Authors' Responses

The authors would like to gratefully acknowledge the insightful comments and the encouraging support of the editor, Prof Fuqiang Tian. We also appreciate the time the anonyms reviewers put in reading our manuscript, and the comments were valuable, refreshing, and encouraging. We have taken the time to think through all the comments and have adequately addressed all the comments item-by-item in the following 14 pages. As a result of these suggestions, we believe that the resulting paper is effectively improved. Before we submit the revision, a native English speaker (Marian Rhys, she is also a professional English editor) was invited to polish the manuscript thoroughly. In the following document, we are providing the responses to reviewers, as we have submitted in the interactive discussion. Please find below your reproduced comments, followed by our point-by-point responses (in blue or red). Below the responses to reviewers, we are providing the marked-up revised document.

Response to Editor

General comments

As you can see from Referees' comments as well as my own comments, a significant revision is still required. Please revise your manuscript by strictly following all comments.

RESPONSE: We warmly thank Professor Fuqiang Tian for the overall favorable impression of the work, and for his thorough review and the detailed, helpful comments. Please find our point-by-point responses.

Especially, I would like to draw the authors' attention to the points below:
1) Be careful with the term used, especially water budget, drainage driver, etc.

RESPONSE: Thanks for the nice suggestion. We agree that misusing the terms could lead to potential confusions for readers. According to the suggestion, "water budget" has been replaced with "water balance" and the "drainage driver" also has been removed from the revision.

2) The major work is the application of inverse Richards approach to obtain drainage and ET. Please clarify its novelty.

RESPONSE: To solve the concern, the introduction section was partly reworded and additional information about the novelty of this work were added (Line 81-104). We also clarify and highlighted the novelty in the discussion section (4.4 Potential for SWBC estimation by using soil moisture measurements). Please check the revised manuscript for details (Line 491-496, Line 519-521).

3) Highlight other possible novelties.

RESPONSE: We pointed out in the introduction section of the revision that "These types of measurements provide critical information for ecohydrology, agricultural, and hydrological researches in the arid environments, but mostly served as either an indicator for drought monitoring and forecasting (Anderson et al., 2012), or boundary conditions and/or calibration data for models (Vereecken et al., 2008). So far, however, relatively few work has been published on testing the potential of using a soil moisture database as a method to systematically estimate the *SWBCs* of farmland in the drylands, where the principal soils are coarse-textured (Grayson et al., 1999;Yang et al., 2018b) and tend to have low water retention capacity and higher drainage (Lal, 2004)". We also highlighted that "…exploring a reliable farmland *SWBC* estimation method that can make the most of the vast amounts of soil moisture data, is crucial for irrigation management optimization (Musters and Bouten, 2000; Sharma et al., 2017), especially for irrigating arid regions with such coarse-textured soils." Please check the revised manuscript for details. (Line 491-496, Line 519-521).

Specific comments

1. Water budget method is actually not water budget; it is actually a water balance method. Budget term often means storage, but in your method only soil moisture is a budget term, other terms (evaporation, percolation, irrigation) are all flux terms. So, it is suitable to name it as water balance method.

RESPONSE: Thanks for the nice suggestion, we fully agree with this point. Following the suggestion, we changed the term of "water budget method" to "water balance method" in this revision.

2. The paragraph starting from L62: the author should pay attention to the following work, which has utilized measurement of soil moisture and ET (by Eddy Covariance) to estimate deep percolation. *Zhang, Z., Hu, H., Tian, F., Yao, X., and Sivapalan, M.: Groundwater dynamics under water-saving irrigation and implications for sustainable water management in an oasis: Tarim River basin of western China, Hydrol. Earth Syst. Sci., 18, 3951-3967, doi:10.5194/hess-18-3951-2014, 2014.*

RESPONSE: We have carefully read the recommended literature, and got many inspires from it. The paper published by Zhang et al. (2014) also was cited in this revision as an case study that calculate deep percolation as a residual of the water balance (See Line 65-67 in the revision for details).

3. The paragraph starting from L121, it is redundant to describe the field experiment in terms of cropping effect on soil property, because the main target of this study is to explore the flux estimation by using water budget methods.

RESPONSE: This paragraph has been slightly shortened to avoid redundancy, and make it more focused on the main target which is to explore the flux estimation by using water budget methods (See Line 128-132 in the revision).

4. The paragraph from L139, more details on irrigation should be given because of its importance, e.g., irrigation method, timing, irrigation quota, during, etc. Table is preferred.

RESPONSE: Although most of the details have been included in the early version of the manuscript. More detailed information (i.e., irrigation method, irrigation quota, etc.) were added as a new table in the revision according to this suggestion (Please see Line 150-155 in the revision for details). A new table was also added to show the irrigation schedule and quota (Table 1). please see Line 168-171 for details.

5. Section 2.3 1), it is unclear how to decide percolation. It is confusing to say deep percolation begins after soil moisture storage reaches its maximum (I assume it is S_{max}) but to say for a specific case percolation occurs before S_{max} occurs. It is unclear in Fig.2(b) how to determine the timing when percolation starts.

RESPONSE: Sorry for the confusing wording. The detailed methods used to determine percolation were descripted in Section 2.3 2), and in Section 2.3 1), we provided an assumption here that "no surface-water excess or steady-state flow took place during any irrigation event, and deep percolation usually occurred after soil moisture storage reached maximum (S_{max}) …". This assumption is the base of percolation determination in next step. We further clarified this point in the revision and the confusing sentence has been reorganized based on the suggestion provided by Professor Tian as below: "Although a few specific cases of percolation could occur before the S_{max} is reached (second panel in Fig. 2b), it had little effect on the estimation of irrigation volume because the maximum soil water storage differed little (by only 1.86 mm) before and after deep percolation began. For instance, we checked all the irrigation events of NT1-NT6 during the entire growing season period, and there were no underestimates of S_{max} except for two irrigation events in NT2, which only had a slight underestimate of 1.86 mm and 10.3 mm, and generated errors of 1.1% and 4.1%, respectively" . The timing when percolation starts in Fig.2(b) was determined whenever the soil water content in the deepest layer (90-110 cm) is measured to be greater than "field capacity" (Θ_{fc}), i.e., Rice et al. (1986)". We have added this information in the revision, please see Line187-194 for details.

6. When the authors adopt Richards Equation to calculate slow drainage term, a lot of uncertainty related with soil hydraulic parameters are introduced. How do the authors deal with this uncertainty?

RESPONSE: This is a very important question. Yes, potential uncertainties could be introduced into the calculation of slow drainage term by soil hydraulic parameters, due to the possible changes over time in the parameters itself (Shein, 2015). This point has been considered when preparing the earlier version of the manuscript, so that all the parameters, including soil bulk density (ρ_b), vertical saturated hydraulic conductivity (K_s), and soil water retention, were determined using standard laboratory procedures on undisturbed soil cores in steel cylinders taken at 20-cm intervals down to 100-cm depth. The measured parameters were further profile-averaged for all the plots to improve the experimental uncertainty. To better solve the concern, we have clarified this point and some related discussions were added in the revision (see 4.5 Uncertainty analysis for details). We also argued "Although this cannot fully prevent the development of uncertainty caused by the parameters, such uncertainties are trivial especially in light of the relatively small proportion of slow drainage in the context of sandy soils, i.e., only about 9.5% of the drainage occurred during this stage according to our calculation (Table 3)". Please see Line 539-543 in the revision for details.

7. The title should be something like: quantification of soil water balance components based on continuous soil moisture measurement and Richards equation.

RESPONSE: According to the comments, the title of this paper has been improved to "*Quantification of Soil Water Balance Components Based on Continuous Soil Moisture Measurement and Richards Equation in an Irrigated Agricultural Field of a Desert Oasis*". Thanks for the nice suggestion.

8. In 4.3, I don't think it is necessary to discuss the impact of cropping system on soil property. It is irrelevant to the topic.

RESPONSE: We agree that this part is a little bit irrelevant to the main topic present in this paper. After careful consideration and discussion with the coauthors, we reorganized this section as a new one "4.3 Effects of the variances in soil hydrophysical properties on the SWBC estimation". Most of the irrelevant discussions and conclusions have been removed from the revision, and potential problems that could be introduced into the SWBC estimation by the variances in soil hydrophysical properties were kept and elaborated in the revision. We stressed that "In this desert oasis and other ones located in arid northwest China, most of the fields belong to smallholder farmers, who usually follow different cropping patterns and tillage methods, resulting in a heterogeneity of soil hydrophysical properties. For the soil-moisture data-based method proposed in this paper, the spatial heterogeneity of the soil hydrophysical properties may restrict its applicability to a large agricultural area". Through a brief analysis of the potential influence of different cropping systems on soil hydrophysical properties, we confirmed that "different cropping systems and agronomic manipulation have limited effects on differing soil physical characteristics in sandy soil, at least at a decade scale", and we argued that "The limited influence of different cropping systems on soil hydrophysical properties in coarse-textured soil environments at a 10-year scale indicates a good stability and representativeness of the measured soil hydrophysical data and thus a good application prospect for applying the soil-moisture data-based method in practice." Please see Line 461-480 in the revision for details.

9. Line 485 - 487, the statement is true. For the extreme case, irrigation lasts throughout the growing season with very small irrigation intensity, which should mean water can only wet surface thin soil layer and it cannot support water to crop root. Also, you should consider the salinity issue. See the discussion in Gao Long, Tian Fuqiang, Ni Guangheng, Hu Heping. Experimental study on soil water and salt movement and irrigation scheduling for cotton under mulched drip irrigation condition. Journal of Hydraulic Engineering, 2010, 41(12):1158-1165. (in Chinese)

RESPONSE: Very nice suggestion. To be more logical and rational, this statement has been rewording as: "Early researches suggested that decreasing the irrigation amount and increasing the irrigation frequency, and thus maintaining a relatively constant level of soil moisture with less stress from "too little or too much", is the potential choice for saving water and improving water use efficiency in arid regions like the middle HRB". We have read the recommended paper and some related ones, and mentioned the salinity issue in this part of the revision, i.e., "This method could also contribute to alleviate salt accumulation in agricultural soils and sustain ability of irrigated lands in arid regions by providing key *SWBCs* information for farmers and other decision makers in agricultural production (Gao et al., 2010)." Please see Line 497-500 in the revision for details.

10. P16: it is hard to understanding the statement 'irrigation is challenge to measure'.

RESPONSE: Sorry for the confusing wording. What I want to express is that "*Site-specific irrigation is challenging to measure*", the reason is that: "the two most common methods of measuring irrigation water—water meters or indirect methods—pose both economic and operational challenges to water managers, due to the wide spatial distribution of small fields throughout rural areas (Folhes et al., 2009)". To solve the concern, we have reorganized the related statement in our revision. Please see Line 61-64 in the revision for details.

11. P25, published SWBCs values at nearby sites: how accuracy are the published SWBCs? How are these values obtained?

RESPONSE: Table 4 has been reorganized to be clearer and more logical. The calculating methods or models of the published ET values at nearby sites have been given in the Table 4 in the earlier version of manuscript, and more details of the published SWBCs were further included in this table of the revised manuscript. Unfortunately, we cannot find the accuracy of the reported values due to lacking more detailed data in the references.

12. P54, in this region. The authors should not be specific to Heihe River basin. If you argue the method to be applicable to arid areas, you should discuss the issue in wider areas especially other similar regions like Tarim River Basin in China and Aral Sea Basin in Central Asia as examples. See the following for reference. *Fuqiang Tian, You Lu, Hongchang Hu, Wolfgang Kinzelbach & Murugesu Sivapalan (2019): Dynamics and driving mechanisms of asymmetric human water consumption during alternating wet and dry periods, Hydrological Sciences Journal, DOI: 10.1080/02626667.2019.1588972*

RESPONSE: Thanks for the constructive suggestion and useful literature. We elaborated this part, and added some more discussions about the methods' applicability in other similar regions. Please see Line 491-496 in the revision for details. The nice reference has been cited to ascertain its importance [i.e., Tian et al. (2019)].

Response to Anonymous Referee #1 (RC1)

General comments

The manuscript uses timeseries of soil moisture data to estimate the soil water budget components, especially evapotranspiration, in an irrigated agricultural filed of a desert oasis. This study is well conducted, and the authors responded the comments well. I think it is worth publishing after minor revisions. I have several comments listed as below.

RESPONSE: We warmly thank the Anonymous Referee #1 for the overall favorable impression of the work, and for his or her thorough review and the detailed, helpful comments. Please find below your reproduced comments, followed by our point-by-point responses.

Specific comments

1) The anonymous reviewer 3# concerns the locations of Section 3.1, 3.2, and 3.3, and the authors insisted the former locations. I think the problem may be arisen by the title of them. The current titles may be misleading to about the dataset, nor the observed or calculated results. For example, Section 3.2 is about calculated irrigation amount. The meteorological data should be introduced in the materials section.

RESPONSE: We have reorganized the sub-titles of Section 3 as: "3.1 Soil hydrophysical characteristics", "3.2 Soil moisture dynamics (SMDs)", and "3.3 Soil water balance components (SWBCs)". The results about irrigation amount has been merged into section "3.3 Soil water balance components (SWBCs)", and the descriptions upon meteorological data has been moved to "2.2 Site description". Thanks to the nice suggestion, this part looks much better than before.

2) I am confused by the S_{stop} and S_{max}. Is S_{stop} larger than S_{max}, as shown in Fig. 2.

RESPONSE: Very nice question, and the answer is: S_{max} is larger than S_{stop}. As we mentioned in "2.3 Calculation methods 1) Water storage and irrigation amounts", S_{max} was defined as the recorded maximum soil water storage of the root zone, and S_{stop} is the recorded soil water storage when irrigation event ends (moisture of uppermost soil layer starts to decrease). Although the real water storage in the entire root-zone soil should keep constant during the short periods between irrigation ends and deep drainage starts, it is not naturally been recorded by the soil moisture sensors at any time of this period, because of the continuously redistributing soil water profile and limited number of soil moisture sensor. In this work, the real water storage in root-zone soil was assumed to be equal to S_{max}, and thus S_{stop} would tend to approach S_{max} if more soil moisture sensors were installed in the soil profile. To clarify this point, more detailed explanations on this point has been included in the revision. Please see the caption of Figure 2 for details in the revision.

3) Please check the captions appeared in the text. For example, Fig.7 appears earlier than Fig. 5. Where is Fig. 6?

RESPONSE: We feel very sorry for the careless. "Fig. 7" appeared in Section 3.2 has been replaced by "Table 3" in the text, and we further checked all the figure captions to avoid any other similar mistakes.

4) Fig.3, It is better to show the specific irrigation amount and compare it with rainfall event.

RESPONSE: Thanks for the suggestion, Fig.3 has been reorganized to show the average amount of each irrigation event during 2016 in the revision. We also corrected an error of the irrigation date in this figure. We feel very sorry for the careless data checking and glad that we find the mistakes and corrected it in this revision.

Response to Anonymous Referee #2 (RC2)

We thank the anonymous Referee #2 for taking the time to review our manuscript and for their generally positive feedback on our study. Please find below your reproduced comments, followed by our point-by-point responses.

Specific comments

1) Lines 14, 61 etc.: drainage is not, and has been never considered as a "driver" of hydrological cycle. Irrigation is taken as a factor that interferes hydrological cycle, and seldomly taken as a "driver". You may call evapotranspiration a driver of the hydrological cycle. It is a component of the hydrological cycle as a matter of fact. Usually, the drivers of the hydrological cycle refer to the climatic factors.

RESPONSE: Thanks for the nice suggestion, we have changed "driven" as "dominated", and changed "driver" as "components".

2) Lines 314, 315. "Because the inverse method proposed by Zuo et al. (2002) and Guderle and Hildebrandt (2015) had never been applied throughout an entire growing season for farmland...", this is hard to say.

RESPONSE: We have removed this sentence in the revision to solve the concern.

3) As indicated in the last paragraph of the introduction section, this work aims to investigate performance of the inverse method to the coarse-textured soils. Thus, "coarse-textured soils" should be focused and highlighted in the discussion. This might have been something new in this paper.

RESPONSE: Nice suggestion. Some related discussion will be added in the Section 4.2 and 4.5 in the coming revision to highlight the "coarse-textured soils". Please see "4.2 Accuracy of the other estimated SWBCs" in the revision for details.

Response to Dr. Michael W. I. Schmidt (SC1)

General comments

*A note upfront from the submitting person:

This review was prepared by Basil Frefel and Michèle Bösiger, both master students in geography at the University of Zurich. The review was part of an exercise during a second semester master level seminar on "the biogeochemistry of plant-soil systems in a changing world", which I organize. We would like to highlight that the depth of scientific knowledge and technical understanding of these reviewers represents that of master students. We enjoyed discussing the manuscript in the seminar, and hope that our comments will be helpful for the authors.*.

Addressing sustainable irrigation in semi-desert regions, Li et al. observed in a soil moisture time series the soil-water holding ability in the Heihe River Basin, northern China. Soil properties such as saturated hydraulic conductivity and soil retention capabilities were combined with the soil water balance method and the inverse Richards equation (water movement in unsaturated soil) in order to estimate the Soil Water Base Components (evapotranspiration, irrigation, drainage). The measurements were taken at six sites in sandy soils, which differed in agricultural technique (rotational, permanent cultivation), plant species and mulching application. The results show that the estimation of the Soil Water Base Components corresponds to the soil-moisture time series and thus should be helpful for future irrigation planning.

Overall, the issue addressed by Li et al. is of great importance regarding future water management. Especially with increasing water scarcity, the study lays the foundation for a sustainable water strategy for one of the biggest agricultural producers worldwide for rice and wheat and thus is a valid contribution to the present scientific knowledge. The article is well structured, and the thinking steps are described profoundly, in addition to the reflected approach to the results. However, we have also found some caveats.

RESPONSE: We would like to thank Dr. Michael W. I. Schmidt for organizing the seminar to discuss our manuscript. We also warmly thank Basil Frefel, Michèle Bösiger for their thoughtful review, and for the specific suggestions, with which our manuscript is significantly improved in both its clarity and organization. We have taken the time to think through all the review comments and have adequately addressed all the comments item-by-item in the following pages.

In general, the type size is too small, and the sentences tend to be too long and interlaced to comprehend the article at the first read (see further comments).

RESPONSE: 1) Following the reviewer's suggestion, we have carefully revised our manuscript and these long sentences that may be unclear or confusing to a reader were rewritten in the revision.

Moreover, the exact time span of the experiment is unclear, and it should be mentioned what (important) role sandy soils play in the agricultural production of China and the world.

RESPONSE: The long-term experiment that was design to investigate the accumulative effect of different cropping systems and agronomic manipulation on soil property evolution was set up in 2007, and will run as long as the funding allows, and the in-situ soil moisture measurements were carried out since 2015, and was designed to continue until the long-term field experiment is ended. We have clarified this point in our revision. In addition, more information about "what (important) role sandy soils play in the agricultural production of China and the world" was included in this revision.

Besides, the abstract should be shortened to stay attractive for the reader and abbreviations such as NT1-NT6 should not be used in this very first paragraph. In our opinion, many explanations are too complicated; Keep explanations short and simple. In contrast to the detailed abstract, the conclusion is too short, again overloaded with abbreviations and therefore not understandable standing alone. More detailed remarks are listed below.

RESPONSE: As suggested, we slightly shortened the Abstract and removed the abbreviations such as NT1-NT6 in this part, and try our best to make the explanations as concise as possible. Also, the Conclusion part has been slightly expanded to solve the reviewer's concern. All the abbreviations that could be ambiguous also were carefully defined in the revision. More details can be found in our below responses to specific comments.

Specific comments

1) Lines 12: SWBC: In this paper the term soil water budget components and its abbreviation SWBC is used as if it were a standard term in soil science or hydrology. is this really the case? Otherwise it should be mentioned that this term as such is only used in this paper.

RESPONSE: Thanks for the nice suggestion. No, this abbreviation is not a standard term both in soil science and hydrology, and it is only used in this paper. We have defined that in the Introduction and then to use it in the following text to reduce repeated use of the term and thus to make the paper as concise as possible. According to the suggestion, we have mentioned that "the abbreviation is used here for simplicity, and effective only in this paper" when it first appeared in the revision.

2) Lines 22: Since the inverse Richards equation is of great importance in this work, but is not necessarily known to the general public, a brief description of what this method is used for, e.g. in parentheses, would be helpful.

RESPONSE: Thanks for pointing out this issue. A brief description of what this method is used for have been added in our revision, i.e., "(which is a model of unsaturated soil water flow based on the Richards equation)".

3) Lines 26: Why only one site without film-mulch? Comparison to other sites without mulching would have been helpful.

RESPONSE: As we mentioned in Section 2.2, this long-term field experiment was set up in 2007, and the six experiment plots have very different treatments, i.e., from NT1 to NT6, they were sequentially set as: (1) continuous pasture cropping, (2) continuous maize cropping, (3) continuous maize cropping with straw return, (4) maize-maize-pasture rotation, (5) maize-pasture rotation, (6) maize-pasture intercropping. In general, only the maize fields need to be film-mulched, and maize were planted in all the plots except NT1 (which was planted with alfalfa in the growing season of 2016), so that NT1 is the only one plot without film-mulch in this study.

4) Lines 29: What should be special about an obvious correlation between the volume of irrigation and drained water? is this really a significant result of the study or could this statement also be omitted?

RESPONSE: Yes, we do think this is a significant result of the study. Although similar results were also reported by other works, we found that this linear positive correlation is particularly noticeable in the coarse textured soils like the desert oasis in arid China, as we also discussed in Section 4.2. We think this is a useful result for further improve irrigation strategies, and thus would like to keep it here.

5) Lines 47: What is a high leaching fraction? Explain.

RESPONSE: Leaching fraction (LF) represent the ratio of the actual depth of drainage to the depth of irrigation (Dudley et al., 2008), we have explained it in the coming revision. Please see Line 48-49 in the revision for details.

6) Lines 40-54 and 55-69: The second paragraph is redundant.

RESPONSE: The second paragraph has been slightly shortened to eliminate any redundant in the revision.

7) Lines 106-107: Reference is needed for the sentence "The annual average precipitation..."

RESPONSE: Added as suggested.

8) Lines 107: What does a dryness index of 15.9 mean. Please put this number into context. Is this a high or a low value compared to the surrounding region or the rest of China? Is the dryness Index a common value which is need to be stated?

RESPONSE: Dryness index adopted here is a climate index that was widely used to reflect the degree of dryness in the atmosphere; it often defined as the ratio of potential evaporation to precipitation (Xiao et al., 2013). A dryness index of 15.9 means a very dry climate, under which potential evaporation rate could be ~15 times higher than the precipitation received. The dryness index of 15.9 is a common value for the arid northwestern China, but much higher than the rest regions of China. We have clarified this point in our revision.

9) Lines 111: What exactly is meant with sandy soil? What official soil name does it correspond to? leave out "...coarse texture and....". Scotch or Scots pine? Use familiar expression.

RESPONSE: According to Yang and Liu (2010), the zonal soils in our study region are loamy sand and sandy soil, which are two soil types typical for arid and semiarid environments (Zhao et al., 2010), we will further clarify this point in our revision. As suggested, "coarse texture" has been removed from the revision, and "Scotch Pine" was replaced with "Scots pine" too.

10) Lines 124-126: Please explain why the different treatments used in the study were chosen.

RESPONSE: As we mentioned at the beginning of this paragraph, the different treatments used in the study were chosen to investigate the accumulative effect of different cropping systems and agronomic manipulation on soil property evolution. More details have been included in the revision to solve this concern.

11) Lines 127: Why using exactly this type of irrigation (furrow irrigation)? Please explain in more detail.

RESPONSE: Because it was the most widely used irrigation type in our study area, and even the entire northwestern China. More details have been added in the revision to solve this concern.

12) Lines 128: Why just using one site with no film-mulching and five with mulching? Not a sufficient comparison possible between the sites.

RESPONSE: Please refer to our response to Question 3 of SC1.

13) Lines 242: Is it not unrealistic to use a ground level of the soil matric potential, even though the water level never reaches that high up?

RESPONSE: I guess this question may be raised by some misleading description about the lower boundary, for example, "i.e., $h = -5$cm". In fact, we adopted a free drainage boundary, which also can be descripted as "a unit vertical hydraulic gradient boundary condition which can account for a variable flux". To clarify this point, we have reorganized this sentence as "A free-drainage boundary condition was applied along the bottom boundary".

14) Lines 245: Which software? Please specify.

RESPONSE: We do this calculation by coding in MATLAB environment. It has been clarified in the revision.

15) Lines 343: In what dimension is the soil water content measured?

RESPONSE: According to the Operator's Manual, each TDR sensor (5TE, Decagon Devices Inc. Pullman, WA, USA) uses an electromagnetic field (dimensions: 9.3 x 2.4 x 6.5 cm) to measure the dielectric permittivity ε and thus the soil water content of the surrounding medium. In this study, the TDR sensors were installed at 5 different depths (20, 40, 60, 80, and 100 cm) at each plot, to monitor the soil water moisture of the root zone (0-110 cm).

16) Lines 55-59: The sentence is too long, therefore hard to follow and should be divided into two or three sentences. End the first sentence with a full stop after (Wright, 1971).

RESPONSE: This sentence has been deleted from in the revision (including the related reference), due to the potential redundancy with the previous paragraph.

17) Lines 92-95: Unorganized sentence order makes it even harder to follow the content.

RESPONSE: To make it clearer and more understandable, we have reorganized this sentence as "Exploring a reliable farmland *SWBC* estimation model, which can make the most of the vast amounts of soil moisture data, is crucial for irrigation management optimization in arid regions with coarse-textured soils (Musters and Bouten, 2000;Sharma et al., 2017)".

18) Lines 165-171: Subdivision into subsets probably better for this sentence.

RESPONSE: Changed as suggested.

19) Lines 219-226: Hard to follow the derivation.

RESPONSE: We have reorganized this part to make the derivation easier to follow in the revision.

20) Lines 42: missing ‘the’ …the Heihe river basin (HRB) is one of the largest…

RESPONSE: Corrected as suggested.

21) Lines 81: Cross out "…quite common and…"

RESPONSE: Corrected as suggested.

22) Lines 83: Cross out "…and more…"

RESPONSE: Corrected as suggested.

23) Lines 85: Also, with this process_, …

RESPONSE: Corrected as suggested.

24) Lines 86: …, almost no work_ have been…

RESPONSE: Corrected as suggested.

25) Lines 112: … (planted since the 1970s), include Haloxylon anmmodendron, … →either no comma or ‘including’

RESPONSE: Corrected as suggested.

26) Figure 1: The figure is not entirely clear: to what do the roots belong on the right? /figure on the left→layout and position of the legend and unprecise placement of the small map of China.

RESPONSE: We have reorganized this figure to make it clearer and more understandable in the revision according to this comment.

27) Figure 2: Probably better ‘day of year’ as axis label instead of DOY.

RESPONSE: We have added the explanation in the note. Please see page 6 line 183 in the revision.

28) Lines 140: 'was' instead of 'were'.

RESPONSE: Corrected as suggested.

29) Lines 195: 'dominates' instead of 'dominants'.

RESPONSE: Corrected as suggested

30) Table 1: we propose to insert this nomenclature-table at the beginning of the chapter.

RESPONSE: We decide to keep them at the original places just for the tidy layout.

31) Table2: Vertical lines between wilting point value of one study site and the saturated water conductivity of the next study site could probably increase readability (see attached pdf).

RESPONSE: Thanks for the nice suggestion, we have added vertical lines for Table 2 in the revision.

32) Figure 5: Does it need this figure at this place? and what exactly, apart from the clearly visible irrigation events, should be shown with it?

RESPONSE: This figure shows all the soil moisture dynamics that we used in this paper to further do our calculations, analysis and discussions, so that we would like to keep it in the manuscript.

33) Figure 6: left graph: use other scaling, since nothing is readable/ right graph: why is the scale in the middle of the graph (a bit weird position), why using such fancy boxplots if normal rectangular ones could be used?

RESPONSE: Both the two panels in Figure 6 have been reorganized to solve the concerns, however, the original box and Whisker plot (with diamond patterns) was kept in this revision, because this design would make the figure looks much better.

34) Lines 437: explains

RESPONSE: Corrected as suggested.

35) Lines 381: 'Literature' instead of 'literatures'?

RESPONSE: Corrected as suggested.

36) Lines 443: ... (Fares and Alva, 2000), suggesting that there is... In general: Reflect on the placement and use of figures and tables in the work, so that these stylistic tools fulfil their purpose of increasing the attractiveness of a scientific paper.

RESPONSE: Added as suggested.

37) Lines 1-2: as the use of soil moisture measurements is a major part of the scientific work, we would adjust the title as follows: Estimation of Evapotranspiration and Other Soil Water Budget Components, Using Soil Moisture Measurements, in an Irrigated Agricultural Field of a Desert Oasis Or also the following possibility seems easier to understand to us: Estimation of Evapotranspiration, Irrigation and Drainage, Using Soil Moisture Measurements, in an Irrigated Agricultural Field of a Desert Oasis

RESPONSE: According the suggestion, we have changed the title as "Estimation of Evapotranspiration and Other Soil Water Budget Components, Using Soil Moisture Measurements, in an Irrigated Agricultural Field of a Desert Oasis".

38) Lines 29-30: Leave out the obvious parts and concentrate on the findings

RESPONSE: Because this part is one of the most important findings and we would prefer to keep in the abstract.

39) Lines 106: lowest and highest temperatures for winter and summer, respectively→that's logical, no need of repetition. Pleonasm. It would be probably better to use the terms 'minimum' and 'maximum' in this context.

RESPONSE: Corrected as suggested.

40) Lines 323-324: water content values are difficult to read in the presented form of a listing.

RESPONSE: We have reorganized this sentence as "For the same interval of time, the water contents in the 40-, 60-, 80- and 100-cm depths of soil decreased from 25.4%, 19.8%, 18.5% and 14.2%, to 15.7%, 14.3%, 15.4% and 12.8%, respectively".

41) Lines 512: Setting upper boundaries would have been a nice addition.

RESPONSE: Yes, we agree, but we don't have more detailed information to set such a special upper boundary for inter-cropping treatments in this study. However, uncertainty that may be caused by this simplicity have been discussed in our manuscript.

42) Lines 566: It would be desirable for the conclusion to mention what would be appropriate irrigation methods for this variety of agricultural soil.

RESPONSE: Good idea, but this is beyond the scope of this article, and we are preparing another paper to discuss this issue.

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Quantification of Soil Water Balance Components Based on Continuous Soil Moisture Measurement and Richards Equation in an Irrigated Agricultural Field of a Desert Oasis

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Abstract

An accurate assessment of soil water balance components (*SWBCs*) is necessary for improving irrigation strategies in any water-limited environment. However, quantitative information of *SWBCs* is usually challenging to obtain, because none of the components (i.e., irrigation, drainage, and evapotranspiration) can be easily measured under actual conditions. Soil moisture is a variable that integrates the water balance components of land surface hydrology, and the evolution of soil moisture is assumed to contain the memory of antecedent hydrologic fluxes, and thus can be used to determine *SWBCs* from a hydrologic balance. A database of soil moisture measurements from six experimental plots with different treatments in the middle Heihe River Basin of China was used to test the potential of a soil moisture database in estimating the *SWBCs*. We first compared the hydrophysical properties of the soils in these plots, such as vertical saturated hydraulic conductivity (K_s) and soil water retention features, for supporting the *SWBC* estimations. Then we determined evapotranspiration and other *SWBCs* through a method that combined the soil water balance method and the inverse Richards equation (a model of unsaturated soil water flow based on the Richards equation). To test the accuracy of our estimation, we used both indirect methods (such as power consumption of the pumping irrigation well, and published *SWBCs* values at nearby sites), and the water balance equation technique to verify the estimated *SWBCs* values, all of which showed a good reliability of our estimation method. Finally, the uncertainties of the proposed methods were analyzed to evaluate the systematic error of the *SWBC* estimation and any restrictions on its application. The results showed significant variances among the film-mulched plots in both the cumulative irrigation volumes (652.1~867.3 mm) and deep drainages (170.7~364.7 mm). Moreover, the unmulched plot had remarkably higher values in both cumulative irrigation volumes (1186.5 mm) and deep drainages (651.8 mm) compared with the mulched plots. Obvious correlation existed between the volume of irrigation and that of drained water. However, the ET demands for all the plots behaved pretty much the same, with the cumulative ET values ranging between 489.1 and 561.9 mm for the different treatments in 2016, suggesting that the superfluous irrigation amounts had limited influence on the accumulated ET throughout the growing season because of the poor water-holding capacity of the sandy soil. This work confirmed that relatively reasonable estimations of the *SWBCs* in coarse-textured sandy soils can be derived by using soil moisture measurements; the proposed methods provided a reliable solution over the entire growing season and showed a great potential for identifying appropriate irrigation amounts and frequencies, and thus a move toward sustainable water resources management, even under traditional surface irrigation conditions.

Keywords

Evapotranspiration, Soil water balance, Desert oasis, Soil moisture, Inverse Richards.

1. Introduction

Arid inland river basins in northwestern China are unique ecosystems consisting of ice and snow, frozen soil, alpine vegetation, oases, deserts, and riparian forest landscapes, in a delicate eco-hydrological balance (Liu et al., 2015). Among these inland basins, the Heihe River Basin (HRB) is one of largest (Chen et al., 2007). The oasis plains in the middle reaches of the HRB have become an important source of grains, including the largest maize seed production center in China (Yang et al., 2015). Crop water requirements in this region are supplied mainly by irrigation from the river and from groundwater (Zhou et al., 2017). According to Wang et al. (2014), agriculture consumes 80 to 90% of the total water resources in the HRB, and has fundamentally altered the regional hydrological processes and even resulted in eco-environmental deterioration (Zhao and Chang, 2014). Traditional irrigation, namely flood irrigation in the HRB, has low efficiency (i.e., a high leaching fraction—the ratio of the actual depth of drainage to the depth of irrigation) (Li et al., 2017; Deng et al., 2006) and the extensive fertilization practices have given rise to higher levels of potential nitrate contamination in the groundwater, because water and pollutants percolate into the deep sandy soils of the desert oasis, which have low water-holding capacities (Zhao and Chang, 2014). It is crucial to adopt a mechanism that can preserve the role of irrigation in food security, yet with minimal consumption of the already scarce water, in order to increase water productivity and conservation. Reducing water drainage and thus nitrate contamination in groundwater, saving water, and increasing water and nitrogen use efficiency, are turning out to be important steps toward sustainable agriculture in this region (Hu et al., 2008; Yu et al., 2019)—steps that are being implemented by developing effective irrigation schedules (Su et al., 2014).

An efficient irrigation scheduling program should aim to replenish the water deficit within the root zone while minimizing leaching below this depth (Bourazanis et al., 2015). Accordingly, an accurate assessment of soil water balance components (*SWBCs*: the abbreviation is used here for simplicity, and effective only in this paper) is necessary for improving the irrigation management strategies in the oasis fields. However, quantitative information of *SWBCs* is usually challenging to obtain (Dejen, 2015). In desert oasis settings, the hydrological process of farmland is principally dominated by irrigation (*I*), drainage (*D*), and evapotranspiration (*ET*). None of these components is easily measured in practice, however. For example, not even the site-specific amount of irrigation can be determined accurately: the two most common methods of measuring irrigation water—water meters or indirect methods—pose both economic and operational challenges to water managers, due to the wide spatial distribution of small fields throughout rural areas (Folhes et al., 2009). Measurement of deep percolation is also difficult (Bethune et al., 2008; Odofin et al., 2012), and reliable data are rare in practice, and thus percolation is often calculated as a residual of the water balance, e.g., Zhang et al. (2014) estimated the deep percolation in an irrigated cropland of the Kaidu-Kongqi River basin through such a water balance approach. ET is another source of uncertainty inherent in water balance estimates (Dolman and De Jeu, 2010), and its estimation at the field scale is usually obtained through the application of mathematical models; it is commonly calculated by relying on reference ET (ET_0) or potential ET (*PET*) (Allen et al., 2011; Suleiman and Hoogenboom, 2007; Wang and Dickinson, 2012; Ibrom et al., 2007).

Soil moisture is a variable that integrates the water balance components of land surface hydrology (Rodriguez-Iturbe and Porporato, 2005), and over time it can be used to develop a record of antecedent hydrologic fluxes (Costa-Cabral et al., 2008). Soil moisture measurements were used to estimate the infiltration for unsaturated porous mediums by numerical solutions as early as the 1950s (Hanks and Bowers, 1962; Gardner and Mayhugh, 1958). With the advent of automated soil moisture monitors (Topp et al., 1980), ET estimation was implemented using continuous soil moisture data with simple water balance approaches (Young et al., 1997), but the computations are usually interrupted during rainfall or irrigation periods, as there is no means of accounting for drainage or recharge, due to inadequate turbulent flux measurements (Naranjo et al., 2011). It has only been during recent years that some researchers, including Zuo et al. (2002), Schelde et al. (2011) and Guderle and Hildebrandt (2015), have started exploring the potential of using highly resolved soil moisture measurements to determine ET, by accounting for vertical flow, demonstrating that such measurements can work when the appropriate approach is used. Rahgozar et al. (2012) and Shah et al. (2012) extended these methodologies to determine other components of the water balances, such as lateral flow, infiltration, interception capture, storage, surface runoff, and other fluxes. Many techniques are now available to automatically measure soil moisture dynamics, however; Time Domain Reflectometry (TDR) is one of the most popular throughout the world (Kirnak and Akpinar, 2016), because of its flexibility and accuracy (Schelde et al., 2011). With the wider applications of TDR (Sr et al., 2003; Fu et al., 2010), methods based on soil moisture data have become one of the most promising ways to quantify *SWBC* information in different ecosystems (Li et al., 2010). For example, the inverse Richards approach was believed to be a practical way of estimating ET based on continuously measured soil moisture data, because it does not require any prior information on root distribution parameters (which is required by most common soil water flux modeling methods even though accurate measurement of them is difficult), and thus can be applicable under under various climatic conditions (Guderle and Hildebrandt, 2015).

TDR probes have also been used in many dryland regions, including arid northwest China, for measurement of soil moisture during the last several decades (Liu et al., 2015). These types of measurements provide critical information for ecohydrology, agricultural, and hydrological researches in arid environments, but have mostly served as either an indicator for drought monitoring and forecasting (Anderson et al., 2012), or boundary conditions and/or calibration data for models (Vereecken et al., 2008). So far, however, relatively few works have been published on testing the potential of using a soil moisture database as a method to systematically estimate the *SWBCs* of farmland in the drylands, where the principal soils are coarse-textured (Grayson et al., 1999;

Yang et al., 2018b) and tend to have low water retention capacity and high drainage (Lal, 2004), and the plant roots are very diverse and complex because of the harsh environments in which they grow. Since frequently occurring soil aridification and nutrient leaching present major threats to food security and sustainable development of regional communities in these environments (Crosbie et al., 2010), development of a reliable farmland *SWBC* estimation method that can make the most of the vast amounts of soil moisture data, is crucial for irrigation management optimization (Musters and Bouten, 2000; Sharma et al., 2017), especially for arid regions with coarse-textured soils. This work used the TDR measurements of soil moisture collected from a long-term field experiment in the ecotones of desert and oasis, which was originally designed to test the accumulative impacts of different cropping systems (i.e., maize and alfalfa) and agronomic manipulation (i.e., succession cropping, crop rotation, row intercropping) on soil property evolution. The inverse Richards method was adopted and improved by combining it with a water balance approach to estimate not only ET but also the other *SWBCs* based on the soil moisture database. Through this effort we aimed 1) to investigate the feasibility of using soil moisture measurements to determine *SWBCs* in the croplands of a desert oasis, to serve as a framework for farmland *SWBC* estimation for coarse-textured soils; 2) to estimate the effects of different cropping systems and agronomic histories, on the hydrophysical soil properties, and to discuss these effects on the practical application of our method in different fields; and 3) to determine the potential for using a soil-moisture data-based method to improve irrigation strategies in a desert oasis.

2. Materials and Methods

2.1 Study area

The study sites were located in the transition zone between the Badain Jaran Desert and the Zhangye Oasis in the middle HRB (Fig. 1). More specifically, they were in the Linze Inland River Basin Research Station of the Chinese Academy of Science (39°21'N, 100°17'E, altitude 1382m). This region has a temperate continental desert climate. The annual average temperature is about 7.6°C, and the minimum and maximum temperatures are -27°C and 39.1°C, respectively. The annual average precipitation is 117 mm and the mean potential evaporation is about 2,366 mm/a (Liu et al., 2015). The annual dryness index (defined as the ratio of potential evaporation to precipitation) is 15.9, which is a common value for arid northwestern China. About 60% of the total precipitation, with low rainfall intensity, is received during July–September, with only 3% occurring during winter. Northwest winds prevail throughout the year, with intense sandstorm activity in spring. This region was part of a sandstorm-eroded area, and the research site was converted into an artificial oasis during the 1970s. As a result, the soil types are dominated by sandy loam and sandy soil (which are the two soil types most widely distributed in arid and semiarid environments, and thus important for potential agricultural production in these regions), and characterized by rapid infiltration (Zhao et al., 2010). The local dominant species are *Scots pine, Gansu poplar, wheat,* and *maize* (Liu et al., 2015), sand-fixation plant species (planted since the 1970s), including *Haloxylon ammodendron*, *Elaeagnus angustifolia*, *Tamarix ramosissima*, *Nitraria sphaerocarpa*, and annual herbaceous species such as *Bassia dasyphylla*, *Halogeton arachnoideus*, *Suaeda glauca* and *Agriophyllum squarrosum*. The growing season of these plants and forages usually starts in early April and normally continues through the month of September (Day of year or DOY 94-288, with temperature above 0°C).

2.2 Site description and data collection

A long-term field experiment with six different treatments was set up in 2007 and will continue as long as funding allows, to investigate the accumulative effect of cropping systems and agronomic manipulation on soil property evolution. Randomized complete block design with three replications was employed in this experiment (Figs. 1b and 1c), and one of the three replications was selected for installing the TDR sensors (Fig. 1d). The applied treatments of NT1 to NT6 were sequentially as follows: (1) continuous pasture cropping; (2) continuous maize cropping; (3) continuous maize cropping with straw return; (4) maize-maize-pasture rotation; (5) maize-pasture rotation; (6) maize-pasture intercropping. Plastic film mulching was applied during the initial growing season, and furrow irrigation was selected for this experiment because it is the most widely used irrigation type in the study area, and in fact in the entire region of northwestern China (Zhao et al., 2015). In 2016, NT1 was planted in alfalfa without plastic film mulch; NT2 to NT5 in maize with plastic film mulch; and NT6 in interlaced maize (mulched) and peas (non-mulched) (Fig. 1d). Maize and peas are annual crops, and about 80% of the maize roots are distributed in the soil layers between 0 and 40 cm. Only a few maize roots can reach 100 cm, while pea roots are usually found within 30-cm depth. Alfalfa is a perennial forage legume that normally lives four to eight years, and about 70% of alfalfa roots are distributed in the soil layers between 0 and 30 cm; only a few alfalfa roots can reach 110 cm in the sandy soils of this region (Sun et al., 2008). The growing season of maize and alfalfa in the region is usually from early April until late September (Zhao and Zhao, 2014). Alfalfa was harvested twice during the growing season of 2016. Harvest 1 was conducted on 16 July, and the subsequent re-growth was harvested on 28 September, 2016.

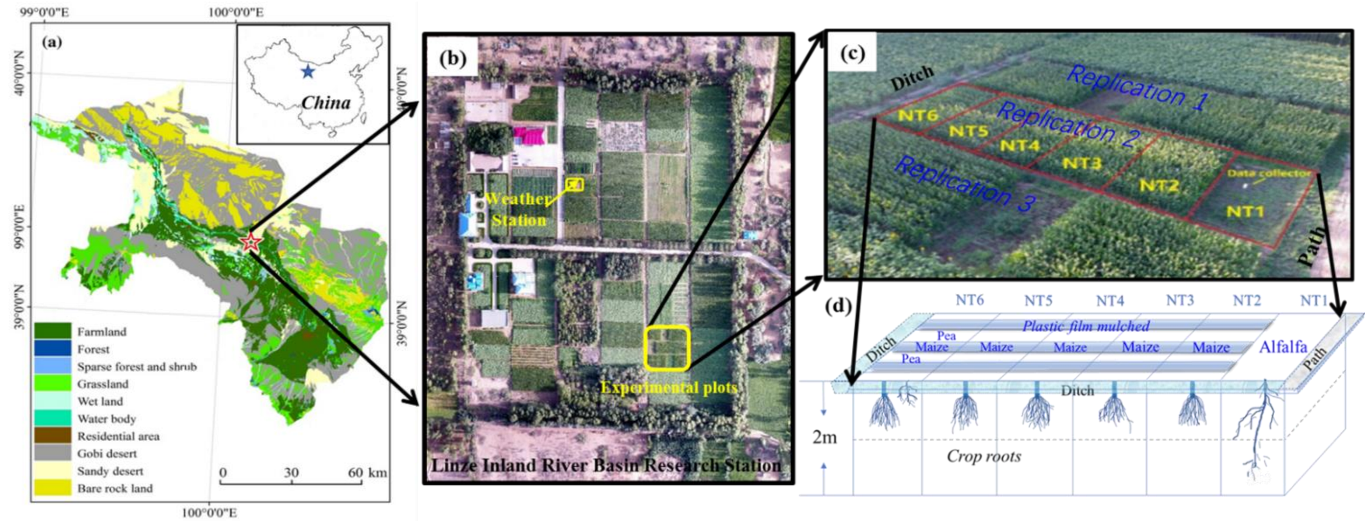

Figure 1. a) *Map of study area and research site;* **b)** *aerial view of the Linze Inland River Basin Research Station,* **c)** *aerial view of the study site;* **d)** *detailed design of the field experiments in 2016.*

The mean temperature of the growing season in 2016 was 27.12°C, or 3.12 degrees Celsius warmer than the long-term average of the growing seasons in 2007-2016 (24.0°C), and the mean rainfall during the period was about 60.2 mm, or 47 percent less than the long-term average of 115.4 mm (2005-2016), indicating that the weather was hotter and drier during the growing season in 2016 than in the previous ten years. The groundwater table depth fluctuated from 5 to 8 m at the experimental field during the year 2016. Irrigation with water extracted from a nearby pumping irrigation well was applied one by one in the plots from NT6 to NT1 during each irrigation event, and this work was usually completed in 3 hours or less. The power consumption of the pumping irrigation well was recorded as an in-situ observation to obtain the actual total irrigation amount of all plots through a well-built relationship at field scale: i.e., it obtained the average actual irrigation amount of the six plots (Table 1). In-situ soil moisture measurements have been carried out since 2015, and are designed to continue until the long-term field experiment is ended. The volumetric soil moisture of the six plots (NT1 to NT6) was measured with a TDR system (5TE, Decagon Devices Inc. Pullman, WA, USA), which was installed at 5 different depths (20, 40, 60, 80, and 100 cm) at each plot, with measurement intervals of 10 minutes. Before use, the TDR was calibrated from soil columns in the laboratory with known volumetric water content (Θ_v). A maximum likelihood fitting procedure was used to correct the observed data to eliminate the potential errors induced by the soil texture and salinity (Muñoz-Carpena, 2004). Soil bulk density (ρ_b), vertical saturated hydraulic conductivity (K_s), and soil water retention were determined using standard laboratory procedures on undisturbed soil cores in steel cylinders (110 cm^3 in volume, 5 cm in height) taken at 20-cm intervals down to 100-cm depth. Soil water retention curves were measured at the pressure heads of -0.01, -0.05, -0.1, -0.2, -0.4, -0.6, -0.8, -1, -2, -5, -10, -15, -20, and -25 bars. K_s was measured with an undisturbed soil core using the constant head method, i.e., measured 36 h after saturated water flow at a constant head gradient (5 cm) (Salazar et al., 2008). These determined parameters of soil hydrophysical properties were further profile-averaged for each of the plots. The values of field capacity (Θ_{fc}) and wilting point (Θ_w) were empirically related to the corresponding soil water (matrix) potentials through the determined soil-water retention curves (-0.1 bar for Θ_{fc} and -15 bar for Θ_w). Hourly climatic data, including precipitation, temperature, radiation, wind, and potential evaporation were recorded by a weather station located about 150 meters away from the experimental site (Fig. 1).

2.3 Calculation methods

1) Water storage and irrigation amounts

Soil water storage (S) was calculated for the soil depth within the root zone (0-110 cm) based on the sensor readings using Equation 1 (see Table 2 for a list of symbols used in this paper):

$$S = \sum_{i=1}^{5} \theta_i Z_i' \qquad (1)$$

where θ_i is the soil moisture of layer i; and Z_i' is the layer thickness between 10 cm above and 10 cm below the sensor installation depth (except for the top 30-cm soil layer, which is represented by the TDR installed at 20 cm). At the field level, examples of inflows are irrigation and rainfall, and examples of outflows are evaporation and deep leakage beyond the root zone. An irrigation event usually lasted 20 to 30 minutes in each of the independent plots depending on the growth stages of the plants. Soil moisture increased rapidly following irrigation events and decreased quickly as well during the subsequent dry-down period. Rapid drying usually occurs for a few hours after a soil has been thoroughly wetted because of high water conductivity (Fig. 2a). The preferential flow was neglected in the selected soil profiles because the larger hydraulic conductivity of sandy soil itself neutralizes the effects of preferential flow, and because coarse soil is relatively inimical to the formation of stable preferential flow paths (Hamblin, 1985). Because of the relatively short irrigation times, which hampered the form of the steady infiltration rate (Bautista and Wallender, 1993; Selle et al., 2011), we hypothesized that no surface-water excess or steady-state flow took place during any irrigation event, and assumed that deep percolation usually occurred after soil moisture storage reached maximum (S_{max}) and whenever the soil water content in the deepest layer (90-110 cm) was found to be greater than "field capacity" (θ_{fc}) (Rice et al., 1986). The irrigation volume (V) could then be calculated as the difference between S_{max} and S_{ini}:

$$V = S_{max} - S_{ini} \qquad (2)$$

where S_{max} is the recorded maximum soil water storage of the root zone (0-110cm) after one irrigation event began and S_{ini} is the initial soil water storage of the root zone before irrigation (Fig. 2a). Although a few specific cases of percolation could occur before the S_{max} is reached (second panel in Fig. 2b), these would have little effect on the estimation of irrigation volume because the maximum soil water storage differed little (by only 1.86 mm) before and after deep percolation began. For instance, we checked all the irrigation events of NT1-NT6 during the entire growing season, and there were no underestimates of S_{max} except for two irrigation events in NT2, which only had slight underestimates of 1.86 mm and 10.3 mm, and generated errors of 1.1% and 4.1%, respectively.

Table 1. Planned and actual application of irrigation water for the plots during the growing season of 2016

Irrigation depth (averaged for the six plots)	UNITS	Growth stages (for maize)					
		Seeding (Apr.10-20)	Elongation (Apr.21-May 27)	Booting/heading (May 28-Jul.9)	Milk done (Jul.10-Sep. 10)	Mature (Sep.10-Sep 16)	Entire growing season (Apr.10-Sep 20)
Planned water application	mm	0~15	110~120	330-370	360~380	0	790~885
Actual water application*	mm	0	133.8	380	355	0	868.8
Estimated irrigation water	mm	0	117	366.5	348.1	0	831.6

Note: The irrigation schedule was designed for maize, and water was applied in all the six plots on the same schedule, for convenience.

**Actual water application was determined based on the power consumption of the pumping well, and the estimated irrigation water was determined based on continuous soil moisture measurements.*

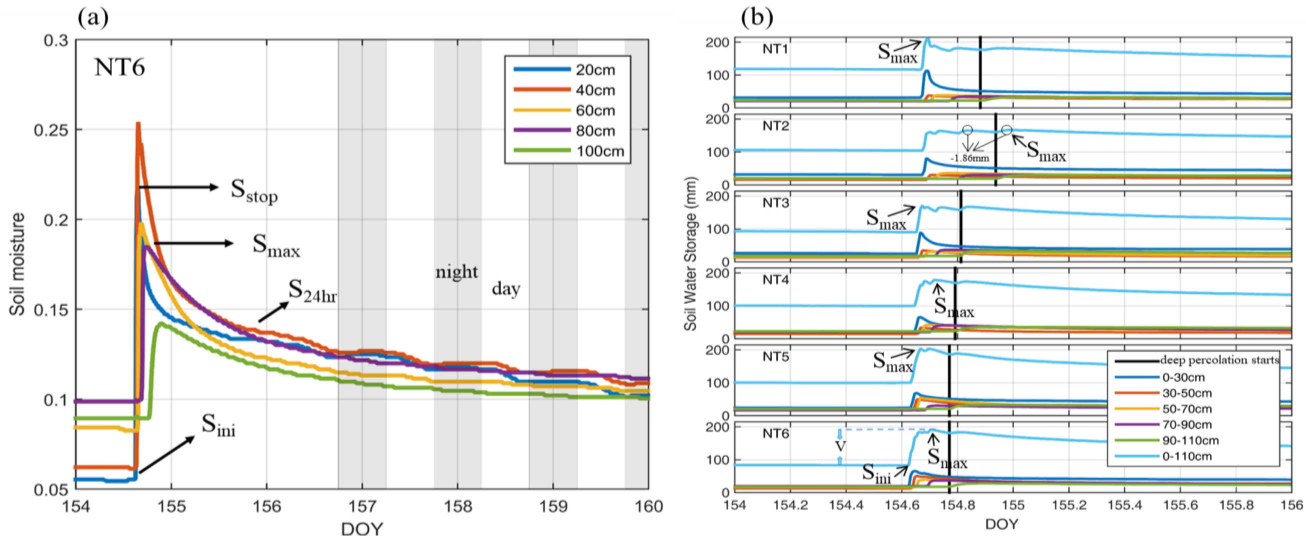

***Figure 2. (a)** Example diagram of the volumetric soil water content at various depths of NT6 during and after the irrigation event of 107.1 mm on DOY (day of year) 154-160 (2016). S_{stop}: irrigation event ends, and moisture of uppermost soil layer starts to decrease; S_{max}: maximum water storage, and the real water storage in root-zone soil was assumed to be equal to S_{max}; S_{24hr}: deep percolation ends one day later; after this point, ET dominates the water-loss processes; S_{24hr} would tend to approach S_{max} if more soil moisture sensors were installed in the soil profile; S_{ini}: pre-irrigation, soil moisture minimum. The gray stripes between 156-160 DOY represent nights, i.e., 6:00 pm to 6:00 am of the next day. **(b)** Verification of the assumption of Equation 2, i.e., that S_{max} appeared before deep percolation began, during the irrigation event on DOY 154-156 (2016). The black solid line represents the time that deep percolation began in each plot (NT1-6).*

2) Drainage and evapotranspiration

Following irrigation water applications, the drainage behavior of the soils consisted of two stages: 1) rapid drainage and 2) slow drainage. During irrigation, the root zone became effectively saturated, and rapid drainage followed, leading to deep percolation.

Then, as the water content in the soil fell, the hydraulic conductivity decreased sharply, as did the rate of drainage. The second phase, slow drainage, may continue for several days or months, depending on the soil texture (Bethune et al., 2008). We assumed that rapid drying or drainage ceased 24 hours after an irrigation event, and thus rapid drainage (Q_1) could be estimated through the variances of water storage and actual ET during the period (Eq. 3). The actual ET during the period was assumed to be equal to the potential ET, because ET occurs unhindered under non-water-stress conditions.

$$Q1 = S_{max} - S_{24hr} - ET_p \qquad (3)$$

where S_{24hr} is the soil moisture storage 24 hours after irrigation; S_{max} is the maximum water storage after irrigation; and ET_p is the potential ET calculated with the Penman-Monteith combination equation during that day.

Slow drainage is also important for sandy soils (Bethune et al., 2008), as along with ET, it constitutes the water loss during the second drying stage before the next irrigation event. Following Zuo et al. (2002) and Guderle and Hildebrandt (2015), an inverse method was employed to estimate the slow drainages and the average root water uptakes by solving the mixed theta-head formulation of the 1-D Richards Equation (Eq. 4) and iteratively searching for the sink term profile that produces the best fit between the numerical solution and the measured values of soil moisture content. ET is then obtained by summing rainfall and the sink term (S_p), and the drainage for this period is estimated as the water flux across the lower boundary of the soil profile. The above-mentioned 1-D Richards Equation is written as:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial t}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - Sp(z,t); \qquad (4)$$

$$h(z,0) = h_0(z) \quad 0 \le z \le L; \qquad (5)$$

$$\left[-K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right]_{z=0} = -E(t) \quad t > 0; \qquad (6)$$

$$h(L,t) = h_l(t) \quad t > 0 \qquad (7)$$

where h is the soil matric potential (cm); C(h) the soil water capacity (cm^{-1}); K(h) the soil hydraulic conductivity ($cm\ d^{-1}$); $h_0(z)$ the initial soil matric potential in the profile (cm); E(t) the soil surface evaporation rate (cm); $h_l(t)$ the matric potential at the lower boundary (cm); L the simulation depth (cm); and z the vertical coordinate originating from the soil surface and moving positively downward (cm). The iterative procedure runs the numerical model over a given time step (Δt) in order to estimate the soil water content profile $\tilde{\theta}_i^{v=0}$ at the end of the time step, assuming that the sink term $\widetilde{Sp}_{im,i}^{(v=0)}$ is zero over the entire profile at the beginning, where ~ depicts the estimated values at the respective soil layer i, and v indicates the iteration step. Next, the sink term profile $\widetilde{Sp}_{im,i}^{(v=1)}$ is set equal to the difference between the previous approximation $\tilde{\theta}_i^{v=0}$ and the measurements θ_i, while accounting for soil layer thickness and the length of the time step for units. In the following iterations, $\tilde{S}p_{im,i}^{(v)}$ was used with the Richards equation to calculate the new soil water content $\tilde{\theta}_i^{v}$. The new average sink term $\widetilde{Sp}_{im,i}^{(v+1)}$ was then determined with Eq. (8):

$$\widetilde{Sp}_{im,i}^{(v+1)} = \widetilde{Sp}_{im,i}^{(v)} + \frac{\tilde{\theta}_i^{v} - \theta_i}{\Delta t} \cdot d_{z,i}; \qquad (8)$$

A backward Euler with a modified Picard iteration finite differencing solution scheme was adopted to inversely obtain the solution, and this implementation follows exactly the algorithm outlined by Celia et al. (1990). Three steps proposed by Guderle and Hildebrandt (2015) were taken to determine when the iteration process could be terminated in this calculation:

a. Evaluate the difference between the estimated and measured soil water contents ($e_i^{(v)}$, Eq. 9) and test the change between this difference and the difference from the previous iteration ($\varepsilon_{GH,i}^{(v)}$, Eq. 10):

$$e_i^{(v)} = \left|\theta_i - \tilde{\theta}_i^{v}\right| \qquad (9)$$

$$\varepsilon_{GH,i}^{(v)} = \left|e_i^{(v-1)} - e_i^{(v)}\right| \qquad (10)$$

b. In soil layers where $\varepsilon_{GH}^{(v)} < 0$, set the root water uptake rate back to the value of the previous iteration $\widetilde{Sp}_{im,i}^{(v+1)} = \widetilde{Sp}_{im,i}^{(v-1)}$. Only if $\varepsilon_{GH}^{(v)} \ge 0$, go to the next step.

c. If $e_i^{(v)} > 1 \times 10^{-4}$, calculate $\widetilde{Sp}_{im,i}^{(v+1)}$ according Eq. (8); otherwise the current iteration sink term ($\widetilde{Sp}_{im,i}^{(v+1)} = \widetilde{Sp}_{im,i}^{(v)}$) is retained, as it results in a good fit between estimated and measured soil water content. More detailed procedures can be found in Guderle and Hildebrandt (2015).

3) Boundary setting and data collection

To reduce computational complexity, uniform soil profiles were assumed because there were no significant stratification differences within the sandy soils (Table 3) (Liu et al., 2015). The upper boundary of the calculation was set as the atmospheric boundary condition, and the calculation involved actual precipitation, irrigation, and potential evapotranspiration rates determined through Penman-Monteith combination equations driven by hourly environmental data during the growing season of 2016 (Fig. 3). The meteorological measurements were monitored at the nearby weather station (150 m away from our study plots, Fig. 1), which had the same underlying surface as the experimental plots (Fig. 1b), and were used to compute the upper boundary condition. The film mulching effects on the upper boundary condition were modeled as proportionally damped $ET_{p,a} = \beta \times ET_p$, where β is the area percentage without plastic film mulching in each experimental plot (i.e., 60%), and ET_p is the potential ET. For coding convenience, the bare soil evaporation (E_a) was determined through a simplified method proposed by Porporato et al. (2002): i.e., the evaporation was assumed to linearly increase with soil moisture (θ) from 0 at the hygroscopic point (θ_h), to $E_{p,a}$ at the field capacity (θ_{fc}). For values exceeding the field capacity, evapotranspiration was decoupled from soil moisture and remained constant at $E_{p,a}$. However, we did not set specific upper boundaries for inter-cropping treatments, because the difference in surface soil evaporation between mono- and inter-cropping treatments was relatively small when compared with the transpiration over a growing season. The surface fluxes were incorporated by using the average hourly rates, distributed uniformly over each hour. The lower boundary was set as a free-drainage boundary condition because the groundwater table depth (deeper than 3.5 m) was far below the crop effective root depth during the growing season, and any capillary rise from groundwater could be ignored in this study. The drainage rate $q(n)$ assigned to the bottom node n was determined by programming (in a MATLAB environment) as $q(n) = -K(h)$, where h is the local value of the pressure head and $K(h)$ is the hydraulic conductivity corresponding to this pressure head (Odofin et al., 2012).

We used soil moisture dynamics measured in the soil profiles as inputs to inversely solve for sink term profiles at each plot for each hour (Lv, 2014). The soil moisture measurements for 10-minute intervals during the period were hourly averaged to numerically filter out the noise associated with highly resolved data. This had the effect of slightly reducing the infiltration and ET estimates, but this effect in the overall results is negligible, according to Guderle and Hildebrandt (2015). The actual amount of water delivered for irrigation (Q_0) was determined from the power consumption of water pumping (P_0), through a relationship established between the two: $Q_0 = P_0 \times \eta$, where η is the ratio of the power consumption per unit water pumped and is likely to be different for different pumping heads. The coefficient was experimentally determined to be $8.5\ m^3 kW^{-1} h^{-1}$ for a head corresponding to 0.95 kg/cm^2 of delivery pressure, in this study.

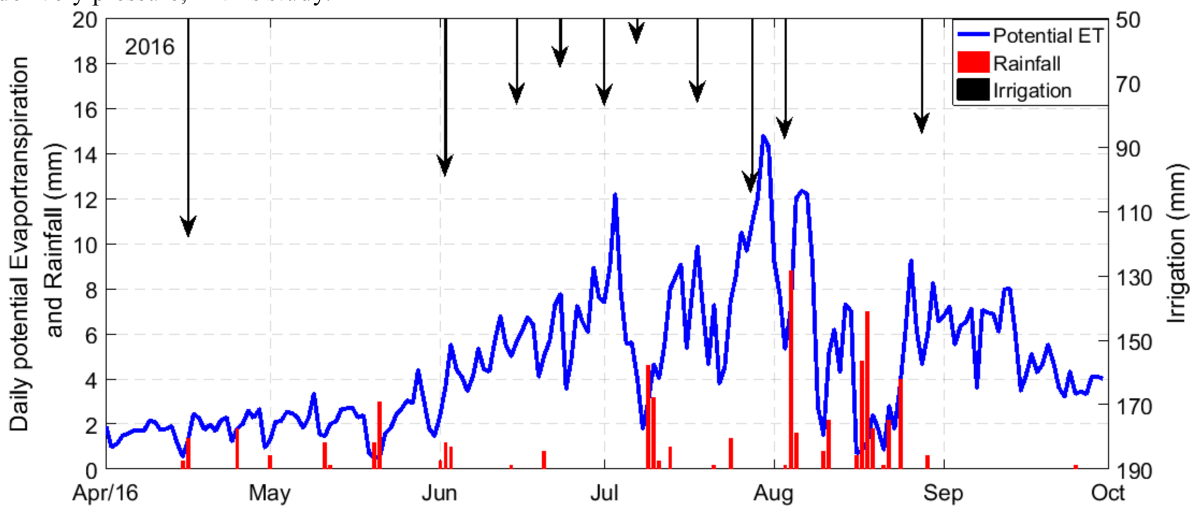

Figure 3. *Measured daily rainfall and potential ET estimated with the Penman-Monteith method during the growing season of 2016 at Linze Station. The cumulative rainfall during the growing season was 69.2mm in 2016, and the black down arrows represent irrigation events and average depths of water applied to the six plots in the events.*

Table 2. *List of symbols and their descriptions*

V	irrigation amount for one irrigation event (mm)	K(h)	soil hydraulic conductivity (cm d^{-1})
S	soil water storage (mm)	$h_0(z)$	initial soil matric potential in the profile (cm)
S_{stop}	soil moisture storage when irrigation was stopped (mm)	E(t)	soil surface evaporation rate (cm)
S_{ini}	soil moisture storage before irrigation began (mm)	$h_l(t)$	matric potential at the lower boundary (cm)
S_{24hr}	soil moisture storage 24 hours after irrigation (mm)	L	simulation depth (cm)
S_{max}	maximum soil water storage during irrigation event (mm)	z	vertical coordinate originating from the soil surface and moving positively downward (cm)

θ_i	volumetric soil water content of layer *i*	$\tilde{\theta}_i^{v=0}$	soil water content profile of soil layer *i* at the beginning of each calculation
Θ_v	theoretical volumetric water content calculated by the ratio of soil volume to water volume	$\widetilde{Sp}_{im,i}^{(v=0)}$	sink term of soil layer *i* at the beginning of irrigation, assuming it is zero
η	ratio of the power consumption per unit water pumped	$d_{z,i}$	thickness of soil layer *i*
t	time	~	estimated values at soil layer *i*
Q	steady-state drainage (mm)	v	iteration step
ET_p	potential ET during irrigation day (mm)	$\tilde{\theta}_i^v$	soil water content of step *v*
Z_i'	detection range of TDR, i.e., 20 cm	$\widetilde{Sp}_{im,i}^{(v)}$	average sink term of step *v*
Sp	sink term, i.e., water extraction by roots, evaporation, etc. (cm)	Δt	given time step
h	soil matric potential (cm)	$\varepsilon_{GH,i}^{(v)}$	difference between $e_i^{(v-1)}$ and $e_i^{(v)}$
C(h)	soil water capacity (cm^{-1})	$e_i^{(v)}$	difference between estimated and measured soil water content
Q_0	actual amount of water delivered for irrigation (m3)	P_0	power consumption (kWh)
D_{seas}	theoretical drainage volume over entire growing season in 2016 (mm)	R_{seas}	cumulative rainfall during entire growing season in 2016 (mm)
V_{seas}	theoretical irrigation volume over entire growing season in 2016 (mm)	ET_{seas}	theoretical ET volume during entire growing season in 2016 (mm)
ΔS	difference in soil water storage before and after the growing season (mm)	ρ_b	soil bulk density (g/cm^3)
K_s	saturated water conductivity (cm/day)	Θ_s	saturated water content
Θ_{fc}	field capacity	Θ^*	water stress point
Θ_w	wilting point	Ψ	soil water (matric) potential
Θ_h	hygroscopic point	β	area percentage without plastic film mulching
E_a	bare soil evaporation	$E_{p,a}$	bare soil evaporation when soil moisture is at field capacity

3. Results

3.1 Soil hydrophysical characteristics

An accurate measurement of soil hydraulic parameters is crucial for this inverse Richards method and is helpful in explaining the movement of soil water flow. A summary of the most important soil hydrophysical characteristics of the soils at 0–100-cm depth (NT1 to NT6, and two other representative fields) in relation to their capacity for water storage is listed in Table 3. The textures were largely loamy sandy in the plots NT1-NT6, in contrast to the sandy loam soil in an old oasis field with a long tillage history (~100 years) and sandy soil in the desert with no tillage history. Their bulk densities were generally between 1.4 and 1.5 g/cm^3— slightly higher than that in the local desert land, but still lower than that in maize fields of the old oasis. Θ_s, Θ_{fc} and Θ_w of the plots showed the same tendency of increasing soil hydrophysical properties (toward better water retention) as the bulk densities (Table 3). However, those parameters of the soil profiles are very similar to each other, especially between the same soil depths (horizontal) of the plots, suggesting that the different planting systems had similar influences on the soil hydrophysical proprieties, at least at the scale of 10 years. The effects of different cropping systems on soil moisture release characteristics are shown in Fig. 4. As expected, the relationship between soil water potential and volumetric water content across all data and treatment combinations followed a curvilinear pattern, where the water potential increased exponentially as soil water content increased.

The large and varying values of saturated drainage velocity (K_s) showed a great drainage potential in the coarse-textured soil and an obvious heterogeneity in both horizontal and vertical profiles across the six plots (Table 3). Soil moisture characteristic curves (SMC) in the six profiles are shown in Fig. 4, which indicates almost the same soil water content for all the plots, NT1-NT6, under the same suction head; i.e., all the soil profiles were nearly saturated when the water potential reached the -0.01 bar and little was available after the soil water potential dropped to the -15 bar. Two obvious inflection points were observed, at $\Theta \cong 0.08$ and 0.3, $\psi \cong -0.32$ and -15.2 bar in each of the soil moisture characteristic curves from NT1 to NT6. The slopes of the soil water potential-moisture, especially the parts between the inflection points of the six plots, were very close to each other, and also similar to that of the desert soil, suggesting similarly poor water capacities of the sandy soils (Sławiński et al., 2002). A very significant difference in water capacities was observed when comparing the SMCs of NT1-NT6 with that of the old oasis field, indicating that a considerably long period of time is still needed, for high soil water capacity to evolve, for these experimental sites.

Table 3. *Soil physical characteristics in the six experimental plots and two other selected plots near the study site*

	NT1					NT2					NT3					NT4				
	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w
20 cm	47.2	1.38	0.36	0.25	0.09	183	1.46	0.34	0.19	0.08	44.3	1.40	0.36	0.21	0.09	54.1	1.39	0.38	0.21	0.08
40 cm	46.8	1.55	0.33	0.21	0.06	82.1	1.55	0.32	0.15	0.05	259	1.54	0.34	0.18	0.06	266	1.50	0.36	0.17	0.06
60 cm	166	1.48	0.35	0.20	0.06	118	1.53	0.34	0.20	0.05	73.8	1.53	0.35	0.19	0.05	355	1.47	0.36	0.16	0.06
80 cm	61.0	1.45	0.33	0.17	0.05	164	1.48	0.35	0.18	0.05	1007	1.46	0.35	0.18	0.05	192	1.47	0.35	0.20	0.06

100 cm	273	1.46	0.34	0.18	0.05	99.7	1.49	0.34	0.15	0.05	46.1	1.44	0.35	0.16	0.05	80.0	1.40	0.37	0.23	0.06
$\bar{X}$	119	1.46	0.34	0.20	0.06	129	1.50	0.34	0.17	0.06	286	1.47	0.35	0.18	0.06	189	1.45	0.36	0.19	0.06
SD	99.6	0.06	0.01	0.03	0.02	42.8	0.04	0.01	0.02	0.01	413	0.06	0.01	0.02	0.02	126	0.05	0.01	0.03	0.01

	NT5					NT6					Maize field in old oasis					Local desert land				
	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w	K_s	ρ_b	Θ_s	Θ_{fc}	Θ_w
20 cm	121	1.42	0.37	0.24	0.09	89.6	1.50	0.32	0.25	0.09	28.8	1.61	0.38	0.29	0.11	42.5	1.46	0.36	0.16	0.05
40 cm	168	1.46	0.34	0.19	0.07	575	1.53	0.33	0.20	0.06	20.2	1.61	0.37	0.28	0.12	48.1	1.46	0.35	0.17	0.05
60 cm	41.3	1.39	0.40	0.29	0.09	66.5	1.45	0.37	0.18	0.05	37.4	1.56	0.38	0.28	0.10	30.9	1.44	0.39	0.20	0.07
80 cm	38.3	1.49	0.37	0.21	0.05	331	1.50	0.34	0.18	0.04	76.3	1.59	0.37	0.24	0.09	33.3	1.45	0.33	0.18	0.05
100 cm	671	1.47	0.34	0.19	0.06	18.6	1.47	0.35	0.14	0.04	47.5	1.58	0.40	0.29	0.12	26.9	1.43	0.28	0.17	0.03
$\bar{X}$	208	1.45	0.36	0.22	0.07	216	1.49	0.34	0.19	0.06	42	1.59	0.38	0.28	0.11	36	1.45	0.34	0.17	0.05
SD	265	0.04	0.02	0.04	0.02	234	0.03	0.02	0.04	0.02	22	0.02	0.01	0.02	0.01	9	0.01	0.04	0.02	0.01

K_s: saturated water conductivity (cm/day); ρ_b: bulk density (g/cm^3); Θ_s: saturated water content (100%); Θ_{fc}: field capacity (100%); Θ_w: wilting point (100 %); $\bar{X}$: mean value of the five soil layers; SD: standard deviation of the five soil layers.

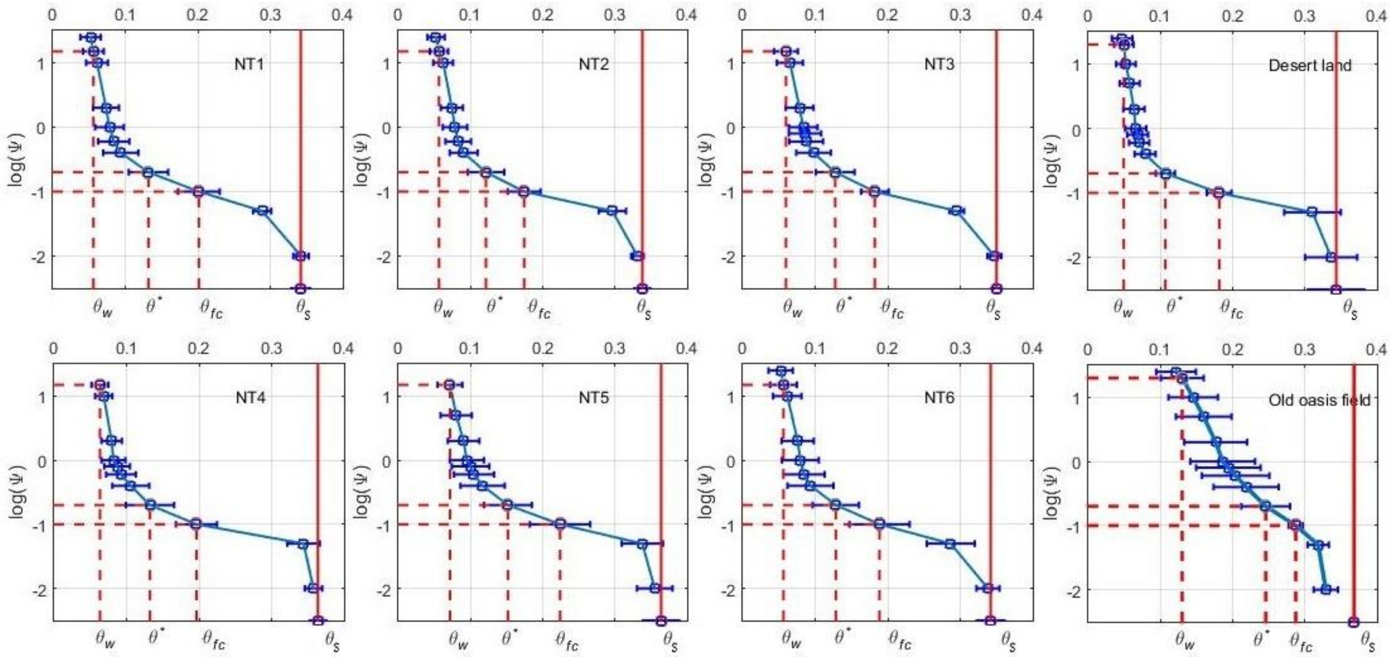

Figure 4. *Soil moisture characteristic curve (SMC) of uniform soil profiles of the six experimental plots and two other representative fields. Soil field capacity (θ_{fc}), wilting point (θ_w), and water stress point, i.e., point of incipient stomatal closure (θ^*) are empirically related to the corresponding soil matric potentials (-0.1 bar for S_{fc}, -0.2 bar for θ^* and -15 bar for S_w); the blue horizontal line represents the error bar, and the solid red line represents saturated water content (θ_s), which was obtained via the traditional soil drying method with 3 repetitions in each layer; for soil water (matric) potential (Ψ) take the absolute value, for example, -0.01 bar is equal to -2 on the Y axis.*

3.2 Soil moisture dynamics (SMDs)

Checking the soil water dynamic of the entire growing season can help us verify the boundary setting and affirm the assumption about the irrigation estimation used. Fig. 2a shows an example of the soil water content responses at various depths of NT6 during and after the irrigation event of 107.1 mm on DOY 154 (in 2016). TDR measurements exhibited a sharp increase when irrigation began and then decreased rapidly as it was turned off, due to the poor water-holding capacity of the sandy soil. The increase in water content occurred layer by layer from the upper horizons, suggesting limited influence from potential preferential flow (Liu and Lin, 2015), while the rapid moistening of the deep horizons could imply the existence of water loss by drainage. The greatest rate decrease in water content was observed in the top 20 cm of soil. During the 12 h after irrigation, the water content at the top sensor decreased from 21.9% to 14.2%. For the same interval of time, the water contents in the 40-, 60-, 80- and 100-cm depths of soil decreased from 25.4%, 19.8%, 18.5%, 14.2% to 15.7%, 14.3%, 15.4%, 12.8%, respectively. After irrigation ended, water continued to move down the soil profile; and thus, the top part of the profile was continuously losing water to the soil below it. The lower soil horizons were leaching water into the horizon below but at the same time were receiving water that had drained from the horizon immediately above, resulting in lower rates of decrease in water content for these layers than for those at the top horizon (20 cm) (Fares and Alva, 2000). Very similar patterns of changes in water content were observed through the six different soil profiles.

The average field capacity value (Θ_{fc}) of NT1-6 determined from laboratory measurement of soil water release curves was 19.2%

(20%, 17%, 18%, 19%, 22% and 19% for NT1-6 respectively). Twenty-four hours after the end of irrigation (June 3, 2016), the soil moisture values for the all the measured horizons (20-100 cm depth) of NT1-6 ranged between 8.9% and 16.9% (13.7-15.7%, 13.7-15.1%, 8.9-14.5%, 9.6-16.9%, 11.7-15.3% and 12.3-14.2% for NT1-6 respectively), lower than the field capacity (Figs. 2 and 5), suggesting that the rapid drainage of water away from the root zone soil (0-100 cm) was terminated during the period, as expected. In the mornings of the subsequent days, the decrease in soil moisture again sped up as the evaporative demand of the atmosphere gradually increased. In the absence of any irrigation during the subsequent nights, a slow-down in the decrease, or even a very light increase, in the soil moisture content was observed in the top soil layer (Fig 2). According to the data, there was also no obvious response of soil moisture regimes to precipitation, indicating a very limited contribution of rainfall to the soil water storage compared with irrigation. In fact, more than 90% of the rainfall events in this region are less than 5 mm (Fig. 3), and canopy interception (about 2-5 mm) may have hampered any effective infiltration from those insufficient precipitation events.

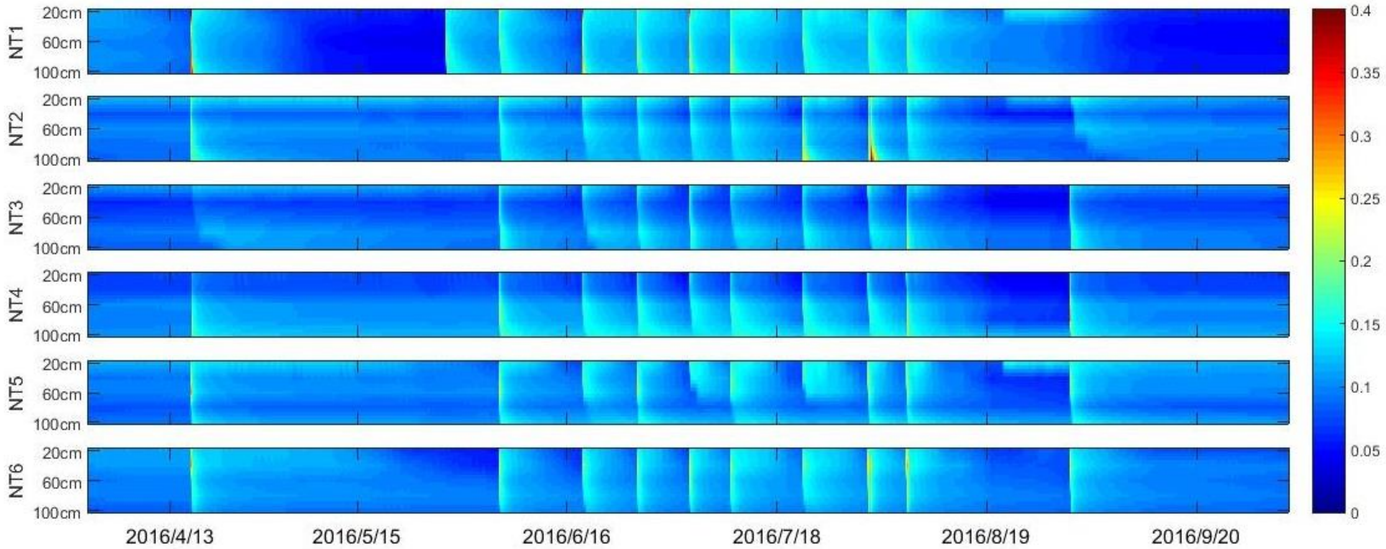

***Figure 5**. Spatial and temporal variations of soil water content with a time resolution of ten minutes. The color bar on the right side represents volumetric soil water content. Time period was from Apr. 1 to Oct. 1, 2016. Irrigation events for NT2-6 occurred on 4/16, 6/2, 6/15, 6/23, 7/1, 7/7, 7/18, 7/28, 8/3, and 8/28. NT1 had one more irrigation event on 5/25 and one less on 8/28.*

3.3 Soil water balance components (*SWBCs*)

The estimated soil water balance components (SWBCs), including total irrigation, evapotranspiration and deep percolation, at the six different plots during the growing season of 2016 are summarized in Table 4, Fig. 6 and Fig. 7. Irrigation applications began in mid-April and continued until late September, every 5 to 25 days, depending upon moisture content and crop growth (Fig. 3). A total of 10 irrigation events were sequentially applied through furrow irrigation for the plot during the entire growing season. Based on the in-situ observations of irrigation—i.e., the power consumption of the pumping irrigation well—the estimated irrigation volumes of the six plots were averaged and tested against the observations at field scale. The estimated average cumulative irrigation volume of the six plots during the entire growing season was 831.6 mm (1187, 760, 652, 840, 683, and 867 mm for NT1-6, respectively), which compares well with the actual average irrigation volume (868.8 mm) determined through power consumption (Table 1), suggesting that the calculated irrigation agrees closely with the real values from the farm fields when accurate irrigation and rainfall data are available. A difference of 4.5% in the irrigation amount was observed between the real values and the estimated values over the entire growing season of 2016, indicating a high reliability of the water balance method used in the *SWBCs* estimation.

Evapotranspiration and deep percolation dominated the outflows of the field soil water balance during the study period. A clear trend in seasonal variation of the water balance components can be observed at the site (Fig. 7). The corresponding ET values were very similar for all the plots. Three different stages of ET could be discriminated throughout the 2016 growing season: ET rate was very low at the initial stage (i.e., the first 50 days of the growing season), and increased gradually as vegetation coverage became greater with crop development, before reaching maximal values at the mid-season stage. After that, ET decreased gradually until harvest time. The estimated daily ET values ranged largely between 0.2- and 12-mm d^{-1}, with an average of 3 mm d^{-1}. No significant differences were detected in the daily ET when Duncan's multiple range test was applied at the 5% level to compare among the six experimental plots (P>0.75). A relatively large difference was observed in irrigation applied to the selected plots in this study, i.e., significantly higher cumulative irrigation volume was found at NT1. The excess of water in the soil produced an important deep percolation, which became greater with the increase in the irrigation quota. Among the plots, 45-79% of the input irrigation water was consumed by way of ET (i.e., for plant growth), while the change in soil water storage before and after the growing season was quite small. It is clear that although there was a high correlation between the volume of irrigation and that of drained water, the superfluous irrigation amount had limited influence on the accumulated ET during the growing season.

Table 4. *Estimated evapotranspiration and other major soil water balance components during the growing season of 2016*

Cumulative SWBCs	NT1	NT2	NT3	NT4	NT5	NT6
Irrigation (in mm)	1186.5	760.1	652.2	840.4	683.2	867.3
Drainage (slow drainage) (in mm)	651.8 (62.4)	288.3 (21.2)	170.7 (25.2)	340.1 (32.3)	212.4 (35.8)	364.7 (38.3)
Evapotranspiration (in mm)	534.6	489.1	508.8	561.9	539.2	538.1
Storage diff.* (in mm)	-52.7	0.17	3.6	2.2	5.44	-11.64

** Storage differences represent the difference in soil water storage before and after the growing season.*

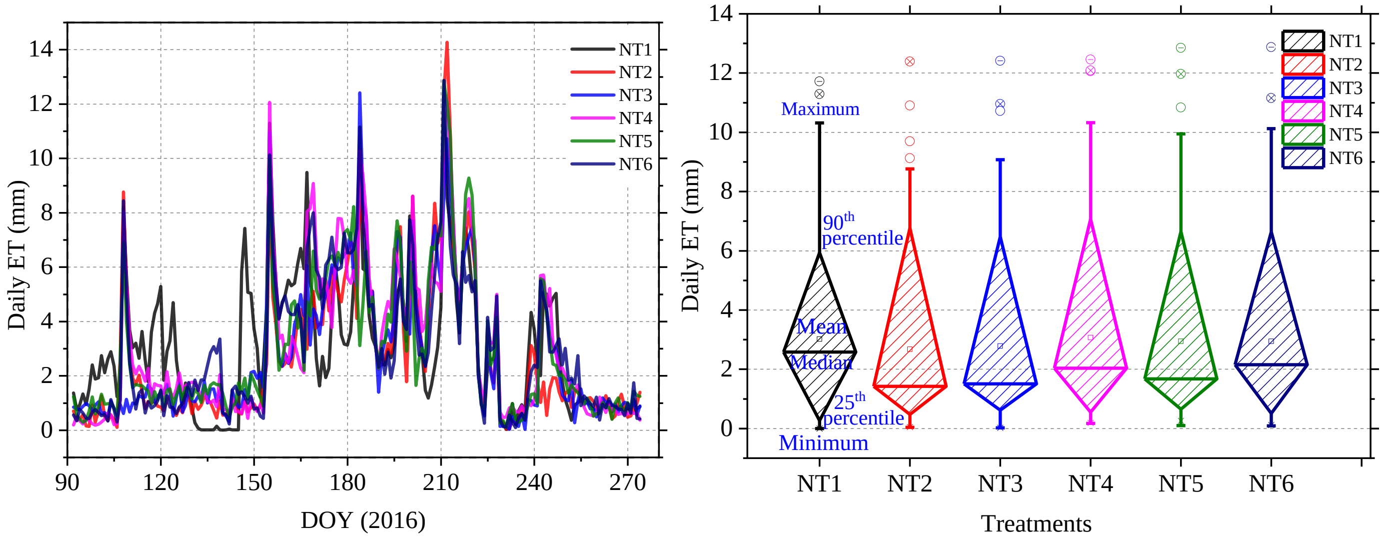

Figure 6. *Daily ET during the growing season of 2016 as determined from the inverse Richards method: a) time series of estimated daily ET; b) box-and-whisker diagrams showing the minimum, median, 25th percentile, 75th percentile, and maximum daily ET. No significant differences were detected when Duncan's multiple range test was applied at the 5% level to compare values among the plots. Note: DOY means day of year.*

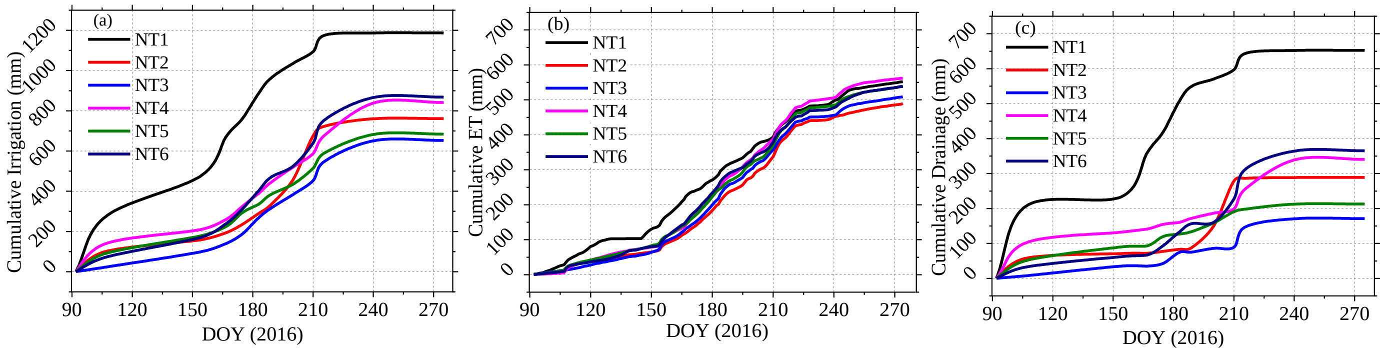

Figure 7. *Estimated water components of the plots during the growing season of 2016: a) cumulative irrigation, b) cumulative ET, c) cumulative drainage. Note: DOY means day of year.*

4. Discussion

4.1 Accuracy of the estimated ET

Cumulative ET values calculated from the inverse Richards method ranged between 489.1 and 561.9 mm for the different treatments in 2016. The values of ET obtained from the current study are well within the range of published ET values at the nearby sites (406-778 mm), and are consistent with the averages from other studies (~585.5mm) also done in this region, including Zhao and Ji (2010); Rong (2012); Yang et al. (2015); You et al. (2015); Zhao et al. (2015), etc. for maize fields similar to the ones present at the study site (Table 5). Compared with the methods used in the literatures listed in Table 5, the soil-moisture data-based method used in this study is more reliable because it produced a better fit between the numerical solution (soil water profile calculated by the inverse

Richards method) and the measured values of soil moisture content (soil water profile measured by TDR), even with vertical flow accounted for (Guderle and Hildebrandt, 2015). The narrow range of cumulative ET (489.1-561.9 mm) observed in 2016 can be attributed to the similar sandy soil texture and mesic moisture regimes caused by frequent irrigation (Figs. 4 and 5), which in tum suggested that for the unmulched alfalfa and mulched maize, both cropping systems and agronomic manipulation had limited influence on the accumulated ET during the growing season (Srivastava et al., 2017). This result is well supported by the evidence reported by early investigators, that the ET differences in different cropping systems are quite small for coarse-textured soils compared with the large differences in the amount of irrigation water (Jalota and Arora, 2002; Ji et al., 2007), and that ET is strictly a function of ambient atmospheric conditions under normal or wet conditions (Rahgozar et al., 2012).

The observed seasonal trend of ET corresponded well to the irrigation frequency and crop water consumption characteristics of the growth stage (Fig. 7), and similar patterns in the ET processes have also been reported by many other researches conducted in this region (Zhao et al., 2015; Zhao et al., 2010). Although we also noticed that the cumulative ET of NT1 was relatively higher than those of the other plots at the beginning of the growing season, this phenomenon can be largely attributed to the plastic film mulching at the other five plots. In the early growing season (seeding to emergence), soil evaporation (E) is the major part of ET (Zhao et al., 2015), and the plastic film mulching applied to NT2 to NT6 was able to significantly retain the soil moisture and thus decrease soil evaporation (Jia et al., 2006). However, the differences in the cumulative ET, between NT1 and the other plots, were quite small after the mid-growing season, most likely because with the plant canopy development, crop transpiration became the major portion of ET, and the influence of plastic film on ET diminished (Zhang et al., 2017; Qin et al., 2014; Jia et al., 2006). Another influence that may have decreased the evapotranspiration at NT1 after the mid-growing season is cutting. Cutting alfalfa lowers the leaf area index and drastically changes the effective diffusive resistance, consequently lowering the daily ET rate of alfalfa at NT1, although for a short time after cutting, evaporation from the soil surface may compensate for the decrease in transpiration (Dong et al., 2003; Su et al., 2010).

Table 5. *Reported evapotranspiration, irrigation, and rainfall data of oasis maize field in the middle Heihe River Basin (HRB)*

Year	Growing period	Soil type	ET (mm)	Methods	Irrigation Amount	Irrigation Methods	Rainfall	Sources
2001	Apr.11-Sep.18	Sandy soil	651.6	Water balance method	690	Ridge furrow	84.4	(Su et al., 2002)
2005	Apr.16-Sep.22	Light loam	513.2	Bowen ratio method	---	Ridge irrigation	153.5	(Wu et al., 2007)
2007	Apr.21-Sep.15	Sandy loam	486.2	Reference ET & crop coefficient				
2007	Apr.21-Sep.15	Sandy loam	777.8	Bowen ratio method	1194	Ridge furrow	102.1	(Zhao et al., 2010)
			693.1	Penman method				
			618.3	Penman-Monteith balance				
			615.7	Water balance method				
			560.3	Priestley-Taylor balance				
			552.1	Hargreaves method				
2009	Apr.10-Sep.20	Sandy loam	671.2	FAO-56-PM & dual crop coefficient	797	Ridge furrow	97.7	(Zhao and Ji, 2010)
2009	Apr.10-Sep.20	---	640	Shuttleworth-Wallace & dual-source model	797	Ridge furrow	97.7	(Zhao et al., 2015)
2010	Apr.22-Sep.23	Loamy sand	570-607	Field experiments	990-1103	Ridge irrigation	75	(Yang et al, 2018a)
2012	Apr.20-Sep.22	Clay loam	405.5	Water balance & isotope method	553	Ridge furrow	95.9	(Yang et al., 2015)
2012	Apr.20-Sep.22	---	450.7	Eddy covariance system method	430	Ridge furrow	104.9	(You et al., 2015)
2012	Apr.20-Sep.22	---	554.0	Penman method			104.9	
2016	Apr.10-Sep.20	Sandy soil	489-562	Inverse Richards method	652-867	Ridge furrow	60.2	This paper

4.2 Accuracy of the other estimated *SWBCs*

The irrigation volume of maize (NT2 to NT6) within our plots ranged between 652.2 and 867.3 mm, with an average value of 760.6 mm, which is well comparable to the range of average maize field irrigation volume in this region, i.e., a range between 604.8 and 811.4 mm reported in the Statistical Yearbook of Zhangye City for the period of 1995 to 2017 (see http://www.zhangye.gov.cn). When compared to the other treatments of plastic film mulching, significantly higher amounts of the applied irrigation (1186.5 mm) were found in NT1, which could be attributed to the larger percentage of infiltrating surface area and the relatively longer irrigation duration caused by the rougher surface of the ground without plastic film mulching. According to Yang et al. (2018a), plastic film mulch has been widely used to increase the productivity of crops in arid or semiarid regions of China. The logic behind this approach is that plastic film mulch improves the soil physical properties, such as the soil water content and temperature in the top soil layers, and thus leads to increased plant growth and yield (Mbah et al., 2010). Our results suggested that plastic film mulching can equally reduce irrigation duration and applied water depth by lowering surface roughness and thus the friction coefficient of the ground. Similar results were also reported by earlier investigators (Zhang et al., 2017; Jia et al., 2006; Qin et al., 2014). A less extreme but still significant difference can be found in the irrigation volumes (~652.2 to 867.3 mm) over the other five plots with plastic film mulching (NT2-6). This may be associated with the inconsistent durations caused by uneven irrigation applications, randomly rough soil surfaces, and mutation of the infiltration rate (i.e., K_s) across the plots (Table 3). Uneven irrigation may be further attributed to the uneven fields and ditches, which may lead to the application of much more water than required for evapotranspiration, in some places (Babcock and Blackmer, 1992). Soil surface texture has a direct effect on soil water and complex interactions with other environmental factors (Yong et al., 2014). The hydraulic behavior and the rate of traditional surface irrigation is eventually influenced by the inflow and duration of each irrigation (Ascough and Kiker, 2002). Although only slight differences exist among the retention curves (Fig. 4), the differences in saturation water conductivity (K_s) can be substantial (varying between 119 cm/day at NT1 and 286 cm/day at NT3), indicating that a slight difference in hydrophysical properties of soil profiles could be amplified to generate wildly varying infiltration behavior, especially during saturated or near-saturated stages under actual irrigation conditions (Ojha et al., 2017).

In desert oasis farmland, the water cycle is primarily driven by evapotranspiration demand under the influence of irrigation, and soil water percolation may occur when too much water is applied to the root zone. Estimated deep drainage rates were observed, ranging from 170.7 mm (NT3) to 651.8 mm (NT1), amounting to about 26.2% and 54.9% of the total irrigation of the two plots, respectively. Drainage within the mulched maize fields ranged from 170.7 mm to 364.7 mm, which are in good agreement with other results from the same region, i.e., 255 mm through isotopes obtained by Yang et al. (2015), and 339.5 mm through the Hydrus-1D model by Dong-Sheng et al. (2015). Compared with the theoretical deep drainage determined by water balance techniques (Rice et al., 1986), an error of -2.6 to 43.1 mm, or 0.2 % to 17.6%, was obtained for the cumulative deep drainage (Table 4), indicating the reliability of the method used to estimate deep drainage in this study. The data expressed in Fig. 2 also explains how easily an excess of water, and therefore deep drainage, can occur in these soils. Indeed, the deep drainage was directly proportional to the amount of irrigation applied during any particular period (Fig. 7, Table 4). This phenomenon is easy to understand because for a given amount of irrigation, the likelihood of a drainage event and its average size both increased naturally with the irrigation amount, because coarse-textured soils in desert-oasis environments contain more sand particles that have large pores, and those soils are highly permeable, allowing the water to move rapidly through the pore system (Fig. 7) (Keller, 2005). It is obvious that drainage is an essential part of irrigation design and management. According to our results (Fig. 6, Table 4), an average of 40.6% of input water was consumed by deep leakage across the six plots, and on average more than 90% of the drainage again occurred during the rapid drainage stage within the first 24 hours after an irrigation event (Table 4); this leakage is unproductive and could even cause nutrient loss and groundwater pollution at field scales (Fares and Alva, 2000), suggesting there is a huge potential for increasing irrigation water-use efficiencies and reducing irrigation water requirements in this region, especially in areas that are mostly dominated by coarse-textured sandy soils.

4.3 Effects of the variances in soil hydrophysical properties on the *SWBC* estimation

In this desert oasis and others located in arid northwest China, most of the fields belong to smallholder farmers, who usually follow different cropping patterns and tillage methods, resulting in a heterogeneity of soil hydrophysical properties (Salem et al., 2015; Ács, 2005; Abu and Abubakar, 2013). For the soil-moisture data-based method proposed in this paper, the spatial heterogeneity of the soil hydrophysical properties—which can be characterized by hydrophysical functions (soil water retention curve and soil water conductivity) and/or hydrophysical parameters (ρ_b, Θ_s, Θ_{fc} and Θ_w) (Ács, 2005)—may restrict its applicability to a large agricultural area. Therefore, evaluating to what extent the variances in the soil hydrophysical properties affect the *SWBCs* estimation is important, in order to reduce unnecessary repetitive measurements of soil hydrophysical information at both spatial and temporal scales, and thus improve the application efficiency of our method, is critical. Crop root systems, for example, may create heterogeneity in soil properties through mechanical actions and the active release of chemicals (Hirobe et al., 2001; Read et al., 2003); and, along with similar feedbacks between long-term planted crops and the soil environment, may change water flow and soil hydraulic characteristics, and thus affect local water balances (Baldocchi et al., 2004; Séré et al., 2012). Our results indicated that although the tillage and planting of past decades have significantly increased the soil's water-holding ability (i.e., higher values of ρ_b, Θ_s, Θ_{fc} and Θ_w compared with the sandier land), the magnitude of increase in most of the parameters, except K_s in soil vertical profiles, was independent of the treatments applied across the six selected plots, suggesting that different cropping systems and agronomic manipulation have limited effects on differing soil physical characteristics in sandy soil, at least at the decade scale, and this agrees well with the reports from Katsvairo et al. (2002). The limited influence of different cropping systems on soil hydrophysical properties in coarse-textured soil environments at a 10-year scale indicates a good stability and representativeness of the measured soil hydrophysical data and thus a good application prospect for applying the soil-moisture data-based method in practice.

4.4 Potential for *SWBC* estimation by using soil moisture measurements

The best estimates of *SWBCs* should be based on models of soil water, because in most cases direct measurements are not available (Campbell and Diaz, 1988). Many studies including modeling work have been conducted in this region during the past decades (Table 5). However, most of these were rough approximations based on meteorological methods and water balance equations (Rong, 2012; Jiang et al., 2016; Yang et al., 2015; Wu et al., 2015; Ji et al., 2007), because there has been a lack of accurate parameters to assess the heterogeneity and complexity involved in modeling (Allen et al., 2011; Suleiman and Hoogenboom, 2007; Wang and Dickinson, 2012; Ibrom et al., 2007). Soil-moisture data-based methods have been considered one of the most promising ways to directly determine ET and other *SWBCs* (Guderle and Hildebrandt, 2015; Li et al., 2002), and many possible options, including single- or multi-step, and single- or multi-layer water balance methods, have been proposed and tested with synthetic time series of water content (Guderle and Hildebrandt, 2015). Our results suggest that a combination of a soil water balance method and the inverse method could be a good candidate for SWBC estimation in this region, and in other arid regions with similar geographic conditions, i.e., the Tarim river basin in China and the Aral Sea basin in Central Asia (Tian et al., 2019). Because plant roots in those dryland environments usually tend to be diverse and complex as a result of adaptation to water-limited conditions, parameterizing the root distribution is likely to be a major challenge in modeling works for SWBC estimation. The soil-moisture data-based methods do not rely on any a priori assumption of root distribution parameters, and thus can provide a reliable solution, especially in regards to estimating ET, root water uptake, and vertical water flow.

Information on *SWBCs* is crucial for irrigation planning at both the field and regional scale (Jalota and Arora, 2002). Early researches suggested that decreasing the irrigation amount and increasing the irrigation frequency, and thus maintaining a relatively constant level of soil moisture with less stress from "too little or too much", is the best choice for saving water and improving water use efficiency in arid regions like the middle HRB (Rong, 2012; Jiang et al., 2016; Yang et al., 2015; Wu et al., 2015; Ji et al., 2007). This scenario can be achieved not only by adopting proper modern irrigation systems but also by integrating new technologies into the effective planning of irrigation schedules, so that plants can be supplied with optimal water volume and minimum water loss. Soil water balance models help in translating irrigation amounts in different time periods to evapotranspiration (ET), which has significance from the standpoint of crop yield (Jalota and Arora, 2002). Our results show that superfluous irrigation has no effect on increasing ET, because of the poor water-holding capacity of the sandy soil in this region, and thus irrigation application should not exceed a specific threshold (i.e., root zone depletion, ~527 mm for maize) to avoid deep percolation (Zotarelli et al., 2016). However, water deficits in crops and the resulting water stress on plants also influences crop evapotranspiration and crop yield (Kallitsari et al., 2011). Thus, a soil moisture measurement-based method makes it possible to quantify *SWBCs* for different time periods, and has great potential for identifying appropriate irrigation amounts and frequencies. This method could also contribute to alleviating salt accumulation in agricultural soils and sustainability of irrigated lands in arid regions, by providing key *SWBC* information for farmers and other decision makers in agricultural production (Gao et al., 2010). As the price of commercial TDR systems has become affordable (Quinones and Ruelle, 2001), they are more and more frequently used for soil water content measurements in desert oases, and thus a soil-moisture data-based method has great potential in irrigation management optimization and in moving toward sustainable water resources management, even under traditional surface irrigation conditions.

4.5 Uncertainty analysis

Uncertainty is inevitable, in any soil water balance components estimate. As summarized by Zuo et al. (2002) and Guderle and Hildebrandt (2015), the accuracy and convergence of estimated evapotranspiration and slow drainage using this inverse method are dependent on several factors, including the accuracy of soil hydraulic parameters and input soil moisture data, the time intervals of soil water content measurements, the spatial interval of the measured data along the depth, the setting of simulation depth and the boundary conditions. For a soil-moisture data-based method, the estimated results are only as good as their input data, i.e., the accuracy, precision and resolution (Guderle and Hildebrandt, 2013; Guderle and Hildebrandt, 2015). In this study, every effort was made to eliminate the uncertainty caused by the quality of the input data: for example, all the sensors and cables were carefully buried according the operator's manual instructions; the soil-specific calibration of TDR was conducted in a well-designed laboratory calibration experiment, which results a good accuracy (±2 %) for TDR measurement in coarse-textured soil; and the high-resolution moisture data (taken at 10-minute intervals) were hourly averaged to numerically filter out the noise and improve the calculation speed of the inverse model. Meanwhile, the simulation depth (0-110cm) is consistent with the root depth, and it can be well represented by 5 TDR probes with a spatial interval of 20 cm in sandy soil (Zhao et al., 2016). The boundary condition is also important for this inverse model (Liao et al., 2016); as mentioned in Section 2.3, we set the upper and lower boundaries as close as possible to natural conditions. However, we did not set specific upper boundaries for inter-cropping treatments, i.e., no bare soil evaporation was considered in the inter-cropping maize-pea field, which may have slightly underestimated the ET of NT6, but within an acceptable range, because the soil evaporation of NT6 was relatively small when compared with the total transpiration over a growing season. Moreover, the high amount of irrigation may have reduced the temperature of the soil profile, because irrigation is often accompanied by an increase in latent heat flux, and thus by an increase in evapotranspi ration (Chen et al., 2018; Haddeland et al., 2006; Zou et al., 2017). Theoretically, a decrease in soil temperature may slightly increase the soil suction under the same moisture conditions (Bachmann et al., 2002), and hence variations in the soil temperature profile under different irrigation scenarios may have affected the accuracy of the inverse model by changing the soil water retention curves. However, irrigation-affected variations of soil profile temperature in this study were small (within 2), ℃)— smaller than the daily variation of soil temperature (2 to 3℃), and thus its effect on soil water retention curves can be ignored for eco-hydrological researches (Bachmann et al., 2002; Gao and Shao, 2015). Even so, it is still an interesting and important research field deserving further investigation. Finally, it seems likely that uncertainty could also be introduced by the soil hydraulic parameters when adopting the Richards Equation to calculate the slow drainage term, as in this work. To reduce the uncertainty, the experimentally determined soil hydrophysical parameters were profile-averaged before being used in the inverse model. Although this caution cannot fully prevent the development of uncertainty caused by the parameters, such uncertainties are trivial, especially in light of the relatively small proportion of slow drainage in the context of sandy soils, i.e., only about 9.5% of the drainage occurred during this stage, according to our calculation (Table 4).

Aside from the uncertainties in estimating evapotranspiration and slow drainages, more limitations may exist in the estimation of irrigation amounts and rapid drainages following irrigation events. All these limitations were strongly dependent on the assumptions of Equations (2) and (3), specifically, the estimation of S_{max}. We checked all the irrigation events of NT1-NT6 during the entire 2016 growing season, and results showed an acceptable accuracy of the estimation of S_{max} (only two irrigation events in NT2 slightly underestimated the S_{max}: 1.86 and 10.3 mm, which accounted for 1.1% and 4.1% of total soil water storage, respectively). This phenomenon—deep percolation that began before irrigation ceased—may have been caused by long irrigation duration time and high K_s of surface soil at NT2, which is the major limitation when applying our method to other regions. Calculating the previously occurring leakage volume, for example, using the unsaturated hydraulic conductivity empirical equation, is one of the possible solutions that needs to be tested in future work. Installing TDR under the film-mulched ridges may also cause an underestimation of the soil moisture content during an irrigation event. We investigated the difference caused by the locatio n of TDR by comparing the soil water dynamics of an unmulched flat plot (NT1, which was independent of TDR location) and film-mulched ridge plots (NT2-6, which were affected by TDR location) after irrigation, and found that the underestimation caused by the location of TDR was mainly significant in the top 30 cm of the soil layer. For example, during the 24 hours after the irrigation on June 2 (DOY 154-155, Fig. 2), in the top 30 cm of the soil layer, the maximum soil moisture value of NT1 was 0.378, while the maximum soil moisture value of the other plots (NT2-6) ranged between 0.219 and 0.299; in other layers, the maximum soil moisture value of NT1 was well within the maximum soil moisture values of other plots at the same layer. The minimum soil moisture val ues were very close between NT1 and the other plots at the same layer (<0.04). Meanwhile, the variances between NT1 and the other plots were 0.006 to 0.009 in the top 30 cm of the soil layer, and generally ranged from 0.001 to 0.004 for the other layers, which showed a good consistency of soil dynamics in the 30- to 110-cm soil layers compared with the top 30 cm of the soil layers. These consistencies may be because 1) the height of ridge shoulders in the experimental plots was relatively low (<3cm), and substa ntial infiltration could occur through the film holes made for maize growth; and 2) lateral water transfers could be substantially enhanced during the period of irrigation because of the soil water potential differences between ridges and furrows. This judgment also can be supported by some research conducted in similar environments, e.g., Zhang et al. (2016). Therefore, we argue here that the uncertainty that TDR location brought to the *SWBC* estimations in this study is acceptable. For now, given that the effect of plastic mulched furrow irrigation on soil water distribution remains elusive (Zhang et al., 2016; Abbasi et al., 2004), installing TDR in both the ridge and the furrow may be a better choice in future studies. Besides, both the heterogeneity of soil hydrophysical properties in sandy soils and the rough artificial irrigation process can introduce uncertainties in the irrigation amount of any oasis cropland. However, the maximum irrigation rate of flood or furrow irrigation is mainly dependent on the K_s of the top soil layer, which is nearly homogeneous in such small experimental plots (6m×9m) because they have the same cropping systems and agronomic history (Table 3), and thus there is no significant infiltration difference within one small plot, and the installed soil moisture probes can well monitor the irrigation process of the entire plot.

Overall, we are confident about the estimation accuracy of ET, which is the most important parameter among all the *SWBCs*, and the one the related researchers are most interested in, because of its direct relevance to crop yield, and because maximizing crop yield is the major objective of agricultural irrigation strategies (Liu et al., 2002; Zhang et al., 2004; Kang et al., 2002). The ET estimation model in this study not only has great advantages in theory (for example, it does not require any root distribution information) (Schneider et al., 2010; Guderle and Hildebrandt, 2015), but at the same time it also considers the hysteresis effect, unlike other common models (Li et al., 2002; Guderle and Hildebrandt, 2015), while also providing a reliable and high-resolution solution because its results are well within the range of published ET values at nearby sites (Table 5). Other *SWBC* estimations such as irrigation also had an acceptable accuracy, even though they were estimated by a relatively simple method, because the results show a good consistency with the observations (actual irrigation calculated from the pumping power consumption) at the field scale and with the average irrigation amounts in other maize fields in the same region at close to the same time.

5. Conclusions

A database of soil moisture measurements taken in 2016 from six experimental fields (which were originally designed to test the accumulative impacts of different cropping systems and agronomic manipulations on soil-property evolution in the ecotone of desert and oasis) in the middle Heihe River Basin of China, was used to test the potential of a soil-moisture time series for estimating the *SWBCs*. We compared the hydrophysical properties of the soils in the plots, and then determined evapotranspiration and other *SWBCs* through a soil-moisture data-based method that combined both the soil water balance method and the inverse Richards equation, and the uncertainties of the employed methods were analyzed at the end of the experiment. Significant variances were observed among the film-mulched plots in both the cumulative irrigation volumes (652.1~ 867.3 mm) and deep drainages (170.7~364.7 mm). We found that the unmulched plot had remarkably higher values in both cumulative irrigation volumes (1186.5 mm) and deep drainages (651.8 mm) compared with the mulched plots. We noticed that although an obvious correlation existed between the volume of irrigation and that of drained water, the ET demands for all the plots behaved pretty much the same, with the cumulative ET values ranging between 489.1 and 561.9 mm for the different treatments in 2016. Our results confirmed that (1) relatively reasonable estimations of the *SWBCs* in a desert oasis environment can be derived by using soil moisture measurements. Although uncertainties exist, our method, which balanced simplicity and accuracy, can provide a reliable solution, especially in regards to estimating ET, for coarse-textured sandy soils; (2) the estimated results of the *SWBCs* will provide a valuable reference for optimizing irrigation strategies at the field scale, but it is still a long way from use on large areas of agricultural land, because of the soil heterogeneity at the regional scale and the small volume that a TDR probe can monitor.

Code/Data availability

The code and data used in this study are available from the authors on request.

Author contributions.

ZL and HL are the co-first authors and contributed equally to this work. HL provided insights, and performed the coding and analysis; ZL and HL drafted the paper with contributions from all the co-authors. QY, ZL, and RY ran the experiments and collected the data. WZ and JL contributed to analysis of the results, the discussion and manuscript editing.

Competing interests.

The authors declare that they have no conflict of interest.

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