Revision Notes (HESS2018581)

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 (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 ground water 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 of 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 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 current manuscript we have 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 rewrite we have used the 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 (ET0) was calculated Penman-Monteith equation (Allen et al., 1998).We assumed that the moisture content was limiting therefore the plant evaporation 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., θ_s, θ_d, φ_b ,λ.) and were obtained by fitting the equation to the soil 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 ground water 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 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 ground water to the rootzone was greater than the plant evaporation rate, the moisture contents in the vadose zone could be found directly form the soil characteristic curve by equating the depth to the groundwater with the absolute value of the matric potential. When plant evaporation rate exceeded the upward

movement moisture contents became less than would be indicated by ground water depth and was predicted by a rootzone 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: Here 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 m3 from 13400 m3 in 1962 to 5900 m3 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 m3 from 13400 m3 in 1962 to 5900 m3 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 m3 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 are 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."

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 rootzone 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 (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 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 ground water 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, usually 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 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; Grdner et al., 1970a,b). For shallow groundwater at less than 3.3 m from the surface equilibrium is reached (i.e. fluxes stopped) 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 (equivalent to -3.3 m in head units)"

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 are 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.

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).), 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 rootzone 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 (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 ground water 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 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 ground water 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 ground water, evaporation 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, Ahner 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. It is 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 ground water with the ultimate goal is to save water in irrigation districts. The experimental field is located in the Hetao irrigation district, Inner Mongolia, China, where on two maize fields, moisture content and the ground water table depth were measured over a two year period. An additional objective is to identify sensitive and insensitive model parameters for simulating moisture content in shallow groundwater area so that future data collection efforts can be optimized

The surrogate model developed is a one dimensional model simulating the moisture content in the root zone using the ground water depth and information of soil 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 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 (ET0) was calculated Penman-Monteith equation (Allen et al., 1998). We assumed that the moisture content was limiting therefore the plant evaporation 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 evaporation 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:

> "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:

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

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

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

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

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

where N is the total number of observations, O_i and P_i are the ith observed and predicted values ($i=1, 2,..., N$), and $\bar{O}$ and $\bar{P}$ 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 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 and D 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.

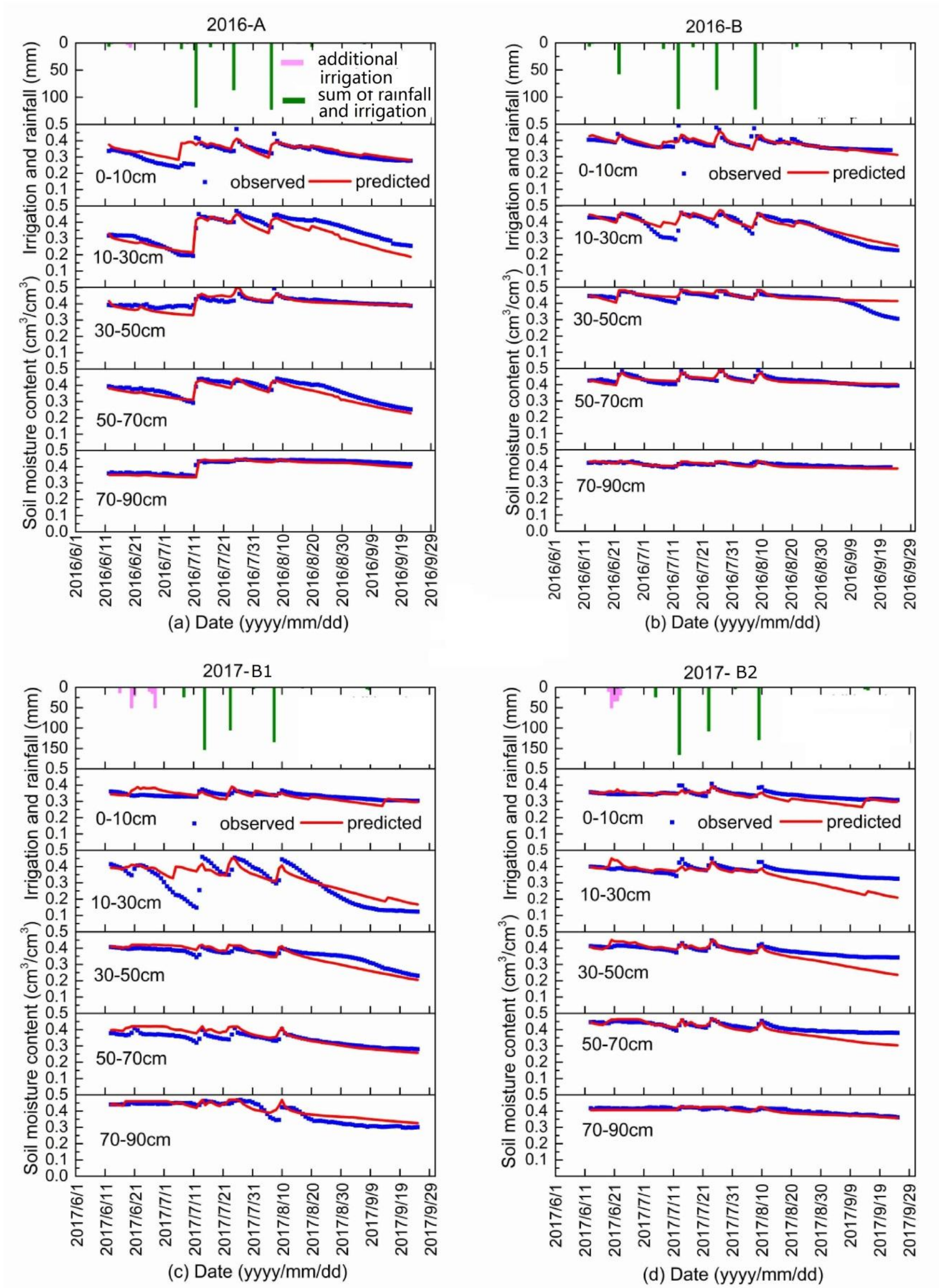

Figure.4 Simulated and observed groundwater depth during the growing period for the Fenzidi experimental fields in the Hetao irrigation district: (a,b) calibration in 2016 and (c,d) validation

in 2017. (Notes: Additional irrigation means the irrigation recharge from the adjacent field which leads to the water table rise and was not planned).

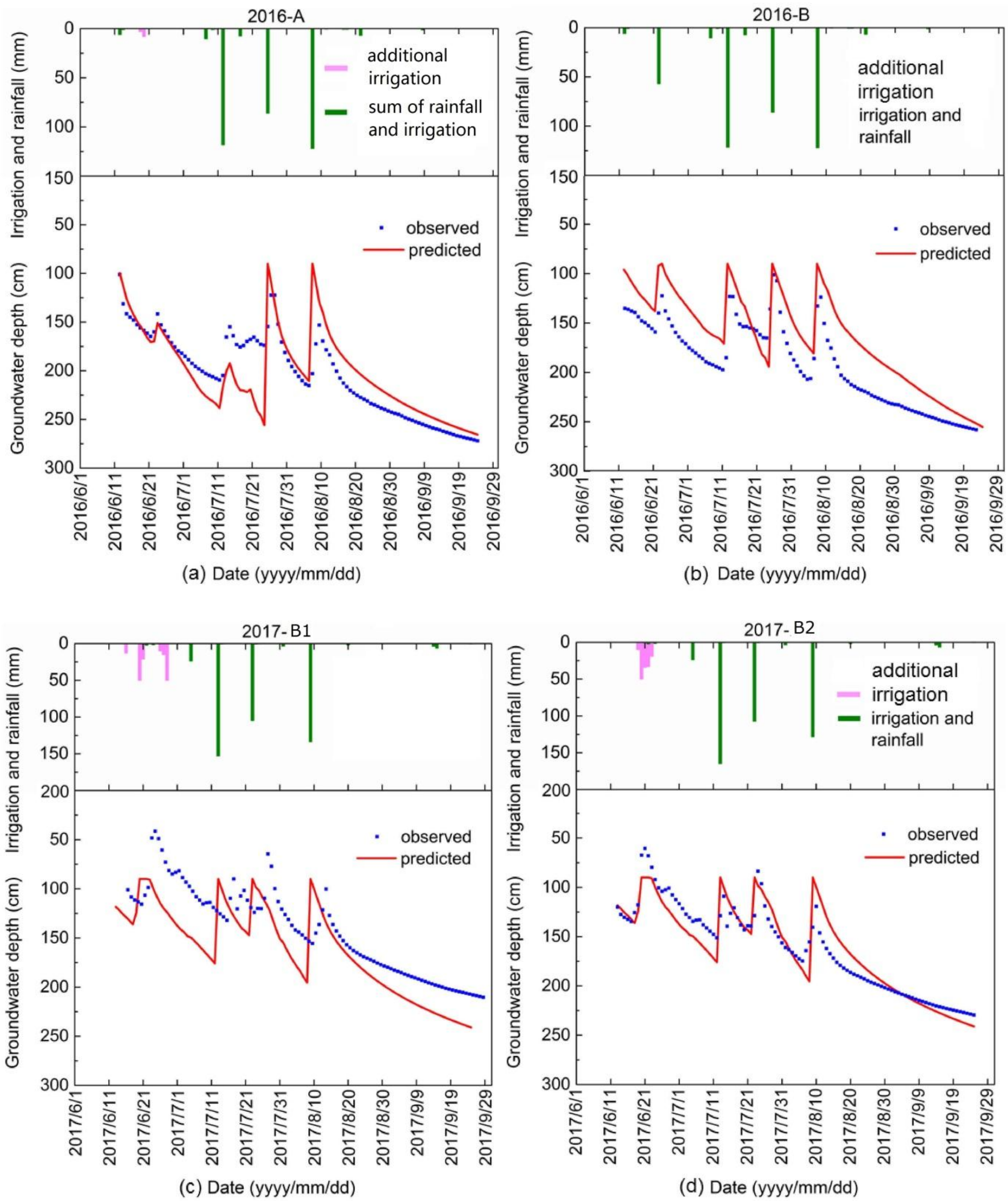

Figure. 5 Simulated and observed soil moisture content for five soil depths during the growing period for the Fenzidi experimental fields in the Hetao irrigation district: (a, b) calibration in 2016 and (c, d) validation in 2017.

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)."

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