

# **The “groundwater benefit zone”, proposals, contributions and new scientific issues**

Ying Zhao, Ji Qi, Qiuli Hu, Yi Wang

College of Resources and Environmental Engineering, Ludong University, Yantai 264025

Email yzhaosoils@gmail.com

## **Abstract**

The groundwater has great potential for water resource utilization, accounting for about a quarter of vegetation transpiration globally and contributing up to 84% in shallow groundwater areas. However, in irrigated agricultural regions or coastal areas with shallow groundwater levels, due to the high groundwater salinity, the contribution of groundwater to transpiration is small and even harmful. This paper proposes a new conception of groundwater benefit zone in the groundwater-soil-plant-atmosphere continuum (GSPAC) system. Firstly, it analyzes the mutual feedback processes of the underground hydrological process and aboveground farmland ecosystem. Secondly, it elaborated on the regional water and salt movement model, proposed vital technologies based on the optimal regulation of the groundwater benefit zone, and is committed to building a synergy that considers soil salt control and groundwater yield subsidies. Finally, based on the GSPAC system water-salt coupling transport mechanism, quantitative model of groundwater benefit zone, and technical parameters of regional water-salt regulation and control, the scientific problems and development opportunities related to the conception of groundwater benefit zone have prospected.

## **Keywords**

Groundwater benefit zone; soil water and salt movement; model simulation; mechanisms; modification technology

## **Introduction**

About 22% to 32% of the world’s terrestrial plants have their roots near or within the groundwater (Fan et al., 2013). As a result, groundwater significantly impacts the transpiration of above-ground ecosystems and net primary productivity (Good et al., 2015; Zipper et al., 2015; White, 1932). On a global scale, groundwater contributes about 23% to vegetation water consumption on average (Evaristo et al., 2017). In areas with shallow groundwater, it contributes up to 84% of the total transpiration of vegetation. In arid areas (Wang et al., 2018), almost all water consumption of the plant comes from groundwater (Yuan et al., 2015). However, groundwater contributes little or even negatively to transpiration in irrigated agricultural or coastal areas with shallow water table depth, due to its high salinity (Gao et al., 2017). At present, with the expansion of the agricultural area, the supply of freshwater resources is becoming more

and more insufficient; agricultural water began to use underground saltwater, or which combined with saline water irrigation, along with the development of water-saving irrigation technology and water conservancy engineering measures suitable for the region. Therefore, further research is strongly needed to promote the efficient use of agricultural moisture in areas with shallow groundwater, to figure out the crop growth process under the influences of irrigation and shallow water replenishment, and the salt balance characteristics under different management measures. Consequently, this is beneficial to find out how to use the abundant shallow underground saltwater in the coastal zone as a resource instead of limitations, realize the recycling of groundwater resources, and solve the source problem of lacking freshwater in terms of water salt regulation.

## **1 The proposed concept of "groundwater benefit zone"**

### **1.1 Mechanism of water transport in salt-affected farmland**

Recently, numerous researches have been done on the water flow process and mechanism of soil-plant-atmosphere continuous (SPAC) systems. However, these studies do not fully consider the role of groundwater and cannot clarify the water transfer mechanism of groundwater-soil-plant-atmosphere continuum (GSPAC) systems. In particular, in saline groundwater areas, water utilization of crop is limited because of salt stress, and it seems impossible to determine how groundwater recharge the root zone nor its root zone contribution to soil evaporation and crop transpiration (Fan et al., 2012). In drought years, plants increase net primary productivity (NPP) by using groundwater to reduce the effect of water stress on  $\text{CO}_2$  fixation, resulting in significant increases in transpiration due to the presence of shallow groundwater. Lowry and Loheide (2010) define the additional water that the plant transpires from shallow groundwater as "groundwater subsidies", and calculate the difference of the root water absorption under shallow groundwater conditions and the deeper one (i.e., free drainage). Furthermore, Zipper et al. (2015) define the yield from this additional water as a "groundwater yield subsidy". In agricultural systems, yield is usually more relevant than total water consumption when characterizing groundwater's positive or negative effects. Therefore, by introducing the concept of "groundwater yield subsidy", the maximum annual contribution of groundwater to transpiration and NPP can be quantified and directly related to the efficiency of water utilization.

On the contrary, when shallow groundwater damages production through oxygen stress, the groundwater yield subsidy is negative and can be considered a loss of groundwater yield. Soylu et al. (2014) quantified annual groundwater subsidies and NPP changes using the AgroIBIS-VSF model. They found that the largest groundwater subsidy happens at 1.5-2 m of water table depth, regardless of long-term precipitation, described here as the optimal water table. However, the current AgroIBIS-VSF model study is carried out in non-saline area, and the applicability of these indicators in saline-alkali land and its conceptual extension still needs to be further studied.

## 1.2 Definition of the "groundwater benefit zone"

In general, to prevent soil salinization, groundwater must be kept below the critical groundwater table (Fan et al., 2012; Ayars et al., 2006). The scientific community currently lacks a recognized definition and quantification method for the critical groundwater table. We define here as the highest groundwater table that does not cause secondary soil salinization. The critical water table depends on soil and groundwater type and climatic evaporation potential, and is also related to the classification criteria for salinization. Theoretically, there is usually an optimal groundwater table in an agricultural ecosystem, ideal for maintaining farmland productivity. However, due to the complex factors which influencing groundwater, it is often difficult to quantify. Figure 1a shows a conceptual diagram of the relationship between groundwater and crop yield under the groundwater yield subsidy framework: (1) In dry years, shallow groundwater will provide groundwater yield subsidy by reducing water stress, while in wet years, it will result in loss of groundwater yield by increasing oxygen stress; (2) in other words, for coarse soils with low matric potential values, the roots must be relatively close to the water table in case groundwater yield subsidies are present.

Theoretically, depending on the objectives of regulation, groundwater control has two criteria (Figure 1b):

(1) It is necessary to control the groundwater table below its critical value to control the salinity of soil (Fan et al., 2012); the critical groundwater table ( $h_0$ ) can be calculated by soil evaporation based on the upward migration of groundwater (E):

$$E = \begin{cases} E_p \left(1 - \frac{h}{h_0}\right)^n \left(1 - \frac{\varphi - \varphi_r}{\varphi_0 - \varphi_r}\right), & h < h_0 \text{ and } \varphi < \varphi_0 \\ 0, & h < h_0 \text{ and } \varphi \geq \varphi_0 \\ 0, & h \geq h_0 \end{cases} \quad 1$$

Where,  $E_p$  is the potential evaporation,  $h$  is the groundwater table,  $\varphi$  is the electrical conductivity,  $\varphi_0$  is the electrical conductivity corresponding to the critical water table,  $\varphi_r$  is the threshold for salt stress,  $n$  is the parameter;

(2) It is also necessary to keep the groundwater table near to the optimal groundwater table (groundwater yield subsidy boundary) (Zipper et al., 2015) to maximize crop transpiration, which can be calculated through groundwater-subsidy-based-transpiration (T):

$$T(h, \varphi, z, t) = \alpha(h, \varphi, z, t) \beta(z, t) T_p(z, t) \quad 2$$

Where,  $z$  is the soil depth,  $t$  is the time,  $\alpha$  is the water-salt stress function of the crop rooting zone with the influence of groundwater, which is usually considered in the model (e.g., HYDRUS) as the product of the water stress function ( $\alpha_h$ ) and the salt stress function ( $\alpha_s$ ). The stress function can be calculated by the following formula:

$$\alpha_h = \begin{cases} 0, & h \geq h_{\max}, h \leq h_{\min} \\ \frac{h_{\max}-h}{h_{\max}-h_c}, & h_c < h < h_{\max} \\ 1, & h = h_c \\ \frac{h-h_{\min}}{h_c-h_{\min}}, & h_{\min} < h < h_c \end{cases}$$

$$\alpha_\varphi = \frac{1}{1+\left(\frac{h_\varphi}{h_{\varphi 50}}\right)^p} \quad 3$$

Where,  $h_c$ ,  $h_{\max}$ ,  $h_{\min}$  is the optimal water table and its maximum and minimum groundwater subsidy boundaries respectively,  $h$  is solute potential, and  $h_{50}$  is the solute potential when the stress in the Van Genuchten salt stress function reduces the water absorption rate by 50%.

In equation (2),  $T_p$  is the distribution of potential transpiration in the root region, which together with  $E_p$  in the equation (1), constitute the potential evapotranspiration in the field, can be calculated by the following formula:

$$E_p(t) = ET_p(t) \bullet \exp^{-k \bullet LAI(t)}$$

$$T_p(t) = ET_p(t) - E_p(t) \quad 4$$

Where  $ET_p$  is the potential evapotranspiration, which is usually calculated using the penman-monteith formula,  $k$  is the extinction coefficient, and  $LAI$  is the leaf area index.

Based on the equation above: (1) while critical groundwater table is an indicator to prevent soil salinization, the optimum groundwater table is an indicator to maximize groundwater subsidies, (2) the optimum groundwater table is an agrological parameter based on the water absorbtion by the root system, whereas the critical groundwater table is a hydrological parameter based on soil capillary theory; (3) the critical groundwater table, associated with soil salt content control, is a fixed value, while the groundwater table associated with groundwater yield subsidy is a range (which changes with the crop rooting pattern and the water-salt environment in the root zone). Although the effects of salinity on plants are also taken into account in some studies for defining the critical groundwater table (similar to the dynamic range of the groundwater table suitable for the crop), due to the complex coupling relationship between crop type, soil salinity and groundwater depth, there is often a lack of quantitative indicators and also methods that are difficult to apply directly (Ayars et al., 2006).

Consequently, in underground saltwater areas, if both soil salt control and groundwater subsidies are to be taken into account, the water table needs to be regulated below the critical water table and overlapping with the area of range of groundwater yield subsidies (as shown in Figure 2 yellow plus area), which we define here as the "groundwater benefit zone" ( $\Delta h$ ), which is mathematically expressed as:

$$h = \begin{cases} 0, & h_0 < h_{\min} \\ h_0 - h_{\min}, & h_{\min} \leq h_0 \leq h_{\max} \\ h_{\max} - h_{\min}, & h_0 > h_{\max} \end{cases} \quad 5$$

Therefore, the groundwater benefit zone proposed in this study is a newly defined index. Take it as the theoretical standard of groundwater regulation, it is easy to create the targeted groundwater level and modify the groundwater level by taking specific control measures. It should be emphasized that, similar to critical and optimal groundwater tables, which define only the characteristics of water levels in vertical directions, the groundwater benefit zone defined by this study is also limited to vertical directions, regardless of their changes in horizontal direction at present (Figure 2).

To sum up, the physical significance of the "groundwater benefit zone" index defined in this study is clear, which can be used to quantify the potential of groundwater's contribution to the productivity of farmland ecosystem under the condition of salt stress and also as the theoretical standard of groundwater regulation in GSPAC system.

## **2 The research focus of "groundwater benefit zone"**

### **2. 1 The feedback mechanism between saline farmland ecosystem and groundwater**

Traditional soil hydrology mainly pays attention to the influence of soil characteristics on non-biological processes such as water and mass transport. In contrast, agricultural hydrology focuses on the occurrence of various hydrological phenomena in agricultural measures and agricultural engineering and their intrinsic relationship, starting with the influence of water on biological processes such as crop growth and development. Studying the Earth's critical zone expands the research scope of farmland ecosystem and groundwater hydrological process and strengthens the critical role of soil physical process in multi-scale mass transport and cycle at land surface system such as soil profile, slope and basin (Yang and Cai, 1993). In recent years, more and more studies have attempted to establish the relationship between shallow groundwater and vegetation physiology and weathering processes, to clarify the critical groundwater table. At the same time, there is still a lack of mathematical expression and field validation for this relationship (Fan et al., 2012). Zipper et al. (2015) found that shallow groundwater table, root length density distribution, and root water compensation effects (i.e., plants adapt to drought conditions by absorbing more water from less-stress parts of the root to compensate for root water in areas where stress is greater; Šimůnek et al., 2009) had a significant impact on transpiration and NPP, emphasizing the importance of incorporating root compensatory water absorption equations into model studies.

### **2.2 GSPAC system Water salt coupling transport model**

At present, many mechanism models of the water-salt coupling transport process of GSPAC systems (e.g., HYDRUS, RZWQM, EPIC, SVAT, SHAW, etc.

(Luo et al., 2016) have been established, in which HYDRUS models are widely used (Šimůnek et al., 2016). Especially based on the concepts of mobile and immobile water bodies, HYDRUS introduce dual-porosity models that simulate large pore flows and preferential flows. These characteristic hydrological parameters and solute reactions are combined to simulate physical equilibrium and chemical nonequilibrium solute transport (e.g. two-region models, two-site models, etc.), which provides convenience for the simulation of water salt migration models under complex soil profile characteristics (such as clay layer, gravel, large pores) with more regional influence factors (e.g. groundwater, irrigation water) (Beven, 2010; Chen et al., 2012; Yao et al., 2019). However, the current model of the water-salt transport mechanism is more thorough in the unsaturated soil area, but it is insufficient in the saturated-unsaturated area, and the influence of groundwater on plant function has not been clarified. In turn, many crop models are good at simulating crop growth processes (e.g., RZWQM, WOFEST, DSSAT, AquaCrop, etc. (Ding et al., 2016), but the expression of soil hydrological processes is insufficient, especially the lack of simulating groundwater dynamics. More methods have been used to couple hydrological and crop models in recent years, for example, HYDRUS-1D and crop model AgroIBIS coupling AgroIBIS-VSF models (Soylu et al., 2014).

It is worth mentioning that although some crop models can simulate the relationship between groundwater and vegetation in some ways, there is a very lack of mechanism models like the AgroIBIS-VSF model that can describe the effects of groundwater dynamics on soil temperature, oxygen and leaf microclimate conditions. Furthermore, Zipper et al. (2017) combined the latest version of the AgroIBIS-VSF model (i.e., the coupling of AgroIBIS and HYDRUS-1D) with the MODFLOW model to create a new model framework, MODFLOW-AgroIBIS (MAGI). The new coupled model simulates vegetation growth dynamics based on environmental conditions and quantifies the movement of water and energy in the GSPAC system (Figure 3). This coupling approach provides three widely-used model benefits for the MAGI model (AgroIBIS (Kucharik et al., 2000), HYDRUS-1D (Šimůnek et al., 2013) and MODFLOW-2005 (Harbaugh, 2005)). However, most of the work related to the current MAGI model is carried out in non-saline conditions, while in areas with high groundwater salinity content, the salt environment in the root zone of the crop will affect the potential of groundwater utilization and limit the applicability of the model framework. This means that models to calculate groundwater yield subsidies in saline agriculture must consider the effects of salt and thus need to be updated (Figure 3).

## 2.2 Scale of water salt migration process and its corresponding research techniques

Although the mechanisms at the field-scaled water and salt transport model through the GSPAC system are considered more comprehensively, the water and salt transport process occurred at an immense scale. Consequently, the spatial variation of influence factors, especially the measures to regulate soil

water and salt changes such as irrigation, drainage, agronomy measures, etc. are carried out on a large scale, the field-scaled model, which is often one-dimensional, can not carry out large-scale saline water process and evaluation (Li et al., 2010). On the other hand, traditional large-scale hydrological models such as MODFLOW, although they are good at dealing with landscape-scale soil-groundwater interaction and groundwater movement process, due to the lack of small-scale soil hierarchy and detailed structural parameters, cannot reflect the small-scale hydrological process neither in saturated zone nor in the unsaturated area (Zhang et al., 2019). Thus, another trend of model development is to develop the coupled models at different scales, such as the model “HYDRUS-MODFLOW” (Twarakavi et al., 2008) is coupled by HYDRUS-1D model and the groundwater model MODFLOW which extends the simulation of the movement of soil water and salt under a dynamic groundwater condition in the regional scale. The model can stimulate the redistribution process of water and salt both in natural and artificial circumstances. In fact, due to the variability of soil spatial structure and the randomness of various factors affecting water salt movement, the water-salt transport process has a strong scale effect and corresponding to the appropriate quantitative techniques and methods in that scale.

Currently, there are effective ways to track the migration of substances in GSPAC systems (Gu et al., 2011; Lv et al., 2018; Peng et al., 2017; Penna et al., 2020), such as isotope, geochemical ions, and rare earth elements. The new Earth Critical Zone study focuses on effectively links between disciplines, scales and data to achieve the mutual transformation of microscales (soil pores and aggregates), mesoscales (soil profiles, fields or catena) and macroscales (basins, regions or global) (Li, 2011). It can be spatially interpolated and aggregated according to soil distribution or soil characteristics at landscape-scale according to soil mapping hierarchical system, and then upscaled and downscaled, or it can be transformed on a scale by establishing a relationship between the hierarchical structure of soil models and typical soil processes of different scales. For example, from the mesoscale to the macroscale, “characterization unit regions” can be constructed in combination with topographical changes and land-use methods, thus linking laboratory and field measurements’ hydraulic characteristics to watershed scales’ ones orderly for spatial scale transformation. On the microscale, soil water and salt movement are mainly influenced by soil structure, soil level, micro-terrain, ion content, soil infiltration, salt leaching, and soil microorganisms. We could quantify the effects of soil and salt effects by soil pore structure, root growth pattern, and water movement, fertilization, soil improvement method, and engineering measures by using X-ray computer tomography, Magnetic Resonance Imaging, and Nuclear magnetic resonance etc. (Tracy et al., 2012; Pohlmeier et al., 2008; Zhang et al., 2019). At the mesoscale, the soil water and salt transport and distribution mainly include evaporation, infiltration, side seepage, groundwater leakage and recharge, and is the basic scope of water salt regulation and ecological environment construction (Li, 2011). Geophysical detection techniques such as Multi-receiver Electromagnetic Induction (EMI),

Electrical Resistance Tomography (ERT) and time-lapse Ground-Penetrating Radar (GPR) are widely used in soil physical properties measurement on scales such as slopes, catchment, and small basins (Guo et al., 2014; Vereecken et al., 2015). In recent years, remote sensing technology has been increasingly used in monitoring the physical properties of soil at the macro-scale and in coupling with other methods. At present, it is a significant scientific issue that how to quantify the water-salt migration flux of large-scale farmland system, through irrigation efficiency, soil salt accumulation and other salt control factors, to build farmland irrigation-fertilization-salt control technology mode, and whereby to carry out multi-scale regulation under water-saving and reduced fertilizers in irrigation areas, so that it can achieve not only the efficient use of water resources but also maintain a good water salt environment.

### **2.3 Optimal regulation of groundwater benefit zone groundwater benefit zones**

At present, there are a variety of measures for the regulation of water and salt, the core of which is to inhibit salt moving-up by reducing soil evaporation (e.g. mulching), to promote salt leaching by improving soil structure (e.g. soil amendments), to block salt moving-up by creating salt-isolation layer (e.g. salt resistant barrier), or increase soil drainage to speed up soil salt discharge (e.g. subsurface pipes), and among other ways (Yang and Yao, 2015; Li et al., 2016; Li et al., 2007). In general, crop salt thresholds, local soil types and groundwater conditions need to be taken into account to clarify the applicability of these methods in saline agricultural production. For salinized farmland with shallow groundwater tables, the utilization of groundwater is greatly influenced by the salt accumulation, salt threshold of crop and salt leaching scheme, so it is essential to clarify the "groundwater benefit zone" and optimize the regulation. Some regulation of water and salt has been made in the Northern Chinese irrigation area, while there was little research based on the model of optimization of groundwater (Liu et al., 2020). Although some models currently proposed appropriate groundwater levels and irrigation strategies for specific crops (Qadir et al., 2000), it is still challenging to promote and summarize the results due to different soil types, irrigation systems, plant rooting patterns, salt tolerance, groundwater depth, and climatic conditions. In general, to make up the limitations of long-term field test and the lack of investigated factors, the technical parameters of water salt regulation can be put forward based on model scenarios analysis and the influence of different factor combinations on the relationship between groundwater table and crop yield can be considered comprehensively. At present, the water-salt transport model of the GSPAC system is applied to predict the trend of water-salt dynamics and the concentration of salt. The response of crop growth conditions to changes in soil water salt environment under different irrigation systems and planting patterns is systematically analyzed based on boundary conditions and parameters obtained from various management measures (Hörtnagl et al., 2018).

On this basis, the model scenario analysis can design different combinations



of influence elements, clarify the balance point of water conservation measures and salt leaching, and establish a plant water supply theory scheme aimed at water-saving and salt control. Thus, the key to regulating groundwater benefit zone can be based on models to construct technical parameters that reflect different regulatory measures. In addition, soil improvement products can be designed based on these technical parameters. For example, we could establish the cause-effect relationship by applying modern analysis means like characterizing the structural morphology, its molecular structure, surface morphology and performance correlation of the soil water and fertilizer, to carry out component screening-structural regulation-fertilization performance determination for material design and optimization, and the optimal technical products for salt-alkali soil water salt regulation. For example, through modern instrumental analysis methods, the structure and morphology of the product are characterized. The relationship between its molecular structure, surface morphology, etc., and soil water and fertilizer storage performance is explored and the structure-function relationship is established. Recently, Swallow and O'Sullivan (2019) proposed a new desalination method based on biomimicry of vascular plants, which is to mimic the principle of water absorption of the vascular plant to produce desalination materials, added to the soil, with the help of natural evaporation, groundwater and soil salt directly removed from the surface through the crystallization process. After 30 days of the indoor test, the method can reduce the soil salt content from 8% to 0.8%, and the desalination effect is pronounced. It provides a new technology for saline soil remediation, but it also needs further verification and evaluation in the field.

### **3. The main scientific issues in the study of "groundwater benefit zone"**

In this study, we proposed the new concept and index of the "groundwater benefit zone" based on the interaction between the saline farmland ecosystem and the groundwater hydrological process, which needs further investigation. Through a combination of field monitoring and model simulation, the next step is to concentrate on the following issues:

(1) How to determine the critical groundwater table in areas with shallow groundwater and their quantitative relationship to soil, climate, and groundwater type? We need to use the theories and methods of soil hydrology and agricultural hydrology, focus on the study of water consumption of agriculture and groundwater-soil water crop carrying capacity. On the one hand, the climate affects soil and groundwater movement and soil biological activities through physical properties such as soil temperature, texture, and bulk density (Zhu et al., 2019). On the other hand, the movement and distribution of groundwater and soil moisture affect the redox environment and microbial activities by regulating the soil oxygen content, thereby affecting the biogeochemical cycle (Soylu et al., 2017). Therefore, the development of the interdisciplinary of the groundwater salt process and biogeochemistry is of great significance for describing the mechanism of groundwater salt migration and simulating its flux (Swallow et

al., 2019).

(2) How to promote a water-salt transport model of GSPAC system based on soil physical process and crop growth dynamics, and quantify the groundwater benefit zone in one location? It is worth noting that the concept of groundwater subsidy is not only water extracted from the unconfined aquifer, but also the edge of the soil capillary rise. Therefore, the calculation of groundwater yield subsidy usually needs to simulate the plant water uptake under shallow groundwater and free drainage conditions respectively and get the difference between the two, which is also an essential aspect of the model application. In addition, water absorption in the root zone is one of the most important processes considered in the GSPAC model, simulating the extent to which plants absorb and utilize soil water and groundwater, thus determining the amount of soil water flow or groundwater recharge (Šimůnek et al., 2009). At present, many root water uptake models with different assumptions and complexities have been developed. The main challenge is the lack of data for parameterizing root water use functions and the numerical expression of the associated important processes (Soylu et al., 2017).

(3) How do crops respond to groundwater changes, and what is the mechanism between salt stress, root distribution, and root water compensation effects? Considering the compensation mechanism of root water absorption in the crop growth model can improve the prediction of soil moisture content. In contrast, during the development of the current model, it is still unclear when there is salt stress and how the model takes the mechanism of crops to obtain groundwater into account, especially how to parameterize the compensatory water absorption process of the root system. It is worth further research on applying technology and methods in this aspect, analyzing the feedback relationship between groundwater salt process and land productivity, ecological environment safety and other functions, and optimizing and enhancing the function of ecosystem services. Mainly due to the influence of salt, it is challenging to clarify the water transmission mechanism of the GSPAC system. In recent years, isotope technology has become an important and effective method for studying the utilization of plant water resources in a complex system (Beyer et al., 2016; Evaristo et al., 2015), which provides a reference for revealing the mechanism of soil water and solute transport in the GSPAC system. In addition, the latest measurement techniques of sap flow and root system scanner (root length and root distribution) also provide ways for soil-root-water interaction mechanism research.

(4) How to combine model simulation with field control measures test, and thus propose the technical parameters of regional water salt control? How to use soil physics model to predict the influence of groundwater salt process change on future food production and ecological environment, formulate and evaluate the adjustment strategy of the sustainable development of saline agriculture. In particular, in recent years, climate change, water shortage and extreme climate are frequent, there is urgently needed to develop the theory and model of crop habitat process regulation and control (Wang et al., 2015), study the process of

non-saturation zone salt migration, driving mechanism and its scale effect, utilize slight saline water/saline water, farmland drainage and other non-traditional water resources in saline field irrigation safely and evaluate its ecological effects.

## References

- Fan, Y., Li, H., Miguez-Macho, G. Global patterns of groundwater table depth. *Science*, 2013, 339(6122): 940–943.
- Fan, Y. Groundwater in the Earth’s critical zone: Relevance to large-scale patterns and processes. *Water Resources Research*, 2015, 51: 3052–3069.
- Good, S., Noone, D., Bowen, G. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science*, 2015, 349: 175–177.
- Zipper, S.C., Soylu, M.E., Booth E.G., et al. Untangling the effect of shallow groundwater and soil texture as drivers of subfield-scale yield variability. *Water Resources Research*, 2015, 51: 6338–6358.
- White, W.N. A method of estimating groundwater supplies based on discharge by plants and evaporation from soil: Results of investigations in Escalante Valley, Utah, U.S. Geol. Surv. Water Supply Pap, 1932, 659-A, 105.
- Evaristo, J., McDonnell, J.J. Prevalence and magnitude of groundwater use by vegetation: a global stable isotope meta-analysis. *Scientific Reports*, 2017, 7: 4110.
- Wang, P., Niu, G.-Y., Fang, Y.-H., et al. Implementing dynamic root optimization in Noah-MP for simulating phreatophytic root water uptake. *Water Resources Research*, 2018, 54: 1560–1575.
- Yuan, G., Luo, Y., Shao, M., et al. Evapotranspiration and its main controlling mechanism over the desert riparian forests in the lower Tarim River Basin. *Science China Earth Sciences*, 2015, 58: 1032–1042.
- Gao, X.Y., Huo, Z.L., Qu, Z.Y., et al. Modeling contribution of shallow groundwater to evapotranspiration and yield of maize in an arid area. *Scientific Report*, 2017, 7: 43122.
- Fan, X., Pedrolí, B., Liu, G., et al. Soil salinity development in the yellow river delta in relation to groundwater dynamics. *Land Degradation & Development*, 2012, 23: 175–189.
- Lowry, C.S., Loheide II, S.P. 2010. Groundwater-dependent vegetation: Quantifying the groundwater subsidy. *Water Resources Research*. 46, W06202, doi:10.1029/2009WR008874.
- Soylu, M.E., Kucharik, C.J., Loheide II, S.P. Influence of groundwater on plant water use and productivity: Development of an integrated ecosystem: Variably saturated soil water flow model. *Agricultural and Forest Meteorology*, 2014, 189–190: 198–210.

- Ayars, J.E., Christen, E.W., Soppe, R.W., et al. The resource potential of in-situ shallow ground water use in irrigated agriculture. a review. *Irrigation Science*, 2006, 24: 147–160.
- Yang, J., Cai, S. A field soil salinity prediction model under the effect of immobile water, Wuhan University of Water and Power Press. 1993, 84–117.
- Šimůnek, J., Hopmans, J.W. Modeling compensated root water and nutrient uptake. *Ecological Modelling*, 2009, 220: 505–521.
- Luo, X., Liang, X., Lin, J. Plant transpiration and groundwater dynamics in water-limited climates: Impacts of hydraulic redistribution. *Water Resources Research*, 2016, 52: 4416–4437.
- Šimůnek, J., van Genuchten, M.Th., Sejna, M. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal*, 2016, 15: <http://dx.doi.org/10.2136/vzj2016.04.0033>.
- Beven, K.J. Preferential flows and travel time distributions: defining adequate hypothesis tests for hydrological process models. *Hydrological Processes*, 2010, 24:1537–1547.
- Chen, L., Feng, Q., Wang, Y., etc. Water and salt movement under saline water irrigation in soil with clay interlayer. *Transactions of the Chinese Society of Agricultural Engineering*, 2012, 28 (8): 44-51.
- Yao, R., Yang, J., Zheng, F., etc. Estimation of soil salinity by assimilating apparent electrical conductivity data into HYDRUS model. *Transactions of the Chinese Society of Agricultural Engineering*, 2019, 35 (13): 90-101.
- Ding, D.Y., Feng, H., Zhao, Y., et al. Impact assessment of climate change and later-maturing cultivars on winter wheat growth and soil water deficit on the Loess Plateau of China. *Climatic Change*, 2016, 138(1-2): 157–171.
- Zipper, S.C., Soyulu, M.E., Kucharik, C.J., et al. Quantifying indirect ground-water-mediated effects of urbanization on agroecosystem productivity using MODFLOW-AgroIBIS (MAGI), a complete critical zone model. *Ecological Modelling*, 2017, 359: 201–219.
- Kucharik, C.J., Foley, J.A., Delire, C., et al. Testing the performance of a dynamic global ecosystem model: water balance, carbon balance, and vegetation structure. *Global Biogeochemical Cycles*, 2000, 14: 795–825.
- Šimůnek, J., Šejna, M., Saito, H., et al. TheHYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 4.17, HYDRUS Software Series 3. Department of Environmental Sciences, 2013. University of California Riverside, Riverside, CA, USA.
- Harbaugh, A.W. MODFLOW-2005: the U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Process (USGS Numbered Series No. 6-A16), Techniques and Methods. U.S. Geological Survey, 2005.

- Li, L., Shi, H., Jia, J., etc. Simulation of water and salt transport of uncultivated land in Hetao Irrigation District in Inner Mongolia. *Transactions of the CSA*, 2010, 1:31-35.
- Zhang, X., Lin, Q., Huang, X., etc. Numerical simulation coupling soil water/groundwater and estimation of groundwater recharge in dagu river basin. *Acta Pedologica Sinica*, 2019, 56 (1): 101-113.
- Twarakavi, N.K.C., Šimůnek, J., Seo, H.S. Evaluating interactions between groundwater and vadose zone using HYDRUS-based flow package for MODFLOW. *Vadose Zone Journal*. 2008, 7: 757-768.
- Gu, W., Pang, Z., Wang, Q., etc. *Isotope Hydrology*, 2011, Beijing, Science Press.
- Lv, Y.J., Gao, L., Geris, J., Verrot, L., Peng X. Assessment of water sources and their contributions to streamflow by endmember mixing analysis in a subtropical mixed agricultural catchment. *Agricultural Water Management*, 2018, 203: 411-422.
- Peng, X., Zhu, Q., Zhang, Z., Hallett, P.D., Combined turnover of carbon and soil aggregates using rare earth oxides and isotopically labelled carbon as tracers. *Soil Biology and Biochemistry*, 2017, 109: 81-94.
- Penna, D., Geris, J., Hopp, L., Scandellari, F., Water sources for root water uptake: Using stable isotopes of hydrogen and oxygen as a research tool in agricultural and agroforestry systems. *Agriculture, Ecosystems & Environment*, 2020, 291: 106790.
- Li, X. Soil - vegetation - hydrological coupling, response and adaptation mechanism in arid areas. *Chinese Science: Earth Science*, 2011, 41 (12): 1721-1730
- Tracy, S.R., Black, C.R., Roberts, J.A., McNeill, A., Davidson, R., Tester, M., Samec, M., Korosak, D., Sturrock, C., Mooney, S.J. Quantifying the effect of soil compaction on three varieties of wheat (*Triticum aestivum* L.) using X-ray micro computed tomography (CT). *Plant and Soil*, 2012, 353: 195-208.
- Pohlmeier, A., Oros-Peusquens, A.M., Javaux, M., et al., Changes in Soil Water Content Resulting from Ricinus Root Uptake Monitored by Magnetic Resonance Imaging. *Vadose Zone Journal*, 2008, 7, 1010-1017.
- Zhang, Z.B., Liu, K.L., Zhou, Z., Lin, H., Peng, X.H., Linking saturated hydraulic conductivity and air permeability to the characteristics of biopores derived from X-ray computed tomography. *Journal of Hydrology*, 2019, 571: 1-10.
- Guo, L., Chen, J., Lin, H., Subsurface lateral preferential flow network revealed by time-lapse ground-penetrating radar in a hillslope. *Water Resources Research*, 2014, 50(12): 9127- 9147.
- Vereecken, H., Huisman, J.A., Franssen, H.J.H., et al. Soil hydrology: Recent methodological advances, challenges, and perspectives. *Water Resources Research*, 2015, 51(4): 2616-2633.

- Yang, J., Yao, R. Management and efficient agricultural utilization of salt-affected soil in China. *Bulletin of Chinese Academy of Sciences*, 2015, 30 (S): 162-170.
- Li, X., Zuo, Q., Shi, J., etc. Evaluation of salt discharge by subsurface pipes in the cotton field with film mulched drip irrigation in Xinjiang, China : Application of the calibrated models and parameters. *Journal of Hydraulic Engineering*, 2016, 47 (5): 616-625.
- Li, M., Kang, S., Yang, H. Effects of plastic film mulch on the soil wetting pattern, water consumption and growth of cotton under drip irrigation. *Transactions of the CSAE*, 2007, 23 (6): 49-54.
- Liu, Z., Huo, Z., Wang, C., Zhang, L., Wang, X., Huang, G., Xu, X., and Steenhuis, T. S.: A field-validated surrogate crop model for predicting root-zone moisture and salt content in regions with shallow groundwater, *Hydrol. Earth Syst. Sci.*, 24, 4213–4237.
- Qadir, M., Ghafoor, A., Murtaza, G. Amelioration strategies for saline soils: a review. *Land Degradation & Development*, 2000, 11(6): 501–521.
- Hörtnagl, L., Barthel, M., Buchmann, N., et al. Greenhouse gas fluxes over managed grasslands in Central Europe. *Global Change Biology*, 2018, 24: 1843–1872.
- Swallow, M.J.B., O’Sullivan, G. Biomimicry of vascular plants as a means of saline soil remediation. *Science of Total Environment*, 2019, 655: 84–91.
- Zhu, Q., Liao, K., Lai, X., Liu, Y., Lu, L. A review of soil water monitoring and modelling across spatial scales in the watershed. *Progress in Geography*, 2019, 38 (8): 1150-1158.
- Soylu, M.E., Loheide, S.P., Kucharik, C.J. Effects of root distribution and root water compensation on simulated water use in maize influenced by shallow groundwater. *Vadose Zone Journal*, 2017, 16, <https://doi.org/10.2136/vzj2017.06.0118>.
- Beyer, M., Koeniger, P., Gaj, M., et al. A deuterium-based labeling technique for the investigation of rooting depths: water uptake dynamics and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, 2016, 533: 627–643.
- Evaristo, J., Jasechko, S., McDonnell, J.J. Global separation of plant transpiration from groundwater and streamflow. *Nature*, 2015, 525: 91.
- Wang, Q., Shan, Y. Review of research development on water and soil regulation with brackish water irrigation. *Transactions of the Chinese Society for Agricultural Machinery*, 2015, 46 (12): 117-126.
- Figure 1. Diagram of crop-groundwater feed-in relationship in shallow groundwater area: a) the hypothetical relationship between shallow groundwater level and crop (in the case of maize) yield; refer to Zipper et al. (2015).

Figure 2. Schematic diagram of definition of groundwater benefit zone

Figure 3 Diagram of MAGI Model Research Framework (quoted from Zipper et al., 2017).

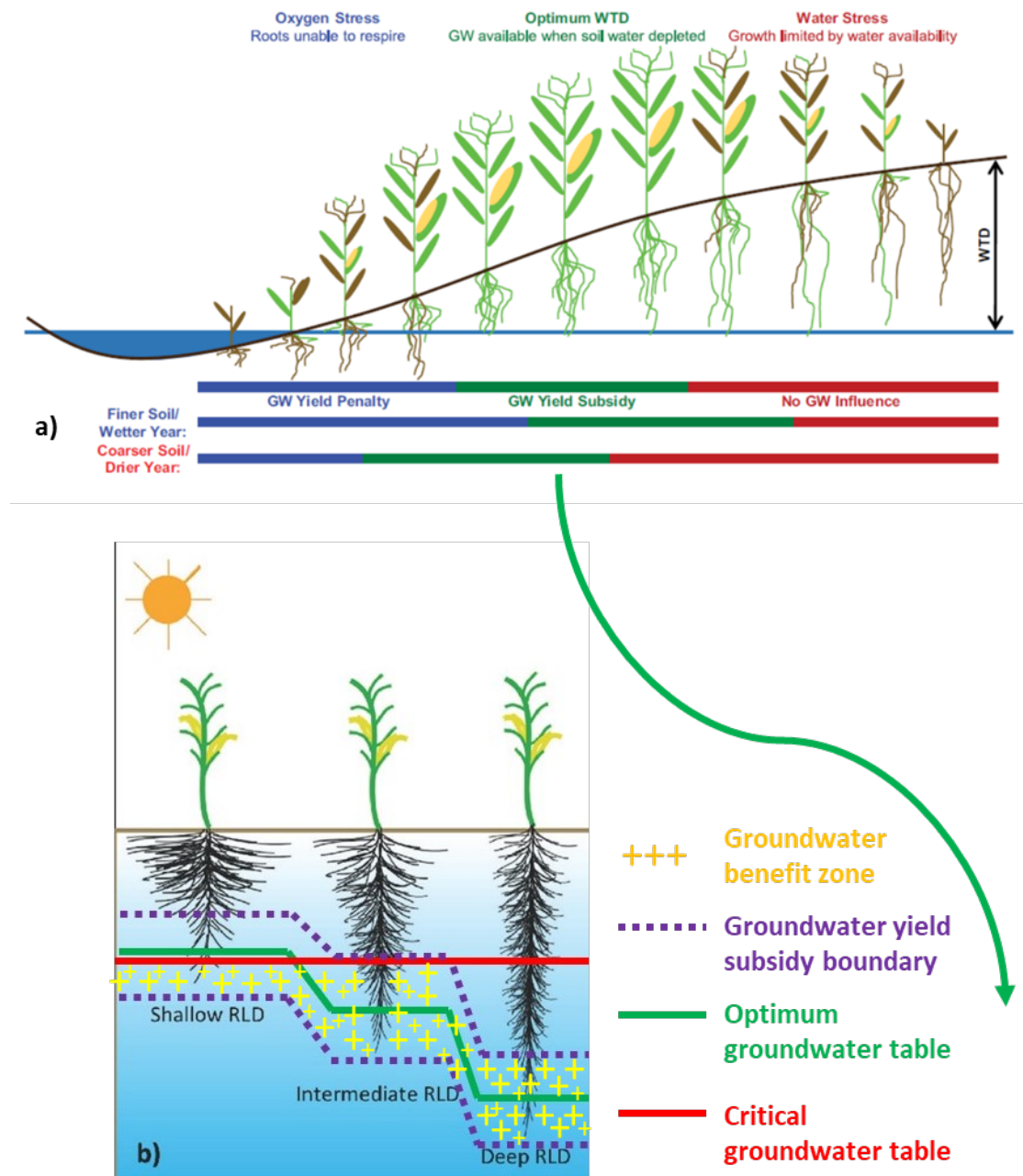


Fig.1

$$\Delta h = \begin{cases} 0, & h_0 < h_{min} \\ h_0 - h_{min}, & h_{min} \leq h_0 \leq h_{max} \\ h_{max} - h_{min}, & h_0 > h_{max} \end{cases}$$

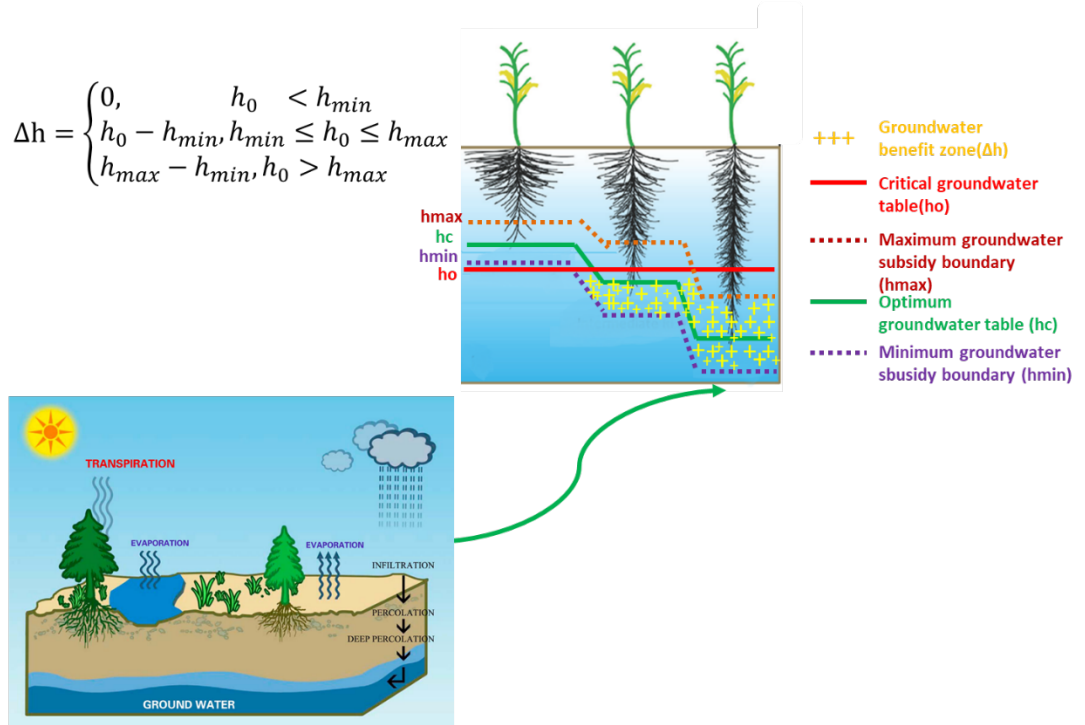


Fig. 2



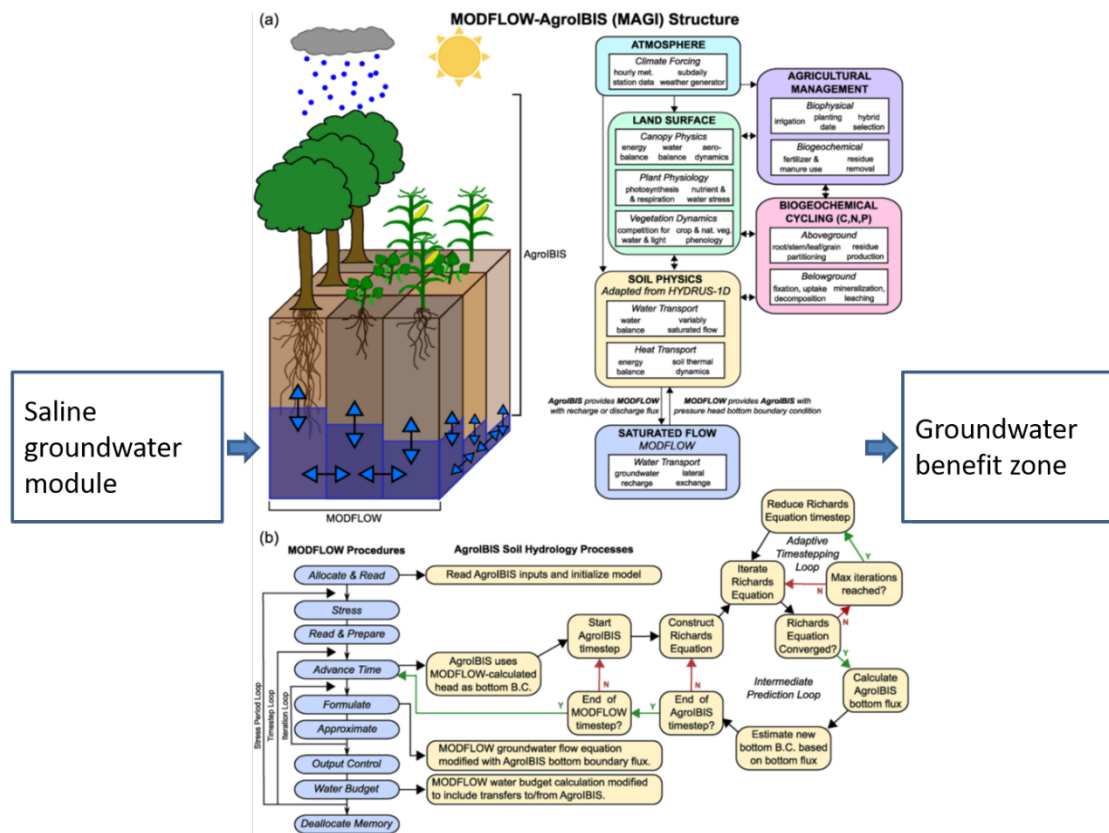


Fig. 3