Hydrol. Earth Syst. Sci. Discuss., 12, C4911–C4925, 2015
www.hydrol-earth-syst-sci-discuss.net/12/C4911/2015/

Hydrology and Earth System Sciences Discussions

Interactive comment on "Soil–aquifer phenomena affecting groundwater under vertisols: a review" *by* D. Kurtzman et al.

D. Kurtzman et al.

daniel@volcani.agri.gov.il

Received and published: 17 November 2015

Response to comments made by Anonymous Referee #1 (Authors answers follow the referee comments)

It should be acknowledged that the line numbers pointing to locations of revisions in the manuscript may not reflect the location in the final revised manuscript. The up-to-now revision is available upon referee's request by Email: daniel@agri.gov.il

1) I applaud the author for attempting to explain some of the mystery's surrounding water flow in cracking clay soils and in the groundwater systems under them. I would encourage you to continue with this but as yet you have not succeeded in mounting convincing arguments around several key points, and as such the paper requires major

revision before it should be published. Some of these weaknesses are:

1) We thank the referee for his/her efforts made on this elaborated and constructive review (and for his/her applaud). We are sure that the comments improved the manuscript.

2) You have not provided convincing evidence that the high deep drainage rates see in many studies on Vertisols, especially when irrigated, require preferential flow in cracks, and that it can't be explained by matrix flow.

2) This review does not claim that relatively high deep-drainage rates in cultivated vertisols (moreover irrigated) require preferential flow in cracks. On the contrary, Section 4 describes the high fluxes that were reported to develop in the matrix of cultivated vertisols and their consequences on salt flushing and salinization.

3) You have not considered the possibility of either palaeo-recharge or river recharge being the source of the low salinity groundwater.

3) This review is on soil-aquifer phenomenon affecting groundwater under vertisols, hence river-bed, paleo, or mountain-front recharge that may cause a situation of relatively fresh aquifer under a saline vadose zone, are not something that should be elaborated upon here. The soil aquifer phenomenon of interest, also in such cases, is the salinization of the aquifer after intensive cultivation begins on land surface, is elaborated upon in section 4. Nevertheless we understand the referee's concern of the text at the end of section 3 and beginning of section 4 being a little biased towards the crack related phenomenon and included other ("non vertisolic") processes that have influence on some aquifers under vertisols (lines 295-306 in the revised text).

4) You should explore the differences in the implications of cracks in dryland/rainfed and irrigated/ponded ('free water') situations. Is water flow in cracks exclusively due to "free water" (e.g. furrow irrigation, ponded water)? How much contribution does the rare instance of rainfall derived runoff occurring when cracks are present?

4) We thank the referee for this suggestion. We did acknowledge some different behavior of deep drainage under different surface-wetting conditions and thanks to this comment did a few changes to highlight the differences (e.g .lines 109 – 110 in the revised text) acknowledging furrow irrigation in Ringrose-Voase and Nadelko (2013) versus spray irrigation in Greve et al., 2010 in lysimeter experiments. Field scale studies that deal with irrigation losses in cracking clays are discussed in a long paragraph in the original manuscript (P. 5 line 21 – P.6 line 6). The effect of cracks on water and vapor fluxes is much smaller in cultivated land than it is in native-vegetation land yet we mention many studies that reported preferential flow also under cultivated land in section 2.1. In non-cultivated verstisols it is not rare that rainfall runoff percolate through cracks at the beginning of the rainy season and after dry weeks within the wet season (see P. lines 7 – 15). Further more some deep cracks do not seal completely (section 2.1). Preferential flow may occur also in cracks between rows in orchards and in non-tiled crop fields in vertisols. A comparison between the strength of deep drainage in rainfed cropping versus irrigated cropping, was added in section 4 (lines 310-318).

5) You have not provided convincing evidence that evaporation from cracks has a large contribution to total water loss compared with transpiration. The hot/cold model does not really help as on hot days the temperatures are usually the other way around.

5) It is obvious that in wet conditions and deep rooted vegetation transpiration is the dominant mechanism that dries up the deep vadose zone, and that will be right for any type of soil. Nevertheless, this article is about cracking clays so in comparison to other soils there are cracks that have additional deep drying capacity, making the phenomenon of dry and saline deep vadose zone more significant under vertsols. We elaborated on that in section 4 of the review. Evaporation through cracks occur at nights when surface temperature falls and warmer air is found deep in the crack while cooler air is on top of it near ground surface, causing instability.

6) You have under played role of the deep roots in native vegetation and of transpiration as main cause of cracks. Also there should be a lack of cracks below the root zone.

One approach is to point out where these weaknesses are and make the need for further work on them a feature of the paper.

6) - We declare in the introduction that this review does not cover cracking dynamics. - In Mediterranean climate some areas are covered with winter vegetation which is completely dry in mid-summer and deep soil cracks are wide open at times when there is no root activity.

7) Abstract A reasonable summation of the paper. 7) Good

8) General/Introduction "Vertisols usually form in lowlands (Yaalon, 1997)" Minor point butthey also occur in upland basalt areas where they usually recharge productive aquifersand rolling lands formed on sedimentary rocks with poor, saline aquifers, at least in Australia.

8) The sentence sais "usually" and for this paper the triplet of vertisol, agriculture, and groundwater is more relevant in lowlands.

9) You could also explain that the evidence for preferential flow is mixed. Many studies of deep drainage/recharge do not explain the mechanism involved (your first section, 2.1) whereas tracer and some lysimeter studies (second section, 2.2) do define the mechanism/proportions involved. Also preferential flow seems to be conditional (e.g. deep rooted vegetation different to cropping, moisture content effects; more likely to occur under furrow irrigation than rainfall).

9) The review is about Soil-Aquifer Phenomena Affecting Groundwater under Vertisols, and highlights the special phenomenon related to cracking clays. Section 2.1 is titled: Preferential flow of water in vertisolsâĂŤevidence from the lysimeter to aquifer scale, it is not a discussion on deep drainage/recharge. Nevertheless, we agree with the referee that some of the field scale observations that reported deep drainage losses in cracking clays may be caused by crack or matrix flows therefore we acknowledged that where its relevant in the revised text (line 130).

10) 2.1. Preferential flow of water in vertisols Lines 127-129. Note that these references do report high rates of deep drainage, but they do not differentiate between matrix and preferential flow. To keep this point clear, you should review the rates of drainage observed without attributing it to preferential flow, and then separately review those studies which have evidence of the flow pathway, or proportions, responsible for the drainage. High deep drainage rate does not necessarily require preferential flow – matrix flow is sufficient. I doubt that Raine and Bakker, 1996; Dalton et al., 2001; Moss et al., 2001; Smith et al., 2005 would have been able to separate the type of flow either.

10) . A clarification acknowledging that deep drainage in these studies may include preferential and matrix flows was introduced in the revised text (line 130)

11) In a variable tension lysimeter (like that of Ringrose-Voase and Nadelko (2013)), Silburn et al. (2013) found the proportion of preferential flow was small compared to total drainage & matrix flow. The soil in this case was not cracked and had been _field capacity for a considerable period, indicating that flow through closed cracks is limited. Rapid flow still occurred but this was attributed to high suction gradients as the wetting front advanced. This does not rule out preferential flow at other moisture contents. See section 'Understanding flow processes in clay soilsâĔŸAĔĞ Tvariable tension lysimeters and tensiometry' in Silburn et al. (2013). "Deep drainage measured at 1m depth was dominated by matrix flow, with only 10% of drainage attributed to preferential flow (note that the soil was never dry enough to crack); that is, 90% of drainage was explained by Darcy flow." You could mention this at line 116.

11) Not sure that preferential flow is lesser than matrix drainage at the Ringrose-Voase and Nadelko (2013) case who acknowledge "Bypass drainage appears to account for most of the drainage during the measurement period". Neverhelless, thank you for pointing to another lysimeter measurement case were matrix flow certainly dominates. We added this observation to the revised text (line 112-117)

12) Your observation on line 122 is compatible with the lysimeter measurements of

Foley/ Silburn; clay soils develop large suction gradients and flow rates.

12) Although gradients are high across the wetting front in the matrix the hydraulic conductivity of the clay is low, and fronts will advance at relatively smaller velocities (m/day, weeks, month). Baram et al., 2012 report wetting-fronts velocities of a few meters per hour in non-cultivated cracking clay which cannot be explained with matrix flow.

13) Line 138: "sandier soils (Alfisols)" .. these soils are highly likely to be hard setting, lacking in aggregation and poorly structured : : : such soils also occur in Australia. They would be expected to have high runoff. For example, Littleboy et al. (1999) Aust. J. Soil Res. calibrated a runoff curve number of 94 for cultivated Alfisol in India, compared to a CNbare of 74 for Vertosols at a number of sites. So calling them sandier is not really correct; they have enough fines to fill the pores between the coarse particles. It is the large plant available water capacity and the good structure and aggregation that explain the lower runoff from the Vertisols.

13) We cite Pathak et al., 2013 work from India in this line. At that work the vertisols had 12-22% by weight in the sand interval of particle size (0.05 – 2mm) whereas the alfisols samples had 42 – 75% of the particles in the sand interval so they are sandier. Generally vertisols will contain 30% or more clay by definition whereas in alfisols will usually have a clay fraction of less than 30%.

14) Lines 145-147. Dafny and Silburn (2014) do mention flow in preferential pathways as an additional mechanism to matrix flow and that diffuse recharge is now included in groundwater models. However, they do not say "modelers had to include a diffuse (areal) recharge flux through soil cracks." The part about soil cracks in incorrect – it might be true but Dafny & Silburn didn't say it.

14) Thank you for the comment, we agree with the referee the citation is a little biased towards the purpose of this section: Preferential flow of water in vertisolsâĂŤevidence from the lysimeter to aquifer scale. The reason for the somehow biased citation is

the sentence from Dafny and Silburn (2014): " Following the growing evidence of the feasibility of percolation through cracking clays, several recent studies have included a component of diffuse recharge in their assumptions or models . . ." the term " percolation through cracking clays" lead to "recharge flux through soil cracks". The paragraph was changed to better reflect Dafny and Silburn (2014) ideas of "diffuse recharge" in the Condamine River Alluvial Aquifer (lines 153-157)

15) Lines 148-150. My memory of Kurtzman and Scanlon (2011) is that they attributed the existence of fresh groundwater to recharge flow through preferential paths that bypassed the saline vadose-zone matrix under pre-agricultural deep rooted native vegetation but that this process ceased once agriculture started, and then recharge through the matrix caused salt export to groundwater and increasing salinities. Adding the latter part of the story gives a richer picture I think.

15) Salinization of groundwater after land use change under some vertisols (including the case studied by Kurtzman and Scanlon 2011) is described in section 4, and shouldn't be introduced in section 2.1.

16) 2.2. Preferential transport in vertisols This section makes a stronger case for your story because the studies directly or indirectly reveal the mechanism involved. The Hardie case is interesting: it reinforces that "free water" is needed for flow to occur through preferential flow paths – in his case by saturation occurring in the sandy A horizon (I assume). Thus preferential flow should be more likely with e.g. furrow irrigation, dairy ponds etc, than under rainfall. You might find the paper by Prendergast (1995) of interest, although it might go against you case for flow in cracks somewhat. "Prendergast (1995) has shown that bypass flow can have the same Cl concentrations as the soil . Soil Science Society of America Journal 59, 1531–1539. doi:10.2136/sssaj1995.03615995005900060004x

16) Deep drainage through soil cracks is a more significant phenomenon in non-cultivated vertisols, where cracks are well developed. It certainly requires substan-

tial rain events that produces runoff. Evidence that soil cracks do not seal completely (Baram et al., 2012) make this phenomenon possible well into the rainy season. In cultivated land significant preferential flow may occur at the edge of rice paddies or in paddies between seasons; in drip irrigation orchards where cracks may develop at the center of the rows between (parallel) drip (tree) lines (the same occurs in some crop fields); in furrow-irrigation as reported by Ringrose-Voase and Nadelko (2013) and others. More uniform distribution of irrigation water (e.g. frequent sprinkling) and tillage are less favorable for desiccation cracks development and deep preferential drainage through cracks. Significant deep percolation of storm water through cracks bypassing the matrix will result in relatively fresh-water deep-drainage. Saline bypass flow is possible in smaller deep drainage events. Salt deposits on the dry crack walls as a result of the DCIS mechanism described in the paper and if the preferential by pass flow is small dissolution of the salt deposits may cause relatively high salinity in the bypass flow similar to matrix flow. Prendergast 1995 shows that using chloride concentrations at 2 depths below the root zone to estimate bypass fluxes assuming the bypass salinity is negligible does not fit tracer fast arrival (bypass), hence the assumption of negligible salinity in the bypass flow should be rejected. The analysis there is based on soil samples and there is no direct observation of bypass salinity versus matrix flow salinity, therefore we do not think it gives a strong contribution and prefer not to mention it.

17) 2.3. Development of flow and transport models in cracking clays Line 207. Form needs to be from.

17) Corrected, thanks.

18) Line 226-227. "Hendriks et al. (1999) used a code named" this sentence does not seem to make sense.

18) Clarified line 231 - 232

19) Line 236. What do these models tell us about the proportion of preferential flow and the conditions where this proportion is larger or smaller? The paper would be improved

if the outcomes of using these models are included.

19) Section 2.3 describes the development of flow and transport models in cracking clays from the general mobile-immobile, to the fracture oriented models and more recently the full dual permeability with cracking dynamics. In other places in the review we mention works where models contributed to understand mechanism (e.g. Sun and Cornish, 2005). The aim of this work is to highlight soil aquifer phenomenon in vertisols. Compilation of works reporting the proportion of matrix and crack deep-drainage in different conditions is not a main theme of the review, nevertheless some works that provide such proportions are discussed in section 2.1.

20) Soil cracks as deep evaporators and unsaturated-zone salinity Why is this section 3 and not 2.4?

20) Section 2 is about preferential flow and transport of water and solutes in cracks and section 3 is about evaporation through cracks and unsaturated zone salinity under vertisols.

21) 247-248. "water uptake by roots was limited to the upper 1 m of the soil profile" – this statement is not justified by the data given in the publications cited: Native vegetation including trees: Silburn et al. 2009 found water use by native vegetation (& pasture, weeds and crops; unpublished data) to the depth of sampling _1.8 m. Radford et al., 2009 found dry soil under native vegetation to 3 m at several sites; other sites presumable had received more rainfall. Silburn et al., 2011 found dryer soil to 4+ m at three out of four Cl sites under native vegetation. The additional 8m deep core had tree water use /dryer soil to at least 3 m and somewhat drier soil to 7-8m. These types of native vegetation have lived in soil with high sub-soil salinity for 1000's of years. The extra osmotic potential created by these salinities is only a few bars (from memory). (Many crops use water to nearly 2 m in many Vertosols, pastures can be to 2.5m; 1 m for native vegetation is unlikely).

21) The text was modified to be clearer that the root depth of 1 m was not the case

in the Australian case studies that reported saline deep vadose zones (lines 252-256). Deep roots evaporate water from deep in the unsaturated zone profile in many type of soils. The main difference between cracking clays and other soils are the cracks. Therefore the hydraulic mechanisms that are facilitated by the cracks are highlighted in this review. Other mechanism like matrix percolation in high water contents and water up take by deep roots occur in vertisols as well as in other soils therefore they are not the focus of the review.

22) 249-250. This is not logical. The salinity profiles can easily be explained by matrix infiltration refilling the soil water to 2-4m (i.e. root zone) and subsequent removal of water by transpiration. The small rates of deep drainage (e.g. 1 mm/yr) below the root zone contain high salinities and have salinised the unsaturated zone over 1000's of year. Raats (1974) simulated this scenario. Large amounts of rainwater/ runoff entering cracks would have been more likely to created low salinities in deep layer. Raats PAC (1974) Steady flows of water and salt in uniform soil profiles with plant roots. Soil Science Society of America Proceedings 38, 717–722. doi:10.2136/sssaj1974.03615995003800050012x

22) We have no argument with the referee that many unsaturated zones under native lands in semi-arid areas are relatively dry, immobile and saline due to 1000s of years of transpiration of deep rooted vegetation. What we are saying that in cracking clays even if no deep roots are found (e.g. dry hot season in places with no perennials where the winter shrubs are totally dry) deep cracks contribute to the same mechanism of drying the deep vadose zone.

23) Sun and Cornish (2005) – they probably needed to do this to explain deep water use by native vegetation (believed to be many meters, Kath et al 2014). "groundwater depth thresholds identified in the range from 12.1 m to 22.6 m for E. camaldulensis and 12.6 m to 26.6 m for E. populnea beyond which canopy condition declined abruptly" i.e. tree decline occurred (only) when groundwater was pumped down to these thresholds; Kath et al (2014) - Kath et al (2014) Groundwater decline and tree change in floodplain

landscapes: Identifying non-linear threshold responses in canopy condition. Global Ecology and Conservation 2 (2014) 148–1.

23) Trees with roots in groundwater may be a source of deep evaporation in dry periods. Another type of evaporation from deep soils that is characteristics of cracking clays, in dry period are deep soil cracks. Text was modified to show both sources of deep evaporation under vertisols (lines 261-267).

24) I don't think you have made a convincing case to this section. You could equally explore the proposition that cracks form where the soil is most dry and further drying is at low rates. The description of DCIS does not at much to the discussion. Also you don't cite actual studies of evaporation from cracks – I assume there are some?

24) We do not agree with this comment. Baram et al., 2013 provides calculations of deep evaporation near a dairy farm waste lagoon in an area with hardly any vegetation and many deep crack, where chloride mass balance (and mechanistic flow models) fitted to observation showed that 85% of the infiltrating water evaporate. The potential of the convective evaporation process suggested by DCIS is very high – of course the moisture flowing to the crack walls is the limitation for actual evaporation. We cited other works that worked on evaporation of the same mechanism in fractured rock which all show the high potential for evaporation through cracks. More indirect (large scale) and laboratory and field works that support the evaporation through soil cracks were added to the revised text (text modified 261-267, 276-278).

25) Line 265. "(Fig. 2). Under non-cultivated soils" – something wrong here.

25) We do not understand this comment (there is no such text in the manuscript)

26) Line 266 In many semiarid regions, : : : add "with native, perennial vegetation". Note it is mainly the large water use compared to rainfall and the large water storage capacity of vertisols that limits deep drainage; the low hydraulic conductivity not really the issue (as seen once they are converted to cropping or irrigation.

26) The water uptake by vegetation comes just a little down the sentence. Dry and saline deep vertisols are found also in areas with very limited perennial vegetation. At high water contents the low hydraulic conductivity of clay (relative to lighter soils) plays a role in the relatively small deep matrix percolation. The retention capacity of clay was added (line 280).

27) Lines 270-278. Yes I can see the logic of this (as per Kurtzman et al). But equally, why are most non alluvial and some alluvial areas of vertisols in Australia underlain by many meter of saline unsaturated zone and groundwater of salinities of 20,000-50,000 uS/cm?? Classic examples of the situation you are describing are the Condamine (Dafny & Silburn 2014), Lockyer and Callide alluvial groundwater systems; in each case recharge from the river is the mechanism used to explain the fresh recharge. In contrast, many of the Vertosol sites of Tolmie et al, Radford et al, Silburn et al 2009, 2011 have the situation you describe in the soil profile but lack fresh groundwater (& a river!). What is the difference between these two cases other than having a river?

27) See answer to comment number 3

28) Impact of cultivation on flushing of the unsaturated zone and aquifer salinization Line 284 "ii) deep soil evaporators". Again, there is strong evidence for 1) deeper native veg roots, 2) large transpiration removing soil water, but relatively little evidence for deep losses by evaporation. Without roots removing deep soil water there will be no cracks.

28) See answers to comments number 21-24

29) Lines 287-288. Yes to that part. 29) Good

30) Lines 308-310. I thought part of your argument (Kurtzman et al) was that conversion to cultivation removed the deep water use and cracking, increased the deep drainage rate and converted more of the drainage to matrix flow, thus the additional salt flushing/leaching. Why go back to preferential flow & deep soil evaporation here –

weakens you argument?

30)We thank the referee very much for this comment, the original organization of the sentence within this paragraph was not very clear. The sentence was rewritten to clear that the salinization of an aquifer due to cultivation may be more pronounced in vertisols rather than only the salt flushing phenomenon described before, which is a result of matrix flow(334-338).

31) Lines 314-316. Did the loamy-sand soils have lower salinities that the vertisols.

31) Concentrations of chloride Under loamy sands: 1933 – mostly 50-100 mg/l; 2007 – mostly 100-250 mg/l Under vertisols: 1933 – mostly 100-300 mg/l; 2007 – mostly 600 – 2000 mg/l

32) Relatively little nitrate contamination in aquifers under Vertisols Line 350: "loams whereas under cultivated vertisols seldom sporadic wells produce water" : : : missing a word

32) a coma was added before whereas

33) Lines 356-360. Silburn et al. (2013) indicate the modern deep drainage and any solutes are still migrating down through the unsaturated zone in these clayey alluvial systems, and that they were very dry to many meters under native veg (water use/root zone). Recent soil sampling indicates large concentrations of nitrate in the deeper subsoil (to 1.6m) under irrigated cotton. Stratification of new water on top of old water would also make detection difficult in normally constructed wells.

33)These lines describe groundwater phenomenon rather than unsaturated zone observations. The reasons for the lack of nitrate contaminations in groundwater under vertisols are discussed in the following paragraphs. As suggested by the referee: A paragraph in which the slow unsaturated flow is mentioned as the reason for little groundwater contamination was added (thou not the case for the Israeli Coastal Aquifer; lines 389-395).

34) Line 368 "DOC in the lighter soils was higher than 15 mg/kg dry soil, only in the top 1 meter in the" move the comma to after "top 1 meter"

34) Corrected as suggested (line 404).

35) Line 379: need pH on <5.5 but more likely less to have anion exchange, but most Vertisols are neutral to alkaline throughout.

35) We thank the referee for this constructive comment. A sentence acknowledging pH as a limiting factor for nitrate adsorption was added (lines 421-423)

36) The Burdekin irrigation area is a large aquifer in Northern coastal Australia. It has two main soil; heavy clays and well drained lighter textured soil ("the delta"). Rising water levels have been occurring for a long time in both. A large excess of nitrogen fertiliser has long been used on the main crop, sugar cane. High nitrates have long been a feature of the aquifer under the lighter textured soil. However, there is now evidence of rising nitrate concentrations in the aquifer under the clay soils as well. To me this is saying the deep drainage and nitrates was delayed in the unsaturated zone and have started arriving at the water table.

36) Good to know the phenomenon of rising nitrate concentration under the lighter soil is observed in other aquifers (any publication available?). Was there salinization under the clays? Can the rising water tables under the clays be explained without accounting for recharge from the irrigated land above? If so, maybe the lack of nitrate-concentration rise under the clay should be explained by the mechanism suggested in this paper. In irrigated areas above exploited aquifers water-level rise comes usually after decline of pumping due to salinization of the aquifer.

37) Overview The fact that cracks are formed mainly by plants extracting water, and that deep cracks can only form if plants extracted water at some time in the past, is not mentioned. Soil evaporation alone is only capable of shallow fine cracking (self-mulching) if starting form an uncracked condition.

37) See answer to comment # 6

38) References Silburn, M. and Montgomery, J.: Deep drainage under irrigated cotton in Australia: a review, Cotton Consultants Association Meeting, Dalby, Queensland, 21–22 June 2001, 2001. Should be replaced with one of these: Silburn DM and Montgomery J (2004). Deep drainage under irrigated cotton in Australia – A review. WATERpak a guide for irrigation management in cotton. Section 2.4. pp. 29-40. (Cotton Research and Development Corporation/Australian Cotton Cooperative Research Centre, Narrabri). Silburn DM, Montgomery J, McGarry D, Gunawardena T, Foley J, Ringrose-Voase A, Nadelko A (2013). Deep Drainage Under Irrigated Cotton in Australia – A Review. WATERpak Chapter 1.5. (Cotton Research and Development Corporation, Narrabri, Australia). pp. 40-58. 2013 is an update of the 2004 paper, which started as the CCA (unpublished) paper.

38) We assume the referee is one of the authors of this publication, and changed the citation as requested to the 2004 version (lines 785-788).

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 9571, 2015.