from wind and water erosion in the salt-affected area due to the lack of vegetative cover.

Saline seeps range in size from a few square meters to 20 hectares. Once established, seep areas can grow at a rate of up to 10% a year, taking large areas out of production (Doering and Sandoval, 1976; Miller et al., 1981). Extrapolation from a 1968 survey indicated that seeps in the Dakotas, Wyoming, and Montana had removed 162,000 ha (400,000 acres) from production with over half occurring since 1960 (Doering and Sandoval, 1976). Within one county in north-central Oklahoma, 1,300 of 65,000 ha of wheatland were known to be affected by seeps, and the extent was estimated to be similar in south-central Kansas (Berg et al., 1991). Soil survey maps of south-central Kansas completed in the 1960's indicate 65,000 ha (160,000 acres) of soils mapped as saline/sodic are particularly susceptible to seep development. In the three decades since these maps were produced, saline seeps have grown visibly in these dryland crop-production areas.

Two general methods have been used to remediate seep areas (Halvorson, 1988). Subsurface drains installed upgradient from the seep can intercept the lateral water flow and reduce the salt loading to the seep area (Berg et al., 1987). Further adoption of this control practice is limited by the high initial cost and problems associated with locating an acceptable outlet for the drainage discharge.

Alternatively, vegetative remediation could be employed. For plants to be effective in removing pollutants from the environment, soil water must be managed appropriately. In the case of saline seeps, appropriate cropping systems can moderate or control water movement and encourage the removal of the salt pollutants by natural processes. Crops can use the water while it is a relatively nonsaline resource and before it percolates below the root zone. This would control seep recharge and arrest seep development and expansion. Berg et al. (1991) recommended warm-season, deep-rooted crops (e.g., sunflower or safflower) or perennial species (e.g., alfalfa or grasses) that use more water than does wheat. Annual warm-season grasses typically root to depths of 1.8 m or less (Berg et al., 1991; Halvorson, 1988), sunflower and safflower roots reach depths of 2.0 to 2.2 m (6.5 to 7.2 ft) (Halvorson, 1988), and alfalfa may extract soil water from as deep as 6 m (20 ft) after several seasons of development (Black et al., 1981; Berg et al., 1991; Halvorson, 1988). One study in North Dakota reported alfalfa extraction of 6.1 cm year^{-1} (2.4 in year^{-1}) in excess of annual precipitation, causing soil beneath alfalfa stands to contain less water than adjacent crop-fallow fields (Brun and Worcester, 1975). Because of its deep rooting and high water use, alfalfa has been identified as the best species for gaining hydraulic control in recharge areas (Black et al., 1981) and has been used successfully to control seep recharge (Halvorson and Reule, 1980; Miller et al., 1981).

In order for vegetative remediation to be successful, the recharge area must be identified clearly and farmers must be willing and able to implement management practices that maximize water use and minimize percolation past the root zone (Halvorson, 1988). Halvorson and Reule (1980) found that when alfalfa was grown on 80% of the recharge area, the decrease in deep percolation of soil water provided hydrologic control within 1 year after establishment. However, an upslope buffer strip of alfalfa grown on 20% of the recharge area did not provide hydrologic control. The appropriate level of management for a given seep area must be determined based on site-specific geology, anticipated climate, and the proposed cropping system for the recharge area.

Once recharge is controlled salts will leach naturally from the surface in the saline seep. Reclamation often has proceeded swiftly. Halvorson (1984) found that once recharge was arrested, salinity of seep areas (0 to 0.3 m depth; 0 to 12 in) was reduced sufficiently to allow successful crop growth after 2 years and average yields after 3 to 4 years of hydrologic control.

In another example, a farmer in Colorado established alfalfa in a seep recharge zone in 1984. This dried the seep area sufficiently to allow machinery crossing in the fall of 1985, and provided three cuttings of alfalfa in 1987 where only salt-tolerant weeds grew in 1984 (Halvorson, 1988).

The extent and nature of saline seeps varies from site to site because of different combinations of soils, climate, and cultural practices. As a general rule, cropping practices alone will control or reclaim only about 60 to 70% of the saline seeps (Miller et al., 1981), which suggests that the local-recharge model is a prevalent but not exclusive mechanism for saline seep development. This also indicates the need for a methodology to guide the design of seep reclamation treatments to improve the probability of success.

OBJECTIVES

1. To demonstrate a hydrologic balance approach using readily available data to analyze and design site-specific bioremediation treatment options.
2. To use this approach to prescribe an amount of wheat land farmers must convert to alfalfa to control seep recharge and reclaim the saline seep at each of five project sites.

METHODS

A simplified hydrologic balance was used as the basis for site design recommendations. Precipitation that is not intercepted by an aboveground canopy or removed by surface runoff infiltrates the soil surface. Subsequently, evapotranspiration (ET) removes a portion of the infiltrated water. When infiltration less ET exceeds soil water storage capacity, percolation occurs to the next deeper soil layer. This basic approach can be used to determine the ability of a crop cover to utilize the available soil water. This is critical in bioremediation applications where percolating water can transport contaminants out of the treatment zone. In the saline seep application, percolation from the root zone is the basis for seep recharge.

THE HYDROLOGIC MODEL

The Potential Yield Model-Revised (POTYLDR) is a continuous water-budget simulation model that estimates water yield (upstream runoff and deep percolation) on a daily basis (Koelliker, 1994b) (Fig. 2). The model was designed to be physically based, to use readily available information to describe conditions in an area of interest, and to be capable of being applied anywhere in the continental U.S. Daily climatic inputs of precipitation and maximum and minimum temperature along with irrigation data are used to create daily outputs of interception, runoff, ET, soil moisture, and percolation. A minimal amount of additional data is needed, as described below.

A watershed can be analyzed using up to 18 combinations of soil types, surface runoff conditions, crops, growing seasons, and rotations. Each land-use combination may or may not contain terraces or drain into a pond. Soil profile depth, texture, and water holding capacity are characterized using 12 irrigation soil classes (USDA-SCS, 1975) based on common NRCS soil classifications in Kansas. Crop selections include wheat, sorghum, corn, soybeans, pasture, alfalfa, and fallow; however, wheat-fallow is the only rotation implemented in the model at this time.

Surface runoff is estimated using the NRCS runoff curve number method. Soil curve number between antecedent moisture condition (AMC) I and AMC III is varied linearly with available soil moisture between 50 and 90%, respectively. AMC II holds when available soil moisture is 70%. A canopy interception account stores up to 2.5 mm (0.1 in) of the first amount of precipitation and draws upon the account at the potential ET rate before allowing other ET to occur. Infiltration for each land subdivision is taken to be precipitation less the sum of interception and runoff.

The subsurface is divided into two zones: the upper zone, 0.3 m (1 ft) deep, and the lower zone, the next 0.9 m (3 ft) or less according to soil profile characteristics. Water infiltrates into the upper 0.3 m zone and can leave by either ET or percolation to the lower zone when soil moisture in the upper zone exceeds field capacity. Percolation losses from the lower zone occur when 90% of field capacity is reached. Both upper and lower zones are available for crop ET, but just the upper zone is available for evaporation in the fallow condition. The pond features of POTYLDR were not used in this analysis and will not be discussed.

Potential ET is estimated from long-term monthly average values of percent sunshine, relative humidity, solar radiation, wind run, and average temperature using the Penman combination equation after Gray (1973). Geographical coefficients, Brunt a and b (Brunt, 1944) as modified for Kansas conditions by Zovne et al. (1977), are based on annual moisture deficit (annual lake evaporation minus annual precipitation) and are used to calibrate Penman's potential ET such that predicted average annual lake evaporation at a location agrees with published values (Zovne and Koelliker, 1979). Actual water use by crops is simulated by multiplying daily potential ET by a monthly Blaney-Criddle crop coefficient (Blaney and Criddle, 1962) and a coefficient based upon available soil moisture. Blaney-Criddle crop coefficients are adjusted for planting and harvest dates without further calibration. The soil-moisture coefficient is 1.0 for available soil moisture greater than 30% and decreases linearly to zero when available soil moisture is zero. When crops are not growing, water loss from bare soil and fallow is simulated by a decay-rate equation (Ritchie, 1972) and adjusted for an assumed amount of residue. Other user-definable Penman coefficients include a wind coefficient and crop reflectance.

The POTYLDR model was modified to accommodate the objectives of designing seep remediation treatments. First, alfalfa was allowed to access soil moisture from a soil depth up to 0.3 m greater than that for wheat (Fig. 2). To accomplish this, available soil water in the lower zone for wheat was decreased by 33% with respect to the alfalfa profile giving alfalfa a 33% greater total root-zone depth than wheat. From the literature on rooting depths of alfalfa and wheat (Black et al., 1981; Berg et al., 1991; Brun and Worcester, 1975; Halvorson, 1988), this increase in rooting depth is felt to be conservative. Second, each field site was divided into two land uses, one upslope from the other. Deep percolation from Land Use 1 was directly input to the lower zone of Land Use 2 to simulate seep-water transport in the vadose zone. This allowed the downslope crop (Land Use 2) to access the shallow groundwater, which would be transported through its root zone on route to the discharge (seep) area. Deep percolation from Land Use 2 was interpreted as groundwater discharge available for seep development. For saline seep remediation, the wheat was selected to be grown upslope (in Land Use 1) from the alfalfa (Land Use 2) to take advantage of alfalfa's higher water-use capacity hydraulically closer to the seep.

The POTYLDR model was selected primarily because it uses well-documented and tested modeling methods (e.g., NRCS runoff, Penman ET) within the framework of a hydrologic mass balance. This provides a reasonable accounting of water fluxes in the seep recharge/discharge system. Several studies under a variety of conditions have examined the effects of land use and management on water yield using the POTYLDR model (Koelliker, 1987, 1994a, 1998; Koelliker et al., 1995) though none of these studies provided comprehensive model validation. Model inputs are minimal and readily available, as will be seen in the following section. This would allow ready adoption of the procedures developed here to the preliminary assessment and design for other remediation sites without costly, time-consuming, and often unavailable site-specific data. Although the following analysis addresses a specific remediation situation (the control of local-recharge saline seeps), the same water balance parameters should be considered in the design of any bioremediation application in which water control is an important factor.

MODEL INPUTS

Inputs to the POTLYDR model were obtained from readily available sources. A site reconnaissance was used to determine current cropping and land use characteristics. Five saline seep sites were studied: three in Rice County (R1, R2, and R3) in central Kansas and two in Harper County (H1 and H2) in south-central Kansas. All fields were cropped to wheat. The R2 and H2 fields were terraced. Based on results of electromagnetic induction surveys of the sites (Mankin et al., 1997), seep recharge areas were estimated to follow the surface contour and all land upslope from the existing seep was assumed to be contributing.

Runoff curve numbers were estimated from standard NRCS curve number tables based on site assessments of land use and conditions. Soil hydrologic groups were estimated from county soil surveys and soil irrigation classes were found in the Kansas Irrigation Guide (USDA-SCS, 1975).

Climatic data were obtained for a 41-year record (1948-1988) of climatic files, daily precipitation, and daily maximum and minimum temperatures from a weather station in Great Bend, KS (approx. 60 km west of the Rice County sites and 120 km northwest of the Harper County sites). Model defaults were used for Blaney-Criddle evapotranspiration crop coefficients for wheat and alfalfa, the two primary crops being studied.

Daily deep percolation, which directly translates into seep recharge in the local-recharge scenario, was simulated for seven combinations of wheat and alfalfa using the modified POTYLDR. Average total recharge volume was estimated for various treatments and expressed as an average depth for the entire recharge area.

RESULTS AND DISCUSSION

The current conditions, estimated by the 100% wheat scenarios, contributed to seep recharge during 9% of the months simulated (Table 1). This provided an average total recharge volume of 23 mm yr^{-1} (0.9 in yr^{-1}). Although we anticipated that increasing the areal percentage of alfalfa would decrease the number of months that contributed deep percolation and decrease average annual recharge to the saline seep, the simulation results indicated that these reductions were not linear. For example the first field site in Rice County (R1) demonstrated a 69% reduction in annual average recharge for the first 20% increase in alfalfa area but essentially 0% reduction with the increase in alfalfa acreage from 80 to 100%. This nonlinear trend was similar for all field sites. Annual recharge rates for the five field sites ranged from 8.1 to 33.0 mm yr^{-1} (0.32 to 1.3 in yr^{-1}) for 100% of the area in wheat and 0.5 to 3.6 mm yr^{-1} (0.02 to 0.14 in yr^{-1}) for 100% in alfalfa (Table 1).

The model simulations allowed the quantification of several factors that contributed to the reduction in deep percolation for alfalfa compared to wheat. First, alfalfa was modeled to have a 33% greater root-zone depth than wheat, which increased both soil water storage capacity and water available for ET. Second, annual alfalfa ET demand generally exceeds that of wheat. Third, wheat and alfalfa have different growing seasons. Timing of the period of active crop water use to rainfall events affects the likelihood of deep percolation. The growing season for alfalfa (April to October) covers a different portion of the high-rainfall period than wheat (October to June). Typically 30% of annual precipitation falls during May and June and 45% occurs between July and September in south-central Kansas. This later period of rainfall is more likely to contribute to deep percolation on a field with wheat stubble than actively transpiring alfalfa.

The modeling results can be helpful in the preliminary design of saline seep reclamation treatments. Figure 3 shows data from Table 1 expressed as a percentage of the maximum value for each field. From this graph, the percentage of alfalfa area needed to achieve a certain percentage reduction in seep recharge can be determined directly. For instance, a 50% reduction in total recharge would require 14% (Rice 1), 24% (Rice 2), 32% (Rice 3), 22% (Harper 1), or 17% (Harper 2) of the recharge area to be converted to alfalfa production. Similarly, a 50% reduction in the number of months contributing to recharge would require 27 to 41% of the recharge area to be converted to alfalfa production depending on the site.

A comparison of these two values demonstrates that a greater acreage of alfalfa is required to stop seep recharge completely in a given month at a given site. For example, conversion of 14% of the recharge area to alfalfa at field site R1 reduced average annual recharge by 50% but reduced the number of months contributing recharge by 25%, whereas 40% of the recharge area in alfalfa was needed for a 50% reduction in months of recharge. This graph also shows the maximum percentage reduction possible using alfalfa at each site. With alfalfa on 100% of the recharge area, average annual recharge volumes were reduced by values ranging from 83% for field H1 to 99% for R2.

This simple modeling approach has three important limitations. 1) The key to successful seep reclamation is reducing seep recharge. But the relationships between recharge rate and seep severity or recharge rate reduction and rate of seep reduction are site-specific, complex, and difficult to establish and verify. Although the hydrologic modeling approach can estimate changes in seep inputs from management, a more sophisticated approach also would account for mass fluxes and total accumulation of salts in the seep, history of the seep development, and soil hydrogeologic characteristics. For example the modeling approach used in this work focused on the local water balance and made a basic assumption that solute concentration was not affected by recharge rate. The implied goal of controlling recharge is to reduce mass influx of salts to the saline seep. If solute concentration increased with decreasing recharge rates, further refinements would be necessary to account directly for solute mass flux. 2) Not all seeps are formed exclusively by local recharge, as was assumed for this analysis. Some seeps tap into groundwater flows from nonconnected recharge areas, are more difficult to control, and are inappropriate for this modeling approach. 3) The model demonstrated that seep development is very sensitive to soil depth and texture. Use of actual field data on depth to impermeable layer, crop rooting depths, and available water capacity could be a reasonable first step toward making this type of analysis more site-specific.

CONCLUSIONS

A simple hydrologic balance model can be used to provide useful information for designing site-specific treatments for saline seep remediation. Using this method the effects of changing crops or management on seep recharge can be estimated. We demonstrated the use of this approach by estimating the percentage of recharge area that should be shifted to alfalfa production to achieve a given percentage reduction in total recharge. In all cases studied, converting one-third of the recharge area immediately upslope from the saline seep from wheat to alfalfa should be effective in reducing seep recharge by at least 50%.

This modeling approach provides a quantitative indication of a system's responsiveness to changes in vegetation. This approach should prove useful for designing and managing other bioremediation systems that require control of seepage out of the root zone or reduction in shallow groundwater recharge.

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Table 1. Effects of land use treatments on saline seep recharge.

Land Use 1	Land Use 2	Months Contributing Recharge					Avg. Annual Recharge Depth				
Wheat	*Alfalfa*	(% of total)					(mm yr^{-1})				
(% area)	(% area)	*R1*†	*R2*	*R3*	*H1*	*H2*	*R1*	*R2*	*R3*	*H1*	*H2*
100	0	3.3	13.4	11.6	7.3	7.3	8.1	27.4	26.9	21.1	33.0
80	20	2.2	8.1	7.3	5.3	5.7	2.5	15.5	18.0	10.9	12.7
60	40	1.6	4.1	4.7	3.7	3.3	1.5	6.9	10.2	7.4	7.9
50	50	1.4	2.8	3.7	3.0	2.8	1.3	4.6	8.1	6.4	6.4
40	60	1.0	2.0	3.0	2.4	2.4	1.0	3.0	6.4	5.6	5.1
20	80	0.8	0.8	1.8	2.0	1.6	0.5	1.0	4.1	4.3	3.6
0	100	0.4	0.2	1.2	1.6	1.2	0.5	0.3	2.8	3.6	2.3

† R1, R2, R3, H1, and H2 refer to three targeted fields in Rice Co., KS and two in Harper Co., KS, respectively.

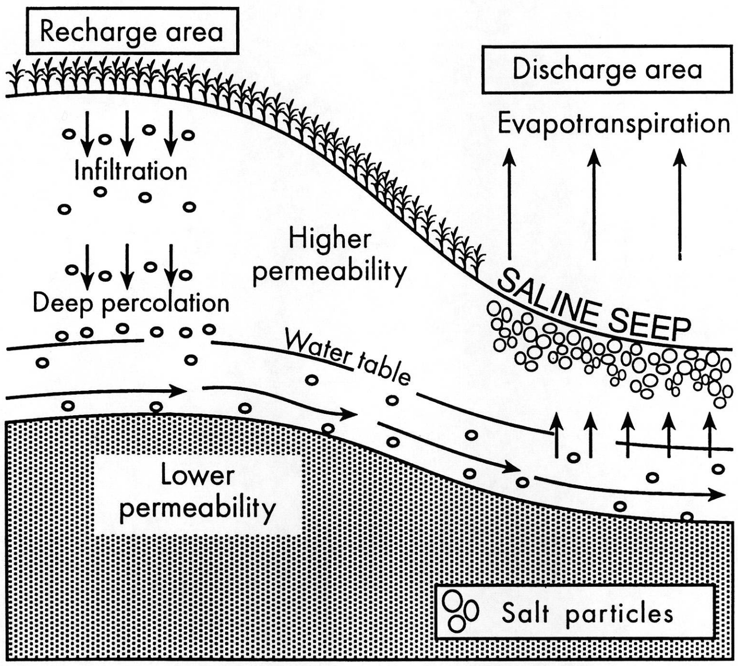

Figure 1—Basic slope-change saline seep mechanism with local recharge.

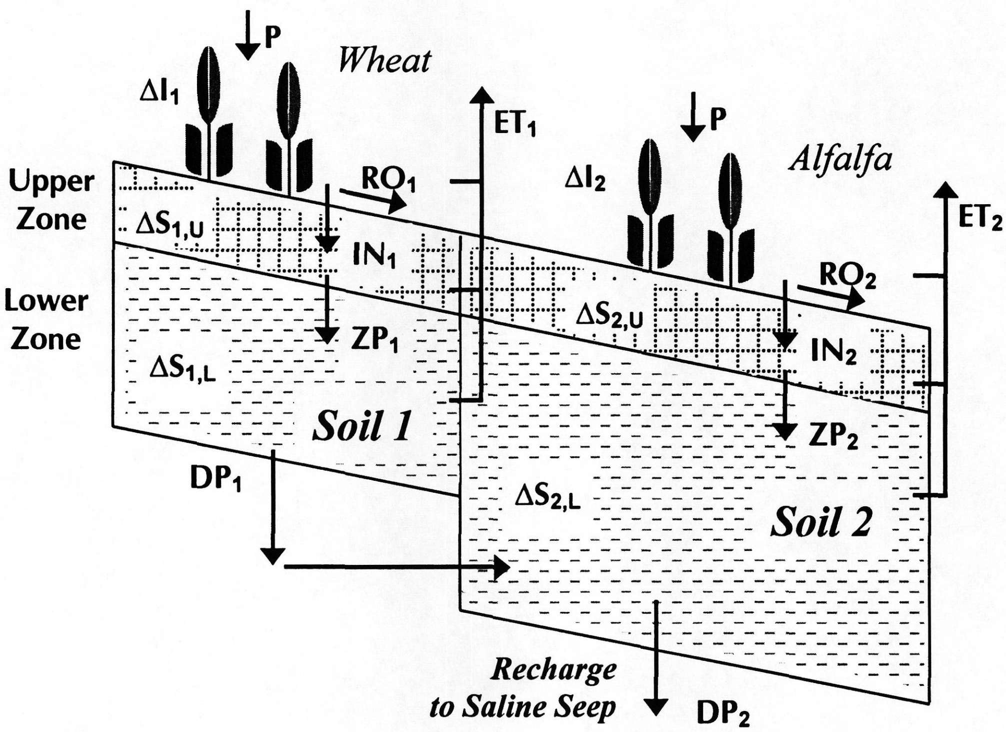

Figure 2—POTYLDR model of saline seep recharge area. Symbols: P = precipitation, ET = evapotranspiration, ΔI = interception storage, RO = runoff, IN = infiltration, ΔS = soil storage, ZP = percolation between zones, DP = deep percolation.

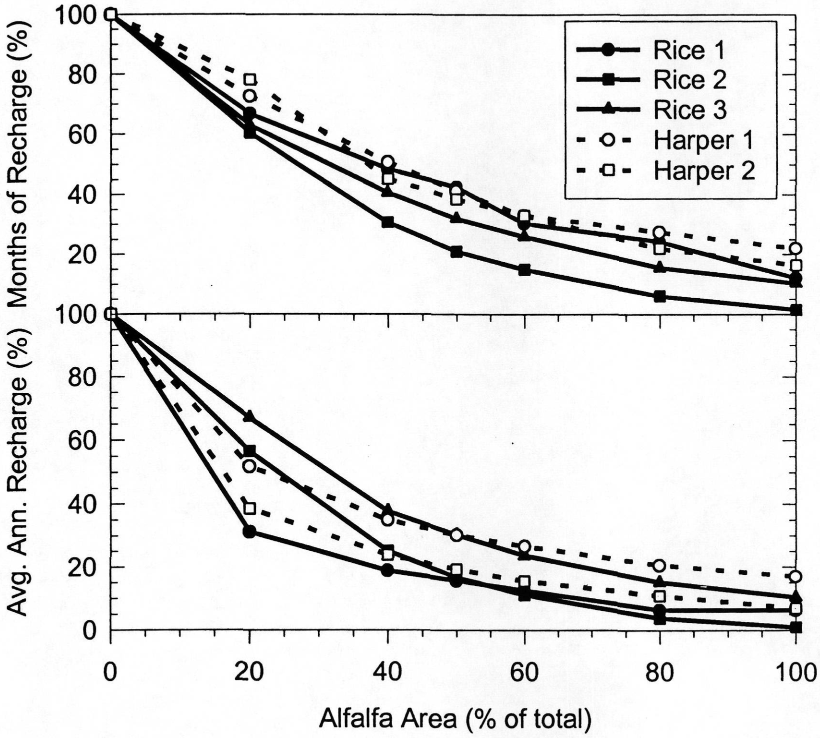

Figure 3—Effect of increasing alfalfa area (and decreasing wheat area) on seep recharge. Values are expressed as a percentage of the peak response for each site.