



# A method for estimating the interaction depth of surface soil with simulated rain



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## ABSTRACT

The effective depth of transfer (EDT) between surface soil and runoff was determined by varying the physical properties of the soil, rain intensities (RIs), slope gradients, initial water contents, and soil amendment. The effects of these factors on the EDT were quantified with simulated rain. The EDT increased (0.12–1.09 cm) with an increase of RI and slope gradient (0–30°), and the effect of RI was attributed to increases in raindrop impact and runoff energy, which enhanced mixing in the surface soil. Slope gradient accelerated the velocity of water flow and decreased the stabilities of soil particles. The EDT increased from 0.192 cm to 0.709 cm with an increase in the initial water content, because variation in initial water content influenced soil infiltrability and detachability. The EDT exponentially decreased from 0.99 to 0.44 cm and from 0.86 to 0.36 cm for increasing amounts of dry granular and dissolved polyacrylamide (PAM), respectively, applied to the soil, likely because PAM improved the soil structure and prevented the formation of a crust. With soil-particle constitution ranging from silty clay to sandy loam, soil infiltration rate increased, and the EDT exponentially decreased with parameters  $K_d$  and  $K_p$ . We obtained an equation describing the combined effects of the various factors on the EDT by regression analysis. Analyses of root mean square errors and the coefficients of multiple determination indicated that calculated values fit the experimental data very well. This relationship provided a method of estimating the EDT and improved the prediction of the transport of adsorbed chemicals in solution, because current models of chemical transport use fixed values.

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## 1. Introduction

Nutrient concentrations in surface waters are driven by soil composition, which also affects groundwater inflow, runoff carrying waste and soil, evaporation, waste deposition directly into the water, and microbial activity (Strauch, 2011; van Puijenbroek et al., 2004). The role of nutrients in surface waters has not been fully explored in many semi-arid environments (Jacobs et al., 2007). Soluble fertilizers, pesticides, terrestrial municipal wastes, and other pollutants are released from a thin layer of surface soil that interacts with rain and runoff, leading to significant economic losses and degradation of surface and groundwater resources (Hutchings, 1998; Sharpley, 1985; Zhang et al., 2006). The release of chemicals to the runoff involves the adsorption and desorption of reactive chemicals by soil constituents and their transport by convection or by ordinary or enhanced diffusion (Wallach et al., 1989).

Analysis of the mechanism of nutrient release from the soil to the runoff is very important for determining the potential of both surface- and groundwater contaminations (Zhang et al., 1997). The development of a “shield” composed of relatively heavy soil particles

protects the underlying soil from erosion (Heilig et al., 2001). Chemicals near the soil surface are most likely to enter the runoff from the impact of raindrops, and the shield is then replaced with the exchange layer (Gao et al., 2004, 2005). Chemical transfer from a mixing zone is postulated below the soil surface in which rainwater, soil water, and infiltrating water mix instantaneously, completely, and uniformly, with no chemical exchange from below the mixing zone (Bailey et al., 1974; Donigian et al., 1977; Steenhuis and Walter, 1980). The thickness of the zone of interaction has usually been determined in models of chemical transport by calibrating the models with experimental data, with depths of 2–6 mm (Donigian et al., 1977), 10 mm or another fixed depth (Defersha and Melesse, 2012; López-Tarazón et al., 2010), or less than 10 mm (Snyder and Woolhiser, 1985), assuming that only a fraction of the chemicals at these depths interacts with rainwater (Frere et al., 1980). Tong et al. (2009) used a two-layer system to model the transfer of chemicals to surface runoff, in which the mixing zone and surface runoff were combined into a single layer. Dong et al. (2013) provided a simple model based on a measured value to study the transport of soil-dissolved chemicals in runoff by raindrops.

The mixing depth is a significant parameter in the transport of solutes from soil water to the runoff (Zhang et al., 1997). Studies using  $^{32}\text{P}$  as a tracer at several soil depths have shown that the interaction between rainwater and soil water was maximum at the surface and

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decreased rapidly with depth (Ahuja et al., 1981). The effective average depth of interaction (EDI) has been determined to be valid only with free infiltration (Snyder and Woolhiser, 1985; Ahuja and Lehman, 1983), and the effective mixing depth based on laboratory experiments was expected to be less than 3–4 mm (Zhang et al., 1997). Ahuja et al. (1981) examined chemical transport to the runoff on fast and slow timescales and proposed that the degree of mixing decreased exponentially with depth to 20 mm. Sharpley et al. (1981) calculated EDI using a model describing the kinetics of the desorption of soil phosphorus by runoff water. Wallach et al. (1988) developed the effective depth of transfer (EDT) model and assumed that the solute concentration in the EDT was equal to the concentration at the soil surface in the absence of infiltration. Wang et al. (1998, 2002) performed laboratory experiments to evaluate the different methods for calculating the depth of interaction between raindrops and the soil surface and developed the EID (equivalent interacting depth) and ETD (equivalent transfer depth) models. These experiments showed that the EID and ETD models were suitable for loessial soils. And then, they proposed an equivalent model of convection based on the concept of the EDT in 1999. This model described the transfer of chemicals from soil water at or near the soil surface to runoff on a loessial slope and assumed a mixing zone below the soil surface in which rainwater, soil–solution water, and infiltrating water mix instantaneously and in which the probabilities of chemicals entering the soil surface from the impact of raindrops are equal. Gao et al. (2004) demonstrated that the release of solutes from soil during storms depended on both the ejection of soil water by raindrop impacts and the diffusion of deeper solutes into the near-surface raindrop-driven “exchange” layer. In an associated study, Dong et al. (2013) integrated the equivalent model of convection by Wang et al. (1999) with physically based solute-transport models. In the new model, the presumed exchange layer was replaced by a mixing zone, and the mass exchange rate was replaced by the variable raindrop-induced water-transfer rate developed by Gao et al. (2004).

Early studies using  $\text{CaSO}_4$  in soil boxes under simulated rain showed that the depth of the mixing zone was influenced by slope gradient, rain intensity (RI), and rain energy (Ingram and Woolhiser, 1980). Walter et al. (2007) reported that initial soil–water content, RI, and slope gradient influenced the solute concentration of the runoff by their effects on the mixing depth. Most conceptual models describe the dependence of mixing depth on chemical transport, but few describe the combined effect of rain energy, slope gradient, and initial water content on the mixing depth. Our objectives were to study the effects of RI, slope gradient, initial water content, soil amendment (polyacrylamide), and soil texture on the interaction depth of loessial soil based on the refined equivalent model of convection (Dong et al., 2013) and then to provide a method of estimating the effective depth of transfer, thereby improving the prediction of the transport of adsorbed chemicals in solution.

## 2. Materials and methods

### 2.1. Experimental materials

Soil samples were collected from the A horizons (10–30 cm depth) of cultivated fields in the districts of Yangling, Ansai, and Shenmu in

Shaanxi Province on the Loess Plateau of China. The samples were air dried (2.3% soil–water content), and visible organic material was removed. The soil was sieved through a 5-mm mesh. The distribution of particle sizes was determined by sieving in combination with the pipette method (Hillel and Rossiter, 1981). Sieving determined that the soil from Yangling comprised 9% sand (>0.05 mm), 59% silt (0.05–0.002 mm) and 31% clay (<0.002 mm). The soil types were silty clay in Yangling, silty loam in Ansai, and sandy loam in Shenmu. The total contents of organic matter, nitrogen, phosphorus, and potassium are detailed in Table 1.

The experiments were conducted in laboratory flumes, 1 m long × 0.4 m wide × 0.5 m deep, in the rain simulation hall at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling, China. The air-dried soils were uniformly supplemented with 740 mg potassium per kg soil as  $\text{KNO}_3$  dissolved in water to simulate the local level of fertilization in Yangling. Water was then added to the soils to produce soil–water contents of 9.2, 13.6, 17.4, and 21.2%. A soil–water content of 2.3% (original after air drying) was also prepared by uniformly mixing the soil with a granular solute. The soils were then packed with plastic film and allowed to stand for approximately 24 h to facilitate the uniform distribution of the potassium for all levels of soil–water content. A 10-cm layer of sand forming a boundary permeable to air and water (Liu et al., 2011) was placed in the flumes, and soil of determined mass was uniformly packed 5 cm deep in the flumes layer by layer to a total depth of 35 cm for all experimental treatments. The angle of the flumes could be adjusted from 0 to 30° for the simulations of solute transport to the runoff at different slope gradients. The flumes were covered with plastic film to prevent evaporation prior to being subjected to simulated rain.

All experiments were performed with a rain simulator, the nozzles of which were placed 15 m above the ground to simulate natural conditions. The simulator was capable of generating computer-controlled RIs of 0.067–0.2  $\text{cm min}^{-1}$  (Fig. 1). Five RIs were studied, and each simulated rain lasted for 1 h. The effluents from the flumes were collected every minute for the first 10 min and then every 2 min for the next 50 min for measuring the amounts of runoff and sediment and the solute concentrations. The runoff volumes were obtained by weighing, the sediments were isolated by filtration onto filter paper and weighed after drying (Dong et al., 2013), and the concentration of potassium in the runoff was determined by atomic absorption spectrophotometry (Perkin-Elmer 5100ZL).

### 2.2. Experimental design

The experimental design included five factors (RI, slope gradient, initial soil–water content, application of polyacrylamide, which is abbreviated as PAM, and soil type) and four treatments. The first treatment tested five RIs (0.067, 0.1, 0.133, 0.167, and 0.2  $\text{cm min}^{-1}$ ), which are typically encountered on the Loess Plateau, and six slope gradients (0, 5, 10, 15, 20, and 30°) at an initial water content of 13.6%. The second treatment tested five initial soil moistures (2.3, 9.2, 13.6, 17.4, and 21.2%), levels relevant for practical decisions of irrigation management, at an RI of 0.133  $\text{cm min}^{-1}$  and a slope gradient of 15°. The third treatment tested the effects of two methods of applying the same amounts of PAM (dry granular and dissolved). The dry granular PAM had four

**Table 1**  
Selected soil properties.

Soil types	Particle size distribution (%)			Organic matter $\text{g kg}^{-1}$	Total nitrate $\text{g kg}^{-1}$	Total phosphorus $\text{g kg}^{-1}$	Total potassium $\text{g kg}^{-1}$	pH	
	Clay silt <0.002 0.002–0.05	Sand >0.05	Texture						
Yangling	31	59	9	Silt clay	21.93	0.12	0.09	2.197	6.5
Ansai	12	60	28	Silt loam	11.53	0.15	0.43	10.22	6.5
Shenmu	5	28	67	Sandy loam	5.64	0.24	0.95	21.4	6.0

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