Advances in Modeling Root Water Uptake – A Review

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Abstract
The simulation of water dynamics at the soil-root interface is of great importance to understand the processes of water and energy transfer, and availability of water to plants in the soil-plant-atmosphere continuum (SPAC) system. This review systematically summarizes various root water uptake models proposed since the 1960s for water dynamics in the SPAC system using macroscopic modeling approaches. Also, critical discussion, based on the review of the existing models, is given in relation to further improvement of root water uptake models and thus the enhancement of the simulation results. It stresses that more efforts should be directed in the key areas of using different modeling techniques such as the inverse, hybrid and water compensation methods, together with the quantification of root growth for the development and calibration of root water uptake models in the future.
Keywords: SOIL-PLANT SYSTEM; SPAC SYSTEM; ROOT WATER UPTAKE; SOIL WATER DYNAMICS; CROP MODELING.

1. Introduction

Water uptake by plant roots is an important process for material and energy transfer in the soil, and plays a crucial role in governing water cycle in the Soil-Plant-Atmosphere Continuum (SPAC) system. It has long been a research focus by scientists from the fields of soil, agricultural and environmental sciences [1-2]. Root water uptake models, based on the studies on mechanisms controlling root water uptake and field experiments, are devised using mathematical tools to quantitatively describe the process of water uptake by roots. Due to the complex processes of root growth and water movement in soil, which are affected by many factors, various root water uptake models have been proposed. Models that simulate water uptake in plant root zones are generally classified into two categories. The first category follows a microscopic approach (bottom-up), and models in this category have contributed significantly to the understanding of root water uptake processes [4-6]. The microscopic approach requires details about root geometry, soil heterogeneity, and the physical interactions among these components. The second category follows a macroscopic approach, in which the entire root system is treated as a single unit to sum up the effects of all individual roots [7-12]. In the macroscopic approach, a sink term representing the water extraction by plant roots is included in the dynamic water flow equation. This allows spatially and temporally variable uptake, and the term is related to water pressure head, osmotic pressure, root length distribution, and meteorological conditions such as soil evaporation and plant transpiration requirements [9,13]. The microscopic model, difficult for practical applications due to the above-mentioned constraints, is usually only used in basic research. The study of root water uptake has mainly focused on macroscopic models in the existing literature [14-15].

On account of this, this paper is limited to 1) review the root water uptake models using macroscopic approaches and identify the associated problems, and

2) highlight the ways for further development of such models.

2. Description of Macroscopic Models

Main text Models based on the macroscopic approach ignore the root water potential gradient at the microscopic scale and implicitly average pore-scale variations in the pressure head or solute concentrations in the immediate vicinity of individual roots. These models do not consider changes in root conductivity with time, which makes the boundary conditions of models with non-uniform water potential easy to identify and control. It is generally known that all macroscopic models calculate water movement based on numerical solutions to the Darcy-Richards equation and include a water uptake term, $S(z,t)$.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}[K(h)\frac{\partial h}{\partial z}-K(h)]-S(z,t) \quad (1)$$

Boundary conditions:

$$\begin{cases} h(z,0)=h_0(z) \;\; 0\le z\le L_r \quad t=0 \\ [-K(h)(\frac{\partial h}{\partial z}-1)]_{z=0}=-T_p \quad t>0 \\ h(z_r,t)=h_1(t) \qquad\qquad t>0 \end{cases} \quad (2)$$

where θ is the soil moisture content (cm^3 cm^{-3}), $K(h)$ is the hydraulic conductivity (cm d^{-1}), h is the soil moisture pressure head (cm), t is the time (d), z is the vertical distance measured positively upwards (cm), $S(z,t)$ is the water uptake by roots expressed as volume of water per unit volume of soil per unit time (cm^3 cm^{-3} d^{-1}), zr is the maximum root growth depth (cm), Tp is the potential transpiration (cm d^{-1}), and h1(t) is the matric potential at the lower boundary (cm).

The purpose of this work is to summarize the functions of the sink term in Eq. (1) formulated from different viewpoints. Gardner (1964) [16] first used the macroscopic approach to investigate root water uptake. He proposed that root water uptake is associated with the distribution of plant roots and can be expressed by the following equation:

$$S(z,t)=B(h_r-h_s-z)K(h)L(z,t) \quad (3)$$

Where B is the dimensionless proportional constant, $L(z,t)$ is the root length density, i.e. the root length per unit volume of soil (cm cm^{-3}), hr is the root water potential (cm), which is related to the soil, vegetation type, and weather conditions, hs is the soil matric potential (cm).

Whisler, F.D. et al, [17] proposed a general root water uptake model based on soil water potential, root water potential and hydraulic conductivity, which also considers the influence of root density variations over depth on the root water uptake rate:

$$S(z,t)=b(z)K(h)(h_r-h_s) \quad (4)$$

where $b(z)$ is the root effectiveness function (cm^{-2}), which is a proportional constant related to z, θ, the average soil water pressure head (ha), resistance of soil to water flow (*Rs*), and resistance of the plant xylem to water uptake (*Rr*). Although $b(z)$ is essentially an empirical parameter that integrates the physics of flow at and across the soil–root interface, in practice $b(z)$ has been assumed to reflect the relative root distribution in the soil profile. As such, it has been equated to the normalized root density function with units of root length per unit volume of soil [17].

Molz, F.J. and Remson, I. [7] and Hoogland, J.D. et al. [18] developed models which extracted water linearly over the root zone. According to Molz, F.J. and Remson, I.'s [17] empirical function, a plant derives 40% of its total potential transpiration in the first quarter of the root depth, 30% from the second, 20% from the third, and 10% from the bottom-most quarter. They proposed the concept of effective root density and assumed that the rate of root water uptake is related to Tp, effective root distribution ($R(z)$), and $K(h)$:

$$S(z,t)=-\frac{1.6T_p}{z_r^2}z+\frac{1.8T_p}{z_r} \quad 0\le z\le v \quad (5)$$

Molz [4] proposed:

$$S(z,t)=\frac{T_pR(z)K(h)}{\int_0^v R(z)K(h)dz} \quad (6)$$

Nimah, M.N. and Hanks, R.J. [8] developed a numerical model to predict soil water content profiles, evapotranspiration, water flow from or to the water table, root extraction, and the root–water potential under transient field conditions. This model predicts a change in root extraction, evapotranspiration, and drainage due to variations in pressure head and water content relations and the rooting depth:

$$S(z,t)=\frac{[h_r+R_rz-h_s-h_0]R(z)K(h)}{\Delta x\Delta z}L(z,t) \quad (7)$$

where h0 is the osmotic pressure head due to the salinity stress (cm), Δz is the depth increment, and Δx is the distance from the root surface to the points hs and h0 (usually assumed to be 1.0).

On the basis of the work by Gardner, W.R. [16] and Whisler, F.D. et al, [17], Feddes, R.A. et al. [9,18] proposed a relatively simple, well-defined empirical function based on soil moisture content variations to describe the impact of water flow geometry on root water uptake. This equation assumes: the root density distribution is uniform; the rate of root water uptake does not change with root depth; the rate of root water uptake is zero when the soil moisture content is lower than the plant's permanent wilting point and higher than that of the microbial anaerobic point; and the root water uptake rate is linear when the soil water content is between the withering point and optimum moisture content. It is expressed as follows:

$$S(z,t) = -K(h)[h_r - h_s]/b(z) \qquad (8)$$

Following the theory proposed by van den Honert, T.H. [19] that water and electric flows were similar, Hillel, D. et al, [20] developed a formula involving a root resistance coefficient to study the change in root water uptake rate:

$$S(z,t) = [h_t - h_r]/(R_s + R_r) \qquad (9)$$

Where ht represents the total soil water potential (cm). With the same theory of van den Honert, T.H. [19], Herkelrath, W.N. et al, [20-21] proposed a root water uptake equation considering soil–root interactions, soil water potential, θ, and the permeability per unit root length:

$$S(z,t) = \frac{\theta(z,t)}{\theta_s} K_r L(z,t)[h_s - h_r] \qquad (10)$$

where θ_s is the saturated moisture content of soil ($cm^3\ cm^{-3}$), and Kr is the permeability coefficient per unit root.

Feddes, R.A. et al, (22-23) found that root water uptake patterns vary differently with changes in soil water content and the root water uptake rate has upper and lower limits. They established a piecewise root water uptake equation under different soil moisture conditions:

$$\begin{cases} S(z,t) = \alpha(h) S_{\max} \\ S_{\max} = T_p / Z_r \end{cases},$$

in which

$$\alpha(h) = \begin{cases} 0 & h \ge h_4 \text{ or } h \le h_1 \\ 1 & h_2 \le h \le h_3 \\ \dfrac{h - h_1}{h_2 - h_1} & h_1 \le h \le h_2 \\ \dfrac{h_4 - h}{h_4 - h_3} & h_3 \le h \le h_4 \end{cases} \qquad (11)$$

where $a(h)$ is the dimensionless water stress reduction function ($0 \le \alpha \le 1$); h1 is the soil water pressure head under anoxic conditions (cm), whose value is close to zero in sandy soil [24,25]; the region between h2 and h3 represents the soil water pressure head (cm) under optimal conditions (i.e., the soil moisture content meets the crop transpiration needs with no water stress); and h4 is the soil water pressure head at the wilting point (cm), i.e., the point at which crops no longer uptake water from the soil. This model is widely used in the SPAC system for dynamic water simulations.

Selim, H. M. and Iskandar, I. K. [26] proposed a root water uptake model containing a soil hydraulic conductivity function:

$$S = \frac{K(h)R(z)}{\int_0^{Lr} K(h)R(z)dz} T_p \qquad (12)$$

Hoogland, J.C. et al. [18] considered the fact that root density and consequently potential root water uptake decreases with depth, z. They proposed a linear relationship between maximum uptake and depth:

$$S_{\max}(Z) = a - bz \qquad (13)$$

where a and b are empirical constants, which in principle should be determined from measured root water uptake data, and Smax has a non-zero value at z=zmax.

Molz, F.J. [10] published a comprehensive review of various root water uptake models. He considered various factors including water potential and hydraulic characteristics of root systems to describe the water flow from soil to root surfaces, and proposed a relatively complex and comprehensive single-root water uptake model. The model has an approximate, axisymmetric formula:

$$S(z,t) = \frac{T(t)\theta(z,t)L(z,t)[h_s - h_r]}{\int_\theta^{z_r} \theta(z,t)L(z,t)[h_s - h_r]dz} \qquad (14)$$

Bresler, E. et al, [27] developed the sink term function based on the work by Whisler, F.D. et al, [17] and introduced an osmosis pressure head parameter π to simulate root water uptake under salinity stress conditions:

$$S(z,t) = R(z)K(h)(h + \pi - h_r) \qquad (15)$$

This model calculates the influence of environmental conditions on root water uptake with the simple addition of water and salt stress. However, it has been shown that this model only applies under low salinity conditions [28].

Based on the study by Feddes, R.A. et al, (22,23), Belmans, C. et al, [29] suggested a simple extraction term that depends only on the water pressure head and maximum/potential transpiration rate:

$$S(z,t) = L(z,t)\alpha(h)T_p \tag{16}$$

Vogel, T. [30] proposed a two-dimensional model to calculate the non-uniform distribution patterns of the potential root water uptake rate of the entire root zone with an arbitrary shape:

$$S(z,t) = b(z)L_t T_p,$$

$$b(z) = \frac{b^{'}(z)}{\int_{\Omega_R} b^{'}(z)dz} \tag{17}$$

Where Lt is the width of the soil surface associated with the transpiration process, Ω_R is the root zone area (cm2) and $b'(z)$ is a distribution function associated with root length density.

Similarly, Perrochet, P. [31] developed another version of the general root water uptake model:

$$S(z,t) = \alpha(h)L(z,t)T_p \tag{18}$$

Prasad [13] proposed a linear model that satisfies the desired extraction at the top and bottom of the root zone and observed that this model is more accurate in comparison to constant rate models:

$$S(z,t) = \frac{2T_p}{z_r}a(h)(1-\frac{z}{z_r}) \tag{19}$$

Shao, M.A. et al, [32] improved upon the work of Molz, F.J. [10] by considering parameters related to soil moisture conditions, energy states, water capacity, plant root density, root zone depth, atmospheric factors, etc. They associated the root water uptake rate with the number of root hairs and proposed a theory suggesting that only effective roots have a close relationship with the root water uptake rate, and not all roots participate in root water uptake activities. The formula is as follows:

$$S(z,t) = \frac{T(t)\lambda(\theta)L_v^{1/n}(z,t)[h_s - h_r]/R_{sr}}{\int_0^{z_r}\left\{\lambda(\theta)L_v^{1/n}(z,t)[h_s - h_r]/R_{sr}\right\}dx} \tag{20}$$

where Rsr the total resistance of a root system during the water uptake process; n represents the soil texture factors; and $\lambda(\theta)$ is the limiting factor of soil moisture.

Ojha, C.S.P. and Rai, A.K. [33] improved upon the above model by developing a nonlinear root-water uptake model. They assumed the maximum water uptake rate occurs at the top of the root zone and the minimum water uptake rate occurs at the bottom of the root zone:

$$S(z,t) = a(h)S_{max}$$

in which,

$$S_{max} = \alpha[1-(\frac{z}{z_r})]^{\beta}, \quad 0 \le z \le z_{rj} \tag{21}$$

where α and β are model parameters; z is the depth below the soil surface; and zrj is the root depth on the jth day. Eq. (21) satisfies the desired extraction conditions: extraction is highest at the top and zero at the bottom of the root zone. However, Smax has to satisfy the following equation:

$$S_{max} = [\frac{T(t)}{z_r}(\beta+1)(1-\frac{z}{z_r})^{\beta}], \quad 0 \le z \le z_r \tag{22}$$

Moreover, under both water and salinity stress conditions, the following equation applies:

$$S(z,t) = \alpha(h)\alpha(\pi)S_{max}(z,t) \tag{23}$$

where $\alpha(\pi)$ is a dimensionless salinity stress function.

On the basis of the work conducted by Feddes, R.A. et al, [22,23] and Prasad, R. [13], Wu, J. et al, [12] proposed the normalized root length density (NRLD) distribution:

$$S(z,t) = \frac{\alpha(h)\alpha(\pi)L_{nrd}(z)(\frac{T_p}{L_{(z,t)}})}{L_{(z,t)}}, \tag{24}$$

in which,

$$\begin{cases} \alpha(h) = \begin{cases} 0 & h(z,t) \le h_1 \\ 1-[\frac{h(z,t)-h_2}{h_1-h_2}]^p & h_1 \le h(z,t) \le h_2 \\ 1 & h(z,t) \ge h_2 \end{cases} \\ \alpha(\pi) = \frac{1}{[1+(\frac{h_s}{h_{s0.5}})^p]} \\ L_{nrd}(\frac{z}{L_{(z,t)}}) = 2.21 - 3.72\frac{z}{L_{(z,t)}} + 3.46(\frac{z}{L_{(z,t)}})^2 - 1.87(\frac{z}{L_{(z,t)}})^3 \end{cases} \tag{25}$$

where $z/L_{(z,t)}$ is the standard depth between 0 and 1; L_{nrd} is the normalized dimensionless root density function, usually expressed with third-order equations; and h1 and h2 are the soil matric potentials at the start and end of root water uptake under water stress conditions, respectively.

Lai, C. T. and Katul, G. [34] constructed a root uptake model accounting for the compensatory water uptake between dry and wet soil layers. They assumed that root water uptake is closely related to the root density distribution function, water stress response function, and transpiration rate. The normalized formula is as follows:

$S(z,t) = R(z)L(z,t)T_p$,

in which,

$$\begin{cases} R(z) = \dfrac{1}{1+[(h+\pi)/h_{s5}]^p} \\ L(z,t) = 2cz/L_r^2 + (1-c)/L_r \end{cases} \quad (26)$$

where π is the soil solute potential, whose value is 0 when soil salinity stress is not considered; p is an empirical constant with a value of 3 for most plants; hs5 is the soil matric potential when the maximum transpiration decreases by 5% and whose value is influenced by plant physiological characteristics; and c is a shape parameter, whose value ranges from -1 to 0 (generally −0.8).

Li, K. Y. et al, [11] built upon the semi-empirical root water uptake model proposed by Feddes R.A. et al, [22,23], and developed a root water uptake model within different soil layers by considering the potential transpiration rate and root length density distribution:

$$S(z,t) = \alpha(h)S_{\max} = \frac{K_{z_1-Z_2}T_p}{|Z_1 - Z_2|} \quad (27)$$

where Z_1 and Z_2 represent different root depths (cm); and $K_{Z_1-Z_2}$ represents the percentage of the root length occurring at depths of Z_1 and Z_2. Li, K.Y. et al, [35] improved the root water uptake model accounting for the compensatory root water uptake between dry and wet soil layers:

$$S(z,t)_i = \frac{\alpha_i^2 F_i^\lambda T_p}{\Delta Z_i \sum_{i=0}^{n} \alpha_i F_i^\lambda} \quad (28)$$

where i represents different soil layers; Fi is the percentage of root length density at layer i; Δz_i is the soil layer thickness at layer i (cm); and α is a dimensionless empirical parameter.

Kang, S. et al, [36] proposed a simplified root water uptake model by considering the diurnal variation in air pressure and the canopy extinction coefficient:

$$S(z,t) = K(h)T_p \frac{1.80e^{-1.80z/z_r}}{(1-e^{-1.80})z_r} \quad (29)$$

Based on the assumption that the root length density exponentially decreases with depth from the shoot-root interface [37-39], Vrugt et al. [40-41] introduced a multidimensional, empirical root water uptake model and showed that this model could be parameterized through inverse modeling for a drip-irrigated tree. This model results in a predefined root water uptake distribution that remains constant with time and does not include water uptake compensation mechanisms. Furthermore, it does not directly give the root length density distribution, which might be needed in alternative, mechanistically based simulation models:

$$S_m(x,z) = \frac{\beta(z)T_p}{\int_0^{Z_r} \beta(z)dz} \quad (30)$$

where $\beta(z)$ is a shape correction factor, which is used to describe the potential distribution of root water uptake along the direction of root growth and the rate of root water uptake is 0 when z=zm and reaches a maximum value when $0 \le z \le$ zm.

To assess the effect of the soil on root water uptake, Feddes, R.A. and Raats. P.A.C. [42] developed a dimensionless sink term by used a function of the soil water potential, and the effect of the soil and the roots are usually considered to be independent:

$$S(z,t) = \alpha_1(h,\theta,z)g(z)T_p(t) \quad (31)$$

Where $g(z)$ is the normalized root distribution function (cm^{-1}), and a_1 is a function that characterizes the effect of the soil (stress function).

Based on Wu, J. et al, [12] above-mentioned, Skaggs, T.H. et al, [43] estimated the volume of water taken by plant roots from unit volume of soil at location z and t by:

$$S(z,t) = a(h)\frac{T_p}{86400 \times 1000 \times L_{(z,t)}} L_{nrd}\left(\frac{z}{L(z,t)}\right) \quad (32)$$

Vogel T. et al, [44] implemented a simple macroscopic, vertically distributed plant root water uptake approximation in a one-dimensional dual-continuum model, which based on a traditional water-potential gradient formulation, to simulate soil water movement at a forested site.

$$S(z) = \frac{\sigma}{r_{soil} + r_{root}}[H_{soil} - H_{root}] \quad (33)$$

Where σ is the specific active root surface (m-1), Hroot is the water potential in the root xylem (m), Hsoil is interpreted as the water potential of bulk soil, rsoil is soil resistance to water extraction by roots, rroot is the radial hydraulic resistance of the root tissues (s).

3. The Future Prospects of Root Water Uptake Models

After 70 years development, research in modeling root water uptake has gradually become more complex and mechanistic. Though various root water uptake models have been developed, these models are similar in nature and have limited applications because some model parameters are difficult to determine accurately. Many researchers have focused on development of new measurement techniques and novel devices for modeling root water uptake processes. For example, Asseng, S. et al, [45] and Clausnitzer, C. and Hopmans, J.W. [46] described a non-destructive technology to simulate the movement of soil water and nutrients, as well as plant root water uptake on a scale of less than 1 mm. In addition, de Willigen, P. et al, [47] used a new technology to quantify the interactions between plant roots and soil. With the development of soil and plant science and root visual observation technology, field parameter measurements will become increasingly advanced. To improve the accuracy of model simulations, the topics described in the following sections should receive more attention.

3.1. Development of the inverse simulation method

Currently, most parameters of simulation models mainly depend on direct measurements, which are not only time-consuming and tedious, but also have high uncertainty. For example, experiments need to include several steady state conditions and analyze many soil samples to determine soil hydraulic parameters. Core soil samples taken for experiments may not represent actual field conditions. Thus, the authenticity of model parameters is uncertain [48,49]. To overcome these limitations and improve the accuracy of simulations, Dane, J.H. and Hruska, S. [50] used an inverse simulation method to optimize the soil permeability coefficient in the hydraulic function proposed by van Genuchten, M.T. [51]. Vrugt J.A. et al, [41] used the same approach to estimate the relevant parameters in a root water uptake model. Ines and Droogers, P. et al, [52] employed a genetic algorithm in their reverse modeling and concluded that the inverse method could avoid unreliable parameters resulting from the infrequency of direct field measurements. Furthermore, they discussed the accuracy of the inferred unsaturated soil hydraulic parameters made with the inverse method and showed that soil water content values simulated with the inferred soil hydraulic properties were more accurate than those directly calculated from the evapotranspiration flux. Jhorar et al, [53] calculated the effective soil hydraulic parameters through the inverse method using evapotranspiration flux data from remote sensing measurements and obtained good results for three different soil types in a semi-arid area in India. Ritter, A. [54] found that soil hydraulic parameters obtained from the inverse simulation method were more accurate than direct measurements in a sprinkler-irrigated banana plantation. Hupet, F. et al, [55] and Bastiaanssen, W.G.M. et al, [56] argued that the required level of expertise of using sophisticated models was too high, leading to the low uptake of soil water movement models, especially in less developed countries with irrigation systems that could benefit the most from such models. They proposed that the inverse method for agricultural hydrological models should be a key research focus in the next decade. Zhang, K.F. et al, [57] showed the effectiveness of a microscopic genetic algorithm in simulating soil hydraulic parameters derived from soil evaporation. Similarly, Zhang, K.F. et al, [58] used the same method to deduce crop coefficients for different plant growth stages, and found that when using parameters obtained from the inverse method, the simulation results from a hydrological simulation model matched well with real measurements. More recently, Zhang, K.F. [59] successfully derived parameters of cabbage root growth with the microscopic genetic algorithm based on the soil water potential in different soil layers during crop growth, and proved that these parameters were reliable. Therefore, the inverse modeling techniques play a very important role in model calibration. With the development and application of new optimization algorithms and wireless communication technologies for sensors date transfer, more attention should be paid to use inverse methods to infer model parameters for the simulations of the SPAC syst em.

3.2. Exploration of compensatory water upatke

Compensatory water uptake, which means plants may respond to non-uniform stress conditions by increasing water uptake from sections of the root zone with more favorable conditions, is a potentially important aspect in irrigation and drainage practices that impose non-uniform water stress in the root zone [43,60]. Stikic, R. et al, [61] and Leib, B.G. et al, [62] found that wild plants can overcome water uptake deficits due to water stress through compensatory water uptake mechanisms. Although Lai, C.T. and Katul, G. [34] and Li, K.Y. [35] described the effect of water stress on root water uptake by compensatory water uptake mechanisms, more work in this area is still required [14]. Specifically, Lai, C. T. and Katul, G. [34] assumed a linear function of root density distribution, which could not accurately represent non-uniform root distribution. Li, K.Y. et al, [35] simulated the root water uptake capacity of cereal crops in different soil layers; however, because the root extinction coefficient in the root exponential distribution function varies with different root growth stages and knowledge of root architecture is limited, the model could not be practically applied. Yadav, B.K.

et al, [14] proposed an agricultural hydrologic model to simulate root water uptake under non-uniform root distribution conditions in different soil layers by compensatory root water mechanisms, and the simulation results showed that the water uptake rate in dry areas could be supplemented by deeper sections of the root zone with more available water. Javaux, M. et al, [63] point out that the water uptake compensation function is one of four variables that can affect the spatio-temporal dynamics of root water uptake and that modifying the sink term, $S(z,t)$, is essential for the development of macroscopic models. In-depth research on root water uptake compensatory mechanisms could help to optimize irrigation management in arid and semi-arid regions and can be used to simulate plant root solute uptake when combined with soil solute transportation functions.

4. Mechanistic research of root distribution models

Main text Deery, D.M. et al, [37,38] reported that root water uptake could be influenced by internal effective factors, such as the osmotic potential of root xylem solutions, root length distribution, root respiration, root moisture permeability and resistance, whereas external factors, such as soil available water, soil temperature, soil resistance, soil aeration, and atmospheric conditions, are non-influential. This is because root growth and root water uptake are closely connected with each other: not only is root growth strongly affected by water uptake, but the growth of root systems can increase the contact surface between roots and water, increase root water uptake from deeper soil layers, and shorten the distance between the root epidermis and water [64,65]. Future research on root water uptake mechanisms should focus on overcoming the shortcomings of plant root water uptake models, especially plant root structure systems and plant root growth processes, such as root density distribution, root stretching patterns, and the interaction between root growth and environmental factors. Moreover, almost all root water uptake models assume a constant root water uptake rate within different soil layers that varies with different growth stages, although this assumption has been proven false [66,67]. Future research should focus on the impacts of root systems on soil porosity and soil water transportation and how to characterize the spatial differences in root water uptake should.

5. Conclusions

This paper gave an overview of macroscopic modeling approaches for root water uptake, discussed the challenge of accurate estimating plant root water uptake, and presented that future improvement to root water uptake simulation models need improve observations of root and plant functioning, developing the inverse simulation method, considering compensate water uptake process, along with integrated modeling schemes. Modeling of root water uptake by plant is a difficult task, Gardner, W.R. [68] once said that "… because of the complexity of the root-soil flow system and our present ignorance about how root systems in the soil really operate, it is not possible to prove using extant data that this moving sink model of uptake is correct…". After incorporation of more dynamic root functions during the past decades, more and more agro-hydrological models could provide decision support information to stakeholders and end-users with policies and practices for sustainable irrigation now, and can be positive expected in the next period of time.

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