



**Soil–aquifer phenomena affecting groundwater under vertisols: a review**

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# Soil–aquifer phenomena affecting groundwater under vertisols: a review

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## Abstract

Vertisols are cracking clayey soils that: (i) usually form in alluvial lowlands where normally, groundwater pools into aquifers, (ii) have different types of voids (due to cracking) which make flow and transport of water, solutes and gas complex, and (iii) are regarded as fertile soils in many areas. The combination of these characteristics results in the unique soil–aquifer phenomena that are highlighted and summarized in this review. The review is divided into the following four sections: (1) soil cracks as preferential pathways for water and contaminants; in this section lysimeter- to basin-scale observations that show the significance of cracks as preferential flow paths in vertisols which bypass matrix blocks in the unsaturated zone are summarized. Relatively fresh-water recharge and groundwater contamination from these fluxes and their modeling are reviewed, (2) soil cracks as deep evaporators and unsaturated-zone salinity; deep sediment samples under uncultivated vertisols in semiarid regions reveal a dry (immobile), saline matrix, partly due to enhanced evaporation through soil cracks. Observations of this phenomenon are compiled in this section and the mechanism of evapoconcentration due to air flow in the cracks is discussed, (3) impact of cultivation on flushing of the unsaturated zone and aquifer salinization; the third section examines studies reporting that land-use change of vertisols from native land to cropland promotes greater fluxes through the saline unsaturated-zone matrix, eventually flushing salts to the aquifer. Different degrees of salt flushing are assessed as well as aquifer salinization on different scales, and a comparison is made with aquifers under other soils, (4) relatively little nitrate contamination in aquifers under vertisols; In this section we turn the light on observations showing that aquifers under cultivated vertisols are somewhat resistant to groundwater contamination by nitrate (the major agriculturally related groundwater problem). Denitrification is probably the main mechanism supporting this resistance, whereas a certain degree of anion-exchange capacity may have a retarding effect as well.

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# 1 Introduction

Vertisols can be briefly defined as soils with 30% or more clay to a depth of 50 cm that have shrinking/swelling properties (Brady and Weil, 2002). More detailed definitions require the existence of a subsurface vertic horizon in which slickenside features are formed by the shrink/swell dynamics (FAO Corporate Document Repository, 2014; IUSS Working Group WRB, 2014). Other names used for these types of soils are: vertisols (common in Australian studies, e.g. Radford et al., 2009; Silburn et al., 2009; Gunawardena et al., 2011; Ringrose-Voase and Nadelko, 2013), and the more general “cracking clays” (e.g. Bronswijk, 1991; Liu et al., 2010). This latter generic term emphasizes both the hydrological complexity of these soils due to the inherent discontinuities (cracks) and their relevance for agriculture, being heavy, relatively fertile soils in many semiarid regions (good water-holding capacity, relatively higher organic content, etc.). Vertisols usually form in lowlands (Yaalon, 1997) where, typically, groundwater pools into alluvial aquifers. Hence, the interface between agricultural activity on these soils and the underlying groundwater resources is both complex and relevant. This review focuses on vertisol studies that have implications for the underlying groundwater resources; it does not cover the substantial body of literature concerning shrinking/swelling dynamics and its modeling (e.g. Bronswijk, 1988; Chertkov et al., 2004; te Brake et al., 2013), the purely agricultural and mineralogical aspects of vertisols (e.g. Bhattacharyya et al., 1993; Ahmad and Mermut, 1996; Hati et al., 2007) or environmental topics like the capacity of vertisols to sequester carbon (Hua et al., 2014).

Vertisols cover 335 million ha out of a total earth land area of 14.8 billion ha (2.3%). The largest areas covered with vertisols are in Eastern Australia, India, Sudan–Ethiopia and Argentina–Uruguay (FAO Corporate Document Repository, 2014). Smaller areas of vertisols are found in various countries (e.g. China, Israel, Mexico, Spain, Tunisia, USA, and many more). Although vertisols are very hard when dry, and very sticky when wet (making them difficult to till), in semiarid regions, irrigated crops such as cotton, corn, wheat, soybeans and others are grown on this soil. We acknowledge

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the dominant contribution of Australia to the literature on agro-hydrological aspects of vertisols. Conclusions from those studies have strengthened and generalized some of the findings obtained by the authors of this review in vertisol–groundwater studies in Israel, and have motivated this review (e.g. Arnon et al., 2008; Kurtzman and Scanlon, 2011; Baram et al., 2012a, b, 2013; Kurtzman et al., 2013).

The review is divided into four sections which are partially connected and together deal with major issues concerning aquifers under agricultural land: recharge, salinization and nitrate contamination (other contaminants are mentioned as well). The following four sections cover the most general and relevant issues concerning soil–aquifers phenomena under vertisols:

- soil cracks as preferential pathways for water and contaminants (Sect. 2);
- soil cracks as deep evaporators and unsaturated-zone salinity (Sect. 3);
- impact of cultivation on flushing of the unsaturated zone and aquifer salinization (Sect. 4);
- the relatively little nitrate contamination in aquifers under vertisols (Sect. 5).

## 2 Soil cracks as preferential pathways for water and contaminants

There are probably hundreds of studies that acknowledge preferential flow and transport through cracks in clays – too many to be mentioned here. This section aims to review works from the soil-column and lysimeter scale to the basin and aquifer scales that show the relations between preferential flow via cracks, deep drainage, and aquifer recharge and contamination. It also provides a short description of the development of models of preferential flow and transport through soil cracks.

## 2.1 Preferential flow of water in vertisols – evidence from the lysimeter to aquifer scale

On a small scale, Kosmas et al. (1991) observed bypass flow through cracks in clayey soils from Greece using undisturbed soil columns (authors' terminology) with a diameter of 23 cm. Ringrose-Voase and Nadelko (2013) measured flow in preferential paths directly using a field lysimeter that was installed 2 m below the surface without disturbing the overlying soil surface. Significant drainage was collected in this study when the hydraulic gradient in the matrix was in the upward direction, advocating drainage through preferential pathways in the cracks that bypasses the matrix. A weighing-lysimeter experiment in irrigated vertisols in eastern Australia revealed a more complex drainage mechanism following spray irrigation, where only deep parts of the cracks act as preferential pathways for the drainage when the top soil is moist and uncracked (Greve et al., 2010).

On the field scale ( $\sim 100\text{--}1000\text{ m}^2$ ), a similar phenomenon – i.e. open cracks at depth when surface cracks are mostly sealed – was reported by Baram et al. (2012b) throughout the rainy season in Israel. These authors compared transient deep (up to 12 m) water-content data collected by vadose zone-monitoring systems (VMSs, Dahan et al., 2009) at various sites, including very sandy soils; the comparison showed that by far, the fastest propagation of wetting fronts in deep vadose zones is observed in cracking clays.

Other field-scale vadose-zone studies reported that preferential flow through cracked clay enhances infiltration from rice paddies (Liu et al., 2004) and can lead to losses of up to 83% of the water to deep drainage during furrow irrigation of cotton and sugar cane (Raine and Bakker, 1996; Dalton et al., 2001; Moss et al., 2001; Smith et al., 2005). Losses to deep drainage in such agricultural practices averaged 42.5 mm per irrigation (Smith et al., 2005), ranging from 50 to 300  $\text{mm yr}^{-1}$  (Silburn and Montgomery, 2001). Chen et al. (2002) and Bandyopadhyay et al. (2010) showed that the transition from flood to micro-sprinkler irrigation and careful scheduling of water-application

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centrated animal feeding operations (CAFOs), such as dairy farms. Arnon et al. (2008) reported deep transport (> 40 m) of estrogen and testosterone hormones into the unsaturated zone under an unlined dairy-waste lagoon constructed in a 6 m thick vertisol in Israel. They concluded that deep transport of such highly sorptive contaminants can only occur by preferential transport. Baram et al. (2012a, b) reported that preferential infiltration of dairy effluents through the cracks at the same site can transport water and solutes into the deep unsaturated zone. Locally, groundwater under dairy farm areas also shows relatively high concentrations of nitrate (Baram et al., 2014).

Figure 1 provides a visual summary of Sects. 2.1 and 2.2. It shows the potential for matrix-bypassing groundwater recharge and pollution under vertisols. Passing the biogeo-active matrix enables both freshwater recharge and transport of reactive substances.

### 2.3 Development of flow and transport models in cracking clays

The field evidence described above motivated the development of quantitative methods to enable better predictions of flow and transport from ground surface to water table under vertisols. Nevertheless, modeling of unsaturated flow and transport as a dual (or multiple) domain (in their different variants, e.g. mobile-immobile, dual-porosity, dual-permeability) did not develop exclusively to deal with cracking clays and “macropores” as voids between aggregates, or worm-holes, are the preferential-flow paths of interest in many agricultural problems. Computer codes for modeling unsaturated preferential flow include among others: MACRO (Jarvis et al., 1994) and nonequilibrium flow and transport in HYDRUS (Šimůnek and van Genuchten, 2008). For further information on the kinematic wave approach used in MACRO, the reader is referred to German and Beven (1985); for comparative reviews of the different models and codes see Šimůnek et al. (2003), Gerke (2006), Köhne et al. (2009) and Beven and Germann (2013). The latter is more critical of the common use of the Richards (1931) formulation in single- and multiple-domain unsaturated-flow simulators.

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the upper 1 m of the soil profile and could not explain the increase in salinization in the deeper layers, whereas deep cracks could support the evaporation-created chloride profiles and low water content in the matrix.

Sun and Cornish (2005) used SWAT to model runoff and groundwater recharge at the catchment scale ( $\sim 500 \text{ km}^2$ ) in a vertisolic catchment in eastern Australia. Considering water balances at this scale, they concluded that recharge models need to have a component that enables taking moisture out of the lower soil profile or groundwater during dry periods. Both local- and higher-scale observations and analyses pointed to the hydrologically significant role of soil cracks as deep evaporators.

Baram et al. (2013) suggested a conceptual model termed “Desiccation Crack-Induced Salinization” (DCIS) based on previous work on subsurface evaporation and salinization in rock fractures (e.g. Weisbrod and Dragila, 2006; Nachshon et al., 2008; Kamai et al., 2009; Weisbrod et al., 2009). In DCIS, vertical convective flow of air in the cracks is driven by instability due to cold (and dense) air in the crack near the surface and warmer air down in deeper parts of the crack at night or other surface-cooling periods. The difference in the relative humidity between the invading surface air (low humidity) and the escaping air (high humidity) leads to subsurface evaporation and salt buildup (Fig. 2).

In many semiarid regions, deep matrix percolation under non-cultivated vertisols is very small due to the clay’s low hydraulic conductivity, root uptake of the natural vegetation in the rainy season, and evaporation through cracks in dry periods. Low water content in the deeper unsaturated zone results in low hydraulic conductivities and makes aquifer recharge through matrix flow very small year-round. Matrix fluxes in the scale of  $1 \text{ mm yr}^{-1}$  under the root/fracture zone were reported in a number of studies (e.g. Silburn et al., 2009; Kurtzman and Scanlon, 2011; Timms et al., 2012). These very low water fluxes contain the conservative ions (e.g. chloride) originating from 200–600  $\text{mm yr}^{-1}$  of precipitation (with salts from wet and dry fallout) that enter the matrix at soil surface. Therefore a dry (relatively immobile) and salty deep unsaturated matrix, developed for centuries–millennia under these non-cultivated vertisols. Nevertheless,

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some fresh recharge to the underlying aquifer through preferential paths related to cracks during heavy rain events creates an anomaly whereby relatively fresh water in the aquifer (e.g.  $\sim 250 \text{ mgL}^{-1}$  chloride, Kurtzman and Scanlon, 2011) lies beneath a salty and immobile unsaturated zone with pore-water chloride concentration of a few thousands of milligrams per liter (O'Leary, 1996; Kurtzman and Scanlon, 2011; Tolmie et al., 2011; Baram et al., 2013).

#### 4 Impact of cultivation on flushing of the unsaturated zone and aquifer salinization

The anomalous situation of fresh groundwater under a saline unsaturated zone found in some native-land vertisols in semiarid regions exists due to the dual function of the cracks, acting as: (i) deep preferential flow paths, and (ii) deep soil evaporators. However, what happens when natural conditions are changed to less favorable for soil cracks' development (e.g. cultivated land and more ever irrigated intensive cropping)? The answer is obvious: higher fluxes may develop in the unsaturated matrix which will flush salts and ultimately cause salinization of the underlying aquifer.

A large bulk of literature from eastern Australia has reported the leaching of salts and in some cases, salinization of aquifers under cultivated vertisols (e.g. Gunwardena et al., 2011; Timms et al., 2012; Silburn et al., 2013; Weaver et al., 2013; Young et al., 2014; Fig. 3). Earlier studies reporting leaching of salts from the vadose zone after clearing of natural eucalyptus trees for cropping include Allison and Hughes (1983) and Jolly et al. (1989), who worked in semiarid zones in Southern Australia. In those studies, neither vertisols nor the role of soil cracks was mentioned; however, deep eucalyptus roots act similar to cracks to form a very saline and immobile deep-unsaturated-zone matrix which becomes more mobile and less saline after the land-use change. Timms et al. (2012) inferred, from combined soil and groundwater data, deep drainage and salt leaching after conversion to cropping under gray vertosols in the Murray–

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observed due to piston-flow recharge pushing relatively saline vadose-zone pore-water down to the water table (Goldenberg et al., 1996, interpreted by Kurtzman and Scanlon, 2011).

## 5 Relatively little nitrate contamination in aquifers under vertisols

5 Whereas the literature concerning salinization of aquifers and draining of salts from the vadose zone under cultivated vertisols is abundant, much less has been written about the contamination of groundwater by nitrate under these soils. Nitrate is the most problematic groundwater contaminant associated with agriculture worldwide (Jalali, 2005; Erisman et al., 2008; Burow et al., 2010; Vitousek et al., 2010; Kourakos et al., 2012).  
10 Both mineral nitrogen fertilizers (e.g. Kurtzman et al., 2013) and organic forms of nitrogen (e.g. Dahan et al., 2014) are often applied in excess with respect to the plants' ability to take up the nitrogen, leaving significant quantities of nitrate as a potential groundwater contaminant.

15 While in the previous sections aquifers under vertisols were shown to be vulnerable to salinization, due to the agricultural practice above, there is an increasing number of observations that indicate lesser nitrate contamination in groundwater under cultivated vertisols relatively to groundwater of the same aquifer located under cultivated land of lighter soils. Kurtzman et al. (2013), dealing with nitrate contamination problems of the Israeli Coastal Aquifer, show that at the groundwater basin scale ( $\sim 2000 \text{ km}^2$ ) the  
20 contamination plumes of nitrate are present in the aquifer only under cultivated sandy-loams whereas under cultivated vertisols seldom sporadic wells produce water with nitrate concentration above the drinking-water standard (Fig. 4). E. Dafny (personal communication, 2014) revealed, by chi-square analysis that groundwater under cultivated vertisols and thick clayey-alluvial unsaturated zone, are less likely than groundwater  
25 under coarser sediments, to get contaminated by nitrate in the Condamine Floodplain Aquifer in Australia.

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kaolinite is found in most vertisols (e.g. Singh and Heffernan, 2002; Krull and Skjemstad, 2003; Baram et al., 2012b). Therefore, retardation of nitrate in the vadose zone due to adsorption to positively charged sites within the clay might also slow down groundwater contamination under cultivated vertisols. Nevertheless, if significant, this mechanism would only retard groundwater contamination, whereas denitrification removes the nitrogen from the soil–unsaturated zone–aquifer system. The idea of nitrate adsorption has been tested as an engineered solution for reducing deep nitrate percolation. Artificially synthesized materials that have nitrate-sorption capacity (e.g.  $[\text{Mg}_{0.82}^{2+}\text{Al}_{0.18}^{3+}(\text{OH})_2]^{0.18+}[(\text{Cl}^-)_{0.18} \cdot 0.5(\text{H}_2\text{O})]^{0.18-}$ ) are being tested as soil additives to buffer nitrate leaching (Torres-Dorante et al., 2009).

## 6 Conclusions

Vertisols are considered arable soils in semiarid climates, and are intensively cultivated. Located in lowlands, vertisols often overlie aquifers. Flow and transport through the cracking clays is complex and results in unique land–aquifer phenomena. Observations from the lysimeter to basin scale have shown (directly and indirectly) the significance of cracks as preferential flow paths in vertisols that bypass matrix blocks in the unsaturated zone. These preferential paths support recharge with relatively fresh water in uncultivated vertisols, and groundwater contamination from point sources such as CAFOs and under some conditions, from crop fields. Deep soil samples under uncultivated vertisols in semiarid regions reveal a dry (immobile), saline matrix, partly due to enhanced evaporation through the soil cracks. This evaporation is related to convective instability due to colder air at ground surface and warmer air deep in the crack during the night. In some aquifers lying beneath vertisols in these regions, relatively fresh groundwater exists under the saline unsaturated zone. Land-use change to cropland promotes greater fluxes through the saline matrix which flush salts into the aquifer and eventually cause groundwater salinization. In contrast to the vulnerability of groundwater under vertisols to salinization, observations show that this soil–aquifer setting

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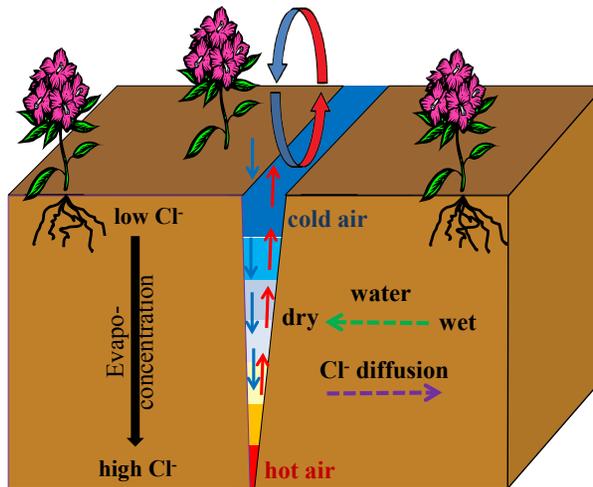


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**Figure 2.** Desiccation Crack-Induced Salinization (DCIS) (Baram et al., 2013). Convective instability of air in soil cracks, occurring mainly at night, leads to drying and salinization of the unsaturated zone.

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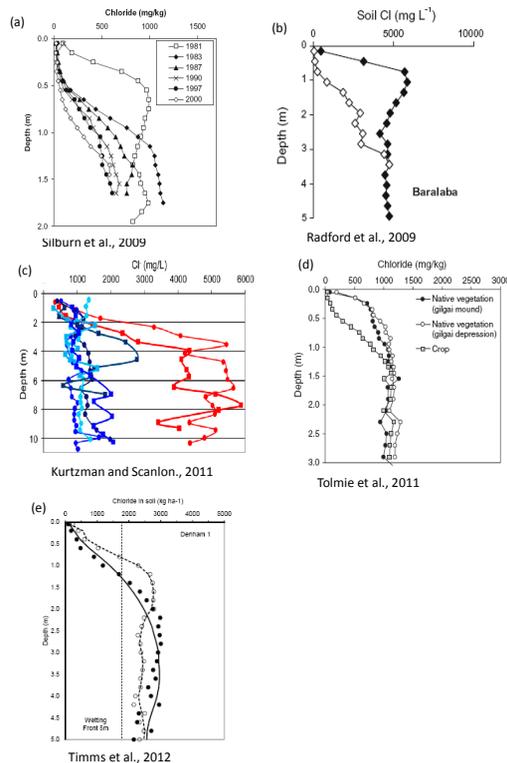
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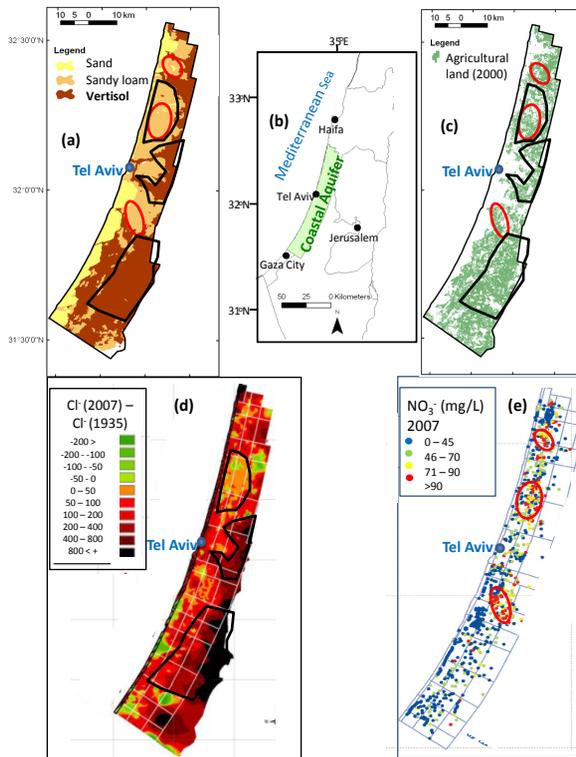
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**Figure 3.** Flushing of chloride down through the unsaturated zone under cultivated vertisols: **(a)** Silburn et al. (2009) – 19 years of flushing; **(b)** Radford et al. (2009) – full diamond, native vegetation; empty, annual cropping; flushing from the top 3 m; **(c)** Kurtzman and Scanlon (2011) – red, natural land; blue, irrigated cropping; flushing from 2–10 m depth; **(d)** Tolmie et al. (2011) – flushing from the top 1.5 m. **(e)** Timms et al. (2012) – black, cropping; empty – grass; flushing from the top 2 m.



**Figure 4.** Plan views of the Israeli Coastal Aquifer. **(a)** Soil type (black polygons and red ellipses for spatial comparisons with **(d, e)**, respectively). **(b)** Location map. **(c)** Cultivated land in the year 2000. **(d)** Difference in chloride concentrations between 2007 and 1935 (modified from Livshitz and Zentner, 2009). Black polygons are characteristic cultivated areas that were severely salinized (southern polygons) and barely salinized (northern polygon) relative to soil type **(a)**. **(e)** Nitrate concentration in groundwater wells in 2007 (modified from Hydrological Service, 2008). Red ellipses – areas with many wells contaminated with nitrate relative to soil type **(a)** (modified from Kurtzman et al., 2013).