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Full Length Research Paper

Evaluation of boron loading to soil profile for basin-scale by using TETrans in irrigated areas

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The research study was carried out in an area of 1500 ha located in Ankara-Kesikkopru Plain left river bank irrigation area. TETrans computer model which is a one dimensional solution transfer model was used in order to determine boron content of the soil profile and groundwater. Boron content which has accumulated in the soil profile between in 2000 to 2002 was estimated in order to determine the potential risk that may occur in the next 10 years. Measured soil boron levels and boron levels estimated from the model were statistically compared. It was seen that the relationship between the estimated levels and measured levels is significant. Results obtained were used as a database in Geographical Information System and alteration maps were prepared for soils that may be formed in time. According to research study results, it was seen that, as long as the present conditions throughout the plain continue, there would be a boron problem to a significant level in the future. Pollution maps that are obtained will help executive and decision-making units in displaying more clearly the problem which may occur in the future and preparing action plans.

Key words: Trace element transport computer, geographical information system, soil and water resources, socio-economical development.

INTRODUCTION

Soil and water resources are among the most significant natural wealth of countries. Improvement and rational use of such resources play a central role in the socio-economical development of societies. Water is an indispensible natural resource for all living creatures; and in its absence, crop production is restricted to a considerable extent. Increase in the use of water, however, causes vital problems. While studies on sustainable agriculture increase agricultural productivity in order to maintain economic stability, they are also performed in order to establish the balance between minimizing harmful environmental effects and utilization of limited resources. The purpose of sustainable agriculture is to meet the present needs without jeopardizing the capabilities of those present in order to meet the needs of the future. Assessing the environmental impact of nonpoint source pollutants at local, regional, and global scales is a key component to achieve these goals since assessment provides a means of evaluating both change and the rate of change. Groundwater has long been regarded as the best water resource for all types of use. The stresses on groundwater, both in terms of quality and quantity, are growing rapidly. Over the past two decades there has been a growing worldwide concern about water quality issues and this has lead to an increased emphasis on a better understanding of groundwater contamination and groundwater quality management (Zektser and Everett, 2004). Underground water quality is a considerably significant factor in the reduction of product efficiency due to the use of low quality irrigation water. That salt, boron, organic chemicals and toxic elements carried towards the underground water in irrigated farming areas increase to dangerous levels is poses a threat. Being able to reduce the harmful environmental effects of these contaminators

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before they reach dangerous levels thanks to the early notice of the effects of salt and boron reaching the underground waters is quite a significant key for the sustainability of agriculture. In order to determine the environmental changes, we must either perform measurements in real time or use forecast methods. Information obtained through both methods is helpful for the user. However, real-time measurements show past activities. Whereas, model estimation allows us to take a look at the future and it plays the role of an instrument to take necessary measures in the start-up phase of the problem.

A functional solution transfer model, TETrans allows us to predict the boron content of the soil profile and to estimate the amount of boron reaching the underground waters. TETrans solution transfer model was associated with geographical information system (GIS) in order to present the boron accumulation in an area of thousands of hectares and changes it undergoes through the years. Maps that are formed serve a modal tool to see the potential effects of boron content in varying depths of soil profile (Corwin, 1996).

This will provide necessary inputs for making management decisions in order to minimize the environmental effects of boron toxicity in the future without jeopardizing agricultural productivity. This study aims to predict potential soil contamination due to the irrigation programs to be implemented in the future through GIS based TETrans model and to propose solutions before bigger problems emerge for the present system.

MATERIALS AND METHODS

Experimental site

The research study was carried out on a land of 1500 ha on the left river bank of Kesikkopru Plain in Central Anatolian Region. Soil of Kesikkopru plain is alluvial in deep layers and collovial in slope lands. Soil is heavy textured in general, but medium and light textured in areas near to Kizilirmak. Bulk density of plain soil varies from 1.17 to 1.56 g cm^{-3}. Favorable moisture capacity is between 20 to 58 mm $30cm^{-1}$ depending on the texture. Based in the results of infiltration test performed, infiltration speed of soil varies from 2 to 28 mm h^{-1} (Aran, 1996). Field agriculture still has the most critical part among agricultural working conditions. 60 to 65% of an area 98.4% of which is occupied with field agriculture involves bean agriculture. The most important crop of the region next to the bean is grain (35 to 40%). While other agricultural products produced in the region are of a lower scale, they can be listed as alfalfa, sunflower, watermelon and sugar beet respectively (Aran, 1996).

Climatical conditions

Kesikkopru Plain has continental climate where winters are cold and snowy, summers are hot and dry. Based on climate data for more than one year, the average amount of precipitation is 398.6 mm. Highest average temperature is 21.1°C in August and the lowest temperature is -3.8°C in January.

Water resources

Waters of Kizilirmak River stored in Kesikköprü dam were used as irrigation water in the experiment area. Average pH of irrigation water was determined as 7.7, electrical conductivity 1.76 dS m^{-1} and boron level 1.17 ppm. Total irrigable land of plain irrigation water supply is 4002 hectares. 1500 hectares of this land is on the left river bank and 2502 ha is on the right.

Model description

The one-dimensional, functional transport model TETrans was developed by Corwin (1990). Model results was transferred into the ArcGIS geographic information system (GIS) to provide spatial distributions of boron concentration in soil profiles over a selected geographic area. TETrans estimates the average concentration of a solute within each defined soil layer or depth increment. Transport through the soil profile is modeled as a series of events or processes for a finite collection of discrete depth intervals. These sequential events or processes include: i) infiltration and drainage to field capacity, ii) instantaneous chemical equilibration for reactive solutes, iii) water uptake by the plant root resulting from transpiration and evaporative losses from the soil surface and iv) instantaneous chemical re-equilibration. TETrans estimates the average concentration of reactive or nonreactive solutes through the vadose zone. The principal design philosophy behind TETrans was to develop a model around data which is commonly collected by irrigation districts or is present in existing soil databases. TETrans use the Langmuir adsorption isotherm model to simulate the adsorption of boron (Corwin and Waggoner, 1991). The TETrans algorithm is a mass balance calculation involving water and a single solute. When an irrigation or precipitation events occur, the water content of the top compartment increases due to infiltration. If the field capacity is exceeded, then water drains into the next lower compartment. This process continues downwards through all compartments until all water from the irrigation/precipitation event is accounted for. Water draining from the bottom compartment is assumed to enter the groundwater (Vaughan et al., 1993). The data need as input into TETrans includes: Initial boron concentration at each depth; initial water content of the soil at the each depth; date and amount of irrigation (or precipitation) water applied; Total evapotranspiration between irrigations; horizonation of the soil with the associated bulk density, water content, field capacity and water content at the wilting point for each horizon depth increment; boron concentration of irrigation water; date of planting, date of maturity, date of harvest, maximum depth root penetration, and plant root distribution of each crop.

The fact that TETRans was developed as a real-world application tool where limited knowledge of sophisticated transport information is available results in inherent strengths and weakness in the model. TETrans's include strengths; specifically designed to address real-world problems of contaminant transport and designed to use input parameters which are readily available, uses capacity input parameters which are less and user friendly. In contrast the weakness TETrans include; does not account for vapor phase flow and upward flux and calculate concentration distributions which are average concentrations for each depth increment (Corwin and Waggoner, 1991). The TETrans model was performed to estimate boron concentration to soil solutions in each sampling location. The estimated results of each georeferenced local data in different depth (from 0 to 20 cm to 80 to 100 cm) were prepared as a local geodatabase in ArcGIS that included observed data in different depth (from 0 to 20 cm to 80 to 100 cm) as well. The model results and observed data in each depth were mapped in ArcGIS spatial analyst and geostatistical analyst module. In this study that mostly model results and observations were discussed Ordinary kriging method was used to produce spatial distribution of boron concentration in each depth. By this way the integration of the model results and local observation points to GIS were provided to produce spatial distribution maps of soil boron concentration in different depth.

Evaluation procedure

A statistical evaluation of model reliability was performed by comparing measured and predicted daily water table elevations, drainage flow, and soil salinity at the end of the each season, drainage water salinity and relative crop yields. The agreement between predicted and measured values was quantified by calculating the standard errors (SE), average absolute deviations (*α*) and coefficient of efficiency (E). The average absolute deviation was calculated for each test period as given in Equation 1 (Janssen and Heuberger, 1995).

$$\alpha = \frac{\sum_{i=1}^{n} \left| Y_m - Y_p \right|}{n} \quad (1)$$

where Y_m is the i^{th} measured value; Y_p is the i^{th} predicted value for a total number of events "n", which is the total number of days in the case of ground water table depth, drain outflow, soil salinity and relative crop yield. The standard error (SE) was calculated as in Equation 2.

$$SE = \sqrt{\frac{\sum_{i=1}^{n} (Y_m - Y_p)^2}{n}} \quad (2)$$

The coefficient of efficiency E has been widely used to evaluate the performance of solute transfer models (James and Burges, 1982; Janssen and Heuberger, 1995; El-Sadek et al., 2001, 2003; Singh et al., 2001; Fernandez et al., 2006; Dayyani et al., 2009). Nash and Sutcliffe (1970) defined the coefficient of efficiency or modeling efficiency (E) as in Equation 3:

$$E = 1 - \frac{\sum_{i=1}^{n} (Y_m - Y_p)^2}{\sum_{i=1}^{n} (Y_m - Y_{avg})^2} \quad (3)$$

Where n is the total number of observations; Y_m is the observed value of the i^{th} observation; Y_p the predicted value of the i^{th} observation; and Y_{avg} the mean of the observed values (i = 1 to n). E values ranges from minus infinity to 1.0, with a value of 1.0 representing a perfect prediction, a value of 0 (zero) representing a prediction no better than using the mean of measured values, and lower values representing a progressively worse prediction. Values of E between 0.50 and 1.00 are considered acceptable.

Field studies

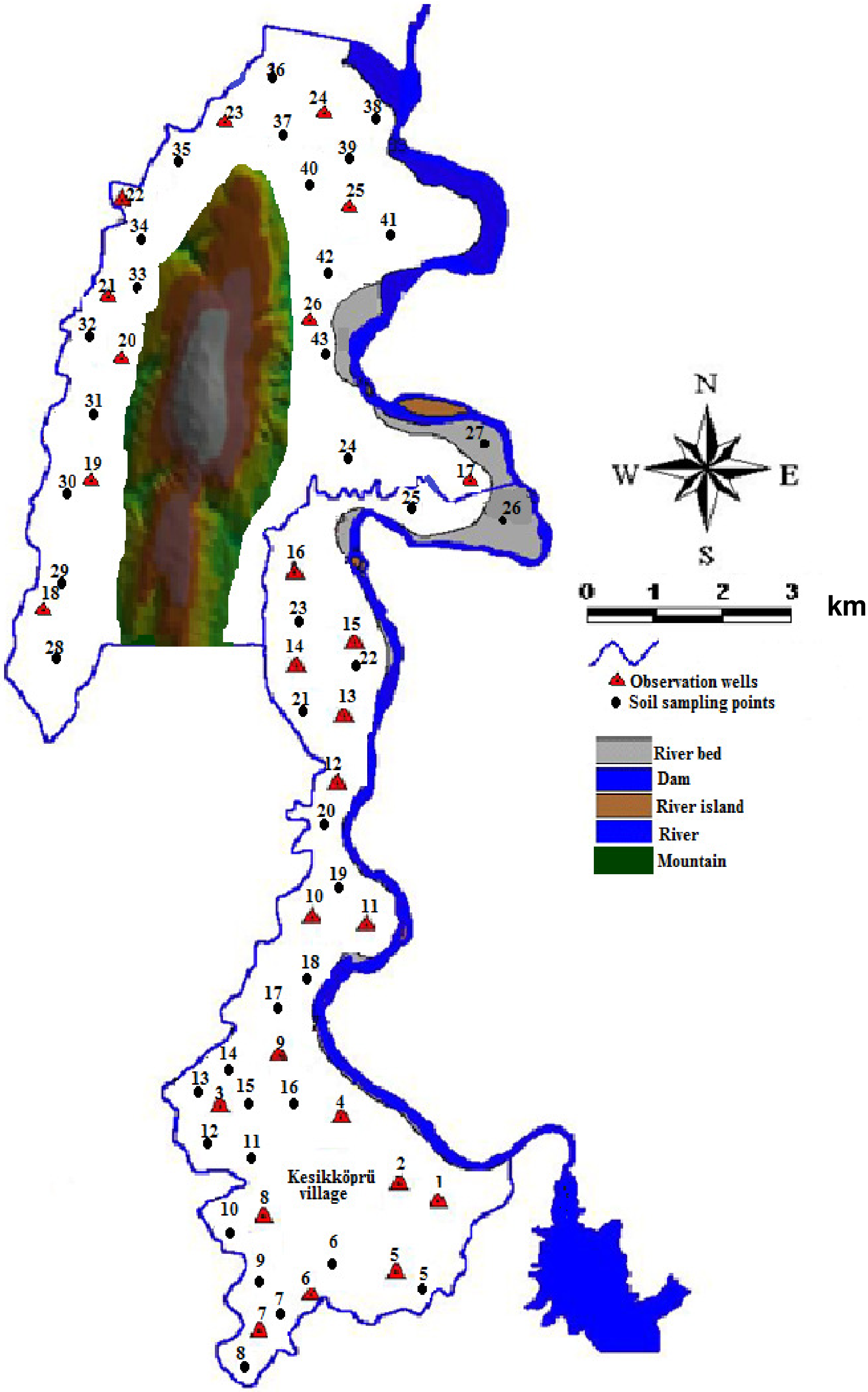
Sampling points were determined in manner to represent the whole irrigation area in the left river bank of Kesikkopru Plain (1500 ha) and coordinates of these points were recorded with GPS. Soil samples were taken from each sampling point from up to 1 m depth in layers of 20 cm, before irrigation period. Chemical and physical analyses were performed on the samples in order to determine the general soil characteristics of the study area and to be used as inputs for the model. Pattern of plant to be grown in the fields with sampling points and the rotation to be applied were determined. Information on the farmers who own the field to be irrigated were collected and the type of plant to be grown, dates of planting, and irrigation start dates and durations were determined. Amount of water given to the field by the farmer on these dates was measured using current meter. Also boron content was observed in the irrigation water samples taken. Soil samples were taken at the end of the irrigation season from the same depths at sampling points with coordinated designated previously in the previous year of the research study in order to compare the field measurements with those estimated by TETrans computer model.

Studies on the evaluation of the model using geographical information systems

Topographical maps covering the irrigation area in the left river bank irrigation area of Kesikkopru was rectified and digitized using Arc/INFO 7.1 GIS software. Irrigation area was digitized over the topographical map and the study area was determined. Study field and sampling points were set on forty three points which were considered to be suitable for topography on digital elevation model, their coordinates were loaded to GPS and georeferenced sampling was performed (Figure 1a). Soil maps for the irrigation area were digitized by rectification and soil map database was formed using ARC/INFO 7.1 and ArcView (Figure 1b). Thematic map for the present status of field use was formed with the help of soil map database. Figure 1c shows the present status of Land use distribution in the research study area. Soil samples were taken from 5 different soil layers at a depth range of 0 to 100 cm at forty three points in Kesikkopru left river bank irrigation area and these samples were analyzed in the laboratory. Krigging interpolation method was used in order to get the soil boron distribution. Interpolation was based on the values of all points. Mountainous and hilly areas where no agriculture is made within the research study area were left out of calculation, so interpolation was performed with the help of the interaction of points on the slopes of the hill with each other.

RESULTS AND DISCUSSION

In the study, carried out on basin level, first, necessary infrastructural arrangements and organizational operations (irrigation program, plant pattern etc.) were performed in 2000. Farmers owning the lands where irrigation is to be carried out were interviewed depending on the pattern of the plant to be grown on the fields with sampling points and planting, irrigation dates and irrigation periods were determined. Amount of water given to the field by the farmer on these dates was measured using current meter. Also boron content was observed in the irrigation water samples taken. Planting, maturing and harvesting dates were determined as 10 to 20 October 2001, 10 to 20 June and 11 to 20 July 2002 for wheat; and 7 to 17 May, 20 to 23 August and 15 to 29 September for bean, respectively. Three irrigation applications were made of about 330 to 350 mm in total in areas where wheat was planted by the points in May and June and generally after October. In areas where dry bean was planted, four irrigation applications were made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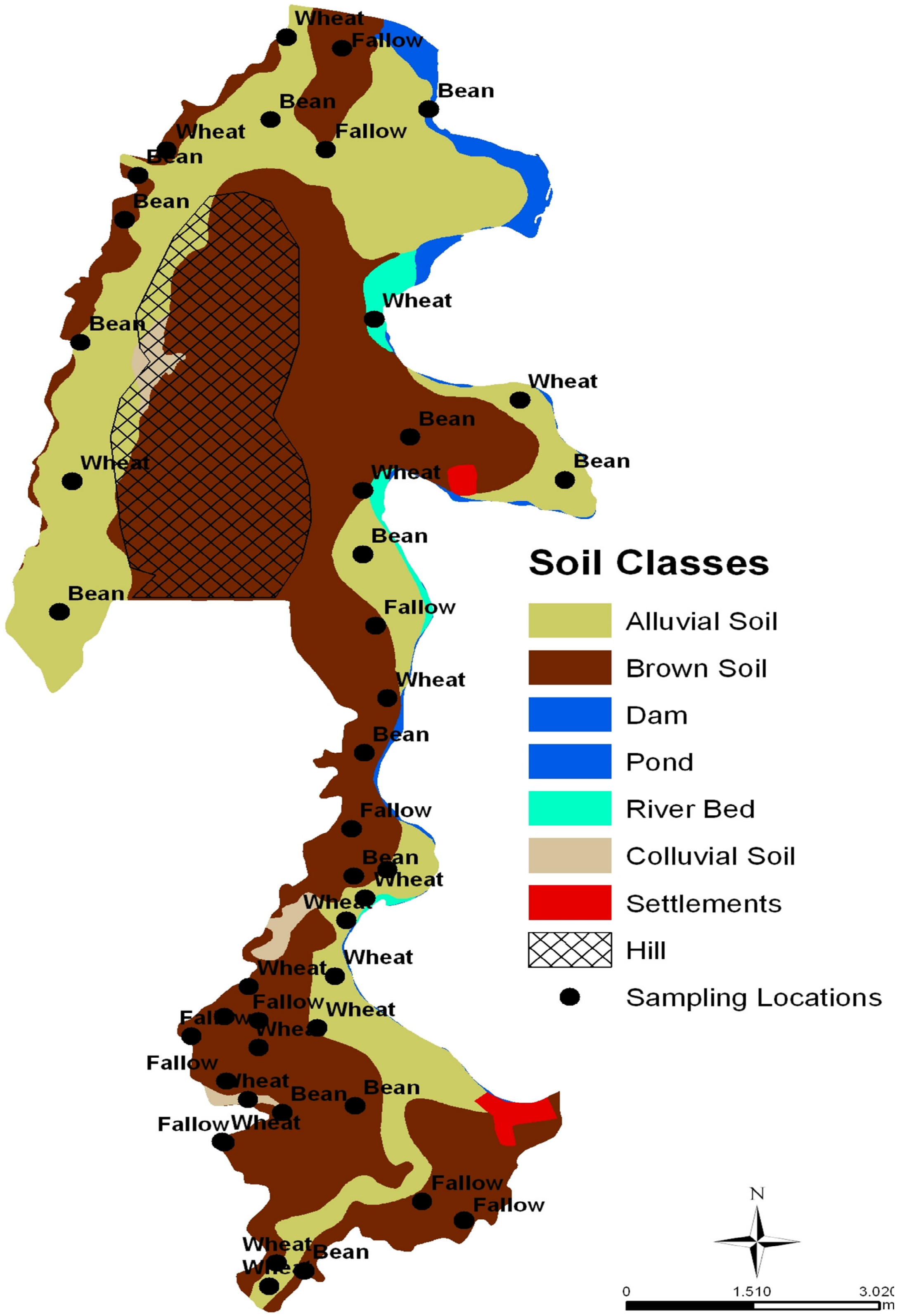
Kesikköprü village

(a)


Soil Classes
Alluvial Soil
Brown Soil
Dam
Pond
River Bed
Colluvial Soil
Settlements
Hill
Sampling Locations
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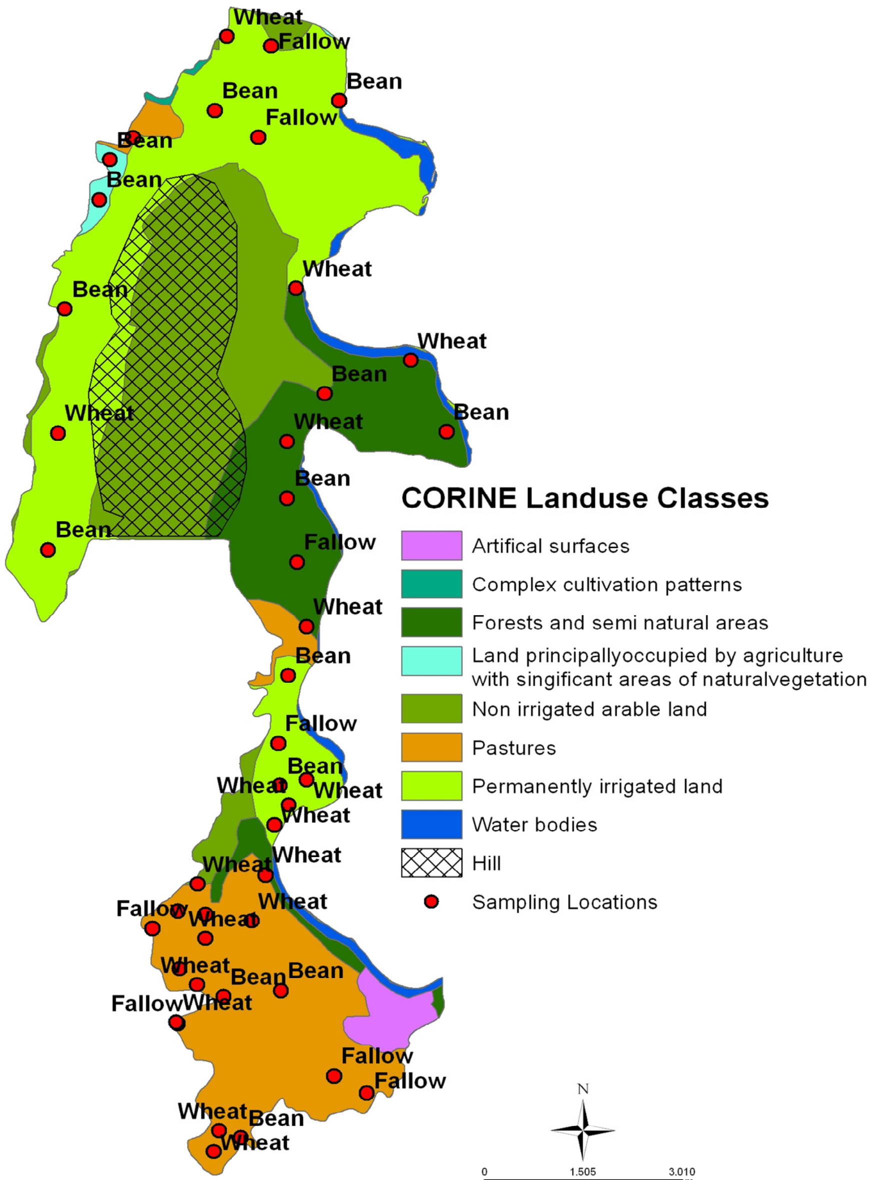
(b)



(c)

Figure 1. Sampling points: (a) Experimental area, (b) soil map and (c) of land use map.

between 390 to 440 mm in May, June, July and August. Irrigation water boron levels during irrigation season varied between 0.27 and 0.67 ppm. Effective root depth values for the plant grown based on the plant pattern in the field corresponding to each point were determined to be 90 cm for wheat and 75 cm for bean using the results of the research performed on these plants previously (Aran, 1996). The root zone was conceptually divided into four quarters, with a typical water uptake distribution pattern of 40: 30: 20: 10 starting with the shallowest profile (Ayers and Westcot, 1994). Crop data were stored in a table and each record consists of a crop ID number.

Model validation

Soil samples were taken at the beginning of the research study (2001) to determine initial boron level of soils. These boron values were used as an input of the model and simulation was made by the end of growing period in 2002. Results of this simulation were compared to the boron levels of soil samples taken from the field to test the capability of the program. Graphics for boron levels measured in five different depths in the field and estimated by the model are given in Figure 2. Tetrans is developed at catchment scale in order to display the

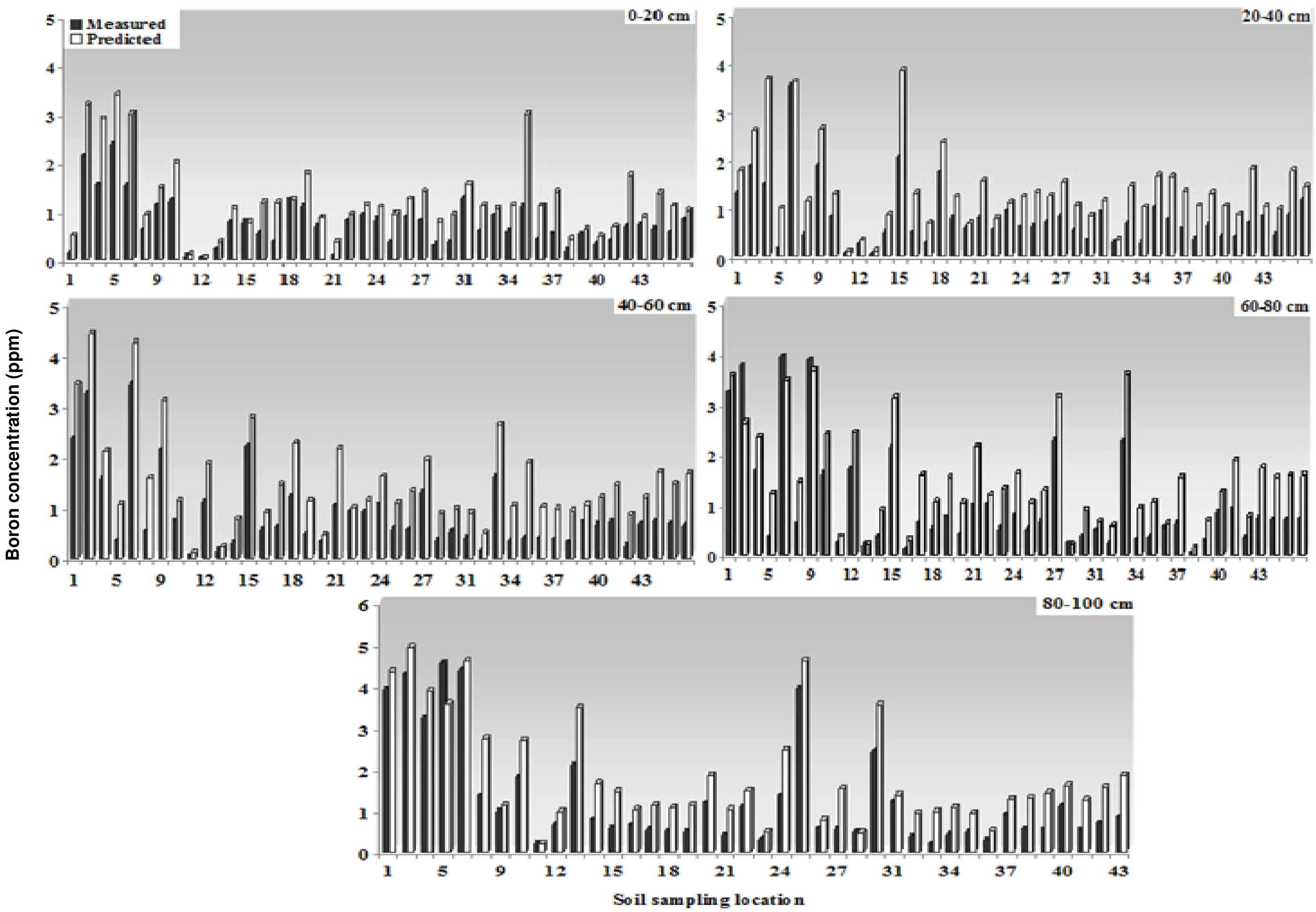


Figure 2. Boron levels measured in five different depths in the field and estimated by the model.

Table 1. Average absolute deviations (*α*) and standard errors of estimate (*SE*) and coefficient of efficiency for measured and predicted soil boron concentration.

Depths (cm)	n	α (ppm)	SE (ppm)	E
0 - 20	43	0.51	0.71	0.59
20 - 40	43	0.61	0.79	0.60
40 - 60	43	0.66	0.80	0.58
60 - 80	43	0.67	0.80	0.60
80 - 100	43	0.69	0.83	0.81

worst scenario on non point source pollutants without complicated inputs. Because of that boron estimation results of the model were observed higher than measured boron concentration in the field soil samples. However, TETrans model was able to simulate the transport of boron with deviations because no functional adsorption equation incorporated all the influences of pH, ionic strength, temperature and kinetic effects into a single equation. Statistical analysis was performed to evaluate of model performance. Average absolute deviations (*α*) and standard errors of estimate (*SE*) and coefficient of efficiency for measured and predicted soil boron concentration were given in Table 1. According to statistical evaluation; average deviation values were 0.51 to 0.69 ppm and standard error values over the simulated period were 0.71 to 0.83 ppm represented a good prediction for soil boron. E values 0.59 to 0.81 also indicate a very good relationship between the observed

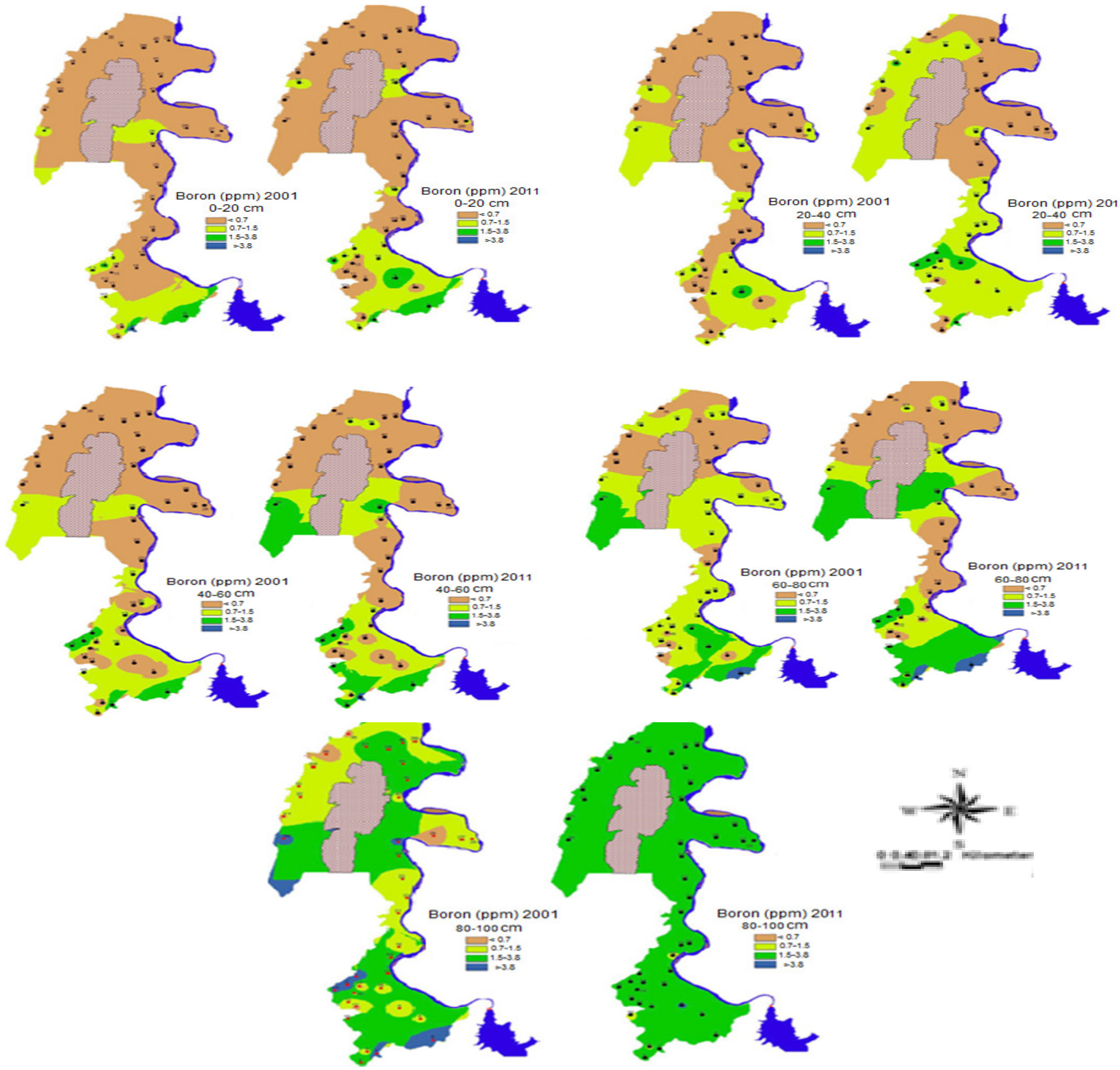


Figure 3. Boron levels in the soil for the year 2001 before irrigation and boron levels for the year 2011 estimated by the model after irrigation.

and predicted soil boron level.

Based on the results of the statistical analysis, it was seen that all model-estimated levels deviated from the measured levels for all depths. Model showed over estimation in general.

Future projection of boron concentration in the experimental field

After the model was check for statistical usability, the model was run using the boron concentration for soil samples taken beginning of the research study (2001) and potential boron risk that may be formed 10 years later (2011) was estimated. Changes in boron levels in ten years were mapped using the results of estimation (Figure 3). In terms of depths, initial boron content of the soil in the year 2001 varied between 0.5 to 1.5 ppm for up to 60 cm and between 1.5 to 5 ppm for 60 to 100 cm. 10 years later, it was observed that there was a certain amount of accumulation in depths of 60 to 80 cm and 80 to 100 cm. Boron concentration did not change very dramatically at the upper layers of the soil. It must be considered that the estimation can be helpful in reaching a general opinion as boron is a highly mobile element in the soil. Simulated boron concentration in soil profile showed that as long as the present conditions throughout the plain continue, there would be a boron problem to a significant level in the future. Pollution maps that are obtained will help executive and decision-making units in displaying more clearly the problem which may occur in the future and preparing action plans.

Conclusion

There has been renewed interest in the application of functional models to the transport of nonpoint source pollutants at farm level and watershed scales because of the ease of their coupling to a geographic information system. However, very little work has been done to evaluate the performance of a functional transient-state model for the transport of a reactive solute over an extensive study period. The reason why the functional model TETrans (trace element transport) was evaluated for model performance with boron transport data collected from 1500 ha irrigated field in this study. Geographic information systems (ARC/INFO) were used and contamination maps that were obtained to integrate, condense and summarize the large-scale (that is, thousands of hectares) behavior of spatially-variable soils to provide management guidance on issues related to boron-loading in the soil profile. Soil boron contamination maps will help executive and decision-making units in displaying more clearly the problem which may occur in the future and preparing action plans. According to study results, based on the estimated model values obtained at the end of the research, as long as the present conditions throughout the plain continue, there would be a boron problem to a significant level in the future. This in mind, urgent measures must be taken on plain basis.

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