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Evaluation of management practices for use of low quality waters for irrigation: model simulations

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Abstract

Use of low quality waters for irrigation is increasingly necessary due to scarcity of high quality water, especially in arid regions. In many regions there is currently a rapid depletion of fresh water supplies, and irrigation as practiced is not sustainable. In order to maintain agricultural productivity, use of low quality waters for irrigation will require new strategies for water management, in some instances including periodic reclamation of the soil. Efficient reclamation practices must minimize cost inputs, as well as water and amendment use while minimizing the degradation of ground and surface waters that receive the discharged drainage water. The computer model UNSATCHEM is well suited to analyze the performance of various management practices since it considers water flow, chemical processes and transport, plant water uptake as related to osmotic and matric stress, relative plant yield and the adverse affect of chemical factors on soil hydraulic properties.

This paper considers the use of low quality high B concentration waters for irrigation, The waters can be used either in a supplemental manner or as the main water supply. We assume that either a limited quantity of high quality water is also available or that there is some rainfall. Although the low quality water is often not usable for sustained agricultural production it can be utilized either in a cyclic fashion with higher quality water, the soil can periodically be reclaimed via leaching, or the waters can be used on separate fields on crops of varying tolerance. There are various published field studies in which the use of saline water of elevated SAR has been combined with a limited amount of high quality water in a cyclic sequence. The low quality water is used for irrigation of salt tolerant crops and the salt tolerant phase of more sensitive crops in a two to three crop rotation. The results of these studies can be extended to the use of high B waters. Model predictions can be made in terms of soil salinity and composition including B (if available) and relative crop yield. Model predictions are extended to a variety of different management options, including cyclic reclamation, maintaining fields either under saline or non-saline conditions, and mixing (blending) of waters of various water qualities. These analyses are extended to the sodic and high B waters as well as the saline waters, under a variety of conditions of crop, soil, and quality of water available.

Keywords: salinity, irrigation, sodic water, modeling

Introduction

Arid and semi arid regions face increasing demands for high quality water. Rapid population increases in these region means increasing requirements for urban water supplies as well as increasing demands for food production from irrigated lands. In most arid regions the present extraction of fresh water is not sustainable, thus agriculture will have to either utilize low quality waters or decrease water use. The potential exists to increase water use efficiency on existing agricultural lands, however the potential savings are much less than suggested by examining water use efficiency in individual projects. In many instances drainage waters are either directly used or they recharge ground water and are then pumped back. Irrigated agriculture will have to reuse irrigation drainage waters, urban wastewaters as well as other brackish waters, all of lower than optimal quality.

Water quality criteria for irrigation were originally developed in and era when high quality waters were generally available thus the criteria could be conservative, rejecting waters that may in *some* instances could be detrimental. Original criteria for salinity hazard (U.S. Salinity Laboratory Staff, Handbook 60, 1954) were for any water above EC 0.25, with high salinity hazard above 0.75 and very high hazard above EC 2.25 dSm^{-1}. These suggested values are now considered unrealistically low and it is generally regarded that waters below EC 1.0 dSm^{-1} can generally be used with out restriction. Furthermore waters of low salinity may be detrimental in that they may cause infiltration problems as soil dispersion and swelling is related to both EC and SAR.

Use of degraded waters for irrigation include saline waters, sodic waters and waters with potentially toxic elements as well as waters with nutrient imbalances and high pH. Use of these waters generally requires special management practices. In some instances constant use of these waters is not a sustainable practice and periodic use of amendments, leaching or cyclic use of higher quality waters is required. Computer models if they consider the necessary variables and interactions, have the potential to be used as management tools to evaluate various practices or options. UNSATCHEM (Suarez and Simunek, 1997) has been shown to successfully predict changes in soil carbon dioxide and water content during a growing season (Suarez and Simunek, 1993), as well as reclamation of a sodic saline soil upon leaching and application of gypsum (Suarez, 2001).

Toxic levels of B in drainage water is one of the major limitations to drainage water reuse in the western U.S. There is a need to develop management practices for use of these waters. Various modeling approaches are utilized to simulate adsorption of oxyanions, including retardation factors, and Langmuir isotherms. Retardation factors do not consider the chemical factors affecting adsorption thus they are valid only for the soil on which it was developed and only under the chemical conditions present during its determination. Langmuir isotherms are limited by the need to characterize the adsorption at a specific pH; thus it is applicable to dynamic systems in which pH conditions may vary. The fitted equations are also soil-specific. The constant capacitance model has proved to be very useful in representing adsorption, especially the variation in adsorption as related to pH (Goldberg, 1993). The model has the additional advantage of having a chemical basis, thus measurable input variables. The model is well suited to incorporation into UNSATCHEM since this model is able to simulate changes in soil pH. Suarez and Simunek (1997) described a generalized application of the constant capacitance model. The surface charge was calculated from

$$\sigma = \frac{CSa}{F}\psi \quad (1)$$

where C is the capacitance density (F m^{-2}), S is the specific surface area (m^2 g^{-1}) a is the suspension density (g L^{-1}) F is the Faraday constant (C mol_c L^{-1}, Ψ is potential (V), and σ is expressed in mol_c L^{-1}. The intrinsic equilibrium constants for B are expressed by (Goldberg and Glaubig, 1985),

$$K_+ = \frac{[SOH_2^+]}{[SOH][H^+]}\exp[F\psi / RT] \quad (2)$$

$$K_- = \frac{[SO^-][H^+]}{SOH}\exp[-F\psi / RT] \quad (3)$$

$$K_B = \frac{[SH_2BO_3]}{[SOH][H_3BO_3]} \quad (4)$$

There are two mass balance equations in this routine, that for the surface functional groups and that for B

$$[SOH]_T = [SOH] + [SOH_2^+] + [SO^-] + [SH_2BO_3] \quad (5)$$

$$B_T = B(OH)_3 + B(OH)_4^- + SH_2BO_3 \quad (6)$$

The charge balance equation for the surface is defined by

$$\sigma = [SOH_2^+] - [SO^-] \quad (7)$$

The model utilizes average soil constants of 9.3, -10.6, and 5.5 for the values of log $K_{+-,}$ log K_-, log K_B, respectively. Using the data of Goldberg and Glaubig, (1985) the following general expression

$$[SOH]_T = 2.53\times10^{-7} + 4.61\times10^{-9}S \quad (8)$$

was found to predict the adsorption site density from the soil surface area (r=0.96). The advantage of this approach is that surface adsorption can be predicted using the generalized constants and a measurement of soil surface area (using EGME). This is especially useful for simulation boron transport in agricultural fields, where it would not be practical to conduct time consuming detailed adsorption studies for each soil horizon in each sample. The predictive capability of this approach is evaluated below, along with applications for use of high B waters for irrigation.

Methods

Air-dried Pachappa soil samples were packed into plastic columns (3.5 cm id) to a depth of 7.5 cm. The samples were initially leached with water containing 0.9 $mmol_c$ L^{-1} Ca and Cl. Next a similar solution was used except that 0.082 mmol L^{-1} of boric acid was also present. The columns were leached with 50 cm of water and the effluent of the columns was collected. Next the columns were leached with 50 mL of Ca and Cl water with addition of Br as a tracer, and with trace amounts of B (0.008 mmol L^{-1}). The solution effluents were analyzed for major ions, pH, B, Cl and Br.

The column experiments were simulated using the UNSATCHEM 3.0 model (Suarez and Vaughan, (2002). The water compositions were those specified above. Conditions simulated included major species, B, the Br tracer and soil solution pH. Both Cl and Br are considered to be non-reactive tracers. The predictive relationships for B were those described above. The EGME surface area of this soil was 100 m^2 g^{-1}.

Results and Discussion

The changes in drainage composition as a function of amount of applied high B water is shown in Figure 1. As shown, the nonreactive Cl rapidly reached a concentration approaching the equilibrium concentration after only 6 cm of water. This soil is of relatively low surface area and thus does not highly adsorb B, especially at this moderate pH. Nonetheless, significant B adsorption was observed, as evidenced by the gradual tailing of the concentration to the equilibrium value after 30 cm of water. The model was able to very accurately predict the Cl breakthrough curve and well predict the B breakthrough curve. The fit is very satisfactory considering that there was no optimization of parameters for this soil based on either this data or related measurements; the only soil specific variable being the measured surface area.

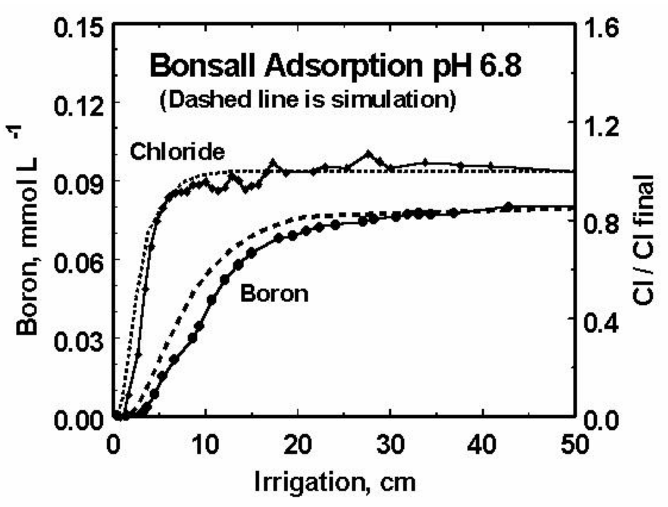

Figure 1 B and Cl drainage water concentrations upon application of water containing 0.082 mmol L^{-1} of B. Comparison of measured and predicted values.

The results of the column leaching (application of low B water) are shown in Figure 2. The Br concentration demonstrated the rapid infiltration and breakthrough of a non-reactive species. The model was again well able to predict the drainage concentration with time. As expected B was slowly released from the soil, requiring almost 40 cm of water to reach the new equilibrium concentration of the input water. The model was again well able to simulate the B release from the soil. These results suggest that the model can adequately predict soil solution B concentrations and thus can be utilized for simulation of various management options relating to use of B irrigation waters. There is a high dependence of both adsorption and desorption on pH, as demonstrated both by additional experiments and model simulations.

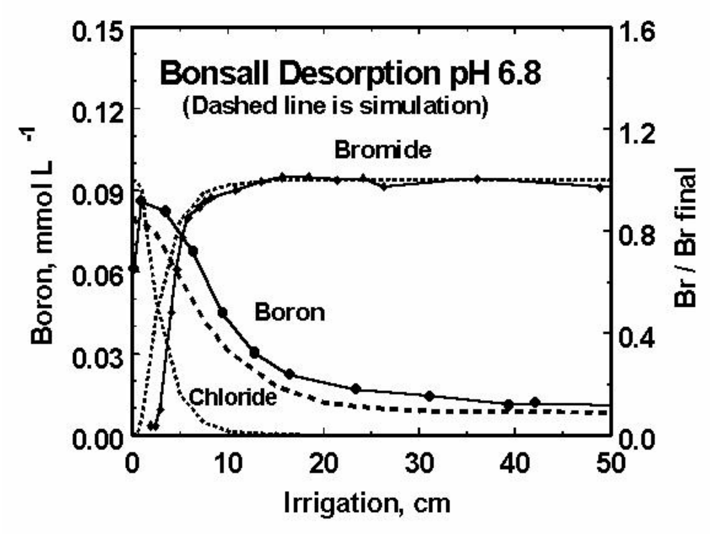

Figure 2 Desorption of B from column as a function of irrigation volume. Comparison of measured and predicted values.

Additional simulations were carried out to demonstrate the use of the model for evaluation of optimal management when irrigating with high B waters. In this instance crop response to B will depend on the B tolerance of the crop, the B adsorption capacity of the soil, the irrigation water B content, the actual evapotranspiration, extent of rainfall during the non-cropping season, the initial B content of the soil and the amount of irrigation water applied.

Irrigation drainage water from the Westside of the Central Valley in California, will typically contain 0.4 to 0.8 mmol L^{-1} B and an electrical conductivity of 8-14 dSm^{-1}. In these simulations we selected a B concentration of 0.8 mmol L^{-1}. We assumed a uniform root distribution and uniform water uptake in a 50 cm root zone. The profile was initially free of B.

For the simulation shown in Figure 3a, the ET was input as 1 cm d^{-1} with irrigations corresponding to an average input of 2 cm/d (leaching fraction of 0.5). A total of 200 cm of water was applied during the 100 day growing season. The surface area of the soil was taken as 100 m^2 g^{-1}, corresponding to a soil with relatively low B absorption capacity. The high leaching and low absorption capacity results in movement of the B front into the soil relatively rapidly, as shown in Figure 3a. The B concentration is initially uniform at 0.00 mmol L^{-1}. A quasi steady state profile is is established in the root zone after 80 days, with a maximum concentration of 1.6 mmol L^{-1}. The concentration below the root zone will eventually be constant at 1.6 mmol L^{-1}.

Shown in Figure 3b is a simulation similar to that described for Figure 3a except that the B adsorption capacity of the soil was 1,000 m^2 g^{-1}, corresponding to a soil with high B absorption capacity. The high adsorption capacity (or site density) results in a steeper B front and less rapid movement of B into the soil profile. This profile is still very far from steady state despite 100 d of irrigation. Note that the B concentrations are significantly lower than those shown in Figure 3a.

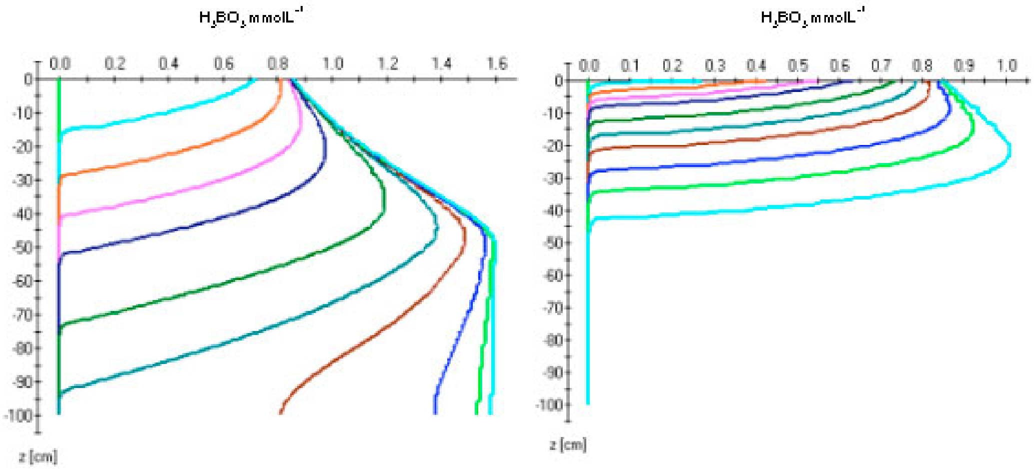

Figure 3 Change in boron concentration with depth and time (0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 days) for leaching fraction of 0.5 and soil surface area of a) 100 m^2g^{-1} and b) 1,000 m^2g^{-1}.

The simulations shown in Figures 4a and 4b correspond to similar simulations to Figure 3a and 3b except that the leaching fraction is now 0.1. The daily ET is still 1.0 cm/day however the water applications were reduced to 1.11 cm day^{-1}. In these simulations a total of 1.11 m of water was applied over the irrigation season. As shown if Figure 4a, after 100 days the profile is still not at steady state and the B front is just reaching the 100 cm depth. The maximum soil B concentration will eventually reach 8.0 mmol L^{-1}. The simulation shown in Figure 4b is for a leaching fraction of 0.1 and a high surface area soil. After 100 days the B concentration front extends only to 25 cm and the maximum concentration is only 0.8 mmol L^{-1}, much lower than the steady state value of 8.0 mmol L^{-1}, and just slightly greater than the irrigation water B concentration. Consistent with high surface area and thus a large numer of adsorption sites, the concentration front is relatively steep.

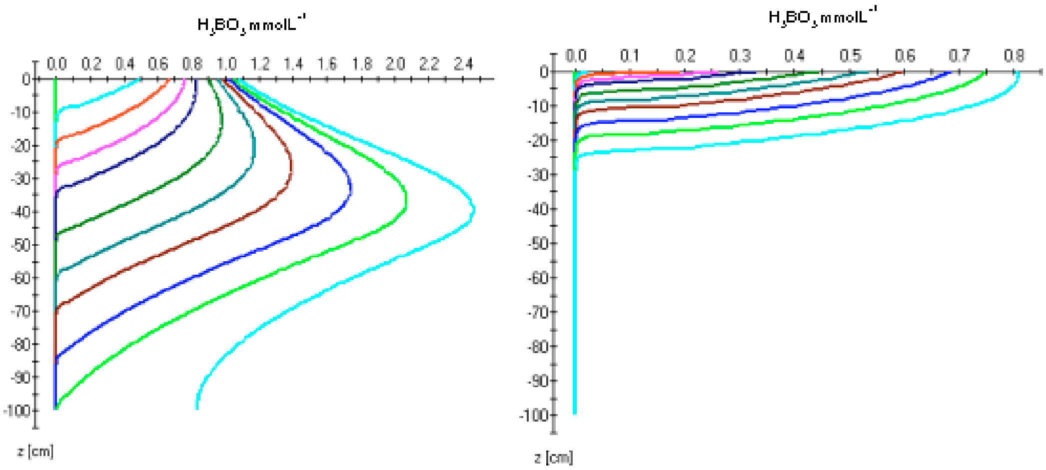

Figure 4 Change in boron concentration with depth and time (0, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 days) for leaching fraction of 0.1 and soil surface area of a) 100 m^2g^{-1} and b) 1,000 m^2g^{-1}.

The mean root zone B concentrations are presented in Figure 5 for each of the 4 simulations. The simulations indicate that for a soil with high affinity there is little B hazard during the initial cropping season. The highly leached high surface area soil had a higher root zone B concentration throughout the growing season. In this instance with a fixed irrigation composition, the effect of elevated B in the water and thus application of more B under high leaching, overcame the counter effect of less concentration of the salts by more leaching. At steady state the lower leaching management would eventually result in considerably higher B concentrations than the more leached soil. However the system can be managed in a continuous transitional state. Under this scenario the recommended management practice (in the absence of salinity considerations) would be minimal water applications. The mean B concentration in the root zone would be sufficiently low that most crops could be grown without yield loss. Sustained management would require winter rains or leaching with higher quality water.

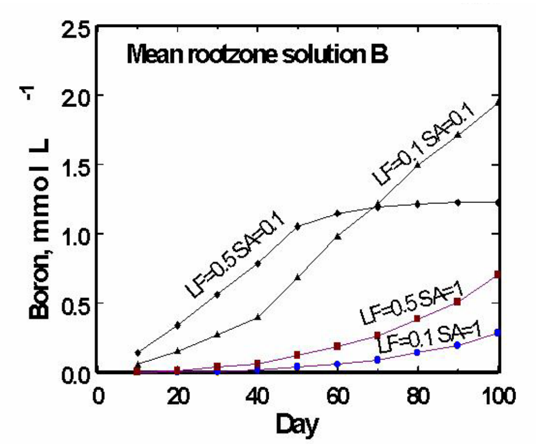

Figure 5 Mean root zone soil solution B concentration with time as related to leaching fraction (LF) and soil surface area (SA), expressed in 10^3 x m^2g^{-1}.

As shown in Figure 5, the low surface area soils rapidly increase in B concentration in the root zone, at both high and low leaching. During the early portions of the season the low leaching management results in lower root zone B, as steady state values are not yet achieved. Around day 70 there is a crossover with the low leaching fraction management increasing to higher root zone B concentrations. In this scenario, it would appear preferable to utilize a low leaching approach at least early in the irrigation season and especially if B sensitivity is greater during early stages of growth. For low surface area soils, most crops would have significant yield reduction due to B toxicity.

Conclusions

The UNSATCHEM model was able to predict both B adsorption and desoprtion observed in column experiments. The utility of the model was demonstrated for irrigation management when using high B waters. High B irrigation waters can be utilized in transient scenarios, especially for soils that strongly adsorb B. The uniqueness of each individual case makes generalization of results difficult and suggests the need for modeling approaches.

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