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The “Groundwater Benefit Zone”, Proposals, Contributions and New Scientific Issues

Ying Zhao, Ji Qi, Qiuli Hu and Yi Wang

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 elaborates 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 been prospected.

Keywords: groundwater benefit zone, soil water and salt movement, model simulation, mechanisms, modification technology

1. Introduction

About 22–32% of the world’s terrestrial plants have their roots near or within the groundwater [1, 2]. As a result, groundwater significantly impacts the transpiration of aboveground ecosystems and net primary productivity [3–5]. On a global scale, groundwater contributes about 23% to vegetation water consumption on average [6]. In areas with shallow groundwater, it contributes up to 84% of the total transpiration of vegetation. In arid areas [7], almost all water consumption of the plant comes from groundwater [8]. However, groundwater contributes little or even negatively to transpiration in irrigated agriculture or coastal areas with shallow water table depth, due to its high salinity [9]. At present, with the expansion of the agricultural area, the supply of freshwater resources is becoming more and more insufficient; agricultural production 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, it 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.

2. The proposed concept of “groundwater benefit zone”

2.1 Mechanism of water transport in salt-affected farmland

Recently, numerous researches have been done on the water flow process and mechanism in soil–plant–atmosphere continuous (SPAC) systems. However, these studies do not fully consider the role of groundwater and cannot clarify the water transfer mechanism in 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 contribution to soil evaporation and crop transpiration [10]. In drought years, plants increase net primary productivity (NPP) by using groundwater to reduce the effect of water stress on CO₂ fixation, resulting in significant increases in transpiration due to the presence of shallow groundwater. Lowry and Loheide [11] defined the additional water that the plant transpires from shallow groundwater as “groundwater subsidies”, and calculated the difference of the root water absorption under shallow groundwater and the free drainage conditions. Furthermore, Zipper et al. [4] defined the yield from this additional water as a “groundwater yield subsidy”. In agricultural systems, yield is usually more relevant to 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. [12] 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 the non-saline area, and the applicability of these indicators in saline-alkali land and its conceptual extension still needs to be further studied.

2.2 Definition of the “groundwater benefit zone”

In general, to prevent soil salinization, groundwater must be kept below the critical groundwater table [10, 13]. The scientific community currently lacks a recognized definition and quantification method for the critical groundwater table. We define it 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

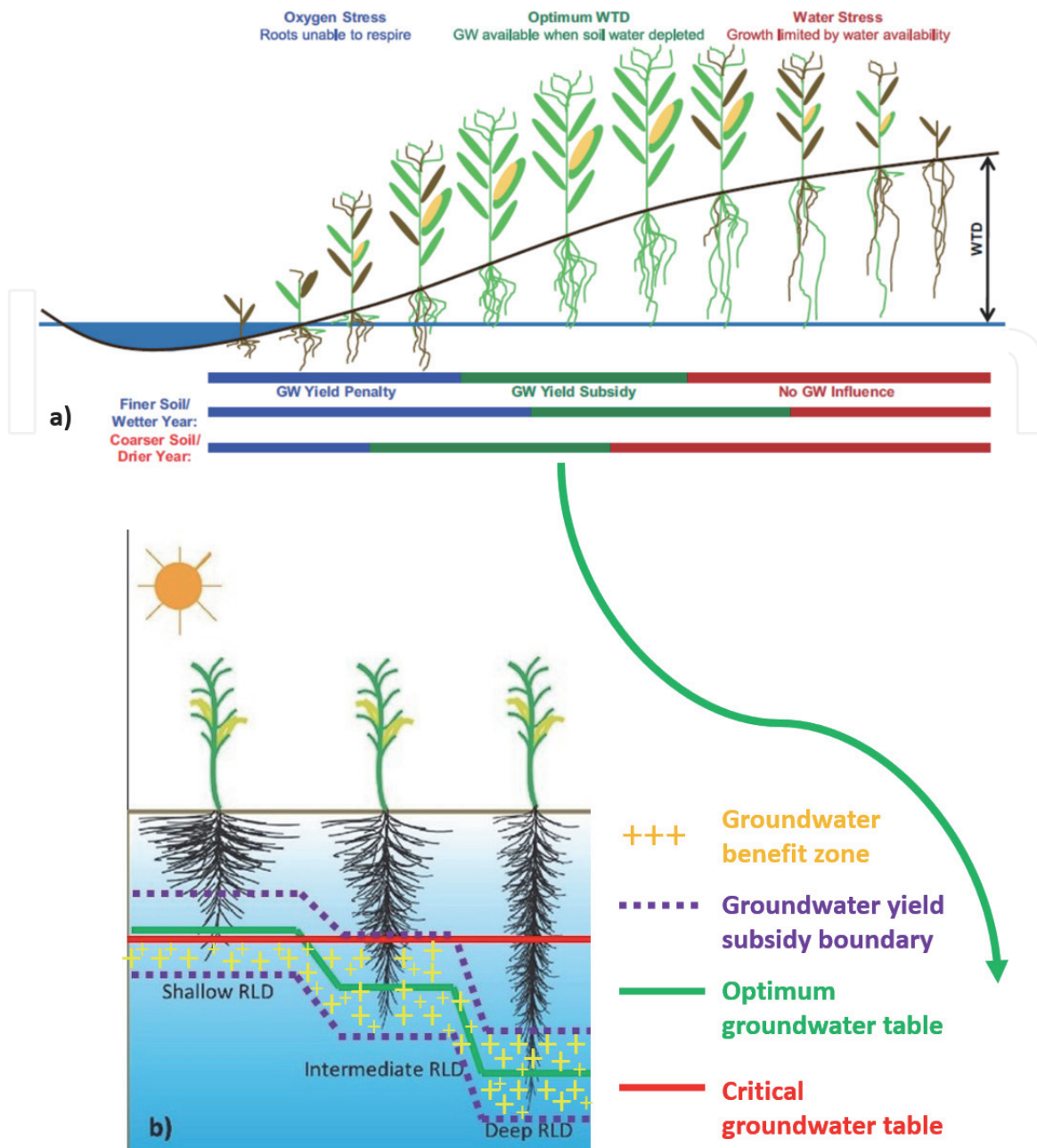


Figure 1. Diagram of crop-groundwater feed-in relationship in shallow groundwater area: (a) the hypothetical relationship between shallow groundwater level and crop (in the case of maize) yield; (b) the conceptual diagram of the groundwater benefit zone. Refer to Zipper et al. [4].

to the complex factors which influence 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 [10]; 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, the φ is the electrical conductivity, φ_0 is the electrical conductivity corresponding to the critical water table, φ_r is the threshold for salt stress, n is the parameter;

2. It is also necessary to keep the groundwater table close to the optimal groundwater table (groundwater yield subsidy boundary) [4] 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, α 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 (α_h) and the salt stress function (α_φ). 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_φ is solute potential, and $h_{\varphi 50}$ is the solute potential when the stress in the Van Genuchten salt stress function reduces the water absorption rate by 50%, p is related parameter.

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

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

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

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 absorption 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 or appropriate methods to apply directly [13].

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

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

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 adjust 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 (**Figure 2**).

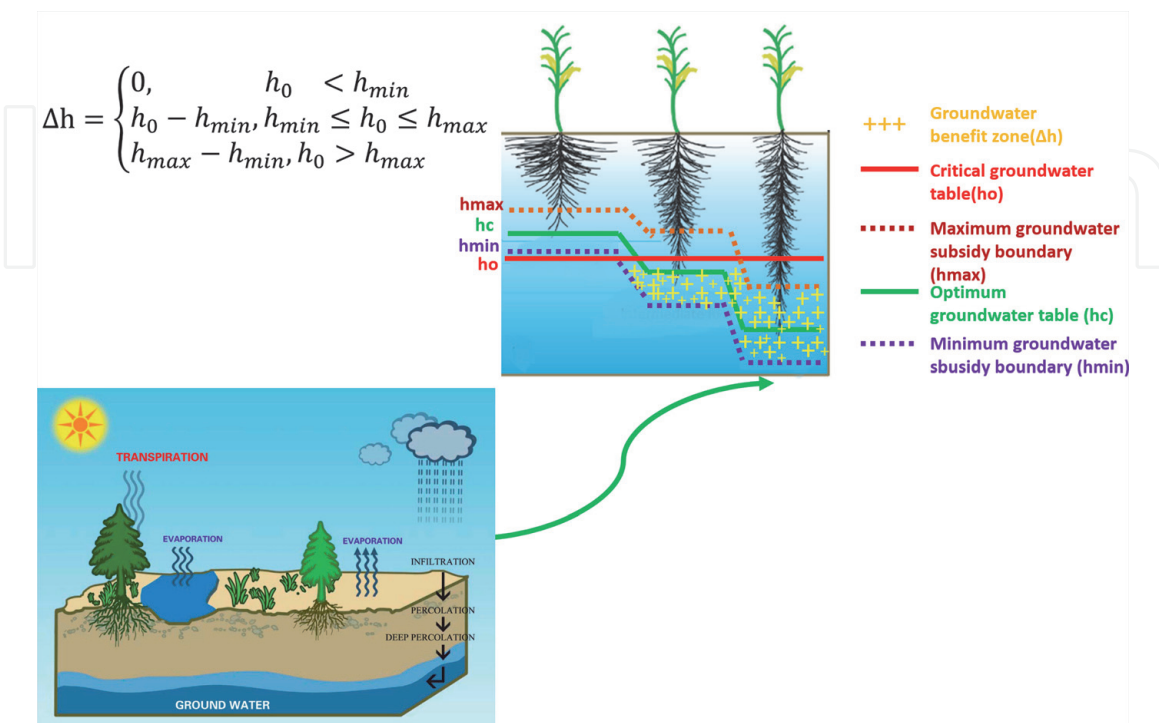


Figure 2.
 Schematic diagram of definition of groundwater benefit zone.

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.

3. The research focus of “groundwater benefit zone”

3.1 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 solute 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 systems such as soil profile, slope, and basin [14]. In recent years, more and more studies have attempted to establish the relationship between shallow groundwater and vegetation physiology and weathering processes, to identify the critical groundwater table. At the same time, there is still a lack of mathematical expression and field validation for this relationship [10]. Zipper et al. [4] 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-stressed parts of the root to compensate for root water uptake in areas where stress is more serious; [15]) had a significant impact on transpiration and NPP, emphasizing the importance of incorporating root compensatory water absorption equations into model studies.

3.2 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. [16]) have been established, in which HYDRUS models are widely used [17]. 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 conditions (such as clay layer, gravel, large pores) with more regional influence factors (e.g., groundwater, irrigation water) [18–20]. However, the current model of the water-salt transport mechanism is limited within 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. [21]), but the expression of soil hydrological processes is insufficient, especially the lack of simulating groundwater dynamics. Many 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 [12].

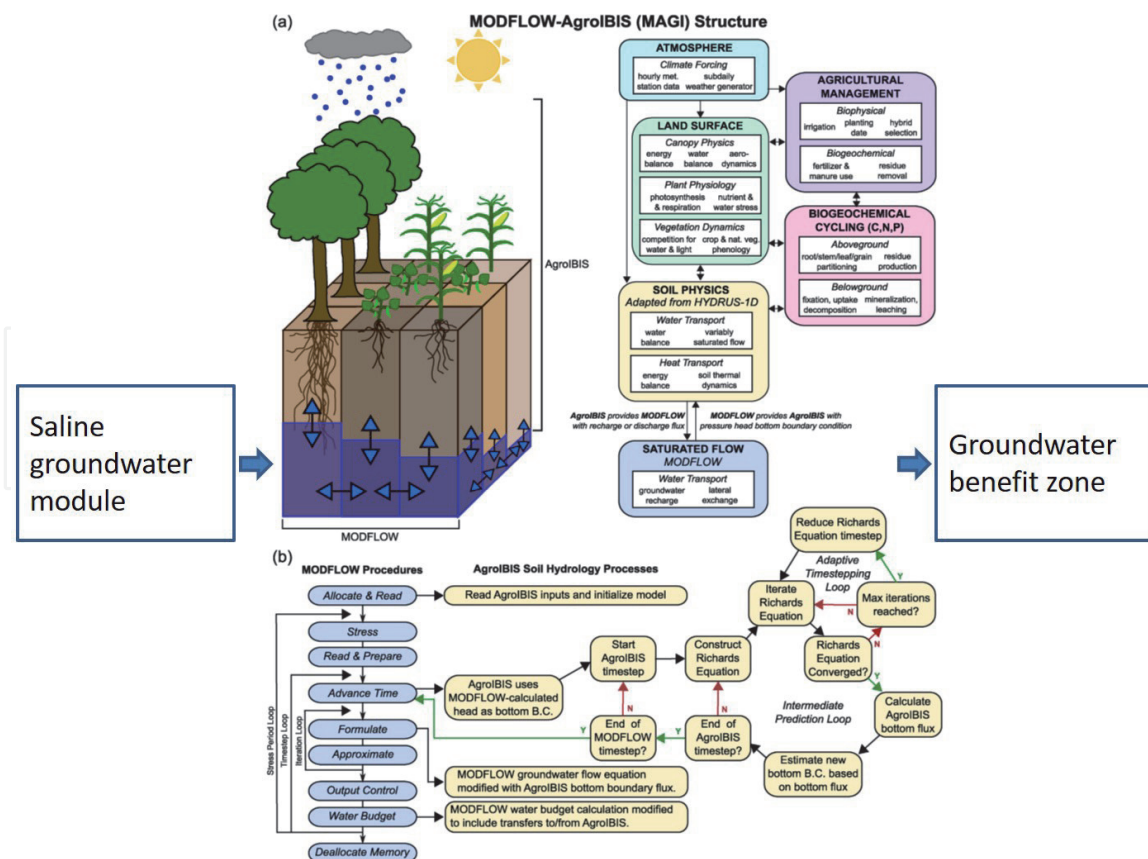


Figure 3.
 Diagram of MAGI Model Research Framework (quoted from [22]).

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. [22] 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 (①AgroIBIS [23], ②HYDRUS-1D [24] and ③MODFLOW-2005 [25]). 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, 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. It means that the effects of salt must be taken into account when use models that need to be updated to calculate groundwater yield subsidies in saline agriculture (Figure 3).

3.3 Scale of water-salt migration process and its corresponding research techniques

Although the mechanisms of water and salt transport through the GSPAC system at field scale are considered more comprehensively, the water and salt transport process occurred at an immense scale. 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.

Consequently, the field-scaled model, which is often one-dimensional, cannot simulate large-scale saline water process or make the related evaluation [26]. 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 cannot reflect the small-scale hydrological process neither in saturated zone nor in the unsaturated area due to the lack of small-scale soil hierarchy and detailed structural parameters [27]. Thus, another trend of model development is to develop the coupled models at different scales, such as the model “HYDRUS-MODFLOW” [28] is coupled with 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 to (extend to) 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-dependent effect and corresponds to the appropriate quantitative techniques and methods in that scale.

Currently, there are effective ways to track the migration of substances in GSPAC systems [29–32], 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) [33]. 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 meso-scale 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. [34–36]. At the mesoscale, the soil water and salt transport and distribution mainly include evaporation, infiltration, lateral seepage, groundwater leakage, and recharge, and is the basic scope of water-salt regulation and ecological environment construction [33]. 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 [37, 38]. 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 environment.

3.4 Optimal regulation of groundwater benefit zone

At present, there are a variety of measures for the regulation of water and salt, the core of which is to inhibit salt building-up by reducing soil evaporation (e.g., mulching), to promote salt leaching by improving soil structure (e.g., soil amendments), to block salt building-up by creating salt-isolation layer (e.g., salt-resistant barrier), or to increase soil drainage to facilitate soil salt discharge (e.g. subsurface pipes), and among other ways [39–41]. 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 simulation of optimization of groundwater [42]. Although some models currently proposed appropriate groundwater levels and irrigation strategies for specific crops [43], it is still challenging to promote and popularize the results due to different soil types, irrigation systems, plant rooting patterns, salt tolerance, groundwater depth, and climatic conditions. In general, to break the limitations of long-term field test and the lack of investigated factors, the technical parameters of water salt regulation can be obtained 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 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 [44].

On this basis, the model scenario analysis can design different combinations of influence factors, to clarify the balance point of water conservation measures and salt leaching, and to 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 [45] 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. After added to the soil, with the help of natural evaporation, groundwater and soil salt are directly separated 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.

4. The main scientific issues in the study of “groundwater benefit zone”

In this paper, we proposed the new concept and index of the “groundwater benefit zone” based on the interaction between the saline farmland ecosystem and the groundwater. Through a combination of field monitoring and model simulation, the next step is to address the following issues:

1. How to determine the critical groundwater table in areas with shallow groundwater and their quantitative relationship with 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 [46]. 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 [47]. 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 [45].
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 their difference, 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 [15]. 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 [47].
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 extracting 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 [48, 49], 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 [50], study the process of non-saturation zone salt migration, driving mechanism and its scale-dependent 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.


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