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Modeling gypsifereous soil infiltration rate under different sprinkler application rates and successive irrigation events

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ABSTRACT

The marked reduction in infiltration rate caused by formation of a soil seal due to water droplets impact on gypsifereous soil surface is a well-known phenomenon, but is rarely considered in infiltration models, especially under center-pivot irrigation systems. A simple empirical model based on the Kostiakov equation was developed. The model was applied to center-pivot irrigation system for soils with different gypsum contents [60.0 (G1), 137.6 (G2), 275.2 (G3), 314.2 (G4), and 486.0 (G5) g kg^{-1}] under two sprinkler application rates (84.6 mm h^{-1} for R3000 red-plate sprinkler and 47.3 mm h^{-1} for R3000 orange-plate sprinkler) and eight successive irrigation events. The impacts of sprinkler droplets kinetic energy as well as specific power on soil surface sealing were evaluated also. A good agreement ($P < 0.05$) between the measured and predicted infiltration rate values was obtained.

1. Introduction

Infiltration is the process by which water enters the soil. It separates water into two major hydrologic components, surface runoff and subsurface recharge. Accurate determination of infiltration rates is essential for reliable prediction of surface runoff (Diamond and Thomas, 2003). The main goal of operating an irrigation system is to apply an adequate water depth over the field with minimum runoff. To avoid runoff problems, it is necessary to have a good understanding of soil infiltration characteristics when designing and managing infiltration systems. Sprinkler irrigation is becoming a preferred method as the water available for irrigation around the world becomes increasingly scarce, especially in arid and semiarid regions. Center-pivot is one of the irrigation systems that apply water with high-application rates, especially when operating with low-pressure sprinklers. The use of this irrigation system in soils with low infiltrability usually produces large amounts of runoff and soil erosion problems (Silva, 2007). Therefore, prediction of potential runoff is a very useful tool for proper design and management of center-pivot irrigation systems. For sprinkler irrigation systems, the soil infiltration rate determines the design application rate to avoid or minimize surface runoff, particularly in areas where water conservation is essentially required (AL-Ghobari, 2002). Infiltration is affected by properties of irrigation water and soil factors. The infiltration response to irrigation depth and application rate has been investigated by many researchers such as Moldenhauer and Kemper (1969), Morin and Benyamini (1977), Moore (1981), Mohammed and Kohl (1987), Gimenez et al. (1992) and Baumhardt et al. (1992). The operational characteristics of center-pivot sprinklers such as wetted diameter, application rate pattern shape and drop size distribution have been studied (e.g. Kincaid et al., 1996; Faci et al., 2001; DeBoer, 2001; Sourell et al., 2003; Playan et al., 2004; Kincaid, 2005). Chu et al., (1987) found a 100% increase in infiltration rate when water application rates were increased from 25 to 125 mm h^{-1}. DeBoer and Chu (1994) found that soil infiltration parameters derived from low application rate tests overestimated runoff values for sprinklers with higher application rates. Infiltration variation results from many causes such as surface sealing and crust formation processes, which can cause infiltration reduction, and are generally associated with the impact energy of water droplets on the soil surface (Moore, 1981; Morin et al., 1981; Thompson and James, 1985; Mohammed and Kohl, 1987; Basahi et al., 1998), can only be simulated in tests where water is sprinkled over the soil surface. Water droplet impact energy is directly influenced by pressure and sprinkler type. Nearly all the researches related to soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (Von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; Silva, 2006). Soil surface seal formation in combination with high water application rates under center-pivot sprinkler irrigation exacerbates potential runoff and erosion hazard. Runoff under center-pivot sprinkler irrigation is a well-recognized problem (Undersander et al., 1985; DeBoer et al.,

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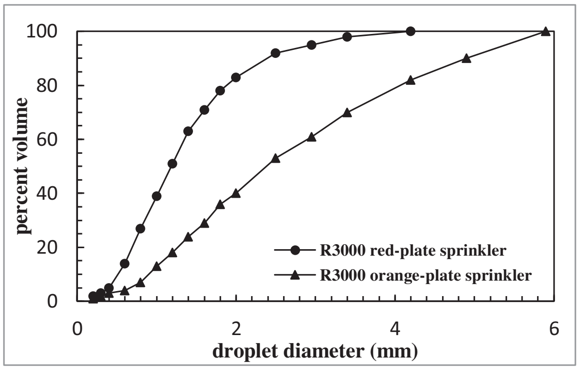

Fig. 1. Measured drop size distribution for R3000 orange-plate and R3000 red-plate sprinklers.

1992; Hasheminia, 1994; Ben-Hur et al., 1995; Silva, 2006), but is normally unseen because runoff often infiltrates before exiting the field boundary as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field. An important performance characteristic of sprinkler water application quality is the droplet size distribution (Dwomoh et al., 2014). According to Molle (2002), droplet size distribution determines the sensitivity of a sprinkler's water distribution to wind, evaporation and its impact on the crop or soil surface and slop. An adequate characterization of drops emitted by a sprinkler irrigation system permits evaluation of the kinetic energy with which drops impact the soil surface. Drop characteristics depend on a number of factors, including the type of sprinkler and nozzle size and configuration the operating pressure, and the environmental conditions (Zhu et al., 2012; Friso and Bortolini, 2010; Hills and Gun 1989; Li et al., 1994). A number of researchers have found strong relations between the kinetic energy of water drops and the change in physical properties of the soil surface. Thompson and James (1985) analyzed the increase in hydraulic resistance of the soil surface layer as the drop kinetic energy per unit soil surface area increased. These authors also reported a decrease in soil infiltration with increasing rainfall intensity, kinetic energy per water droplet, and water droplet energy flux. Kohl et al. (1985) reported an increase in kinetic energy per unit volume of discharged water when the operating pressure was reduced. Similar results were obtained by Basahi et al. (1998), when determining the specific power of experimental water drops impacting on a surface. Mohammed and Kohl (1987), discussed previous experiments performed by Duley (1939) and Ellison (1947), whose results showed that water drops destroyed surface aggregates and gradually formed a surface seal characterized by much lower hydraulic conductivity than the original soil surface.

Surface seal development has been linked to rainfall energy and intensity, as well as to soil aggregate stability (Thompson and James, 1985; Lehrsch and Kincaid, 2010). Large droplets may lead to erosion of the soil resulting from a reduction in water infiltration rate (Dwomoh et al., 2014). This is because large droplets possess high kinetic energy and on impart they disrupt soil surface, especially in soils with crustiness problems, leading to sealing of the soil surface (Kincaid, 1996). For this reason, it is becoming convenient for irrigators to reduce runoff and erosion by converting from sprinklers that emit large drops to those that emit smaller droplets (Friso and Bortolini, 2010; Chi, 2010).

However, studies evaluating the effect operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types are limited (Undersander et al., 1985; DeBoer et al., 1992; Silva, 2006; King and Bjorneberg, 2011).

Gypsum is rock-forming mineral that also occurs in soils. In arid and semi-arid environments, gypsum can be a major soil component. However, its composition sometimes overlooked or misexpressed even though its chemical formula ($CaSO_4{\cdot}2H_2O$) is quite simple (Herrero et al., 2009). The total estimated area of gypsifeerous soils in the world is 100 million hectares (FAO, 1990). Among this area, 5.42 million hectares are prevalent in Iraq (the study area) and it constitutes about 12% of the total area of Iraq and 38% of the total arable land. The gypsifereous soils are characterized by poor structure, aggregate stability, low water holding capacity and fertility. These soils are mainly cultivated with wheat (*Triticum aestivum* L.) and yellow corn (*Zea mays* L.) crops which completely depends on irrigation. The relative moderate solubility of gypsum in water renders such soils susceptible to sink-hole formation and caving. As the gypsum dissolves during flow creating more free space for the soil particles to orient themselves to a closer state of packing, causing a sudden fluctuation of hydraulic conductivity. The dissolution process is influenced by the type and amount of gypsum (Shihab et al., 2002 and Al-Saoudi et al., 2013). Recent agricultural development in Iraq has led to the increase of the number of center-pivot irrigation systems and this has led to higher water application rates and hence the increase of potential runoff, gypsum dissolution, sink-hole formation and caving problems in a country of limited water supply.

The objective of this study was to develop an empirical soil infiltration model based on Kostiakov equation capable of predicting infiltration rate under variable sprinkler application rates and successive water applications for gypsifereous soils with different gypsum constants.

2. Materials and methods

The study was conducted at the experimental farm of the University of Tikrit, Iraq, located at 34° 36′ N latitude and 43° 41′ E longitudes at an altitude of 250 m above mean sea level. The climate of the study area is semi-arid and sub-tropical with an average annual rainfall of 150 mm. the rain occurs from October to April (rainy season), which has uneven distribution. Averages of annual temperature, relative humidity, wind speed, sunshine duration per day and potential evapotranspiration were 17.4 °C, 52.9%, 2.8 m s^{-1}, 11.2 h and 1986 mm, respectively.

The soil of the experimental site is a Typic Calcigypside with a loam texture (composed 41.0% sand, 43.5% silt and 15.5% clay). The soil is shallow (0–13 cm deep), very poor in organic matter (0.67%) and low plant nutrient. The available water holding capacity of the soil is low (0.158 and 0.099 $m^3 m^{-3}$ for surface and subsurface horizons, respectively) with a moderate to high infiltration rate (3.72 and 10.98 cm h^{-1} for surface and subsurface horizons, respectively). Some physical characteristics and gypsum content of the soil at the experimental site are presented in Table 1.

Table 1
Some physical properties of soil at the experimental site.

Soil depth	Bulk density	Porosity	Particle-size fractions			Soil texture	FC*	PWP**
cm	Mg m^{-3}	%	Sand g kg^{-1}	Silt	Clay		$m^3 m^{-3}$	
0–13	1.42	46.28	410	435	155	Loam	0.231	0.073
13-72	1.37	48.20	–†	–†	–†	–†	0.124	0.025