Appendix B

Modeling Phytoremediation of Saline Seeps using a Hydrologic Balance

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ABSTRACT. *Saline seeps are an increasing concern in south-central Kansas. To remediate salt-affected seep areas, site hydrology must be modified to reduce seep recharge. A hydrologic model, POTYLDR, was 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. Practical applicability of this modeling procedure was encouraged by using only readily available published data. Percentage of recharge area to be shifted from current wheat cropping to alfalfa was determined for a given target percentage reduction in total recharge or in number of months contributing to recharge. A 50% reduction in total recharge required 14 to 32% alfalfa acreage, while a 50% reduction in the number of contributing months required 27 to 41%. The major limitation in application of these results is in 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 ground water discharges fed from upslope recharge areas. Excess rainfall, after evaporation, transpiration, and runoff losses, percolates into the soil profile. If one layer in the soil profile has lower or higher permeability than overlying layers, percolating water is transported down-gradient on or within that layer. This local ground water 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). Saline seeps occur when percolating water dissolves salts in 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. Due to field-management considerations, seeps often receive full inputs of tillage, fertilizer, and seed even though no crop is produced. In addition, the salt-affected areas are subject to serious wind and water erosion due to the total absence of vegetation under current management.

Once established, seep areas can grow at an average rate of about 10% a year, taking large areas out of production (Doering and Sandoval, 1976; Miller et al., 1981). Saline seeps range in size from a few square meters to 20 hectares and are growing in number, area, and severity. Seeps in the Dakotas, Wyoming, and Montana have removed 162,000 ha (400,000 acres) from production (Doering and Sandoval, 1976). Within one county in north-central Oklahoma, 1,300 of 65,000 ha of wheatland was known to be affected by seeps, and the extent was estimated to be similar in south-central Kansas (Berg et al., 1991). Saline seeps are also an increasing concern in the dryland crop production areas of south-central Kansas. Approximately 65,000 ha (160,000

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acres) of south-central Kansas soils mapped as saline/sodic are particularly susceptible to seep development.

Two general methods have been used to remediate seep areas (Halvorson, 1988). Subsurface drains installed up-gradient from the seep can intercept the lateral water movement 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, a form of phytoremediation could be employed. Phytoremediation, or the use of plants to remove pollutants from the environment, often begins with hydrologic control of the site. In this case, hydrologic control with agronomic cropping systems allows and encourages the removal of the salt pollutants by natural processes. Cropping practices can be modified to use the water while it is a relatively non-saline resource before it percolates below the root zone, thus controlling seep recharge and arresting seep development and expansion. Berg et al. (1991) recommended warm-season, deep-rooted crops (sunflower, safflower, etc.) or perennial species (alfalfa, grasses, etc.) that use more water than does wheat. While annual warm-season grasses 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). In one study in North Dakota, alfalfa was found to extract 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 phytoremediation to be successful, the recharge area must be clearly identified and farmers must be willing and able to implement management practices which 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 one 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 the hydrology is controlled, salts will naturally leach from the surface in the saline seep. Reclamation has often proceeded swiftly. Once recharge was arrested, Halvorson (1984) found salinity of seep areas (0-0.3 m; 0-12 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 the 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 farm to farm due to 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). This indicates the need for a design methodology to assist in selecting where biological remediation is possible and to determine the extent of treatment required.

OBJECTIVES

1. Demonstrate the use of a basic hydrologic balance model with readily available data to analyze saline seep bioremediation treatments.
2. Determine the feasibility of saline seep phytoremediation using alfalfa at five south-central Kansas sites.
3. Estimate the reductions in saline seep recharge at each site in response to a range of recharge area treatments.

METHODS

POTYLDR HYDROLOGIC MODEL

The Potential Yield Revised (POTYLDR) model is a water budget simulation model designed to estimate water yield on a daily basis (Koelliker, 1994). The latest version of the model is based on previous work reported in Zovne et al. (1977), Zovne and Kolliker (1979), and Koelliker et al. (1981 and 1982). Precipitation, from daily weather station data, that is not evaporated, intercepted, or removed by surface runoff is allowed to infiltrate the profile. Estimates of evapotranspiration are based on the modified Penman equation, adjusted for crop and soil moisture conditions. Blaney-Criddle type crop coefficients, scaled according to planting and harvest dates, are used without further calibration. 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.

The POTYLDR model was further modified to accommodate the objectives of designing seep remediation treatments. First, alfalfa was allowed to access soil moisture from up to a 0.3 m (1 ft) greater soil depth than wheat. To accomplish this, available soil water in the lower zone for wheat was decreased by 33% with respect to the alfalfa profile. 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 ground water 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 basic components of the POTLYDR model are shown schematically in Figure 1.

This model was selected for several reasons. 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 of other saline seep remediations without costly, time-consuming, and often unavailable site-specific data. Nonetheless, the model includes the important hydrologic-balance parameters necessary for a reasonable accounting of water fluxes in the seep recharge/discharge system.

MODEL INPUTS

Inputs to the POTLYDR model were purposely taken 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) and two in Harper County (H1 and H2). 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., 1996), 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 from the Kansas Irrigation Guide (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. Model defaults were used for Blaney-Criddle evapotranspiration crop coefficients for wheat and alfalfa, the two primary crops being studied. Seven combinations of wheat and alfalfa were modeled using the modified POTYLDR.

RESULTS AND DISCUSSION

The POTYLDR model was used to simulate daily deep percolation, which directly translates into seep recharge in the local-recharge scenario. The current conditions, estimated by the 100% wheat scenarios, contributed to seep recharge during 9% of the months simulated, on average, providing an average total recharge volume of 23 mm yr^{-1} (0.9 in yr^{-1}), expressed as an average depth for the entire recharge area. While it was anticipated that increasing the areal percentage of alfalfa decreased the number of months that contributed deep percolation and decreased 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 non-linear 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.

The model simulations allowed the quantification of several factors that contributed to the reduction in deep percolation for alfalfa compared to wheat. Alfalfa was modeled to have a 25% greater root-zone depth than wheat, which increased both soil water storage capacity and available water for evapotranspiration. From the literature on rooting depths of alfalfa and wheat, this increase in rooting depth is felt to be conservative. Also, 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. Rainfall that occurs between July and September 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 2 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 average annual recharge would require from 14 to 32% of the recharge area to be converted to alfalfa production, depending on the field. Similarly, to achieve 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. 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 volume was reduced by values ranging from 83% for H1 to 99% for R2.

This simple modeling approach has several important limitations. 1) The key to successful seep reclamation is reducing seep recharge. But the relationship between recharge rate and seep severity, or recharge rate reduction and rate of seep reduction, is site-specific, complex, and difficult to establish. While the hydrologic model approach can estimate changes in seep inputs due to management, a more sophisticated approach should also 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 hydrology 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 for solute mass flux directly. 2) It is important to note that not all seeps are formed exclusively by local recharge, as was assumed for this analysis. Such seeps tap into ground water flows from non-connected 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 was used to provide useful information to design saline seep remediation treatments. Percentage of recharge area requiring a shift to alfalfa production was determined for a given target percentage reduction in total recharge. 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.

Final selection of remediation treatments will be made in collaboration with the landowner and operator at each of the five sites discussed in this paper. Remediation treatments will be monitored to assess the accuracy of model predictions and the effectiveness of the chosen remediation treatments.

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Table 1. Effects of each remediation treatment on saline seep recharge

Land Use 1 (% area)	Land Use 2 (% area)	Months Contributing Recharge (% of total)					Avg. Annual Recharge Depth (mm yr^{-1})				
Wheat	*Alfalfa*	*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

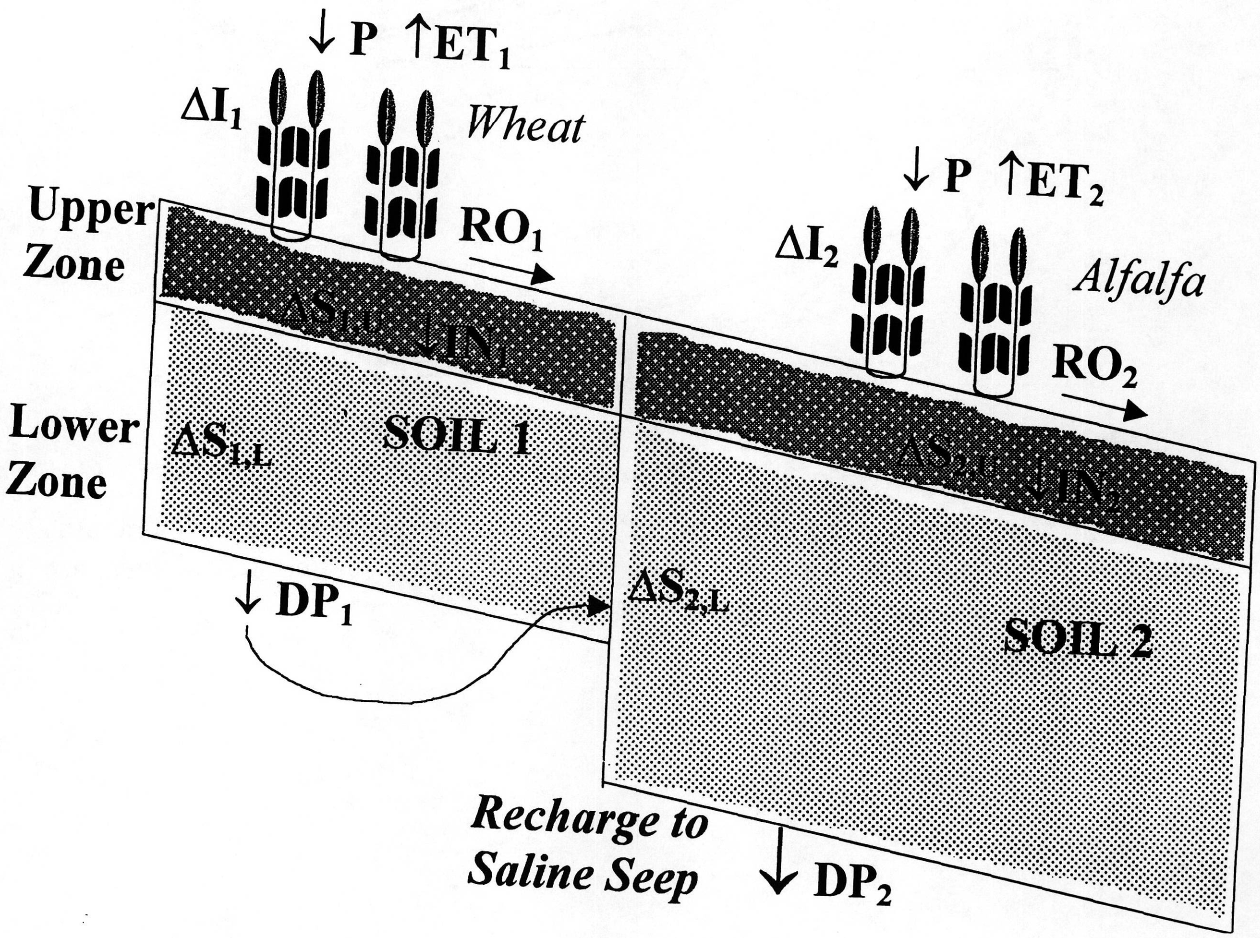

Figure 1—POTYLDR model of saline seep recharge area. Symbols: P = precipitation, ET = evapotranspiration, ΔI = interception storage, RO = runoff, IN = infiltration, ΔS = soil storage, DP = deep percolation.

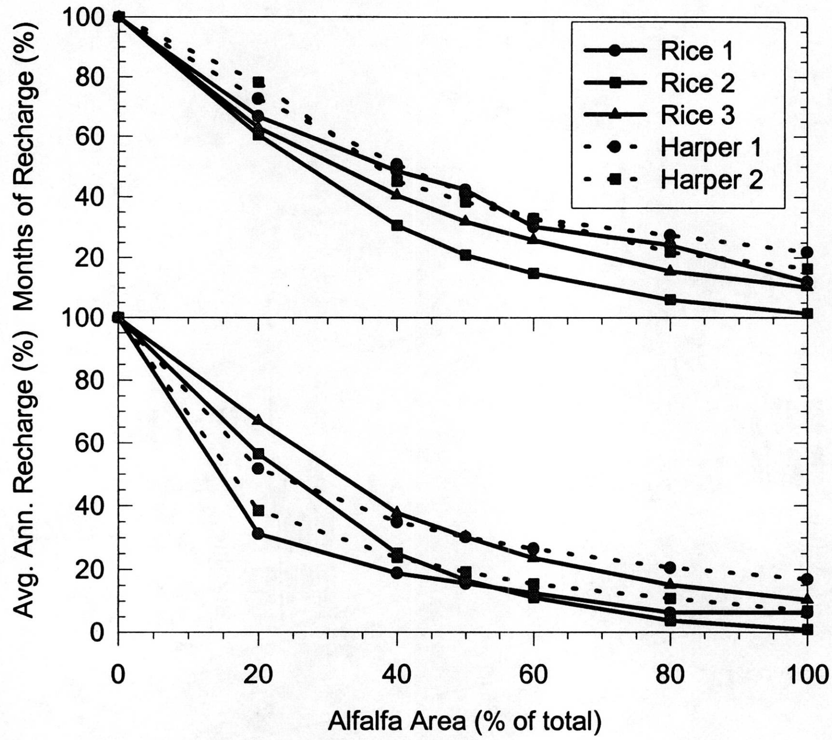

Figure 2—Effect of vegetative treatment on seep recharge, by number of months with seep contributions and by average annual recharge depth. Values are expressed as a percentage of the peak for each site.