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Stochastic simulation of water drainage at the field scale and its application to irrigation management

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ABSTRACT

To estimate water drainage at the field scale, a frequently adopted approach is using a deterministic model with field-averaged hydraulic parameters. However, spatial variability of soil hydraulic properties in the field is a potential source of error. This study evaluated the effect of spatial variability of surface soil saturated hydraulic conductivity (K_s) on water drainage. A conditional simulation (CS) method was used to generate a random field of surface soil K_s based on 117 observed values in the study area. The random field of surface soil K_s was then coupled with a dynamic soil water movement model (HYDRUS-1D). Water drainage during a period of 3 months was stochastically simulated with a total water input of 354 mm (including 270 mm of irrigation). Accumulated drainage beyond 2 m soil depth ranged from 23.7 to 64.7 mm, which accounted for 8.8–24.0% of the irrigation input. In addition, the accumulated drainage was also calculated using the measured K_s data and K_s estimated by an ordinary kriging (OK) method. Results obtained from the three methods showed that the accumulated quantities of water drainage obtained by the CS method agreed well with those from measured K_s data, while the water drainage range was narrowed by the OK method because of its apparent 'smoothing effect'. The effect of spatial variability of surface soil K_s on water drainage was demonstrated by the three methods and their results were all better than a traditional method that did not consider the spatial variability of surface soil K_s. An irrigation schedule was finally determined using the CS method. When the irrigation input was controlled between 190 and 200 mm, the schedule saved about 747 m^3 of water in a 1 hm^2 field, accounting for about 28% of the traditional irrigation applied, and the mean accumulated quantity of water drainage was only 2.3 mm, far lower than the 58.9 mm generated by the traditional method.

1. Introduction

The water resource per capita in China is about one fourth of the world average. Agricultural irrigation water accounts for 84% of the total water consumption in China. In most regions of the North China Plain (NCP), where most irrigation water comes from pumped groundwater, the groundwater level continually declines and large areas of groundwater funnels have formed due to continuous over-pumping in recent years (Zhang et al., 2000). Water drainage is one of the most common problems arising from improper irrigation management and low water use efficiency. Furthermore, water drainage at a field scale is closely related to solute leakage (salinity, nutrients and pollutants), and consequently improper water

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management usually leads to soil secondary salinization (Triantafilis et al., 2004) and groundwater contamination by nitrate and pathogens (Pang et al., 1997; Jin et al., 2000). Therefore, reducing water drainage, saving the water resource and increasing water use efficiency are key issues for sustainable agricultural development in the NCP.

In recent years, many researchers have used model-based simulation methods to quantitatively evaluate water drainage at the farm level. Li et al. (2000) systematically introduced the types and applications of soil water movement models in the field. De Jong and Bootsma (1997) used the SWATRE model to estimate water drainage in the root region and crop water deficiency. Heng et al. (2001) applied a water balance model to analyze multiple-year water drainage of a pasture in Australia. Mack et al. (2005) compared water drainage under different water and fertilizer management practices. In China, Huang et al. (1996) found that, in a winter wheat field in the suburb of Beijing, water drainage mainly occurred during the turning-green to elongation stage and the quantity was strongly related to the irrigation rate. Cao and Gong (2003) studied characteristics of field water drainage under different weather conditions using the HYDRUS-1D model. Hu et al. (2004) compared two types of models in predicting field water drainage.

The methods adopted in these studies are mainly based on deterministic models, which assume the whole studied area to be homogeneous. Few studies took into account the effect of spatial variability of soil properties on water drainage, and hence their results did not reflect the real conditions of their study areas. Therefore, deterministic models should give way to stochastic models, or at least stochastic parameters should be applied in deterministic models (Finke, 1993).

As soil hydraulic properties directly affect water movement, some researchers have simulated the effect of soil spatial variability on water and solute movement in bare soils (Russo, 1984; Indelman et al., 1998; Yang et al., 2000). But studies focusing on the effect of spatial variability on soil water movement under a growing crop are still rare. Due to the integrated influences of soil texture, bulk density and porosity, soil saturated hydraulic conductivity (K_s) significantly differs, especially for surface soil K_s in tilled lands (Xu and Mermoud, 2003; Iqbal et al., 2005). Thus, the objectives of this study include: (i) evaluating the effect of spatial variability of surface soil K_s on water drainage, (ii) comparing the results of water drainage calculated by different methods to determine the best method, including a method using measured K_s values, an ordinary kriging (OK) method and a conditional simulation (CS) method, which all consider spatial variability of surface soil K_s, and a traditional method which does not consider spatial variability, and (iii) determining an irrigation schedule using the best method. The results should be useful for developing effective strategies for irrigation management and environmental protection at field and regional scales.

2. Materials and methods

2.1. Field experiment

The study area was a 1 hm^2 field located at the Quzhou Experiment Station of China Agricultural University, Quzhou

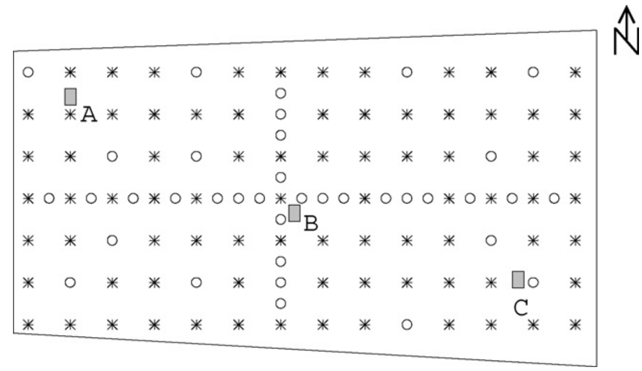

Fig. 1 – Diagram of the field sampling sites at Quzhou Experimental Station Field arrangement. A, B and C stand for the soil profile locations; '○' shows where K_s was measured by the disc permeameter; '⁎' represents the sampling location for estimating soil K_s.

County, Hebei Province in the NCP. The soil type is a Cambisol. The double cropping system is winter wheat-summer maize. The groundwater depth fluctuated from 3.0 to 4.5 m during the experiment period. In March 1999, we sampled the topsoil (0–20 cm) at 117 locations (Fig. 1) on a grid spacing of 10 m × 10 m, and 19 added points in the east–west and north–south directions of the centre of the field (5 m by 5 m). In addition, three soil profile pits (A–C) were excavated to 2.0 m depth, and 15 tensiometers and soil suction cups were installed at 10 cm intervals above 1 m depth, and at 20 cm intervals below 1 m in each profile. A 2.2 m long neutron access tube and a 6.0 m long piezometer were also installed in each profile. TDR was used to monitor topsoil (0–20 cm) water content.

Surface soil (0–20 cm) bulk density, particle-size fractions and saturated water content were measured at the 117 locations. The surface soil K_s at 37 locations was measured by a disc permeameter (see Fig. 1), and the K_s of the other 80 locations was calculated by a pedotransfer function (PTF) model using the Rosetta software, based on measured soil bulk density, clay, silt and sand content, and saturated water content of the topsoil (Schaap, 1999). Due to the small spatial variability in the subsoil (see Table 1), K_s in the different texture layers was measured by a Guelph permeameter in the three profile pits only.

Winter wheat was planted in early October and harvested in middle June. Winter irrigation was in the middle of December. The second irrigation was at the turning-green to jointing stage and the last irrigation at grain-filling stage. The amount of water applied each time was about 90 mm by flood irrigation. Ammonium carbonate (at 150 kg N hm^{-2}) as basal fertilizer was buried to 20 cm depth before sowing, and urea (at 150 kg N hm^{-2}) was surface-applied with the second irrigation. An automatic weather station was used to collect weather data. Soil moisture was measured by TDR and by neutron probes every 3 or 5 days. Total dry matter, leaf area index, crop height, root density and plant growth stage, etc. were also measured and have been reported in related literature (Hu et al., 2004).