Revision Notes (HESS2018581)

April 15, 2019

Dear Professor Nunzio Romano

Thank you for allowing us to resubmit a substantially changed manuscript hess-2018-581 entitled "A Unique Vadose Zone Model for Shallow Aquifers: the Hetao Irrigation District, China". Your evaluation of the manuscript was as follows:

> "Your manuscript was evaluated by three reviewers, who provided useful comments that were also discussed, even though not completely so since you also stated that there will be "a lot of work to do in clarifying ideas". Actually, two out of three reviewers were rather critical and raised important comments that should be included in a revised version of your paper, unless you conduct a clear rebuttal of the relevant point. Therefore, I release your study with major revisions and look forward to receiving the revised version together with detailed point-by-point replies to all of the three referees' comments received so far."

Below we have addressed all the helpful comments of the reviewers point by point. These responses reflect the substantive changes in the manuscript to clarify our ideas, as we indicated that we would do in our initial (December 25) reply. In our response and in the revised manuscript we have shown in blue the changed text. For clarity we have not marked the deleted text. We answered each comment in full. This means that if the comment was similar for two reviewers, we repeated some of the earlier text. It should make it easier for the reviewers to check our revisions.

We would like to thank the three reviewers and you for the thoughtful comments and for your time. We are looking forward to hearing your evaluation and whether more changes are needed.

With high regard

Zailin Huo, Tammo Steenhuis and Zhongyi Liu.

Responses to the comments of Reviewer #1:
We would like to thank reviewer 1 for his extensive and thoughtful comments. In December 2018, we provided a general response to the comments of reviewer 1. In this document we give a detailed response to all comments repeating some of our earlier responses. Below we cite first the comment, this is followed by our response and often by a section how the text will be revised in the manuscript. The text in blue are changes and additions in the original text. For clarity we do not show any of the removed text.

Major comments:

Comment 1.The introduction needs to be revised. Authors divide models based on whether they are capable of solving the full Darcy's law or whether they follow only a simplified and regionalized solution. In my opinion, such classification is not very practical making the introduction section quite confusing. On one hand, authors group very distinct models such as fully distributed catchment models, plot scale vadose zone models, and groundwater models as those based on the full solution of the Darcy's law (L82-84). On the other hand, semi-distributed catchment models are given as examples of those using simplified and regionalized solutions of the Darcy's law (L89-90). Authors should review the introduction section to focus only on similar models as theirs using comparable or alternative approaches for simulating soil moisture.

Response: Thank you for your suggestion. We agree that the description of the type of models in the original models was adhoc and confusing. In the revised manuscript we follow the categorization of models proposed by Todini (2007) and Asher et al. (2015). As a consequence, we have rewritten the entire introduction. The section that relates to the model classification was changed as follows:

> "There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al. 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW ((Mcdonald and Harbaugh, 2003; Langevin et al., 2017). These models have long run times when applied to real world problems, In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002).. This makes the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al 2017).
>
> To overcome the disadvantages of the full and completer models, computationally efficient surrogate models have been developed that speed up the modeling process without sacrificing accuracy or detail. Surrogate models are known under several names such as metamodels reduced models, model emulators, proxy models and response surfaces (e.g., Razavi et al., 2012a; Asher et al., 2015). The complex models we will call "full" or comprehensive models.
>
> Computational efficiency is the main reason for applying surrogate models in place of full models. Other advantages of surrogate models are shortening the time needed for calibration; identifying insensitive and irrelevant parameters in the full models (Young and Ratto, 2011). Most importantly, surrogate models allow investigating structural

model uncertainty (Matott and Rabideau, 2008). Finally, surrogate models might be able to deal with better with the self- organization of complex system prevalent in hydrology than the full models (Hoang et al., 2017. For example, full models based on small scale physics (Kirchner, 2006) not necessarily can model the repetitive wetting patterns observed in humid watersheds and for that reason simple surrogate models often outperform their complex counterparts in predicting runoff when a perched water table is present in sloping terrains (Moges et al., 2017; Hoang et al., 2017).

Surrogate models can be classified in two categories (Todini, 2007; Asher et al., 2015): data driven and physics derived. Data driven surrogates analyze relationships between the data available and physically derived surrogates simplify the underlying physics or reduce numerical resolution. In recent years, most emphasis in the research literature has been data driven surrogate approaches (Razavi et al. 2012a). Relatively little research has been published on physically derived approaches. Despite its popularity, data-driven surrogates can be an inefficient and unreliable approach to optimizing complex field situations especially when data is scarce such as in groundwater systems (Razavi et al., 2012b). The physically derived surrogates overcome many of the limitations of data-driven approaches and are therefore superior over data driven methods (Asher et al., 2015)

Comment 2. As a result of a confusing introduction section, it is not clear whether authors are trying to develop a model to be applied at the plot scale (which they are) or at the regional scale. Nothing is said about that in L114-118.

Response: We agree that we did not address if the model was intended for the plot scale or field scale. We are developing a surrogate field scale model that is tested in a small part of the field. We do not have the sufficient data to the do the whole field. We added the following to the revised text to address this shortcoming

"The surrogate model developed is a one dimensional model simulating the moisture content in the root zone using the groundwater depth and information of soil moisture characteristic curve. It can be easily adapted to field scale by including the lateral movement of the regional groundwater. However, in over short times, lateral movement can be neglected in nearly level areas outside a strip of 5-100 m from the river (Saleh et al., 1989) such as deltas and lakes but not over long times (Dam et al., 1997; Kendy et al, 2003)".

Comment 3. This is a clear misunderstanding of the evapotranspiration process throughout the paper, with authors referring many times simply as evaporation. Another example is given in L391 where authors refer to crop evapotranspiration (because then they refer to crop coefficients) as reference evaporation (?).

Response:

The reviewer notes that there is misunderstanding of the evapotranspiration process throughout the paper. The misunderstanding is not caused by faulty modeling of evaporation processes (some of us are modeling water balances for over 40 years!), but more likely related to the fact that we used the word "evaporation" instead of "evapotranspiration". In the original manuscript

we followed the recommendation of Savenije (2004) who points out shortcomings in measuring transpiration due to interception and dew forming of the plants. Savenije (2004) writes in the conclusion of his paper.

> "It may be clear that I would like the word evapotranspiration to disappear from the hydrological jargon. I propose that we use the much simpler and more correct word evaporation instead. I hope that my fellow hydrologists find these arguments convincing. If not, then I look forward to a continued debate."

It is now obvious to us that the debate envisioned by Savenije only happened in a small group of people. Therefore, in the rewritten manuscript, we have used the term "evapotranspiration" instead of "evaporation".

Comment 4. Soil water dynamics is pretty much dependent on soil evapotranspiration rates. However, there is nothing in the Material and Methods section describing how crop evapotranspiration is computed in the model or given as input.

Response: Our apologies for the oversight. We used the FAO-56 Penman-Monteith method (Allen et al., 1998) to calculate the reference crop potential evapotranspiration ET_0 (mm/day). The evapotranspiration of ETp is calculated by the simplified single crop coefficient method. We calibrated the value of the crop coefficient and found as expected that it was dependent on the canopy cover and the salinity of the groundwater. We added this information in the revised manuscript as follows

"The plant evapotranspiration was calculated in two steps. First the daily reference evapotranspiration (ET_0) was calculated Penman-Monteith equation (Allen et al., 1998).We assumed that the moisture content was limiting therefore the plant evapotranspiration rate was obtained by multiplying the reference evapotranspiration by a crop coefficient. Values for the crop coefficients were calibrated according to the water balance in the soil and found to agree with published values for stage of crop development and soil salinity."

Comment 5. The Material and Methods section does not detail about the approach used for calibrating/validating the model except for some vague sentence in L282-283. This information is critical and needs to be given. Not later in the results section (L385-387) when readers already gave up understanding what was done in the paper.

Response: This is an excellent suggestion. Thanks. We moved the sentence from lines 385-387 to the material and methods section and provided in addition more details about the calibrating and validating process in the revised manuscript as follows: .

> **"2.3.4 Model calibration and validation**
>
> The soil moisture contents were measured from May 30th to September 25th in 2016 and 2017. Groundwater depth was observed from June 13th to September 26th in 2016 and 2017. For the convenience of simulation, the period of June 13th to September 25th was set as the simulation period. The model parameters were calibrated with the 2016 data and the validation with data collected in 2017 growing seasons. Soil moisture content of the top 90 cm (0-10 cm, 10-30 cm, 30-50 cm, 50-70 cm, 70-90 cm) and the groundwater depth were simulated for model calibration and validation.

Relatively few parameters can be calibrated in the Shallow Aquifer-Vadose Zone Model. These are the crop coefficients *Kc* value, the two groundwater parameters and the root function. The other input data needed for model were the parameters in the Brooks and Corey equation (e.g., $\theta_s, \theta_d, \varphi_b, \lambda$.) and were obtained by fitting the equation to the soil moisture characteristic curve of each layer of the soil. The saturated moisture content was measured indepently as well and agreed with values obtained from the fit. Reference evapotranspiration was calculated directly from observed meteorological data.

For better understanding the model fitting performance, statistical indicators were used to evaluate the hydrological model goodness-of-fit (Ritter and Muñoz-Carpena, 2013). The statistical indicators including the mean relative error (*MRE*) (Dawson et al., 2006), the root mean square error (*RMSE*, Abrahart and See, 2000; Bowden et al., 2002), the Nash-Sutcliffe efficiency coefficient (NSE, Nash and Suscliff, 1970), the regression coefficient (*b*) (Xu et al., 2015), the determination coefficient ($R^{2)}$ and the regression slope (Krause et al., 2005) were used to qualify the model fitting performance during the model calibration and validation in this study. These statistical indicators can be expressed as follows.

Comment 6. Authors apparently believe that groundwater dynamics is solely dependent on irrigation and evapotranspiration, and that groundwater flow and river connectivity are not relevant processes. This assumption seems to explain statements such as those in L328-336 which are obviously incorrect. The fact is that groundwater depth cannot be modeled using a 1D approach as in this paper, but only by considering the regional scale. Groundwater depth can only be considered as boundary condition for 1D simulations.

Response: The reviewer is correct that the groundwater is a regional phenomenon. However, the regional flows might not be the main component of the groundwater flow since the experiment takes place in a plain with a hydrologic gradient between 0.1 and 0.25‰ (line 124). Assuming the hydraulic conductivity is 10 m/day (It is certainly less than that since the all the soils have a high clay and silt content). This would mean a water velocity less than 5 cm/day (assuming a porosity of 0.4). The field dimensions are approximately 40 by 90 m. Consequently, it will take much more than a year (800 days) to travel across the shortest distance. We showed early in the career of the oldest author, that even in Bangladesh where the level of the rivers change over several meters between the rain and dry monsoon phase that the influence of the river was only significant in a strip of less than 100 m along the river (Saleh et al., 1989). Groundwater would rise. Hence, our assumption that the dynamics in the vadose zone determines the groundwater depth seems acceptable for the locations that are nearly level.

In spite of the argument above, we found that irrigation in a nearby field affected the groundwater table in the beginning of growing season (lines 328-336):

> "In general, groundwater rose during an irrigation event and then decreased slowly due to upward movement of water to the plant roots to meet the transpiration demand. However, in the beginning of the growing season, we can see that the water table increased without an irrigation event. This occurred on Field A on June 24, 2016 and Fields C and D on June 20, 2017 (Fig. 5). This is curious and could be due to water originating from irrigation in a nearby field."

Note that Field C and D were revised as Field B1 and B2 in the revised manuscript.

One of the hypotheses of the increase in groundwater level due to irrigation in a nearby field is that early in the season the cracks in the structured clays were not fully closed and these could have transported some of the water across the field. It is not something that can be predicted by a standard finite difference or element model since the conductivity is so small for this site. So it is unexpected (or curious).

Another is that that a wetting front can proceed rapidly laterally through the root zone when the groundwater is near the surface. In this case only a very small amount of water μ is needed to bring the soil from nearly saturated to fully saturated. It could be as little as 0.1 cm^3cm^{-3}. The wetting front velocity can then be found by $v=q/\mu$. Thus the wetting from can move faster by the ratio of θ_s/μ which could be in the order of hundreds greater than the bulk of the water. Moreover, when the soil has been plowed the conductivity of plow layer could be greater than the bulk density. So, taken both effects together, we can imagine a wetting front movement of 10-20 m/day through the root zone. Although the effect on the groundwater table is significant flux wise only a small amount of water is involved.

Since this "curious effect" only occurs with the first irrigation we believe that water movement either through cracks or root zone somehow plays an important role. Finally, we should point out that our surrogate model cannot predict it, but it is also unlikely that any "full" model will have the required equations and more importantly the input data to simulate this phenomenon.

Comment 7. The Conclusions section shows a brief summary of the paper, not its conclusions.

Response: We are grateful for this useful suggestion and we modified this part in the revised manuscript. The conclusion is formulated as:

> **"5 Conclusion**
>
> A novel surrogate vadose zone model for an irrigated area with a shallow aquifer was developed to simulate the fluctuation of groundwater depth and soil moisture during the crop growth stage in the shallow groundwater district. To validate and calibrate the surrogate model we carried out a two-year field experiment in the Hetao irrigation district in upper Mongolia with groundwater close to the surface. Using meteorological data and the soil moisture characteristic curve and upward capillary movement, the surrogate model predicted the soil water content with depth and groundwater height on daily time step with acceptable accuracy during validation and was an improvement two previous models applied in the Hatao district that could predict the overall water content in the rootzone but not the distribution with depth.
>
> The surrogate modeling results show that after an irrigation event as long as the upward flux from the groundwater to the root zone was greater than the plant evapotranspiration rate, the moisture contents in the vadose zone could be found directly from the soil moisture characteristic curve by equating the depth to the groundwater with the absolute value of the matric potential. When plant evapotranspiration rate exceeded the upward movement moisture contents would be indicated by groundwater depth and was predicted by a root zone function. Another finding was that the daily moisture contents were simulated without using the unsaturated hydraulic conductivity function in

the surrogate model. For a daily time step equilibrium (defined as the hydraulic potential being constant) in moisture contents in the profile was attained so that precise unsaturated conductivity was not needed. Of course, for shorter time steps, predicting the transient fluxes and groundwater the conductivity function is needed. For management purposes a daily time step is acceptable.

Future improvement to this model will focus on coupling the EPIC model and apply it to simulate other crops and other location with shallow groundwater table. The surrogate model should be also be compared with a "full" model, to test under what conditions the surrogate model will fall short."

Additional comments:

Comment 1.L49: Authors should explain why they feel water scarcity was ignored before in many parts of the world. By whom? Certainly not by population living in those areas that have to deal daily with that problem; certainly not by the scientific community that has been addressing that problem for decades.

Response: In the original manuscript we tried to address the urgency of taking the water scarcity more seriously. It was revised as

"With global climate change and increasing human population, much of the world is facing substantial water shortage (Alcamo et al., 2007). The water crisis has caused widespread concern among public governmental officials and scientists (Guo and Shen, 2016; Oki and Kanae, 2006). Years of rapid population growth has squeezed the world water resources. The available fresh water per capita decreased 7500 m^3 from 13400 m^3 in 1962 to 5900 m^3 in 2014 (World Bank Group, 2019)" .

Comment 2.L52: Authors give an estimate of 5100 m^3 of available fresh water per capita by the year 2025. How much is it now? There is no point in advancing numbers for the future if they cannot be compared with some baseline.

Response: We are grateful for your suggestion. Usually, the thresholds 1700 m^3 and 1000 m^3 per capita per year are used as thresholds of water stressed and water scarce, respectively. We added this information in the revised manuscript as follows:

"……..Years of rapid population growth has squeezed the world water resources. The available fresh water per capita decreased 7500 m^3 from 13400 m^3 in 1962 to 5900 m^3 in 2014 (World Bank Group, 2019).

Water supply in China is especially stressed. When averaged over the whole country, available water per capita is at the water stress threshold of 1700 m^3 per year (Falkenmark, 1989; Brown and Matlock, 2011). It is even less in the arid to semi-arid yellow river basin that produces 33% of the total agricultural production in China…….. ".

Comment 3.L56: Are these SI units? What does the "a" in "m3 a^{-1}" stands for? Please check also other lines throughout the text (e.g. L127)

Response: Here, "a^{-1}" means "per annum" or "per year". "a" is the official SI unit for year (see for example: https://www.iau.org/publications/proceedings_ruesl/units/). It is therefore being used in manuscript but we agree it is not very common. We have reverted back to "y" for year in the manuscript.

Comment 4.L62-64: Authors should refer the environmental problems that resulted from the shallow irrigation water in Hetao, namely soil salinization risks and land degradation.

Response: Thanks for your suggestion. As we know, the water from the shallow water table is a main recharge to the plant growth (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010) . However, the salt accumulated with the upward migration of shallow groundwater table and lead to salinization (Ren et al., 2016; Yeh and Famiglietti, 2009). The Hetao district in China suffered long-term soil salinization which leads to the land degradation (Guo et al., 2018; Huang et al., 2018). This information was added in the revised manuscript. With the comment in mind we have rewritten the paragraph as:

> "In the Yellow River basin, crop irrigation accounts for 96% of the total water use (Li et al., 2004). Due to the increased demand for irrigation, the river has stopped flowing downstream for an average of 70 days per year (Hinrichsen, 2002). Saving water upstream in Inner Mongolia by improved management practices means that more water will be available downstream (Gao et al., 2015). In addition, the Hetao district is suffering from salinization which leads to the land degradation (Guo et al., 2018; Huang et al., 2018) . Salinization is caused by upward migration of water (and salt) from shallow groundwater table that leads to salt accumulation at the surface (Ren et al., 2016; Yeh and Famiglietti, 2009). Designing improved management practices to save water and decrease salinization can be achieved by field trials or with the aid of computer simulation mode measuring the fluxes. Field trials are time consuming, expensive and only a limited set of water management practices can be investigated. Models can test many management practices; however, the modeling results are often questionable because they have not been validated under local field condition and have not been validated for the future conditions. A combination of field experiments together with models has the benefits of both approaches with few negative effects."

Comment 5.L69-73: Authors should likely state that better management practices (new irrigation scheduling, alternative irrigation methods, and so on) are needed in the region. Otherwise, why the need for field trials and modeling?

Response: Please see our response to comment 4 above.

Comment 6.L74-77: One sentence does not make a paragraph.

Response: Thank you for your comment. The paragraph was amended as follows"

> "Central to modeling irrigation management practices under shallow groundwater conditions (such as in the Yellow river basin) is simulating the soil moisture content accurately (Batalha et al., 2018, Gleeson et al., 2016; Jasechko and Taylor, 2015;

Venkatesh et al., 2011a) because the moisture content plays a critical role in the growth of crops (Rodriguez-Iturbe, 2000), groundwater recharge (Hodnett and Bell, 1986), upward movement of water to the root zone in areas (Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a; Batalha et al., 2018). The latter is unique to shallow groundwater areas where the moisture content and thus the unsaturated conductivity are high and where the drying of the surface soil sets up hydraulic gradient that causes the upward capillary movement from the shallow groundwater (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009). The upward moving water contains salt that is deposit in the root zone and at the surface."

Comment 7.L83-84: The references for the HYDRUS and SWAP models were not given correctly. I'm sure authors of those models would appreciate seeing their work being recognized. If authors' intentions were to give applications in the Hetao region, they can be given below in the text.

Response: Apologies for the inappropriate references. References of the HYDRUS (Šimůnek et al., 1998) and SWAP (Dam et al., 1997) models were corrected in the revised manuscript. The changed text is as follows:

"There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al. 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW ((Mcdonald and Harbaugh, 2003; Langevin et al., 2017). These models have long run times when applied to real world problems, In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002). This makes the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al 2017). "

Comment 8.L92: What is the point of referring the computation method here? Are authors referring later to models using, for example, the finite volume method later?

Response: Thanks. We have rewritten the paragraph cited above and left out the reference to specific models. The paragraph is written as follows:

"In the Yellow River basin various models have been developed to simulate the soil water content and water fluxes. Full models that have been used are the HYDRUS-1D (Ren et al., 2016), and finite difference model application by Moiwo et al., (2010). Surrogate models for the North China plain where the groundwater is more than 20 m deep have been published by Wang et al. (2001); Kendy et al (2003); Chen et al. (2010); Ma et al. (2013); Yang et al. (2015, 2017); Li et al., (2017). In these models, the matric potential is ignored, and the hydraulic potential is equal to the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). Under these conditions the water flux becomes negligible when the soil reaches field capacity at -33 KPa (equivalent to -3.3 m in head units) at what point the hydraulic

conductivity becomes limiting. These models are not valid for irrigation projects along the Yellow river with shallow groundwater because the matric potential cannot be ignored over the short distance between the water table and the surface of the soil. Since the gravity and matric potential are of the same order, the water moves either down to the groundwater or up from the groundwater to the root zone depending on the matric potential at the soil (Gardner 1958; Gardener et al, 1970a,b). In summary, thus for shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes negligible) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) and thus not when the conductivity becomes limited at a matric potential of -33 KPa."

Comment 9.L93: The same as before. The correct reference of the HYDRUS-1D model was not given. Authors need to reword the text if their intention is to cite a modeling application.

Response: Please see our response in comment 7 where we have cited the models correctly

Comment 10.L94-96: I don't understand what authors are trying to say here. Apparently all models can be applied regardless the depth of the groundwater.

Response: We intended to say that equilibrium is reached (i.e. fluxes stopped) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) in Darcy's law when the groundwater is close the surface at less than 3.3 m. When the groundwater is deeper than the 3.3 m the hydraulic conductivity becomes limiting before the hydraulic gradient become zero. Because it was confusing, we removed the information from the paragraph. Please see the citation of the text in the responses to comment 8 and 11.

Comment 11.L96-100: Models cited here apparently use a water bucket approach to simulate soil moisture. Is it correct? How do these fit in the model classification used in L78-79.

Response: Since all the reviewers noted that our classification was silly, we changed the classification of the models. It is now more obvious how the models are classified. The main characteristic of the surrogate model in the North China Plain with deep groundwater is that the hydraulic potential is determined by the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). The models cited not necessarily assume a delta function for the hydraulic gradient (e.g. bucket model). The section reads now

"In the Yellow River basin various models have been developed to simulate the soil water content and water fluxes. Full models that have been used are the HYDRUS-1D (Ren et al., 2016), and finite difference model application by Moiwo et al., (2010). Surrogate models for the North China plain where the groundwater is more than 20 m deep have been published by Wang et al. (2001); Kendy et al (2003); Chen et al. (2010); Ma et al. (2013); Yang et al. (2015, 2017); Li et al., (2017). In these models, the matric potential is ignored, and the hydraulic potential is equal to the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). Under these conditions the water flux becomes negligible when the soil reaches field capacity at -33 KPa (equivalent to -3.3 m in head units) at what point the hydraulic conductivity becomes limiting. These models are not valid for irrigation projects along the Yellow river with shallow groundwater because the matric potential cannot be ignored

over the short distance between the water table and the surface of the soil. Since the gravity and matric potential are of the same order, the water moves either down to the groundwater or up from the groundwater to the root zone depending on the matric potential at the soil (Gardner 1958; Gardener et al, 1970a,b). In summary, thus for shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes negligible) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) and thus not when the conductivity becomes limited at a matric potential of -33 KPa"

Comment 12. L101-103: Why are those models not valid? Usually, water bucket approaches use empirical solutions to consider capillary rise. Couldn't those models be adapted by considering similar solutions? Apparently research in the region is quite extensive to be simply put aside.

Response: Usually, for the areas with deep groundwater table, the matric potential of the soil below the root zone is ignored and thus the hydraulic potential is equal to the gravity potential. Thus the boundary condition of the root zone is free drainage. The matric potential at the groundwater is zero and therefore cannot be ignored in areas where the groundwater is close to the surface. The matric potential and the gravity potential are of the same order and depending on what the matric potential is at the surface the water moves either up or down. Please see for further detail the response to comment 11.

Comment 13. L103-107: I don't understand how the two models given here fit in the general scope of modeling research in the region. Some additional explanation should be given.

Response: Please see our response to comment 11 and 12. Hopefully this makes it clear.

Since this is the end of the remarks on the introduction, we have cited the rewritten introduction below. This helps to understand the various parts in the introduction relates to each other

"1 Introduction

With global climate change and increasing human population, much of the world is facing substantial water shortage (Alcamo et al., 2007). The water crisis has caused widespread concern among public governmental officials and scientists (Guo and Shen, 2016; Oki and Kanae, 2006). Years of rapid population growth has squeezed the world water resources. The available fresh water per capita decreased 7500 m^3 from 13400 m^3 in 1962 to 5900 m^3 in 2014 (World Bank Group, 2019).

Water supply in China is especially stressed. When averaged over the whole country, available water per capita is at the water stress threshold of 1700 m^3 per year (Falkenmark, 1989; Brown and Matlock, 2011). It is even less in the arid to semi-arid Yellow river basin that produces 33% of the total agricultural production in China. To overcome water shortages in the Yellow river basin, crops are irrigated from surface and groundwater. This irrigation has directly changed the hydrology of the basin. While, 50 years ago, the semi-arid North China Plain had springs, shallow groundwater and rivers feeding the Yellow River, at the present rivers and springs have dried up where groundwater is used for irrigation (Yang et al., 2015a). At the same time, in the arid Inner Mongolia, along the Yellow River, the once deep groundwater is now within 3 m of the soil surface in the large irrigation projects such as the Hetao irrigation district because of downward percolation of the excess irrigation water that has been applied.

In the Yellow River basin, crop irrigation accounts for 96% of the total water use (Li et al., 2004). Due to the increased demand for irrigation, the river has stopped flowing downstream for an average of 70 days per year (Hinrichsen, 2002). Saving water upstream in Inner Mongolia by improved management practices means that more water will be available downstream (Gao et al., 2015). In addition, the Hetao district is suffering from salinization which leads to the land degradation (Guo et al., 2018; Huang et al., 2018) . Salinization is caused by upward migration of water (and salt) from shallow groundwater table that leads to salt accumulation at the surface (Ren et al., 2016; Yeh and Famiglietti, 2009). Designing improved management practices to save water and decrease salinization can be achieved by field trials or with the aid of computer simulation mode measuring the fluxes. Field trials are time consuming, expensive and only a limited set of water management practices can be investigated. Models can test many management practices; however, the modeling results are often questionable because they have not been validated under local field condition and have not been validated for the future conditions. A combination of field experiments together with models has the benefits of both approaches with few negative effects.

Soil moisture content plays a critical role in quantifying the fluxes in the soil (Batalha et al., 2018), especially in the areas with shallow groundwater area (Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a). Drying of the surface soil sets up hydraulic gradient that causes the upward capillary water movement from the shallow groundwater to sustain the evapotranspiration demands and crop water use (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009).),

Central to modeling irrigation management practices under shallow groundwater conditions (such as in the Yellow river basin) is simulating the soil moisture content accurately (Batalha et al., 2018, Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a) because the moisture content plays a critical role in the growth of crops (Rodriguez-Iturbe, 2000), groundwater recharge (Hodnett and Bell, 1986), upward movement of water to the root zone in areas (Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a; Batalha et al., 2018). The latter is unique to shallow groundwater areas where the moisture content and thus the unsaturated conductivity are high and where the drying of the surface soil sets up hydraulic gradient that causes the upward capillary movement from the shallow groundwater (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009). The upward moving water contains salt that is deposit in the root zone and at the surface.

Modeling moisture contents

There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al. 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW (Mcdonald and Harbaugh, 2003; Langevin et al., 2017) These models have long run times when applied to real world problems, In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002).. This makes

the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al 2017).

To overcome the disadvantages of the full and completer models, computationally efficient surrogate models have been developed that speed up the modeling process without sacrificing accuracy or detail. Surrogate models are known under several names such as metamodels reduced models, model emulators, proxy models and response surfaces (e.g., Razavi et al., 2012a; Asher et al., 2015). The complex models we will call "full" or comprehensive models.

Computational efficiency is the main reason for applying surrogate models in place of full models. Other advantages of surrogate models are shortening the time needed for calibration; identifying insensitive and irrelevant parameters in the full models (Young and Ratto, 2011). Most importantly, surrogate models allow investigating structural model uncertainty (Matott and Rabideau, 2008). Finally, surrogate models might be able to deal with better with the self- organization of complex system prevalent in hydrology than the full models (Hoang et al., 2017. For example, full models based on small scale physics (Kirchner, 2006) not necessarily can model the repetitive wetting patterns observed in humid watersheds and for that reason simple surrogate models often outperform their complex counterparts in predicting runoff when a perched water table is present in sloping terrains (Moges et al, 2017; Hoang et al 2017).

Surrogate models can be classified in two categories (Todini, 2007; Asher et al., 2015): data driven and physics derived. Data driven surrogates analyze relationships between the data available and physically derived surrogates simplify the underlying physics or reduce numerical resolution. In recent years, most emphasis in the research literature has been data driven surrogate approaches (Razavi et al. 2012a). Relatively little research has been published on physically derived approaches. Despite its popularity, data-driven surrogates can be an inefficient and unreliable approach to optimizing complex field situations especially when data is scarce such as in groundwater systems (Razavi et al. 2012b) The physically derived surrogates overcome many of the limitations of data-driven approaches and are therefore superior over data driven methods (Asher et al., 2015)

In the Yellow River basin various models have been developed to simulate the soil water content and water fluxes. Full models that have been used are the HYDRUS-1D (Ren et al., 2016), and finite difference model application by Moiwo et al., (2010). Surrogate models for the North China plain where the groundwater is more than 20 m deep have been published by Wang et al. (2001); Kendy et al (2003); Chen et al. (2010); Ma et al. (2013); Yang et al. (2015, 2017); Li et al., (2017). In these models, the matric potential is ignored, and the hydraulic potential is equal to the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). Under these conditions the water flux becomes negligible when the soil reaches field capacity at -33 KPa (equivalent to -3.3 m in head units) at what point the hydraulic conductivity becomes limiting. These models are not valid for irrigation projects along the Yellow river with shallow groundwater because the matric potential cannot be ignored over the short distance between the water table and the surface of the soil. Since the gravity and matric potential are of the same order, the water moves either down to the groundwater or up from the groundwater to the root zone depending on the matric potential at the soil

(Gardner 1958; Gardener et al, 1970a,b). In summary, thus for shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes negligible) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) and thus not when the conductivity becomes limited at a matric potential of -33 KPa.

For the irrigation perimeters with shallow groundwater in the Yellow River basin, we could find only two surrogate models developed by Xue et al., (2018) and Gao et al., (2017a,c). These two models do not consider the dynamics of groundwater depth and matric potential. By including these dynamics more realistic predictions of moisture contents and upward flow can be obtained and would give better results when extended outside the area where they are developed for (Wang and Smith, 2004). The reason is that for areas with shallow groundwater, evapotranspiration sets up hydraulic gradient that causes the upward capillary water movement to sustain the evapotranspiration demands and crop water use (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009).

Advantages of physically driven surrogates are particularly relevant groundwater studies where water tables are simulated over entire large area as shown by Brooks et al (2007 Despite this, Asher et (2015) poses that physically driven methods have not been applied widely to groundwater problems and even fewer with the interaction of moisture contents in the vadose zone which are key in salinization and plant growth of the many cropped irrigated field in arid and semi-arid regions. In these water short areas it is extremely important to develop models that show directions how to save water. The main objective of this study is, therefore, to develop a novel surrogate model and validating this approach using experimental data collected in a field with shallow groundwater with the ultimate goal is to save water in irrigation districts. In addition, sensitive and insensitive model parameters were identified for simulating moisture content in shallow groundwater area to optimize future data collection efforts. The experimental fields are located in the Hetao irrigation district, Inner Mongolia, China, where on two maize fields, moisture content and the groundwater table depth were measured over a two-year period.

The surrogate model developed is a one dimensional model simulating the moisture content in the root zone using the groundwater depth and information of soil moisture characteristic curve. It can be easily adapted to field scale by including the lateral movement of the regional groundwater. However, over short times, lateral movement can be neglected in nearly level areas outside a strip of 5-100 m from the river (Saleh et al., 1989) such as deltas and lakes. (Dam et al., 1997; Kendy et al., 2003).

Comment 14. L163: This should be “-33 kPa”.

Response: Apologies for the mistake. We corrected it as “-33kpa” in the revised manuscript.

Comment 15. L180: The particle size distribution is usually presented as percentage values, not fractions.

Response: We have revised it as percentage values in the revised manuscript**.**

Table 4: *Soil texture of Fields A and B*

Site	Depth (cm)	Soil type	Sand (%) (50-2000μm)	Silt (%) (2-50μm)	Clay (%) (0.01-2μm)
A	0-30	silty clay loam	5	75	2
	30-50	silty loam	22	7	8
	50-70	silty clay loam	3	8	17
	70-100	silty loam	39	57	4
B	0-30	silty loam	15	67	18
	30-50	silty loam	35	6	5
	50-70	silty clay loam	3	74	23
	70-100	silty clay loam	8	69	23

Comment 16.L192: Equation 1 needs to be revised. Where is θ (volumetric moisture content) and θs (volumetric saturated soil moisture content)? This text seems to be extra here.

Response: Thanks, the text in the manuscript is revised as:

"The Brooks-Corey model can be expressed as (Gardner et al., 1970a; Gardner et al., 1970b; Mccuen et al., 1981; Williams et al., 1983).

$$S_e = \left(\frac{\varphi_m}{\varphi_b}\right)^{-\lambda} \qquad for\ |\varphi_m| > |\varphi_b| \qquad (1a)$$

$$S_e = 1 \qquad for\ |\varphi_m| \leq |\varphi_b| \qquad (1b)$$

in which S_e is the effective saturation, φ_b is the bubbling pressure (cm), φ_m is matric potential (cm), and λ is the pore size distribution index. The effective saturation is defined as

$$S_e = \frac{\theta - \theta_d}{\theta_s - \theta_d} \qquad (2)$$

in which θ is the volumetric moisture content, θ_s is the volumetric saturated moisture content, θ_d is the residual moisture content (all in cm^3/cm^3). Equation 2 can be simplified to the form by setting $\theta_d = 0$

$$S_e = \frac{\theta}{\theta_s} \qquad (3)$$

For cases when the groundwater is close to the surface, under equilibrium conditions when

the water flow is negligible, (i.e., hydraulic potential is constant with depth) the matric potential can be expressed as height above the water table. For our field experiment the bubbling pressure, φ_b, and the pore size distribution index, λ, in the Brooks and Corey model can be obtained through a trial and error procedure by using the measured moisture content and matric potential derived from the groundwater depth after an irrigation event when equilibrium state was reached and sum of the gravity potential and matric potential was constant with depth. "

Comment 17. L197: The text should say "For cases. . . when the flow is assumed to stop. . ." since flow never actually stops.

Response: We agree. We changed it to "when the water flow is negligible". This equivalent what was suggested to see the response to comment 16 for the change in the text

Comment 18.L201: Please revise text as it makes little sense.

Response: Hopefully our rewrite is clear. Please see the response to comment 16 for the change in the text

Comment 19.L237-244: Authors intention here is likely to describe the role of evapotranspiration on model computation, not evaporation. Otherwise, the assumptions are completely wrong as evaporation rates are not maximum when the plant canopy is closed. Soil evaporation is limited by the amount of energy available at the soil surface during that period in conjunction with the energy consumed by transpiration.

Response: That was indeed our intent. Thanks. Throughout the text, we have changed evaporation into evapotranspiration to avoid this type of confusion. The text is as follows

Evapotranspiration

1. The plant evapotranspiration was calculated in two steps. First the daily reference evapotranspiration (ET_0) was calculated by Penman-Monteith equation (Allen et al., 1998). We assumed that the moisture content was limiting therefore the plant evapotranspiration rate was obtained by multiplying the reference evapotranspiration by a crop coefficient. Values for the crop coefficients were calibrated according to the water balance in the soil and found to agree with published values for stage of crop development and soil salinity.
2. (a) On days without rain or irrigation, the evapotranspiration lowers the water table and the moisture content in the soil decreases due to upward movement of water to the plant roots and soil surface.

   (b) On days with rain or irrigation, the potential evapotranspiration is subtracted from the irrigation and/or rainfall and water moves downward

Comment 20. L238-239: How is the osmotic stress considered in the model?

Response: Osmotic stress is included as crop coefficient

Comment 21.L288: I have some doubts on whether Ren et al. (2016) is the most appropriate reference for citing statistical indicators. Did those authors develop those indicators or at least elaborated on them? Or did they simply used them like here? Please revise.

Response: The text is revised as follows:

"For better understanding the model fitting performance, statistical indicators were used to evaluate the hydrological model goodness-of-fit (Ritter and Muñoz-Carpena, 2013). The statistical indicators including the mean relative error (*MRE*) (Dawson et al., 2006), the root mean square error (*RMSE*, Abrahart and See, 2000; Bowden et al., 2002), the Nash-Sutcliffe efficiency coefficient (NSE, Nash and Suscliff, 1970), the regression coefficient (*b*) (Xu et al., 2015), the determination coefficient (R^2) and the regression slope (Krause et al., 2005) were used to qualify the model fitting performance during the model calibration and validation in this study. These statistical indicators can be expressed as follows:

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\frac{(P_i - O_i)}{O_i} * 100\% \quad (15)$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \quad (16)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \quad (17)$$

$$b = \frac{\sum_{i=1}^{N} O_i * P_i}{\sum_{i=1}^{N} O_i^2} \quad (18)$$

$$R^2 = \left[\frac{\sum_{i}^{N}(O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i}^{N}(O_i - \overline{O})\right]^{0.5}\left[\sum_{i=1}^{N}(P_i - \overline{P})\right]^{0.5}}\right]^2 \quad (19)$$

where N is the total number of observations, O_i and P_i are the i^{th} observed and predicted values ($i=1, 2,..., N$), and $\overline{O}$ and $\overline{P}$ are the mean observed values and mean predicted values, respectively. For *MRE* and *RMSE*, the values closest to 0 indicate good model predictions. NSE=1.0 means a perfect fit, and the negative NSE values indicate that the

mean observed value is a better predictor than the simulated value (Moriasi et al., 2007). For b and R^2, the values closest to 1 indicate good model prediction."

Comment 22.L290-293: Usually, the Nash and Sutcliff modeling efficiency test is also used to assess model performance. This test allows to understand whether the residuals variance is much smaller than the observed data variance, hence that the model predictions are good. Please include it in the analysis

Response: Thanks for your suggestion. The Nash and Sutcliff efficiency (NSE) is critical for the model performance and we added the value of the NSE in the revised manuscript**.** Please see response to comment 21 for the revised text in the manuscript.

Comment 23.L300-305: This text should likely be moved to the Material and Methods section. What is the relevance of including it here to the analysis of the results?

Response: In the material and method section we described how the various meteorological variables were collected. Here we describe the results of what the data indicated. The text really did not fit very well in the material and methods section and we prefer to keep it in the results section.

Comment 24.L316: Figure 4 and 5 present something defined as additional irrigation. Please explain. It does not correspond to the irrigation events given in Table 2. Also, why is it not possible to distinguish between irrigation and rainfall? Both represented by green color and during the same day. Rainfall in Figure 4 does not seem to rainfall in Figure 2.

Response: In the beginning of the growing season, the groundwater table increased without an irrigation event. This occurred on field A on June 24, 2016 and field C (B1) and D (B2) on June 20, 2017 which is shown in Fig.5. This phenomenon is curious and we believe that it related to irrigation in the nearby field. Therefore, we used "additional irrigation" to simulate this increase. In the response to comment 6 we speculate on the actual causes of this phenomenon

In Figure 4 and 5, we plot the sum of the irrigation and rainfall. We changed the legend in Figure 4 and 5 to the "sum of irrigation and rainfall". Note Figure 4 was change to Figure 5 and Figure 5 was changed to Figure 4 as the Reviewer 2' suggestion for matching the order of describing groundwater and soil moisture results in the revised manuscript.

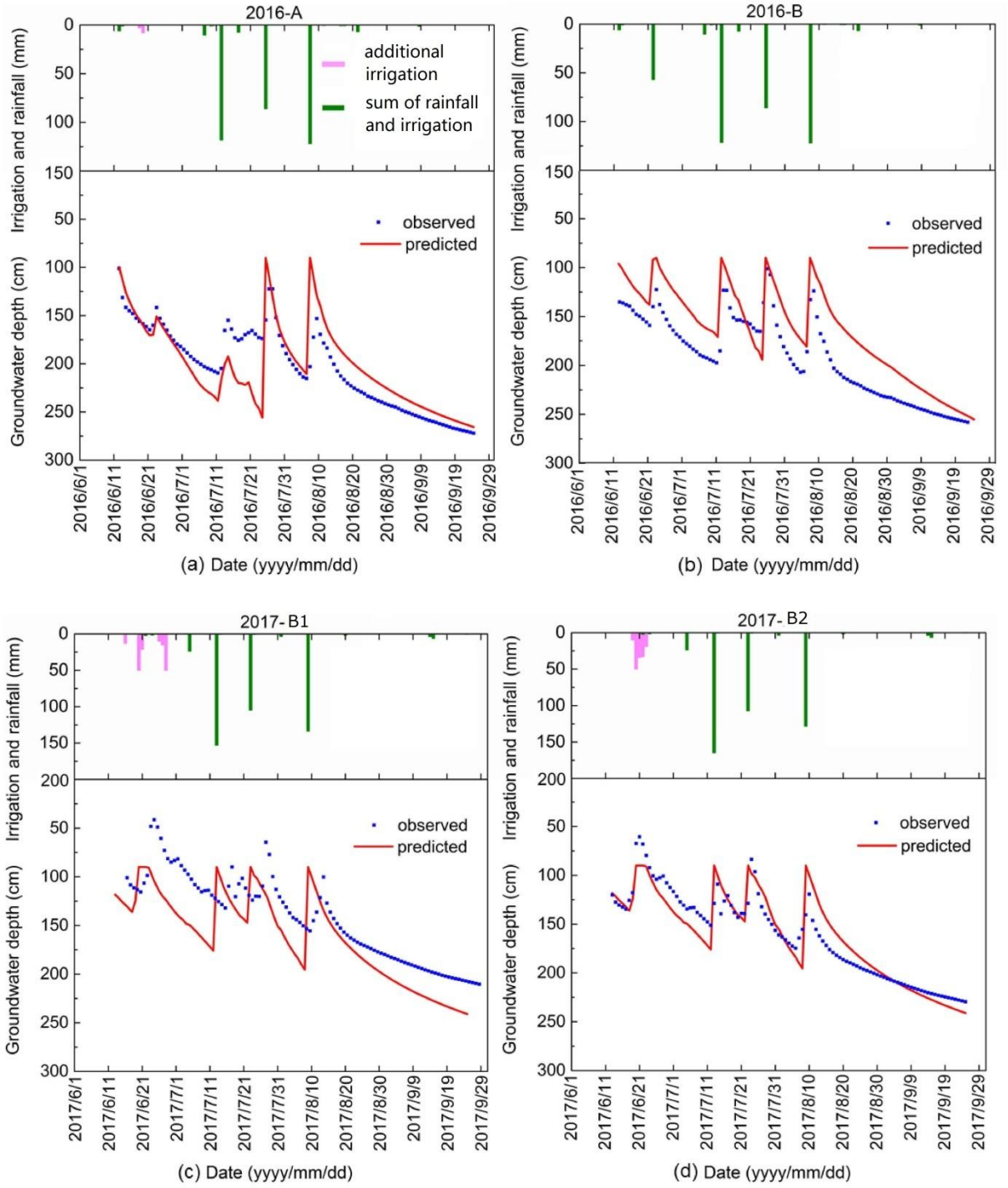

Figure.4 Simulated and observed groundwater depth during the growing period for the Fenzidi experimental fields in the Hetao irrigation district: (a,b) calibration in 2016 and (c,d) validation in 2017. (Notes: Additional irrigation means the irrigation recharge from the adjacent field which leads to the water table rise and was not planned).

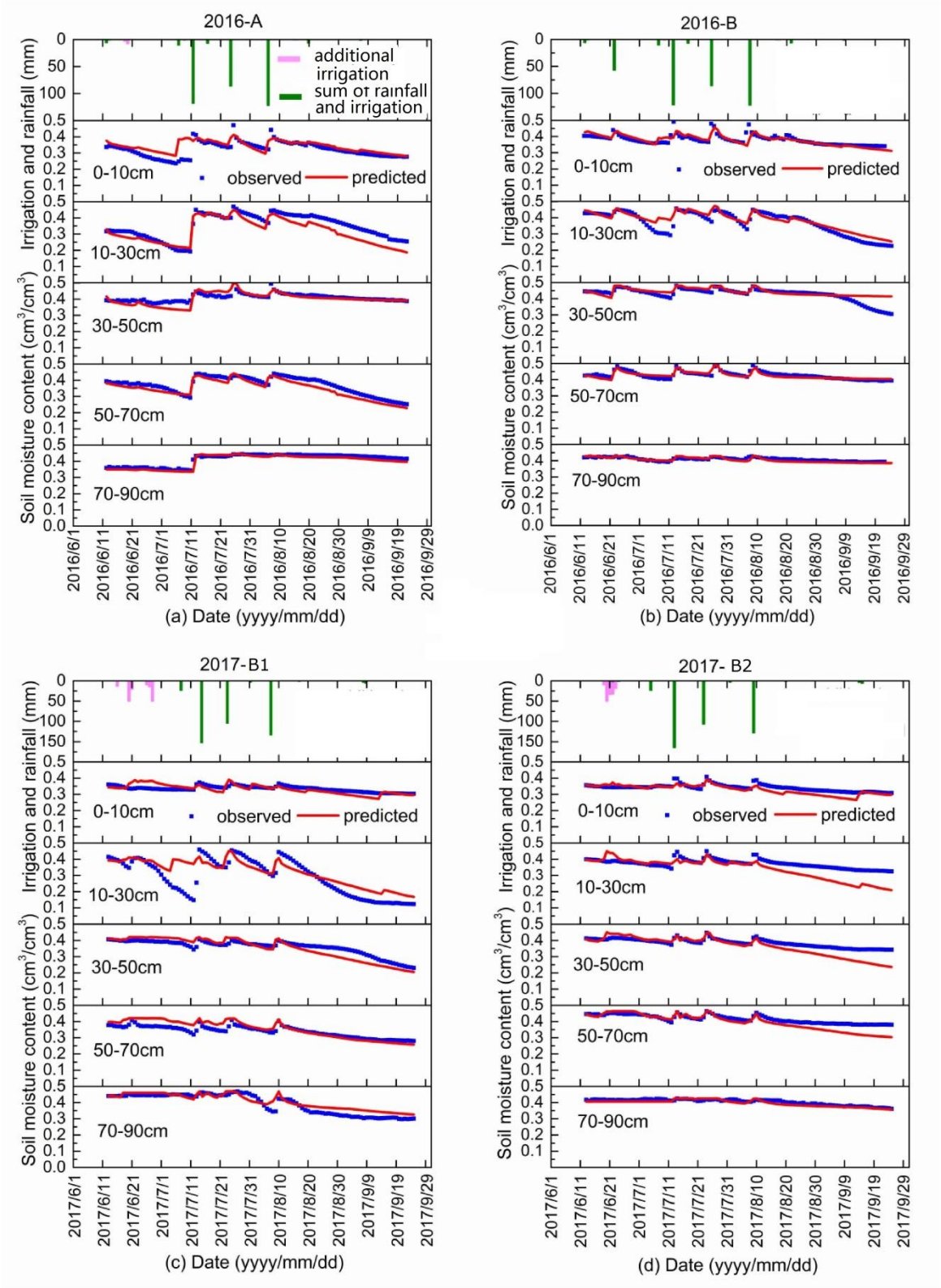

Figure. 5 Simulated and observed soil moisture content for five soil depths during the growing period for the Fenzidi experimental fields in the Hetao irrigation district: (a, b) calibration in

2016 and (c, d) validation in 2017.

Comment 25. L365: I'm not sure what authors are trying to say here. Please revise.

Response: We are not sure what is unclear in line 365. The line states that: **"**the saturated moisture contents in Table 5 agree in general with the one measured in Table 1 but not exact."

Comment 26.L393: Which were the salinity levels in the field?

Response: The information about the salinity levels in the field was added in the section of 3.2.1 as follows:

> "The first step in the calibration was to fit the K_c value from the water balance. From the moisture contents and the groundwater depth, we can calculate approximately the amount of water lost to evaporation. By comparing these values to the reference evaporation calculated with the Penman-Monteith equation, we found that initially during the early stages the crop coefficient was 0.3 until the filling stage and then increased to 0.7 during the filling stage to the maturing stage (Table 6). These values are in accordance with the findings of Katerji et al., (2003) that salinity reduces the evapotranspiration (Katerji et al., 2003).The observed salt content of experiment fields in 0-100cm soil layer during crop growth period were 2.29g/kg in field A, 1.79g/kg in field B, 2.33g/kg in Field B1, 2.09g/kg in Field B2, respectively."

Comment 27.L394-395: Allen et al. (1998) does not give Kc values for soils with median salinity. Please revise.

Response: We are still looking for the correct citation.

Comment 28.L466-467: The EPIC model was already applied to simulate crop growth in the Hetao region. Those studies should be cited.

Response: We are grateful for your suggestion. The studies about the EPIC model that applied to simulate the crop growth in Hetao irrigation district, such as Jia et al. (2015) and Xu et al. (2015).

The reference was added in the revised manuscript as:

> "……A mature crop model, such as the EPIC model (Williams et al., 1989) that needs relatively few parameters, will certainly help to predict the crop yield but might not change the water use predictions. Actually, the EPIC model already applied in Hetao irrigation district by many researchers to analyze the crop growth during the crop growth period (Jia et al., 2012; Xu et al., 2015)."

References:

Abrahart, R.J and See, L.: Comparing neural network and autoregressive moving average techniques for the provision of continuous river flow forecasts in two contrasting catchments. Hydro. Processes. 14: 2157-2172. http: // doi.org/10.1002/1099-1085(20000815/30)14:11/12<2157::AID-HYP57>3.0.CO;2-S. 2000.

Alcamo, J., Florke, M., and Marker, M.: Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrolog Sci J., 52:247-275, https:// doi.org/ 10.1623/hysj.52.2.247. 2007.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M.: Crop evapotranspiration. Guidelines for computing crop water requirements-FAO Irrigation and Drainage Paper 56, FAO, Rome. 1998.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R.: Large area hydrologic modeling and assessment part I: model development. J Am Water Resour As 34:73-89. https:// doi.org/10.1111/j.1752-1688.1998.tb05961.x.1998.

Asher, M.J., Croke, B.F.W., Jakeman, A.J. and Peeters, L.J.M.: A review of surrogate models and their application to groundwater modeling. Water Resour Res 51:5957-5973. http://doi.wiley.com/10.1002/2015 WR016967. 2015.

Beven, K.J., and Kirkby, M.J.: A physically based, variable contributing area model of basin hydrology. Hydrolog Sci J., 24:43-69. https:// doi.org/10.1080/02626667909491834. 1979.

Bowden, G.J., Maier, H.R. and Dandy, G.C.. Optimal division of data for neural network models in water resources applications. Water Resour Res 38:2-1-2-11. https://doi.org/10.1029/2001WR000 226.2002

Chen, C., Wang, E., and Yu, Q.: Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agr Water Manage 97:1175-1184. https:// doi.org/10.1016/j.agwat.2008.11.012.2010.

Cui, T., Peeters, L., Pagendam, D., Pickett, T., Jin, H., Crosbie, R., Raiber, M., Rassam, D., and Gilfedder, M.: Emulator-enabled approximate Bayesian computation (ABC) and uncertainty analysis for computationally expensive groundwater models. J Hydrol 564:191-207. https:// doi.org/10.1016/j.jh ydrol.2018.07.005

Dam, JC. Van., Huygen, J, Wesseling, JG, Feddes, RA., Kabat, P.,Walsum, PEV. Van.,Groenendijk, P., Diepen.: Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment. Report 71, Deparment Water Resources, Wageningen Agricultural University. Technical document 45, DLO Winand Staring Centre, Wageningen,152pp, 1997.

Dawson, C.W., Abrahart, R.J., Shamseldin, A.Y., Wilby, R.L.: Flood estimation at ungauged sites using artificial neural networks. J Hydrol.319: 391-409. http://doi.org/10.1016/ .jhydrol.2005.07.032. 2006.

Falkenmark, M.: The Massive Water Scarcity Now Threatening Africa: Why Isn't It Being Addressed? Ambio.18: 112-118.1989

Flint, A.L., Flint, L.E., Kwicklis, E.M., Fabryka-Martin, J.T., and Bodvarsson, G.S.: Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeol. J., 10:180-204. https:// doi.org/ 10.1007/s10040-001-0169-1. 2002.

Gao, X., Huo, Z., Bai, Y., Feng, S., Huang, G., Shi, H., and Qu, Z.: Soil salt and groundwater change in flood irrigation field and uncultivated land: a case study based on 4-year field observations. Environ. Earth Sci., 73:2127-2139. https:// doi.org/10.1007/s12665-014-3563-4. 2015.

Gao, X., Huo, Z., Qu, Z., Xu, X., Huang, G., and Steenhuis, T.S.: Modeling contribution of shallow groundwater to evapotranspiration and yield of maize in an arid area. Sci. Rep-UK 7. https:// doi.org/10.1038/srep43122. 2017a.

Gao, X., Bai, Y., Huo, Z., Xu, X., Huang, G., Xia, Y., and Steenhuis, T.S.: Deficit irrigation enhances contribution of shallow groundwater to crop water consumption in arid area. Agr. Water Manage., 185:116-125. https:// doi.org/ 10.1016/j.agwat.2017.02.012. 2017b.

Gardner, W.: Some study-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci., 85:228-232. 1958.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement Soil Water 1. Redistribution. Water Resour. Res., 6:851-860. https:// doi.org/ 10.1029/WR006i003p00851. 1970a.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement of Soil Water 2. Simultaneous Redistribution and Evaporation. Water Resour. Res., 6:1148-1153. https:// doi.org/ 10.1029/WR006i004p01148. 1970b.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E., and Cardenas, M.B.: The global volume and distribution of modern groundwater. Nat. Geosci., 9:161-167. https:// doi.org/10.1038/NGEO2590. 2016.

Guo, S., Ruan, B., Chen, H., Guan, X., Wang, S., Xu, N. and Li, Y.: Characterizing the spatiotemporal evolution of soil salinization in Hetao Irrigation District (China) using a remote sensing approach. Int J Remote Sens 39:6805-6825. https:// doi.org/10.1080/01431161.2018.1466076. 2018.

Guo, Y., and Shen, Y.: Agricultural water supply/demand changes under projected future climate change in the arid region of northwestern China. J. Hydrol, 540:257-273. https://doi.org/ 10.1016/j.jhydrol.2016.06.033. 2016.

Hinrichsen, D., Henrylito D.T.: The Coming Freshwater Crisis is Already Here. Finding the Source: The Linkages Between Population and Water. Environmental Change and Security Program, Washington, DC, 26pp, 2002.

Hoang, L., Schneiderman, E.M., Moore, K.E.B., Mukundan, R., Owens, E.M., and Steenhuis, T.S.: Predicting saturation-excess runoff distribution with a lumped hillslope model: SWAT-HS. Hydrol. Process, 31:2226-2243. https:// doi.org/ 10.1002/hyp.11179. 2017.

Hodnett, M., and Bell, J. Soil moisture investigations of groundwater recharge through black cotton soils in Madhya Pradesh, India. Hydrolog Sci J 31:361-381. https:// doi.org/10.1080/0262666860949 1054. 1986.

Huang, Q., Xu, X., Lu, L., Ren, D., Ke, J., Xiong,Y., Huo, Z. and Huang, G.: Soil salinity distribution based on remote sensing and its effect on crop growth in Hetao Irrigation District. Transactions of the Chinese Society of Agricultural Engineering 34:102-109. 2018.

Jasechko, S., and Taylor, R.G.: Intensive rainfall recharges tropical groundwaters. Environ Res Lett 10:124015. https:// doi.org/10.1088/1748-9326/10/12/124015. 2015.

Jia, H., Wang, J., Cao, C., Pan, D., Shi, P.: Maize drought disaster risk assessment of China based on EPIC model. International Journal of Digital Earth. 5:488-515. https:// doi.org/10.1080/17538947.2011.590535. 2012.

Kahlown, M., Ashraf, M., and Zia-Ul-Haq.: Effect of shallow groundwater table on crop water requirements and crop yields. Agr. Water Manage., 76:24-35. https:// doi.org/10.1016/j.agwat.2005.01.005. 2005.

Kendy, E., Gérard-Marchant, P., Walter, M. T., Zhang, Y., Liu, C., and Steenhuis, T.S.: A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Process., 17:2011-2031. https:// doi.org/10.1002/hyp.1240. 2003

Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resour. Res:42, W03S04, doi:10.1029/2005WR004362.

Krause, P., Boyle, D.P. and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5:89-97. https:// doi.org/ 10.5194/adgeo-5-89-2005. 2005.

Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, Sorab, and Provost, A.M., 2017, Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 p., https://doi.org/10.3133/tm6A55.

Liu, Z., Chen, H., Huo, Z., Wang, F., and Shock, C.C.: Analysis of the contribution of groundwater to evapotranspiration in an arid irrigation district with shallow water table. Agr. Water Manage., 171:131-141. https:// doi.org/10.1016/j.agwat.2016.04.002. 2016.

Luo, Y., and Sophocleous, M.: Seasonal groundwater contribution to crop-water use assessed with lysimeter observations and model simulations. J. Hydrol, 389:325-335. https:// doi.org/10.1016/j.jhydrol.2010.06.011. 2010.

Ma, Y., Feng, S., and Song, X.: A root zone model for estimating soil water balance and crop yield responsesto deficit irrigation in the North China Plain. Agr. Water Manage., 127:13-24. https:// doi.org/10.1016/j.agwat.2013.05.011. 2013.

Matott, L.S., and Rabideau, A.J.: Calibration of complex subsurface reaction models using a surrogate-model approach. Adv Water Resour 31:1697-1707. https:// doi.org/10.1016/j.advwatres10.10 16/j.advwatres.2008.08.006. 2008.

Mcdonald, M., and Harbaugh, A.: The history of MODFLOW. Groundwater 41:280-283. https:// doi.org/10.1111/j.1745-6584.2003.tb02591.x. 2003.

Moges, M., Schmitter, P., Tilahun, S., Langan, S., Dagnew, D., Akale, A. and Steenhuis, T.S.: Suitability of Watershed Models to Predict Distributed Hydrologic Response in the Awramba Watershed in Lake Tana Basin. Land Degrad Dev 10:1386-1397. https:// doi.org/10.1002/ldr.2608. 2017.

Mccuen, R., Rawls, W., and Brakensiek, D.: Statistical Analysis of the Brooks-Corey and the Green-Ampt Parameters. Water Resour. Res., 17:1005-1013. https:// doi.org/10.1029/WR017i004p01005. 1981.

Moiwo, J.P., Lu, W., Zhao, Y., Yang, Y., and Yang, Y.: Impact of land use on distributed hydrological processes in the semi-arid wetland ecosystem of Western Jilin. Hydrol. Process., 24:492-503. https:// doi.org/10.1002/hyp.7503. 2009.

Nash, J.E., and Sutcliffe, J.V.: River flow forecasting through conceptual models part I – a discussion of principles. J Hydrol 10:282-290. 1970.

Oki, T., and Kanae, S.: Global Hydrological Cycles and World Water Resources. Science, 313:1068-1072. https:// doi.org/10.1126/science.1128845. 2006.

Razavi, S., Tolson, B.A. and Burn, D.H. Review of surrogate modeling in water resources. Water Resour Res 48. https:// doi.org/10.1029/2011WR011527. 2012a.

Razavi, S., Tolson, B.A. and Burn, D.H.: Numerical assessment of metamodelling strategies in computationally intensive optimization. Environ Modell Softw. 34:67-86. https:// doi.org/10.1016/ j.envsoft.2011.09.010. 2012b.

Ren, D., Xu, X., Hao, Y., and Huang, G.: Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: Application to maize, sunflower and watermelon. J. Hydrol, 532:122-139. https:// doi.org/10.1016/j.jhydrol.2015.11.040. 2016.

Renewable internal freshwater resources per capita (cubic meters). https://data.worldbank.org/indicator/ER.H2O.IN TR.PC.2019.

Ritter, A., and Muñoz-Carpena, R.: Performance evaluation of hydrological models: Statistical significance for reducing subjectivity in goodness-of-fit assessments. J Hydrol 480:33-45. 2013.htt p:// doi.org/ 10.1016/j.jhydrol.2012.12. 004. 2013.

Rodriguez-Iturbe, I.: Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. Water Resour Res 36:3-9. https:// doi.org/10.1029/1999WR900210 .2000.

Rosa, R., Paredes, P., Rodrigues, G., Alves, I., Fernando, R., Pereira, L. and Allen, R.: Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. Agr Water Manage. https:// doi.org/103:8-24. 10.1016/j.agwat.2011.10.0132012.

Saleh, A., Steenhuis, T.S., and Walter, M.: Groundwater table simulation under different rice irrigation practices. J Irrig Drain Eng 115:530-544. https:// doi.org/10.1061/(ASCE)0733-9437(1989)115:4(530). 1989.

Savenije, H.H.G. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrol Process 18:1507-1511. https:// doi.org/10.1002/hyp.5563. 2004.

Šimůnek, J., Šejna, M. and van Genuchten, M.T.: The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. IGWMC-TPS-70. Int. Ground Water Modeling Ctr., Colorado Schoolof Mines, Golden. 1998.

Venkatesh, B., Lakshman, N., Purandara, B.K., and Reddy, V.B.: Analysis of observed soil moisture patterns under different land covers in Western Ghats, India. J. Hydrol, 397:281-294. https:// doi.org/10.1016/j.jhydrol.2010.12.006. 2011.

Todini, E.: Hydrological catchment modelling: past, present and future. Hydrol Earth Syst Sc 11:468-482. https:// doi.org/10.5194/hess-11-468-20072007.

Jasechko, S., and Taylor, R.G.: Intensive rainfall recharges tropical groundwaters. Environ Res Lett 10:124015. https:// doi.org/10.1088/1748-9326/10/12/124015.2015.

Wang, H., Zhang, L., Dawes, W.R., and Liu, C.: Improving water use efficiency of irrigated crops in the North China Plain - measurements and modelling. Agr. Water Manage., 48:151-167. https:// doi.org/10.1016/S0378-3774(00)00118-9. 2001.

Williams, J., Prebble, R., Williams, W., and Hignett, C.: The influence of texture, structure and clay mineralogy on the soil moisture characteristic. Aust. J. Soil Res., 21:15-32. https:// doi.org/10.1071/SR9830015. 1983.

Xu, X., Sun, C., Qu, Z., Huang, Q., Ramos, T.B., and Huang, G.: Groundwater Recharge and Capillary Rise in Irrigated Areas of the Upper Yellow River Basin Assessed by an Agro-Hydrological Model. Irrig. Drain., 64:587-599. https:// doi.org/10.1002/ird.1928. 2015.

Xue, J., Huo, Z., Wang, F., Kang, S., and Huang, G.: Untangling the effects of shallow groundwater and deficit irrigation on irrigation water productivity in arid region: New conceptual model. Sci. Total Environ., 619-620:1170-1182. https:// doi.org/10.1016/j.scitotenv.2017.11.145. 2018.

Yang, X., Chen, Y., Steenhuis, T.S., Pacenka, S., Gao, W., Ma, L., Zhang, M., and Sui, P.: Mitigating Groundwater Depletion in North China Plain with Cropping System that Alternate Deep and Shallow Rooted Crops. Front. Plant Sci., 8. https:// doi.org/ 10.3389/fpls.2017.00980. 2017.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Ma, L., Wang, G., Yan, P., Sui, P., and Steenhuis, T.S.: Effect of diversified crop rotations on groundwater levels and crop water productivity in the North China Plain. J. Hydrol., 522:428-438. https:// doi.org/ 10.1016/j.jhydrol.2015.01.010. 2015a.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Zhang, M., Sui, P., and Steenhuis, T.S.: Recharge and Groundwater Use in the North China Plain for Six Irrigated Crops for an Eleven Year Period. Plos One 10:e0115269. https:// doi.org/10.1371/journal.pone.0115269. 2015b.

Yeh, P.J., and Famiglietti, J.S.: Regional Groundwater Evapotranspiration in Illinois. J. Hydrometeorol., 10:464-478. https:// doi.org/ 10.1175/2008JHM1018.1. 2009.

Young, P.C., and M. Ratto. Statistical Emulation of Large Linear Dynamic Models. Technometrics 53:29-43. http://

Doi.org/ 10.1198/TECH.2010.07151. 2011.

Responses to the comments of Reviewer #2:

We would like to thank Professor Jan Boll for his detailed comments. As noted before all changes in the text are marked in blue

Major comments:

Comment1. Why does the introduction refer to Darcy type models while this manuscript does not include Darcy's law? Please clarify in the manuscript.

Response: The intent was to make a distinction between our model and other models. However, this review and the other reviews noted that we missed the mark. Therefore, we rewrote the introduction.

In the revised manuscript, the section that relates to the model classification is as follows.

> "There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al., 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW (Mcdonald and Harbaugh, 2003; Langevin, et al., 2017). These models have long run times when applied to real world problems. In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002). This makes the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al., 2017).
>
> To overcome the disadvantages of the full and completer models, computationally efficient surrogate models have been developed to speed up the modeling process without sacrificing accuracy or detail. Surrogate models are known under several names such as metamodels, reduced models, model emulators, proxy models and response surfaces (e.g., Razavi et al., 2012a; Asher et al., 2015). The complex models we will call "full" or comprehensive models.
>
> Computational efficiency is the main reason for applying surrogate models in place of full models. Other advantages of surrogate models are shortening the time needed for calibration; identifying insensitive and irrelevant parameters in the full models (Young and Ratto, 2011). Most importantly, surrogate models allow investigating structural model uncertainty (Matott and Rabideau, 2008). Finally, surrogate models might be able to deal with better with the self- organization of complex system prevalent in hydrology than the full models (Hoang et al., 2017). For example, full models based on small scale physics (Kirchner, 2006) not necessarily can model the repetitive wetting patterns observed in humid watersheds and for that reason. Simple surrogate models often outperform their complex counterparts in predicting runoff when a perched water table is present in sloping terrains (Moges et al, 2017; Hoang et al 2017).
>
> Surrogate models can be classified in two categories (Todini, 2007; Asher et al., 2015): data driven and physics derived. Data driven surrogates analyze relationships between the data available and physically derived surrogates simplify the underlying physics or reduce numerical resolution. In recent years, most emphasis in the research literature has

been data driven surrogate approaches (Razavi et al. 2012a). Relatively little research has been published on physically derived approaches. Despite its popularity, data-driven surrogates can be an inefficient and unreliable approach to optimizing complex field situations especially when data is scarce such as in groundwater systems (Razavi et al. 2012b) The physically derived surrogates overcome many of the limitations of data-driven approaches and are therefore superior over data driven methods (Asher et al., 2015)."

Comment2. The importance of the shallow water table effects on soil moisture content is important, as this manuscript shows. Authors should refer to Brooks et al. (2007) who showed the importance of the drainable porosity to establish water table heights, and presented a similar calculation. The manuscript can emphasize more clearly the truncation of the soil moisture characteristic curve when water tables become less than 3.3m below the soil surface as part of the equilibrium moisture content calculation. (Brooks, E.S., J. Boll, and P.A. McDaniel. 2007. Distributed and integrated response of a GIS-based distributed hydrologic model. Hydrologic Processes 21:110-122.)

Response: The Brooks et al (2007) paper is indeed very interesting. It should have been cited in our original manuscript because the approaches are very similar. There is a small difference however. We are interested in the drainable porosity due to a change in water table, while the Brooks et al. (2007) in interested in the total porosity in the soil that can be filled up before overland flow occurs.

The explanation similar to Brooks et al. (2007) but modified to the conditions with a decreasing water table is given with the description of the model.

"The drainable porosity, or specific yield, is defined as the amount of water drained from the soil for a unit decrease of the groundwater table when the soil moisture is at equilibrium. It is a crucial parameter in modeling the moisture content in our case or amount of runoff for a shallow perched water table when there is rain (Brooks et al., 2007).

By subtracting the total moisture content at equilibrium in the profile at the initial water table depth and at the new position one unit lower, we obtain the drainable porosity. For example, the area between the orange and blue curve is the amount of water drained for a decrease in the water table from 130cm to 150cm (Fig.3).

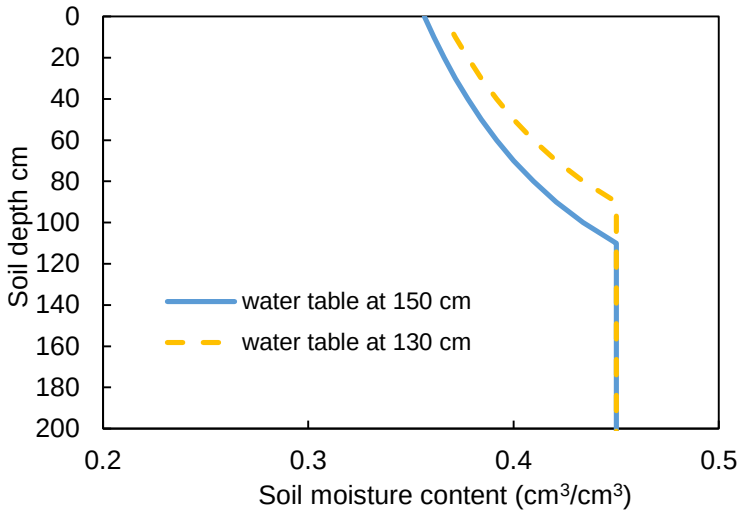

Figure. 3 Illustration of drainable porosity for a soil characteristic curve with a bubbling pressure of 40 cm. The yellow and the blue line are the equilibrium moisture contents for the groundwater depth at 130 and 150 cm, respectively. The area between the two lines represents the amount of water for the decrease of groundwater table drained from the profile when the groundwater decreases from 130 to 150 cm.

The total water content amount of the soil over a prescribed depth with a water table at depth h can be expressed as

$$W_{eq}^{h} = \sum_{j=1}^{n} L_j \overline{\left(\theta_{eq}^{z,h}\right)}_j \qquad (6)$$

where $\overline{\theta_{eq}^{z,h}}$ is the average equilibrium moisture content of layer j for h taken at the midpoint of the layer, n is the number of layers in the profile, L_j is the height of soil layer j. And the drainable porosity, μ^h, with the groundwater at depth h, can simply be found as

$$\mu^h = \frac{W_{eq}^{h-\Delta h} - W_{eq}^{h+\Delta h}}{2\Delta h} \qquad (7)$$

where $\Delta h = 0.5 L_j$."

Comment3. What is the reason that the fit of soil moisture is so close and the water table depths are not? Is it entirely due to soil variability or something that the model does not represent physically? Please clarify in the manuscript.

Response: One of the main problems is that the soil properties are only obtained till 90 cm. In addition the equation is likely to simple. I would be interesting if a full model can do better. The text was revised as follows:

"3.2.3 Calibration of the parameters related to groundwater depth

The final step was to calibrate the groundwater table coefficients with the 2016 data for

both fields. We found that for fields not in the same location (e.g., A, B) the subsurface was sufficiently different so that the same set of parameters could not be used (Table 6). The difference between the calibrated parameters for the two fields was small (Table 6). The measured and simulated groundwater depths were in good agreement with the chosen set of parameters (Fig. 4a, b) with coefficient of determination R^2 being 0.67 for Field A and 0.85 for Field B (Table 7-1). Only from July 15 to July 25 did the observed water table on Field B decrease slower than the simulated water table. This is partly related to the fact that the properties of the soil below 90 cm were not measured, and the assumption was made the soil characteristic curve below 90 cm was the same as that from 70-90 cm. Thus the drainable porosity of the soil which is very sensitive parameter might be different than what was used in the model. Another reason might be that the equation for upward movement might be too simple. Other statistical indicators showed the good fit as well (Table 7-1)".

Note that Figure 4 was revised as Figure 5 and Figure 5 was revised as Figure 4 in the revised manuscript.

Comment4. The manuscript includes 'additional irrigation' from an adjacent field. I assume this means water moved laterally to the study fields. This begs the question if the reverse did not also occur when the study fields were irrigated and water moved laterally to adjacent fields (some type of 'mounting' in the experimental fields). Three out of the four fields show layers with increased hydraulic conductivity, which can be responsible for such lateral movement. Please clarify.

Response: We discovered this increase in water table without rainfall or irrigation during testing of the model. It is therefore difficult to reconstruct exactly what happened. It is indeed likely that the opposite occurred as well, however since the field was close to saturation only a small amount of water is needed to increase the water table. This might have not been noticeable on the field that was irrigated since it was only as small portion of the water applied.

As stated in the response comment 6 reviewer1: One of the hypotheses of the increase in groundwater level due to irrigation in a nearby field is that early in the season the cracks in the structured clays were not fully closed and these could have transported some of the water across the field. It is not something that can be predicted by a standard finite difference or element model since the conductivity is so small for this site. So it is unexpected (or curious).

Another is that that a wetting front can proceed rapidly laterally through the root zone when the groundwater is near the surface. In this case only a very small amount of water μ is needed to bring the soil from nearly saturated to fully saturated. It could be as little as 0.1 cm^3cm^{-3}. The wetting front velocity can then be found by $v=q/\mu$. Thus the wetting from can move faster by the ratio of $\theta s/\mu$ which could be in the order of hundreds greater than the bulk of the water. Moreover, when the soil has been plowed the conductivity of plow layer could be greater than the bulk density. So, taken both effects together, we can imagine a wetting front movement of 10-20 m/day through the root zone. Although the effect on the groundwater table is significant flux wise only a small amount of water is involved.

Since this "curious effect" only occurs with the first irrigation we believe that water movement either through cracks or root zone somehow plays an important role. Finally, we should point

out that our surrogate model cannot predict it, but it is also unlikely that any "full" model will have the required equations and more importantly the input data to simulate this phenomenon.

Editorial comments:

Comment1. Choose 'ground water' or 'groundwater' throughout the manuscript.

Response: Sorry for the inconsistent writing. It has been corrected as "groundwater" in the revised manuscript**.**

Comment2. Line 39: change 'physical' to 'physically' (also elsewhere)

Response: Thanks for your suggestion. It has been changed to "physically" in the revised manuscript**.**

Comment3. Line 51-54: break up this long sentence.

Response: Thank you for your suggestion. The long sentence was amended in the revised manuscript as

> "Years of rapid population growth has squeezed the world water resources. The available fresh water per capita decreased 7500 m^3 from 13400 m^3 in 1962 to 5900 m^3 in 2014 (World Bank Group, 2019).".

Comment4. Line 68: change 'is' to 'will be'

Response: We changed it to "will be" in the revised manuscript as your suggestion.

Comment5. Line 72-73: the positive and negative effects are not clearly defined. In addition, the sentence needs rewording to: "A combination of field experiments and physically- based modeling has the benefits of both approaches with few negative effects.

Response: Apologies for the unclear statement. We revised the paragraph as follows:

> "In the Yellow River basin, crop irrigation accounts for 96% of the total water use (Li et al., 2004). Due to the increased demand for irrigation, the river has stopped flowing downstream for an average of 70 days per year (Hinrichsen, 2002). Saving water upstream in Inner Mongolia by improved management practices means that more water will be available downstream (Gao et al., 2015). In addition, the Hetao district is suffering from salinization which leads to the land degradation (Guo et al., 2018; Huang et al., 2018) . Salinization is caused by upward migration of water (and salt) from shallow groundwater table that leads to salt accumulation at the surface (Ren et al., 2016; Yeh and Famiglietti, 2009). Designing improved management practices to save water and decrease salinization can be achieved by field trials or with the aid of computer simulation mode measuring the fluxes. Field trials are time consuming, expensive and only a limited set of water management practices can be investigated. Models can test many management practices; however, the modeling results are often questionable because they have not been validated under local field condition and have not been validated for the future conditions A combination of field experiments together with models has the benefits of both approaches with few negative effects."

Comment6. Line 74-77: this is a single sentence paragraph without any relevant information.

Response: Thank you for your comment. The paragraph was amended as

> "Central to modeling irrigation management practices under shallow groundwater conditions (such as in the Yellow river basin) is simulating the soil moisture content accurately (Batalha et al., 2018, Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a) because the moisture content plays a critical role in the growth of crops (Rodriguez-Iturbe, 2000), groundwater recharge (Hodnett and Bell, 1986), upward movement of water to the root zone in areas (Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a; Batalha et al., 2018). The latter is unique to shallow groundwater areas where the moisture content and thus the unsaturated conductivity are high and where the drying of the surface soil sets up hydraulic gradient that causes the upward capillary movement from the shallow groundwater (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009). The upward moving water contains salt that is deposit in the root zone and at the surface. "

Comment7. Line 78: suggest to change 'grouped' with 'divided' Line

Response: Thank you for your suggestion. Since we revised the introduction section, this line was deleted in the revised manuscript**.**

Comment8. Line 79: it is not clear what is meant here with the 'full Darcy's law'. I would expect it to be the full Richards equation. – Delete 'the'

Response: As stated above we rewrote the introduction. Hopefully the following is an improvement:

> "There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al. 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW ((Mcdonald and Harbaugh, 2003; Langevin et al., 2017). These models have long run times when applied to real world problems, In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002).. This makes the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al 2017).
>
> To overcome the disadvantages of the full and completer models, computationally efficient surrogate models have been developed that speed up the modeling process without sacrificing accuracy or detail. Surrogate models are known under several names such as metamodels reduced models, model emulators, proxy models and response surfaces (e.g., Razavi et al., 2012a; Asher et al., 2015). The complex models we will call "full" or comprehensive models.
>
> Computational efficiency is the main reason for applying surrogate models in place of full models. Other advantages of surrogate models are shortening the time needed for

calibration; identifying insensitive and irrelevant parameters in the full models (Young and Ratto, 2011).Most importantly, surrogate models allow investigating structural model uncertainty (Matott and Rabideau, 2008). Finally, surrogate models might be able to deal with better with the self- organization of complex system prevalent in hydrology than the full models (Hoang et al., 2017. For example, full models based on small scale physics (Kirchner, 2006) not necessarily can model the repetitive wetting patterns observed in humid watersheds and for that reason simple surrogate models often outperform their complex counterparts in predicting runoff when a perched water table is present in sloping terrains (Moges et al, 2017; Hoang et al 2017)

Comment9. Line 90: are you sure SWAT uses a regionalized Darcy's law model?

Response: We agree that the whole section was poorly written. The SWAT hydrology model is based on the water balance equation (Arnold et al., 1998). The TOPMODEL (Beven and Kirkby, 1979) and SAWT model are both mainly focused on studies in watersheds and large river basins. This study is focused on field hydrological process and we amended the narration about the model classification method in the revised manuscript. And the statement about the TOPMODEL and SWAT model was deleted in the revised manuscript.

To the question if SWAT used a regionalized Darcy Equation: In SWAT uses Darcy's law for each HRU that can be at many places in the landscape. Not sure if we can call this regionalized.

Comment10. Line 91: delete 'water'

Response: The "water" was deleted in the revised manuscript**.** Please see the response to comment 6 for the whole paragraph. Here are the specific sentences

"The latter is unique to shallow groundwater areas where the moisture content and thus the unsaturated conductivity are high and where the drying of the surface soil sets up hydraulic gradient that causes the upward capillary movement from the shallow groundwater (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009)."

Comment11. Line 95: why is this cutoff 3.3m? If this is related to field capacity water tension, please mention it here.

Response: Yes, it was related as indicated in the comment. The paragraph is as follows

"In the Yellow River basin various models have been developed to simulate the soil water content and water fluxes. Full models that have been used are the HYDRUS-1D (Ren et al., 2016), and finite difference model application by Moiwo et al., (2010). Surrogate models for the North China plain where the groundwater is more than 20 m deep have been published by Wang et al. (2001); Kendy et al (2003); Chen et al. (2010); Ma et al. (2013); Yang et al. (2015, 2017); Li et al., (2017). In these models, the matric potential is ignored, and the hydraulic potential is equal to the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). Under these conditions the water flux becomes negligible when the soil reaches field capacity at -33 KPa (equivalent to -3.3 m in head units) at what point the hydraulic conductivity becomes limiting. These models are not valid for irrigation projects along

the Yellow river with shallow groundwater because the matric potential cannot be ignored over the short distance between the water table and the surface of the soil. Since the gravity and matric potential are of the same order, the water moves either down to the groundwater or up from the groundwater to the root zone depending on the matric potential at the soil (Gardner 1958; Gardener et al, 1970a,b). In summary, thus for shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes negligible) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) and thus not when the conductivity becomes limited at a matric potential of -33 KPa ".

Comment12. Line 113: change to 'soil moisture characteristic curve' .

Response: Thank you for your suggestion. It has been revised as "soil moisture characteristic curve" all over the manuscript**..**

Comment13. Line 125: delete 'main'

Response: We deleted it in the revised manuscript**.**

Comment14 .Line 127: check on the unit a-1 (not superscripted) as a valid metric unit for 'year' as you do later.

Response: "a" is the official SI unit for year (see for example https://www.iau.org/publications/proceedings_rules/units/). It is therefore being used in manuscript but we agree it is not very common. We have reverted back to "y" for year in the manuscript. The particular sentence was revised as

"The average annual precipitation is 180 mm and the annual potential evapotranspiration is 2225 mm (Luan et al., 2018)".

Comment15. Line 129: what is the reason to mention the number of daylight hours per year?

Response: We were of the opinion that it was the basic information for the study. Actually, it is not necessary, and we deleted this in the revised manuscript**.**

Comment16. Line 135-136: Change to 'The sowing dates were respectively.

Response: We revised the sentence to

"The sowing dates were April 24, 2016 and May 13, 2017, respectively".

Comment17. Line134: for clarity, call the fields in 2017 B1 and B2?

Response: Thank you for your suggestion and we changed the fields C and field D to the fields B1 and B2 in the revised manuscript**.**

Comment18. Line 140: change 'on' to 'at'.

Response: Thanks for your suggestion. We changed "on" to "at" in the revised manuscript.

Comment19. Line 142: change 'were showed' to 'are shown'; I think you mean to say 'during the growing season' because you are not identifying any growth stages explicitly in the figures.

Response: The sentence has been revised as

> "Precipitation and ET_0 during the growing season are shown in Fig. 2" in the revised manuscript**.**

Comment20. Line143: change 'experiment' to 'experimental'

Response: We corrected "experiment" to "experimental" in the revised manuscript.

Comment21. Line 159: change 'crop growth period' to 'the growing season'

Response: Thanks for your suggestion. The Title of the Figure 2 was changed to

> "Daily reference evapotranspiration (ET_0), and Precipitation during the growing season".

Comment22. Line 161: reword to 'soil moisture at field capacity () and at saturation ()

Response: We changed the "field capacity" to "soil moisture at field capacity" and "saturated soil moisture" to "soil moisture at saturation" in the revised manuscript**.** The text is now as follows

> "Soil samples were collected in rings from the same five layers where moisture contents were measured and used for determining soil physical properties including soil moisture at field capacity (θ_{fc}), soil moisture at saturation (θ_s), dry bulk density (ρ), and saturated hydraulic conductivity (K_s) (Table 3). For Fields A, B, B1 and B2, the saturated hydraulic conductivity was determined by the constant head method. Field capacity was determined at -33 kPa and bulk density was determined by oven drying and dividing by the volume of the ring…"

Comment23 Line 163: change 'measured' to 'determined' twice in this sentence.

Response: Thank you for your suggestion. The sentence was revised as

> "For Fields A, B, B1 and B2, the saturated hydraulic conductivity was determined by the constant head method. Field capacity was determined at -33kPa and bulk density was determined by oven drying and dividing by the volume of the ring." in the revised manuscript.

Comment24 Line 166: please add texture classification to

Response: The American soil texture classification was used in this study and this information was added in the revised manuscript.

Comment25 Line 168: change Table heading to 'Soil physical properties : : :.' – If fields C and D are the same as field B, what might explain the difference in soil properties shown? I suggest you add standard deviations for the average values provided.

Response: The soil in the field was deposited when the Yellow River flooded and therefore variable, explain the differences in properties.

The heading of the table was changed to

> "Soil physical properties of the Fenzidi experimental fields" in the revised manuscript as your suggestion."

Comment26. Line 180: change heading to 'Soil texture of Fields A and B'

Response: Thank you for your suggestion and we changed the heading to

> "Soil texture of Fields A and B".

Comment27. Line 188: change to 'in hydrological and soil sciences'

Response: we change in the revised manuscript, the phrase to

> "in hydrological and soil sciences"**.**

Comment28. Line 192: add comma after 'effective saturation'; note that only S and phi variables are used in this equation, so theta variables do not need to be defined.

Response: Thanks. The paragraph is as follows

> "The Brooks-Corey model can be expressed as (Gardner et al., 1970a; Gardner et al., 1970b; Mccuen et al., 1981; Williams et al., 1983).
>
> $$S_e = \left(\frac{\varphi_m}{\varphi_b}\right)^{-\lambda} \qquad for\ |\varphi_m| > |\varphi_b| \qquad (1a)$$
>
> $$S_e = 1 \qquad for\ |\varphi_m| \leq |\varphi_b| \qquad (1b)$$
>
> in which S_e is the effective saturation, φ_b is the bubbling pressure (cm), $\varphi_m$is matric potential (cm), and λ is the pore size distribution index. The effective saturation is defined as
>
> $$S_e = \frac{\theta - \theta_d}{\theta_s - \theta_d} \qquad (2)$$
>
> in which θ is the volumetric moisture content, θ_s is the volumetric saturated moisture content, θ_d is the residual air dry moisture content (all in cm^3/cm^3). Equation 2 can be simplified to the form by setting $\theta_d = 0$
>
> $$S_e = \frac{\theta}{\theta_s} \qquad (3)$$

For cases when the groundwater is close to the surface, under equilibrium conditions when the water flow is negligible (i.e., hydraulic potential is constant with depth), the matric potential can be expressed as height above the water table. For our field experiment the bubbling pressure, φ_b, and the pore size distribution index, λ, in the Brooks and Corey model can be obtained through a trial and error procedure by using the measured moisture content and matric potential derived from the groundwater depth after an irrigation event when equilibrium state was reached and sum of the gravity potential and matric potential was constant with depth.

Comment29. Line 196: reword (is it reasonable here to assume theta_d = 0? Figure 6 does not support this assumption.

Response: θ_d is the airdry moisture content. Thus, the assumption is fine especially since we are only interested in the "wet" part of the soil moisture characteristic curve. The words "air dry" are added the residual moisture content to clarify the meaning. See response to comment 28.

Comment30. Line 201: check wording here

Response: The changed wording is given at the end of the response to comment 28.

Comment31. Line 204: delete the second 'the'

Response: Thanks. We removed "the" as shown below

"The soil of the crop root zone is divided into several soil layers and each soil layer has its specific soil moisture characteristic curve. After a sufficiently large irrigation and rainfall event, the moisture content is at equilibrium after the drainage stops. After such an event, the soil moisture of vadose zone stays at the equilibrium moisture content as long as the evapotranspiration is less than upward flux from the groundwater"**.**

Comment32. Line 203-206: the paragraph needs better wording; should the vadose zone stay at equilibrium moisture content instead of the groundwater?

Response: Hopefully we clarified the confusion in the rewrite. The changed text can be found in the response to comment 31.

Comment33. Line 209: change to 'dependent on' Figure 3: does this Figure assume a capillary fringe (bubbling pressure) of _40cm? Maybe make note of this in the Figure caption

Response: We changed "dependent of" to "dependent on" in the revised manuscript and revised the figure 3 title to

"Figure. 3 Illustration of drainable porosity for a soil moisture characteristic curve with a bubbling pressure of 40 cm. The yellow and the blue line are the equilibrium moisture contents for the groundwater depth at 130 and 150 cm, respectively. The area between the two lines represents the amount of water for the decrease of groundwater table drained from the profile when the groundwater decreases from 130 to 150 cm"

Comment34. Line 224: delete ‘drained’

Response: We deleted ‘drained’ in the revised manuscript.

Comment35. Line 254: should the first ‘and’ be deleted, or is a word missing? Add ‘flux’ after second ‘upward

Response: Thanks for finding the mistake. The first “and” was deleted and we add “flux” in the revised manuscript**.**

Comment36. Line 255: check spelling in ‘prede[te]rmined’ Figure 5: what explains the earlier predicted changes in groundwater depths compared to observed in 2017C and D?

Response: “Predermined” was corrected to “predetermined” in the revised manuscript.

The honest answer is that we do not know. If the initial water table for field C (B1) would have been greater and similar to that in field D (B2) the prediction in field C (B1) would have been closer to the observed value. .

Comment37. Line 321: the term ‘additional irrigation’ is not explained well here (but better in Lines 328-332). Does it mean that irrigation was applied to an adjacent field causing lateral inflow? If this is a possible effect, is there a similar lateral outflow flux possible to surrounding fields?

Response: We attempted to answer this comment under comment 4. Please see that response.

Comment38. Line 334: change ‘while’ to ‘whereas’

Response: Thank you for your suggestion and we changed “while” to “whereas” in the revised manuscript.

Comment39. Line338: switch the order of Figures 4 and 5, so they match the order of describing ground- water and soil moisture results.

Response: Thanks, we switched the order of Figures 4 and 5 in the revised manuscript.

Comment40. Line 345: change ‘at’ to ‘during’

Response: “at” is changed to “during” as your suggestion in the revised manuscript.

Comment41. Line 352: Can you include the value of the bubbling pressure?

Response: The values of the bubbling pressure were shown in Table 5 and we added this information in this sentence in the revised manuscript.

> “It is interesting that while the soil profile was saturated (Fig. 4), the groundwater table was between 75-100 cm (Fig. 5). Before equilibrium moisture content was reached the water table was likely near the surface during the irrigation event. Because the drainable

porosity was extremely small, even a minimum amount of evapotranspiration or drainage would cause the water table to decrease to roughly the height of the capillary fringe equal to the bubbling pressure, φ_b, in Eq. 5. The bubbling pressure are listed in Table 5."

Comment42. Line 377: change 'indicates' to 'indicate'

Response: Done, thanks.

Comment43. Line 392: add 'the' in 'to the maturing stage'

Response: Thank you for your suggestion and we amended it to "the maturing stage" in the revised manuscript.

Comment44. Line 393: move parenthesis for the citation to just around the year (and remove the comma)

Response: We amended the phrase as your suggestion in the revised manuscript**.**

Comment45. Line 399: change to ': : : in general are in agreement : : :'

Response: Thank you for your suggestion. The sentence was revised in the revised manuscript.as

"The calibrated soil moisture contents of the five soil layers for the two fields in general are in agreement with the measured values in 2016 (Fig 4a, b)"

Comment46. Line 400: change 'one' to '1'

Response: This is indeed an exception to the general rule**.** It is changed.

Comment47. Line 403: change to 'realistically'

Response: We changed "realistic" to "realistically" in the revised manuscript**.**

Comment48. Line408: change 'less good' to 'worse'

Response: Thanks. We made the change.

Comment49. Line 409: change to 'coefficient of determination'

Response: Thank you for your suggestion and we changed it to "the coefficient of determination" in the revised manuscript.

Comment50. Line 416: change to 'depths'

Response: We made the change. The text is now as follows:

"The moisture contents predicted by the Shallow Aquifer-Vadose Zone Model were

validated with the 2017 data on Fields B1 and B2. Although the validation statistics of the five layers were slightly worse than for calibration in Table 7, the overall fit was still good as shown in Fig. 4c, d. The coefficient of determination varied between 0.39 and 0.90. The *MRE* varied between -9.34% and 19.48%, and the mean *RMSE* range was from 0.01 to 0.07 cm^3/cm^3 for the five soil layers (Table 7-2)."

Comment51. Line 421: no need to write out RME; change 'is' to 'being'

Response: Thanks for your suggestion. The information about RME was deleted here. We amended the sentence as

"Others statistical indicators show a good fit as well (Table 7-1)" in the revised manuscript."

Comment52. Line 422: no need to write out RMSE

Response: We delete the sentence about the RMSE in the revised manuscript.

Comment53. Line 428: insert 'to' as in 'related to groundwater depth'

Response: We corrected the phrase as "related to the groundwater depth" in the revised manuscript**.**

Comment54. Line 454: add period after 'al'

Response: We changed the sentence as follows:

"In general, this surrogate model simulated the soil moisture content in each soil layer well, certainly when compared to other models that attempted the soil moisture contents in the Yellow River basin such as North China Plain (Kendy et al., 2003) and the Hetao Irrigation District by Gao et al. (2017b) during the crop growth period."

Comment55. Line 459: change to 'indicate'

Response: We changed "indicates" to "indicated" in the revised manuscript**.** Past tense is more appropriate.

Comment56. Line 466: change to 'relatively'

Response: We corrected it as "relatively" in the revised manuscript**.**

Thank you so much for the careful reading and all your suggestions**.**

References:

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R.: Large area hydrologic modeling and assessment part I: model development. J Am Water Resour As 34:73-89. https:// doi.org/10.1111/j.1752-1688.1998.tb05961.x.1998.

Asher, M.J., Croke, B.F.W., Jakeman, A.J. and Peeters, L.J.M.: A review of surrogate models and their application to groundwater modeling. Water Resour Res 51:5957-5973. http://doi.wiley.com/10.1002/2015 WR016967. 2015.

Brooks, E.S., Boll, J., McDaniel, P.A.: Distributed and integrated response of a geographic information system-based hydrologic model in the eastern Palouse region, Idaho. Hydro. Processes. 21:110-122. http://doi.org/10.1002/hyp.6230. 2007

Chen, C., Wang, E., and Yu, Q.: Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agr Water Manage 97:1175-1184. https:// doi.org/10.1016/j.agwat.2008.11.012.2010.

Cui, T., Peeters, L., Pagendam, D., Pickett, T., Jin, H., Crosbie, R., Raiber, M., Rassam, D., and Gilfedder, M.: Emulator-enabled approximate Bayesian computation (ABC) and uncertainty analysis for computationally expensive groundwater models. J Hydrol 564:191-207. https:// doi.org/10.1016/j.jh ydrol.2018.07.005

Dam, JC. Van., Huygen, J, Wesseling, JG, Feddes, RA., Kabat, P.,Walsum, PEV. Van.,Groenendijk, P., Diepen.: Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment. Report 71, Deparment Water Resources, Wageningen Agricultural University. Technical document 45, DLO Winand Staring Centre, Wageningen,152pp, 1997.

Flint, A.L., Flint, L.E., Kwicklis, E.M., Fabryka-Martin, J.T., and Bodvarsson, G.S.: Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeol. J., 10:180-204. https:// doi.org/ 10.1007/s10040-001-0169-1. 2002.

Gardner, W.: Some study-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci., 85:228-232. 1958.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement Soil Water 1. Redistribution. Water Resour. Res., 6:851-860. https:// doi.org/ 10.1029/WR006i003p00851. 1970a.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement of Soil Water 2. Simultaneous Redistribution and Evaporation. Water Resour. Res., 6:1148-1153. https:// doi.org/ 10.1029/WR006i004p01148. 1970b.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E., and Cardenas, M.B.: The global volume and distribution of modern groundwater. Nat. Geosci., 9:161-167. https:// doi.org/10.1038/NGEO2590. 2016.

Guo, S., Ruan, B., Chen, H., Guan, X., Wang, S., Xu, N. and Li, Y.: Characterizing the spatiotemporal evolution of soil salinization in Hetao Irrigation District (China) using a remote sensing approach. Int J Remote Sens 39:6805-6825. https:// doi.org/10.1080/01431161.2018.1466076. 2018.

Guo, Y., and Shen, Y.: Agricultural water supply/demand changes under projected future climate change in the arid region of northwestern China. J. Hydrol, 540:257-273. https://doi.org/ 10.1016/j.jhydrol.2016.06.033. 2016.

Hinrichsen, D., Henrylito D.T.: The Coming Freshwater Crisis is Already Here. Finding the Source: The Linkages Between Population and Water. Environmental Change and Security Program, Washington, DC, 26pp, 2002.

Hoang, L., Schneiderman, E.M., Moore, K.E.B., Mukundan, R., Owens, E.M., and Steenhuis, T.S.: Predicting saturation-excess runoff distribution with a lumped hillslope model: SWAT-HS. Hydrol. Process, 31:2226-2243. https:// doi.org/ 10.1002/hyp.11179. 2017.

Hodnett, M., and Bell, J. Soil moisture investigations of groundwater recharge through black cotton soils in Madhya Pradesh, India. Hydrolog Sci J 31:361-381. https:// doi.org/10.1080/0262666860949 1054. 1986.

Jasechko, S., and Taylor, R.G.: Intensive rainfall recharges tropical groundwaters. Environ Res Lett 10:124015. https:// doi.org/10.1088/1748-9326/10/12/124015. 2015.

Kahlown, M., Ashraf, M., and Zia-Ul-Haq.: Effect of shallow groundwater table on crop water requirements and crop yields. Agr. Water Manage., 76:24-35. https:// doi.org/10.1016/j.agwat.2005.01.005. 2005.

Kendy, E., Zhang, Y., Liu, C., Wang, J. and Steenhuis, T.S.: Groundwater recharge from irrigated cropland in the North China Plain: case study of Luancheng County, Hebei Province, 1949–2000. Hydrol Process 18:2289-2302. https:// doi.org/ 10.1002/hyp.5529. 2004.

Kendy, E., Gérard-Marchant, P., Walter, M. T., Zhang, Y., Liu, C., and Steenhuis, T.S.: A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Process., 17:2011-2031. https:// doi.org/10.1002/hyp.1240. 2003.

Kirchner, J. W. Getting the right answers for the right reasons: Linkingmeasurements, analyses, and models to advance the science of hydrology,Water Resour. Res.,42, W03S04, https://doi.org/10.1029/2005WR004362.2006

Krause, P., Boyle, D.P. and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5:89-97. https:// doi.org/ 10.5194/adgeo-5-89-2005. 2005.

Li, C., Yang, Z., and Wang, X.: Trends of Annual Natural Runoff in the Yellow River Basin. Water Int., 29:447-454. https:// doi.org/10.1080/02508060408691807. 2004.

Liu, Z., Chen, H., Huo, Z., Wang, F., and Shock, C.C.: Analysis of the contribution of groundwater to evapotranspiration in an arid irrigation district with shallow water table. Agr. Water Manage., 171:131-141. https:// doi.org/10.1016/j.agwat.2016.04.002. 2016.

Luo, Y., and Sophocleous, M.: Seasonal groundwater contribution to crop-water use assessed with lysimeter observations and model simulations. J. Hydrol, 389:325-335. https:// doi.org/10.1016/j.jhydrol.2010.06.011. 2010.

Ma, Y., Feng, S., and Song, X.: A root zone model for estimating soil water balance and crop yield responsesto deficit irrigation in the North China Plain. Agr. Water Manage., 127:13-24. https:// doi.org/10.1016/j.agwat.2013.05.011. 2013.

Matott, L.S., and Rabideau, A.J.: Calibration of complex subsurface reaction models using a surrogate-model approach. Adv Water Resour 31:1697-1707. https:// doi.org/10.1016/j.advwatres10.1016/j.advwatres.2008.08.006. 2008.

Mcdonald, M., and Harbaugh, A.: The history of MODFLOW. Groundwater 41:280-283. https:// doi.org/10.1111/j.1745-6584.2003.tb02591.x. 2003.

Moges, M., Schmitter, P., Tilahun, S., Langan, S., Dagnew, D., Akale, A. and Steenhuis, T.S.: Suitability of Watershed Models to Predict Distributed Hydrologic Response in the Awramba Watershed in Lake Tana Basin. Land Degrad Dev 10:1386-1397. https:// doi.org/10.1002/ldr.2608. 2017.

Mccuen, R., Rawls, W., and Brakensiek, D.: Statistical Analysis of the Brooks-Corey and the Green-Ampt Parameters. Water Resour. Res., 17:1005-1013. https:// doi.org/10.1029/WR017i004p01005. 1981.

Moiwo, J.P., Lu, W., Zhao, Y., Yang, Y., and Yang, Y.: Impact of land use on distributed hydrological processes in the semi-arid wetland ecosystem of Western Jilin. Hydrol. Process., 24:492-503. https:// doi.org/10.1002/hyp.7503. 2009.

Razavi, S., Tolson, B.A. and Burn, D.H. Review of surrogate modeling in water resources. Water Resour Res 48. https:// doi.org/10.1029/2011WR011527. 2012a.

Razavi, S., Tolson, B.A. and Burn, D.H.: Numerical assessment of metamodelling strategies in computationally intensive optimization. Environ Modell Softw. 34:67-86. https:// doi.org/10.1016/ j.envsoft.2011.09.010. 2012b.

Ren, D., Xu, X., Hao, Y., and Huang, G.: Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: Application to maize, sunflower and watermelon. J. Hydrol, 532:122-139. https:// doi.org/10.1016/j.jhydrol.2015.11.040. 2016.

Renewable internal freshwater resources per capita (cubic meters). https://data.worldbank.org/indicator/ER.H2O.INTR.PC.2019.

Rodriguez-Iturbe, I.: Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. Water Resour Res 36:3-9. https:// doi.org/10.1029/1999WR900210 .2000.

Rosa, R., Paredes, P., Rodrigues, G., Alves, I., Fernando, R., Pereira, L. and Allen, R.: Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. Agr Water Manage. https:// doi.org/103:8-24. 10.1016/j.agwat.2011.10.0132012.

Šimůnek, J., Šejna, M. and van Genuchten, M.T.: The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. IGWMC-TPS-70. Int. Ground Water Modeling Ctr., Colorado Schoolof Mines, Golden. 1998.

Todini, E.: Hydrological catchment modelling: past, present and future. Hydrol Earth Syst Sc 11:468-482. https:// doi.org/10.5194/hess-11-468-20072007.

Wang, H., Zhang, L., Dawes, W.R., and Liu, C.: Improving water use efficiency of irrigated crops in the North China Plain - measurements and modelling. Agr. Water Manage., 48:151-167. https:// doi.org/10.1016/S0378-3774(00)00118-9. 2001.

Yang, X., Chen, Y., Steenhuis, T.S., Pacenka, S., Gao, W., Ma, L., Zhang, M., and Sui, P.: Mitigating Groundwater Depletion in North China Plain with Cropping System that Alternate Deep and Shallow Rooted Crops. Front. Plant Sci., 8. https:// doi.org/ 10.3389/fpls.2017.00980. 2017.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Ma, L., Wang, G., Yan, P., Sui, P., and Steenhuis, T.S.: Effect of diversified crop rotations on groundwater levels and crop water productivity in the North China Plain. J. Hydrol., 522:428-438. https:// doi.org/ 10.1016/j.jhydrol.2015.01.010. 2015a.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Zhang, M., Sui, P., and Steenhuis, T.S.: Recharge and Groundwater Use in the North China Plain for Six Irrigated Crops for an Eleven Year Period. Plos One 10:e0115269. https:// doi.org/10.1371/journal.pone.0115269. 2015b.

Yeh, P.J., and Famiglietti, J.S.: Regional Groundwater Evapotranspiration in Illinois. J. Hydrometeorol., 10:464-478. https:// doi.org/ 10.1175/2008JHM1018.1. 2009.

Young, P.C., and M. Ratto. Statistical Emulation of Large Linear Dynamic Models. Technometrics 53:29-43. http:// Doi.org/ 10.1198/TECH.2010.07151. 2011.

Responses to the comments of Reviewer #3:

We thank reviewer 3 for the detailed comments. The text in blue are changes and additions in the original text. For clarity we do not show any of the removed text.

Major comments:

Comment1. L78-100: The introduction discusses about Darcy based and simplified models for soil moisture simulations. In which class does the model developed in this manuscript belong? Assuming the latter (simplified), why is this class chosen for this work?

Response: The introduction seemed to have a good logic when we wrote it. At the end of the paper we conclude that the exact value of the hydraulic conductivity is irrelevant for daily predictions of moisture content in areas for shallow groundwater. In other words Darcy's law was only important for the long-term behavior of the groundwater. The idea was to convey this information about Darcy's law in the introduction, but this was obviously a bad idea given the reviewers' comments.

We have, therefore, completely rewritten the introduction. In the revised manuscript, the part that relates to class of the model is below

> Modeling moisture contents
>
> There is tendency with the ever increasing computer power, to include all processes and the highly heterogeneous field conditions in hydrological models (Asher et al 2015). In case of simulating moisture contents these models become complex and often fully distributed in 3-D (Cui et al. 2017). Examples of these fully developed models are HYDRUS (Šimůnek et al., 1998), SWAP (Dam et al., 1997) and MODFLOW (Mcdonald and Harbaugh, 2003; Langevin, et al., 2017). These models have long run times when applied to real world problems. In addition, calibration effort increases exponentially with the number of model parameters (Rosa et al., 2012; Flint et al., 2002). This makes the use of the complex models for real time management and decision support cumbersome where many model runs are needed (Cui et al., 2017).
>
> To overcome the disadvantages of the full and completer models, computationally efficient surrogate models have been developed that speed up the modeling process without sacrificing accuracy or detail. Surrogate models are known under several names such as metamodels reduced models, model emulators, proxy models and response surfaces (e.g., Razavi et al., 2012a; Asher et al., 2015). The complex models we will call "full" or comprehensive models.
>
> Computational efficiency is the main reason for applying surrogate models in place of full models. Other advantages of surrogate models are shortening the time needed for calibration; identifying insensitive and irrelevant parameters in the full models (Young and Ratto, 2011). Most importantly, surrogate models allow investigating structural model uncertainty (Matott and Rabideau, 2008). Finally, surrogate models might be able

to deal with better with the self- organization of complex system prevalent in hydrology than the full models (Hoang et al., 2017. For example, full models based on small scale physics (Kirchner, 2006) not necessarily can model the repetitive wetting patterns observed in humid watersheds and for that reason. Simple surrogate models often outperform their complex counterparts in predicting runoff when a perched water table is present in sloping terrains (Moges et al, 2017; Hoang et al 2017).

Surrogate models can be classified in two categories (Todini, 2007; Asher et al., 2015): data driven and physics derived. Data driven surrogates analyze relationships between the data available and physically derived surrogates simplify the underlying physics or reduce numerical resolution. In recent years, most emphasis in the research literature has been data driven surrogate approaches (Razavi et al. 2012a). Relatively little research has been published on physically derived approaches. Despite its popularity, data-driven surrogates can be an inefficient and unreliable approach to optimizing complex field situations especially when data is scarce such as in groundwater systems (Razavi et al. 2012b). The physically derived surrogates overcome many of the limitations of data-driven approaches and are therefore superior over data driven methods (Asher et al., 2015)

In the Yellow River basin various models have been developed to simulate the soil water content and water fluxes. Full models that have been used are the HYDRUS-1D (Ren et al., 2016), and finite difference model application by Moiwo et al., (2010). Surrogate models for the North China plain where the groundwater is more than 20 m deep have been published by Wang et al. (2001); Kendy et al (2003); Chen et al. (2010); Ma et al. (2013); Yang et al. (2015, 2017a,b); Li et al., (2017). In these models, the matric potential is ignored, and the hydraulic potential is equal to the gravity potential and thus the gradient of the hydraulic potential is unity (at least when it is expressed in head units). Under these conditions the water flux becomes negligible when the soil reaches field capacity at -33 KPa (equivalent to -3.3 m in head units) at what point the hydraulic conductivity becomes limiting. These models are not valid for irrigation projects along the Yellow river with shallow groundwater because the matric potential cannot be ignored over the short distance between the water table and the surface of the soil. Since the gravity and matric potential are of the same order, the water moves either down to the groundwater or up from the groundwater to the root zone depending on the matric potential at the soil (Gardner 1958; Gardener et al, 1970a,b). In summary, thus for shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes negligible) when hydraulic gradient is zero (i.e., matric potential and gravity potential add up to constant value) and thus not when the conductivity becomes limited at a matric potential of -33 KPa.

Comment2.L88-89"The disadvantage is that each landscape type has a different set of regionalized landscape parameters is not very clear and explicit. Please make the motivation of choosing the specific modelling approach clearer for the broad readership of the journal.
Response: We found that the soil characteristic curve and the groundwater depth determine the

moisture content in the soil for some time after irrigation. So, these two regional characteristics determine the value of the regionalized parameters for finding the moisture contents. Determining the two parameters that determine the upward flux from the groundwater is not simple and more research is needed how to define these parameters a priori.

Comment3.L108-113: The modelling approach in the manuscript assumes that lateral groundwater flow is negligible (i.e., groundwater dynamics is based on water input at the land surface and ET). This is a very strong assumption and should be discussed clearly in the manuscript. This is especially important because the authors mentioned

Response: It was an oversight not to include this information in the original manuscript. We added the following in section "Calculating the fluxed in the soil" in the revised manuscript.

> The groundwater in Hetao irrigation district has a small hydraulic gradient of 0.10-0.25‰ (Ren et al., 2016). In addition, the soils vary from a silt loam to a clay loam (Table 4) that has a saturated hydraulic conductivity of less than 2 m/day. This means that the lateral fluxes are small compared the vertical fluxes and can therefore neglected for the calculation of the groundwater depth. Based on this assumption, the net change in groundwater depth, Δh, can be calculated on days without rainfall or irrigation as
>
> $$\Delta h = \frac{U_g^h}{\mu^h} \qquad (13a)$$
>
> and days with rain or irrigation as
>
> $$\Delta h = -\frac{R_5}{\mu^h} \qquad (13b)$$
>
> where the upward flux, U_g^h, is calculated with Eq 9, the percolation of the bottom layer R_5 with Eq 12 and the drainable porosity, μ^h with Eq 7……..

Comment4. "This is curious and could be due to water originating from irrigation in a nearby field (L331-332). Which gives an impression that lateral flow affects hydrology over the study area. Despite that, only vertical movement of water is considered in this study.

Response: As we explained in the last comment, the hydraulic gradient in this irrigation district is very small (0.1-0.25‰). In the original manuscript, we wrote that irrigation in a nearby field affected the groundwater table in the beginning of growing season (lines 328-336).

> "In general, groundwater rose during an irrigation event and then decreased slowly due to upward movement of water to the plant roots to meet the transpiration demand. However, in the beginning of the growing season, we can see that the water table increased without an irrigation event. This occurred on Field A on June 24, 2016 and Fields C and D on June 20, 2017 (Fig. 5). This is curious and could be due to water originating from irrigation in a nearby field."

One of the hypotheses of the increase in groundwater level due to irrigation in a nearby field is that early in the season the cracks in the structured clays were not fully closed and these could have transported some of the water across the field. It is not something that can be predicted by a standard finite difference or element model since the conductivity is so small for this site. So it is

unexpected (or curious).

Another is that that a wetting front can proceed rapidly laterally through the root zone when the groundwater is near the surface. In this case only a very small amount of water μ is needed to bring the soil from nearly saturated to fully saturated. It could be as little as 0.1 cm^3cm^{-3}. The wetting front velocity can then be found by v=q/μ. Thus the wetting from can move faster by the ratio of θs/μ which could be in the order of hundreds greater than the bulk of the water. Moreover, when the soil has been plowed the conductivity of plow layer could be greater than the bulk density. So, taken both effects together, we can imagine a wetting front movement of 10-20 m/day through the root zone. Although the effect on the groundwater table is significant flux wise only a small amount of water is involved.

Since this "curious effect" only occurs with the first irrigation we believe that water movement either through cracks or root zone somehow plays an important role. Finally, we should point out that our surrogate model cannot predict it, but it is also unlikely that any "full" model will have the required equations and more importantly the input data to simulate this phenomenon.

Comment5. How is evaporation calculated? Please make that clear in Section 2.
Response: In the revised manuscript we describe how the evapotranspiration is calculated as follows in

Evapotranspiration

1. The plant evapotranspiration was calculated in two steps. First the daily reference evapotranspiration (ET_0) was calculated by Penman-Monteith equation (Allen et al., 1998). We assumed that the moisture content was limiting therefore the plant evapotranspiration rate was obtained by multiplying the reference evapotranspiration by a crop coefficient. Values for the crop coefficients were calibrated according to the water balance in the soil and found to agree with published values for stage of crop development and soil salinity .
2. (a) On days without rain or irrigation, the evapotranspiration lowers the water table and the moisture content in the soil decreases due to upward movement of water to the plant roots and soil surface.

   (b) On days with rain or irrigation, the potential evapotranspiration is subtracted from the irrigation and/or rainfall and water moves downward

Comment6. Under section 2.3.2, maximum and potential evaporation are mentioned. How are they calculated/represented? Without this information, the results presented in the manuscript are not reproducible.
Response: The rewrite of section 2.3.2 concerning the calculation is given in the response to the previous comment.

Comment7. The conclusion section of the manuscript is very weak. It is basically an incomplete summary of the work and fails to present the necessary elements that a conclusion section requires (e.g., usefulness and limitations). "This model is simplified, so it can be used for management purposes" is vague and does not add value.

Response: We are grateful for your suggestion. We revised the conclusion section as follows:

"A novel surrogate vadose zone model for an irrigated area with a shallow aquifer was developed to simulate the fluctuation of groundwater depth and soil moisture during the crop growth stage in the shallow groundwater district. To validate and calibrate the surrogate model we carried out a two-year field experiment in the Hetao irrigation district in upper Mongolia with groundwater close to the surface. Using meteorological data and the soil characteristic curve and upward capillary movement, the surrogate model predicted the soil water content with depth and groundwater height on daily time step with acceptable accuracy during validation and was an improvement two previous models applied in the Hatao district that could predict the overall water content in the root zone but not the distribution with depth.

The surrogate modeling results show that after an irrigation event as long as the upward flux from the groundwater to the root zone was greater than the plant evapotranspiration rate, the moisture contents in the vadose zone could be found directly from the soil characteristic curve by equating the depth to the groundwater with the absolute value of the matric potential. When plant evapotranspiration rate exceeded the upward movement moisture contents indicated by groundwater depth and was predicted by a root zone function. Another finding was that the daily moisture contents were simulated without using the unsaturated hydraulic conductivity function in the surrogate model. For a daily time step equilibrium (defined as the hydraulic potential being constant) in moisture contents in the profile was attained so that precise unsaturated conductivity was not needed. Of course, for shorter time steps, predicting the transient fluxes and groundwater the conductivity function is needed. For management purposes a daily time step is acceptable.

Future improvement to this model will focus on coupling the EPIC model and apply it to simulate other crops and other location with shallow groundwater table. The surrogate model should also be compared with a "full" model, to test under what conditions the surrogate model will fall short."

Minor comments

Comment1. I would suggest replacing physical-based with either physics-based or physically-based.
Response: Thank you for your suggestion and we settled on "physically-based" in the revised manuscript**.**

Comment2. Please use "groundwater" consistently throughout the manuscript. Currently, both groundwater and groundwater have been used.
Response: We used "groundwater" consistently in the revised manuscript.

Comment3. L74-77: This paragraph (just one sentence!) does not fit with the previous or next one. Please re-structure and merge.

Response: Thank you. The paragraph was amended as

"Central to modeling irrigation management practices under shallow groundwater conditions (such as in the Yellow river basin) is simulating the soil moisture content

accurately (Batalha et al., 2018, Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a) because the moisture content plays a critical role in the growth of crops (Rodriguez-Iturbe, 2000), groundwater recharge (Hodnett and Bell, 1986), upward movement of water to the root zone in areas (Gleeson et al., 2016; Jasechko and Taylor, 2015; Venkatesh et al., 2011a; Batalha et al., 2018). The latter is unique to shallow groundwater areas where the moisture content and thus the unsaturated conductivity are high and where the drying of the surface soil sets up hydraulic gradient that causes the upward capillary movement from the shallow groundwater (Kahlown et al., 2005; Liu et al., 2016; Luo and Sophocleous, 2010; Yeh and Famiglietti, 2009). The upward moving water contains salt that is deposit in the root zone and at the surface. ”

Comment4. L264: “the groundwater will be recharged and increase in depth”. Generally, recharge decreases the depth to groundwater table from the surface.

Response: This is poorly worded. The total depth of the groundwater is increasing. To make the writing clear, we formulated it as follows:

“The rules for downward flux on days with the effective rain and/or irrigation are relatively simple. If the net flux at the surface (irrigation plus rainfall minus actual evaporation) is greater than needed to bring the soil up to equilibrium moisture content, the groundwater will be recharged and the distance to soil surface decreases and the moisture content will be equal to the equilibrium moisture content at the new depth. “

References

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M.: Crop evapotranspiration. Guidelines for computing crop water requirements-FAO Irrigation and Drainage Paper 56, FAO, Rome. 1998.

Asher, M.J., Croke, B.F.W., Jakeman, A.J. and Peeters, L.J.M.: A review of surrogate models and their application to groundwater modeling. Water Resour Res 51:5957-5973. http://doi.wiley.com/10.1002/2015 WR016967. 2015.

Batalha, M.S., Barbosa, M.C., Faybishenko, B., van Genuchten, M.T.: Effect of temporal averaging of meteorological data on predictions of groundwater recharge. J Hydrol Hydromech, 66(2):143-152. https://doi.org/ 10.1515/johh-2017-0051. 2018.

Chen, C., Wang, E., and Yu, Q.: Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agr Water Manage 97:1175-1184. https:// doi.org/10.1016/j.agwat.2008.11.012.2010.

Cui, T., Peeters, L., Pagendam, D., Pickett, T., Jin, H., Crosbie, R., Raiber, M., Rassam, D., and Gilfedder, M.: Emulator-enabled approximate Bayesian computation (ABC) and uncertainty analysis for computationally expensive groundwater models. J Hydrol 564:191-207. https:// doi.org/10.1016/j.jh ydrol.2018.07.005

Dam, JC. Van., Huygen, J, Wesseling, JG, Feddes, RA., Kabat, P.,Walsum, PEV. Van.,Groenendijk, P., Diepen.: Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment. Report 71, Deparment Water Resources, Wageningen Agricultural University. Technical document 45, DLO Winand Staring Centre, Wageningen,152pp, 1997.

Flint, A.L., Flint, L.E., Kwicklis, E.M., Fabryka-Martin, J.T., and Bodvarsson, G.S.: Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeol. J., 10:180-204. https:// doi.org/ 10.1007/s10040-001-0169-1. 2002.

Gardner, W.: Some study-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci., 85:228-232. 1958.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement Soil Water 1. Redistribution. Water Resour. Res., 6:851-860. https:// doi.org/ 10.1029/WR006i003p00851. 1970a.

Gardner, W., Hillel, D., and Benyamini, Y.: Post-Irrigation Movement of Soil Water 2. Simultaneous Redistribution and Evaporation. Water Resour. Res., 6:1148-1153. https:// doi.org/ 10.1029/WR006i004p01148. 1970b.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E., and Cardenas, M.B.: The global volume and distribution of modern groundwater. Nat. Geosci., 9:161-167. https:// doi.org/10.1038/NGEO2590. 2016.

Hodnett, M., and Bell, J. Soil moisture investigations of groundwater recharge through black cotton soils in Madhya Pradesh, India. Hydrolog Sci J 31:361-381. https:// doi.org/10.1080/0262666860949 1054. 1986.

Jasechko, S., and Taylor, R.G.: Intensive rainfall recharges tropical groundwaters. Environ Res Lett 10:124015. https:// doi.org/10.1088/1748-9326/10/12/124015. 2015.

Kendy, E., Gérard-Marchant, P., Walter, M. T., Zhang, Y., Liu, C., and Steenhuis, T.S.: A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Process., 17:2011-2031. https:// doi.org/10.1002/hyp.1240. 2003.

Kirchner, J. W., Getting the right answers for the right reasons: Linkingmeasurements, analyses, and models to advance the science of hydrology, Water Resour. Res., 42, W03S04, https://doi.org/10.1029/2005WR004362. 2006.

Krause, P., Boyle, D.P. and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences 5:89-97. https:// doi.org/ 10.5194/adgeo-5-89-2005. 2005

Li, C., Yang, Z., and Wang, X.: Trends of Annual Natural Runoff in the Yellow River Basin. Water Int., 29:447-454. https:// doi.org/10.1080/02508060408691807. 2004.

Li, X., Zhao, Y., Xiao, W., Yang, M., Shen, Y., Min, L.: Soil moisture dynamics and implications for irrigation of farmland with a deep groundwater table. Agr. Water Manage.,192:138-148. https:// doi.org/ 10.1016/j.agwat.2017.07.003.2017.

Liu, Z., Chen, H., Huo, Z., Wang, F., and Shock, C.C.: Analysis of the contribution of groundwater to evapotranspiration in an arid irrigation district with shallow water table. Agr. Water Manage., 171:131-141. https:// doi.org/10.1016/j.agwat.2016.04.002. 2016.

Luo, Y., and Sophocleous, M.: Seasonal groundwater contribution to crop-water use assessed with lysimeter observations and model simulations. J. Hydrol, 389:325-335. https:// doi.org/10.1016/j.jhydrol.2010.06.011. 2010.

Ma, Y., Feng, S., and Song, X.: A root zone model for estimating soil water balance and crop yield responsesto deficit irrigation in the North China Plain. Agr. Water Manage., 127:13-24. https:// doi.org/10.1016/j.agwat.2013.05.011. 2013.

Matott, L.S., and Rabideau, A.J.: Calibration of complex subsurface reaction models using a surrogate-model approach. Adv Water Resour 31:1697-1707. https:// doi.org/10.1016/j.advwatres10.10 16/j.advwatres.2008.08.006. 2008.

Mcdonald, M., and Harbaugh, A.: The history of MODFLOW. Groundwater 41:280-283. https:// doi.org/10.1111/j.1745-6584.2003.tb02591.x. 2003.

Moges, M., Schmitter, P., Tilahun, S., Langan, S., Dagnew, D., Akale, A. and Steenhuis, T.S.: Suitability of Watershed Models to Predict Distributed Hydrologic Response in the Awramba Watershed in Lake Tana Basin. Land Degrad Dev 10:1386-1397. https:// doi.org/10.1002/ldr.2608. 2017.

Moiwo, J.P., Lu, W., Zhao, Y., Yang, Y., and Yang, Y.: Impact of land use on distributed hydrological processes in the semi-arid wetland ecosystem of Western Jilin. Hydrol. Process., 24:492-503. https:// doi.org/10.1002/hyp.7503. 2009.

Razavi, S., Tolson, B.A. and Burn, D.H. Review of surrogate modeling in water resources. Water Resour Res 48. https:// doi.org/10.1029/2011WR011527. 2012a.

Razavi, S., Tolson, B.A. and Burn, D.H.: Numerical assessment of metamodelling strategies in computationally intensive optimization. Environ Modell Softw. 34:67-86. https:// doi.org/10.1016/ j.envsoft.2011.09.010. 2012b.

Ren, D., Xu, X., Hao, Y., and Huang, G.: Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: Application to maize, sunflower and watermelon. J. Hydrol, 532:122-139. https:// doi.org/10.1016/j.jhydrol.2015.11.040. 2016.

Rosa, R., Paredes, P., Rodrigues, G., Alves, I., Fernando, R., Pereira, L. and Allen, R.: Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. Agr Water Manage. https:// doi.org/103:8-24. 10.1016/j.agwat.2011.10.0132012.

Šimůnek, J., Šejna, M. and van Genuchten, M.T.: The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. IGWMC-TPS-70. Int. Ground Water Modeling Ctr., Colorado Schoolof Mines, Golden. 1998.

Venkatesh, B., Lakshman, N., Purandara, B.K., and Reddy, V.B.: Analysis of observed soil moisture patterns under different land covers in Western Ghats, India. J. Hydrol, 397:281-294. https:// doi.org/10.1016/j.jhydrol.2010.12.006. 2011.

Todini, E.: Hydrological catchment modelling: past, present and future. Hydrol Earth Syst Sc 11:468-482. https:// doi.org/10.5194/hess-11-468-20072007.

Wang, H., Zhang, L., Dawes, W.R., and Liu, C.: Improving water use efficiency of irrigated crops in the North China Plain - measurements and modelling. Agr. Water Manage., 48:151-167. https:// doi.org/10.1016/S0378-3774(00)00118-9. 2001.

Yang, X., Chen, Y., Steenhuis, T.S., Pacenka, S., Gao, W., Ma, L., Zhang, M., and Sui, P.: Mitigating Groundwater Depletion in North China Plain with Cropping System that Alternate Deep and Shallow Rooted Crops. Front. Plant Sci., 8. https:// doi.org/ 10.3389/fpls.2017.00980. 2017.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Ma, L., Wang, G., Yan, P., Sui, P., and Steenhuis, T.S.: Effect of diversified crop rotations on groundwater levels and crop water productivity in the North China Plain. J. Hydrol., 522:428-438. https:// doi.org/ 10.1016/j.jhydrol.2015.01.010. 2015a.

Yang, X., Chen, Y., Pacenka, S., Gao, W., Zhang, M., Sui, P., and Steenhuis, T.S.: Recharge and Groundwater Use in the North China Plain for Six Irrigated Crops for an Eleven Year Period. Plos One 10:e0115269. https:// doi.org/10.1371/journal.pone.0115269. 2015b.

Yeh, P.J., and Famiglietti, J.S.: Regional Groundwater Evapotranspiration in Illinois. J. Hydrometeorol., 10:464-478. https:// doi.org/ 10.1175/2008JHM1018.1. 2009.

Young, P.C., and M. Ratto. Statistical Emulation of Large Linear Dynamic Models. Technometrics 53:29-43. http://doi.org/ 10.1198/TECH.2010.07151. 2011.