

# Progress of Water and Salt Transport in Saline Lands and Hydrus Model: A Review

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**Abstract:** The key to saline land management and improvement is to understand the soil water and salt transport laws and to carry out scientific regulation. In order to propose a scientific and reasonable model for soil salinity control, it is necessary to study the principle of water and salt transport in soil, the transport law with time and space, which is also the theoretical basis for understanding the occurrence and evolution of saline soils in the region and preventing secondary salinization of soil. In recent years, the study of water-salt transport and its simulation model has become one of the research hotspots in the field of agriculture, especially in the northwest of China. This paper systematically summarizes the research progress and applications of water-salt transport characteristics, models, influencing factors and the popular software Hydrus at home and abroad, and summarizes the advantages and disadvantages of the models and the influencing factors of water-salt transport, and introduces the research results of many scholars in the field of water-salt transport, and gives an outlook on the future research and development trend of water-salt transport.

**Keywords:** Water and salt transport, Influencing factors, Model, Hydrus.

## 1. Introduction

Saline lands in China are widely distributed and huge in area, with a total area of about 99.13 million hm<sup>2</sup>, accounting for about one-tenth of the total saline land area in the world. It is important to understand the principle of water and salt transport in saline land, to master the law of water and salt transport, to observe the dynamic changes of water and salt, and to simulate and predict the effects of different influencing factors on water and salt distribution in saline land for the guidance of irrigation, management and prediction of saline land [1]. Since the 19th century, people began to pay attention to and study water and salt transport, and nowadays, the research on water and salt transport in saline land is still in progress, and with the help of many The water-salt transport process is simulated with the help of numerous software to explore the methods to accurately simulate the water-salt transport process.

## 2. Research Progress

### 2.1. Research on water and salt transport characteristics

As early as 1856, Darcy, a French engineer, conducted infiltration tests using a saturated sand layer and derived Darcy's law [2] applicable to laminar saturated soil water flow, which clarified the mechanism of movement of saturated water in soil with the following equation:

$$v = K_s \frac{\Delta H}{L} \quad (1)$$

Where,  $v$  is the infiltration flow rate;  $K_s$  is the infiltration coefficient;  $\Delta H$  is the total head difference;  $L$  is the linear length of the seepage path.

The concept of energy was introduced to soil water by Buckingham [3] in 1907. In 1931, Richards [4] first introduced Darcy's law to unsaturated soil water flow and

described it using the partial differential equation, whose expression is shown below:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K_x(\theta) \frac{\partial \varphi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y(\theta) \frac{\partial \varphi}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K_z(\theta) \frac{\partial \varphi}{\partial z} \right] \quad (2)$$

where  $x, y, z$  are the three directions in space;  $\theta$  is the water content;  $K(\theta)$  is the unsaturated hydraulic conductivity;  $\varphi$  is the total water potential, cm;  $t$  is time.

In 1944, Bodman [5] used soil column tests to investigate the distribution of water content during downward infiltration of water, dividing the soil column in the wet zone into saturated, transitional, conductive and moist zones. In 1956, Bruse [6] proposed the use of the horizontal soil column method to determine the soil water diffusivity. In the 1960s, foreign scholars began to use the homeopathic profile method to determine unsaturated soil hydraulic conductivity. Water-salt transport refers to the movement of water and dissolved salts, which are carried along with water in the soil medium, with the characteristic of "salt following water" [7].

In 1855, Fick [8] proposed Fick's law, describing the law of diffusion of solute molecules in free water, which laid the foundation for solute transport in soil water and is now a fundamental theory in describing the dynamics of soil water-salt transport [9]. In 1905, Slichter pointed out that the rates of ionic movement of different types of solutes in soil are different; in 1941, Martin and In 1952, Lapidus [10] and Amundson proposed a model similar to the convection-dispersion equation, and this led to the study of solute transport theory; in 1954, Scheklegger [11] built on the previous studies In 1961 and 1962, Nielsen and Blaggar [12-16] showed the simultaneous existence of dispersion, convection and diffusion in the solute transport process through experiments and models, and proposed the CED equation, as follows shown:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial x} \left[ D_{ij} \frac{\partial c}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D_{ij} \frac{\partial c}{\partial y} \right] + \frac{\partial}{\partial z} \left[ D_{ij} \frac{\partial c}{\partial z} \right] - \frac{\partial(q_i \theta)}{\partial z} \quad (3)$$

where:  $c$  is the solute concentration;  $q_i$  is the water flow;  $D_{ij}$  is the dispersion coefficient;

In 1987, Grove and Stollenwerk carried out a study on the physicochemical processes of groundwater salt transport and made a systematic summary, marking progress in describing solute transport in terms of physical and chemical processes [17-20].

In 1983, Zhang Weixuan [9] applied potential energy to study soil water and solute transport and proposed a model for predicting soil water and salt dynamics. In 1986, Yuanchun Shi [21,22] proposed the "theory of water-salt movement in the semi-humid monsoon climate zone", and established a prediction model to monitor water-salt movement and developed PWS1.0 software. In 1987, Zhang Xuxian [23,24] proposed a method for calculating hydrodynamic dispersion coefficients and described the derivation process of the finite analytical method in a two-dimensional scenario. In 1988, Huang Kangle [25,26] proposed the alternating direction characteristic finite unit method (ADCG for short) for solving two-dimensional saturated-unsaturated solute transport problems, and found that the ADCG method was significantly superior after verification by example. In 1996, Shi Binhai [27] established a soil sorption model and a soil immobile water body model, and found that soil sorption and immobile water body have a large influence on solute transport, which should not be neglected in the quantitative study of soil water-salt movement. Guo Weidong [28] and Wang Bingguo [29] established a two-dimensional unsaturated soil water and solute transport model for numerical simulation to investigate the infiltration pattern of soil water and water-salt transport characteristics. Li Baoguo [30] summarized the process and research results of 30 years of soil water and salt transport research at China Agricultural University and summarized a large amount of literature, which is of good reference value. Yang Yujian [31] summarised the limitations of the numerical solution of the traditional convective dispersion equation and proposed the integration of GIS with other water-salt transport models for use. Crosstalk [32] established a two-dimensional mathematical model to simulate soil water movement under drip irrigation with film, and the results showed that the model is practical and objective, and its numerical solution can be used to simulate soil water movement under drip irrigation with film. By establishing a two-dimensional unsaturated soil water infiltration model, Li Hongwei [33] found that the soil water content increased with the increase of rain intensity, and the soil water infiltration coefficient and the change of soil water content decreased when the rain intensity was small and comparable, and the research results were applied to the prevention and control of landslides on soil slopes. Yang Hongmei [34] simulated and studied the water-salt transport pattern of salinized soil under drip irrigation conditions and found that soil salts were transported in the vertical direction and influenced by transpiration and evaporation. Chen Naijia [35] used freeze-thaw tests to find that freeze-thaw caused water-salt migration

inside the soil from the bottom up, which increased the salt content of the soil surface layer and tended to salinization. Fan Liqin [36] quantitatively described the relationship between the amount of drench water and the salinity of the soil profile of salinized alkaline soils under FGD gypsum application by indoor soil column tests. Zhou Liying [37] used indoor soil column simulation tests to study the effects of different sand dosing amounts on soil infiltration characteristics and water-salt transport. The results of the study provide theoretical support for sand dosing in topsoil to improve heavily saline soils in the river-loop irrigation area.

The basic theory of soil water and solute movement is the basis for research on soil water and solute transport, and much of the experimental work is based on this theory.

## 2.2. Soil water-salt transport model study

The study of soil water-salt transport can be achieved by two methods: field or indoor tests and model simulations. However, long-term observation of soil water-salt movement in field layout tests is difficult and time-consuming due to many uncontrollable factors [38], while indoor tests are tedious and require demanding and difficult control of various influencing factors. Currently, scholars at home and abroad have established water and salt transport models based on water and salt transport theories and environmental conditions to simulate the water and salt transport processes in soils, so as to clarify the influencing factors and dynamic changes of soil water and salt transport in different contexts, and finally achieve prediction functions.

In the 1960s, water-salt transport studies relied only on the calculation of simple material equilibria, but nowadays it is possible to quantitatively characterise water-salt transport processes using computers by building mathematical models. With the continuous improvement of water and salt transport models and the rapid development of computer application technology, as well as the application of GIS and remote sensing, water and salt transport models are constantly being expanded and improved [39]. At present, soil water and salt transport models at home and abroad can be divided into water and salt balance models, physical models and system models [40]. The advantages and disadvantages of different water-salt transport models are shown in Table 1.

For different actual field conditions and research purposes, suitable models need to be selected, different types of experimental data need to be obtained, and model parameters need to be adjusted in order to improve the simulation accuracy of the models, better reflect the field conditions, and obtain simulation results that meet the needs.

## 2.3. Study of factors influencing soil water and salt transport

There are many factors influencing soil water and salt transport, and the transport process is often governed by multiple influencing factors. The influencing factors of soil water and salt transport are shown in Table 2. To understand the main influencing factors of soil water and salt transport in the study area and to master the law of water and salt transport, we can make reasonable irrigation strategy to prevent the occurrence of soil salinization.

**Table 1.** Advantages and disadvantages of different water and salt transport models[9, 41-43]

Category	Type	Principle	Model	Advantage	Disadvantage
Water-salt balance model	Macroscopic hydrological salinization	Regional and watershed water and salt balance	SWAT, SahyMod, SaltMod	Quantitative understanding of complex, large-scale soil salt transport	Requires a large amount of data support, only applies to a specific area under certain conditions, without continuity
	Certainty	Conservation of mass, momentum, and mass balance	CDE, DrainMod-S	Parameters, variables, and boundary conditions are clearly defined	Physico-chemical effects not considered
Physical model	Randomness	Convective dispersion and random parameters	STM, Hydrus, SWAP, GSWAP	Flexible handling of boundary conditions for more efficient models	Requires a large amount of data support, and the simulation range and model accuracy need to be improved
	Transfer function	Black box model, without considering the transport mechanism	TFM	Randomly treat the process of water and salt transport without delving into its characteristics and processes, while considering soil spatial variability	Not generalizable, TFM models between different regions cannot be mutually generalized
System Model	Artificial Neural Networks	Unidirectional propagation of multilayer feedforward networks	BP Neural Network	Simple structure, good non-linear mapping capability, good prediction and persistence	Model calibration and validation requires a large number of samples and data support to ensure that deviations are within allowable limits

**Table 2.** Factors influencing soil water and salt transport

Classification	Impact Factor	Mode of influence
Natural Factors	Groundwater	The shallower the groundwater depth, the stronger the diving evaporation, the more likely it is to lead to soil salinization.
	Soil texture	The more small particle sizes in the mechanical composition of the soil, the more viscous the texture, the worse the drainage, and the more susceptible to salinization.
	Freeze-thaw cycle	The migration of water salts to the freezing peak leads to redistribution of salts within the soil.
	Precipitation and evaporation	When evaporation is greater than precipitation, when the climate is dry, or when precipitation is unevenly distributed during the year, and when soil leaching is weak, soil salinization is prone to occur.
	Terrain	Flat topography, shallow water table depth, and poor groundwater drainage areas are prone to soil salinization.
Human Factors	Irrigation and drainage measures	Irrational irrigation measures such as diffuse irrigation and brackish water irrigation make the groundwater level elevated, and when evaporation is also stronger, soil salinization is prone to occur.
	Agricultural farming Modified materials	Incorrect tillage practices damage the soil structure and change the hydraulic properties of the soil, which can easily cause the phenomenon of secondary soil salinization. Use inorganic materials to replace sodium ions or use organic materials to improve soil structure and increase the permeability of the soil.

There are many research results on water and salt transport patterns under single influencing factors, but few scholars have explored the water and salt transport patterns under the combined effect of various influencing factors.

#### 2.4. Research and application of Hydrus model

Hydrus model is very suitable as one of the software for simulating water and salt transport process in the field due to its advantages of flexible boundary conditions and easy operation. Combining with some indoor experiments to obtain some parameters for rate model parameters and verify model accuracy not only reduces the difficulty of experiments, but also improves the accuracy and reliability of model simulation.

Hydrus is a physical model for simulating water and salt transport. It was developed by the National Center for Saline Soil Improvement (NCSSI) to simulate soil water movement, solute transport, heat transfer, and root uptake in specific situations, and is a finite element Windows computer simulation software. In recent years, after continuous improvement and development, Hydrus has gained more applications and higher recognition in simulating soil water and salt transport, pollutant migration and other agricultural and environmental problems, and it is more effective in simulating the spatial and temporal changes of water and solute, and it can also be combined with groundwater and surface water and other related models. The Worm model has been improved by the American Center for Saline Soil Improvement to form Hydrus-1D software, which can be used to simulate saturated and unsaturated soil hydrothermal salt transport and contains modules for water, solute, thermal movement and root uptake.

##### (1) Soil water and solute movement model

Assuming that each soil layer is homogeneous and all homogeneous, the influence of meteorological factors is not considered, and the water infiltration does not affect the soil structure, the Richards equation is used to solve the water flow simulation process [29].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial t} \left[ K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K(h) \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} \right] - \frac{\partial K(h)}{\partial z} \quad (4)$$

Where:  $\theta$  is the soil volumetric water content,  $\text{cm}^3 \cdot \text{cm}^{-3}$ ;  $h$  is the soil negative pressure head, cm;  $K(h)$  is the soil unsaturated water content,  $\text{cm} \cdot \text{h}^{-1}$ ;  $t$  is the time, h;  $x, y, z$  are spatial coordinates.

Solute transport in soil is the result of both convective and dispersive effects, and the convective dispersion equation is used in the Hydrus model to solve the solute transport problem [29], and the basic equation is as follows.

$$\frac{\partial (qc)}{\partial t} = \frac{\partial}{\partial x} \left( D_{ij} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{ij} \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{ij} \frac{\partial c}{\partial z} \right) - \frac{\partial (q, \theta)}{\partial z} \quad (5)$$

Where:  $c$  is the solute mass salt content, g/100g;  $q$  is the water circulation, cm/h;  $D_{ij}$  is the diffusivity,  $\text{cm}^2/\text{h}$ ;  $\varepsilon_i$  is the evaporation intensity, cm/h;  $X, Y, Z$  are the maximum distance in the radial and vertical directions of the simulated calculation area, cm, respectively.

##### (2) Hydrus model hydraulic parameters

Obtaining soil moisture parameters is an essential part of

water and salt transport simulation using Hydrus. The scientific and reasonable parameters are directly related to the accuracy and reliability of the model, so it is important to obtain parameters with high accuracy as much as possible for the simulation results. Soil water movement parameters are  $\theta$  soil water content ( $\text{cm}^3/\text{cm}^3$ ),  $\theta_r$  residual water content ( $\text{cm}^3/\text{cm}^3$ ),  $\theta_s$  saturated water content ( $\text{cm}^3/\text{cm}^3$ ),  $\alpha, n, m, l, \beta$  as relevant empirical parameters,  $S_e$  effective saturation,  $K(\theta)$  unsaturated soil hydraulic conductivity,  $D(\theta)$  unsaturated soil water diffusivity, etc. According to different experimental purposes, it is necessary to obtain the Depending on the purpose of the test, it is necessary to obtain specific values of some or all of these parameters. The acquisition methods are mainly obtained through experiments and through simulations. The experimental acquisition is difficult to operate, has a long time span, and has many uncontrollable factors, so the approach of combining experiments with the software Rosetta prediction module is adopted to obtain the experimental parameters.

According to a large number of experimental verifications by scholars, the medium van Genuchten-Mualem hydraulic model simulation is the best, and its calculation equation is as follows:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^n\right)^m} \quad (6)$$

$$K(h) = K_s \frac{\{1 - (\alpha h)^{n-1} [1 + (\alpha h)^n]^{-m}\}^2}{\left(1 + (\alpha h)^n\right)^{m/2}} \quad (7)$$

where  $\theta$  is the soil volumetric water content,  $\text{cm}^3 \cdot \text{cm}^{-3}$ ;  $h$  is the soil negative pressure head, cm;  $\theta_r$  is the residual water content,  $\text{cm}^3 \cdot \text{cm}^{-3}$ ;  $\theta_s$  is the saturated water content,  $\text{cm}^3 \cdot \text{cm}^{-3}$ ;  $\alpha$  is the shape parameter,  $n$  is the soil characteristic curve parameter, and  $m$  is the empirical parameter;  $K(h)$  is the unsaturated soil hydraulic conductivity, cm/min;  $K_s$  is the saturated hydraulic conductivity, cm/min.

##### (3) Model accuracy validation

Before conducting simulations, it is necessary to facilitate statistical tests of the measured and simulated data in order to test the accuracy and reliability of the model simulation, using the root mean square error (RMSE) and the coefficient of determination ( $R^2$ ) to test the consistency of the measured and simulated data [44]:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2} \quad (8)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (S_i - \bar{O})^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (9)$$

Where,  $S_i$  is the measured value;  $O_i$  is the simulated value;  $n$  is the number of samples;  $\bar{O}$  is the average of the measured values.

##### (4) Model Application

Hydrus model has been widely used in China since its introduction in 2000. Hydrus model has Hydrus-1D, Hydrus-2D and Hydrus-3D models, which can better simulate the distribution and trends of water and salt in soil with time through a total of three dimensions of 1D, 2D and 3D

according to different research purposes [45], and output graphs and data files [46]. Hydrus model can flexibly handle various types of water flow and solute boundaries according to the demand, mesh the simulation area, and then take the finite element method to solve, the software simulation is less time consuming, less costly, and easier to operate [47], and it has become the most widely used model for quantitative description of water-salt transport [48-52].

The Hydrus model was mainly applied to agricultural irrigation [53], salt leaching [54], elemental transport [55], pollutant transport [56], and model coupling [57]. Ji Baoliang [58] applied Hydrus software to analyze and compare the movement of soil water under different soil conditions, and the simulated values fit well with the measured values; Zhang Hua et al [59] used the Hydrus numerical simulation method to simulate and validate the model for 3 g/L sea ice water irrigation, and the validation results showed that the model has good reliability; Gao Yue [60] used the Hydrus model to simulate He Kangkang [51] used the Hydrus-1D model to simulate the changes of water and salt fluxes within the soil over a long time series of 6 years, which provided theoretical guidance for the water saving potential and sustainability of brackish water use in the low plains of North China; Yu Yang [61] combined GMS Dou Xu [62] used the Hydrus-2D model to simulate soil water-salt dynamics in the 0-100 cm range, and used the measured soil water-salt content values in 2020 and 2021 to rate and validate the Hydrus-2D model. Tian Huiwen [63] used Hydrus-2D to develop a two-dimensional model of soil water, salt, and heat transport under drip irrigation and semi-membrane cover conditions, and considered kinetic sorption during salt transport. yang Ting [64] used the Hydrus-1D model to inverse perform water and solute transport parameters from soil column test data, and used the Hydrus-2D model simulated water and salt transport under actual field practices and constant frequency irrigation conditions under the same field conditions. Lu Peirong [65] simulated winter wheat growth in SPD application fields by using water levels predicted by Hydrus.

### 3. Summary and Outlook

In recent years, as people pay more attention to food security, the exploration of water and salt transport in saline lands has gradually become a focus of attention. Different study areas have different soil and water conditions, and water and salt transport patterns vary under different soil and water conditions and anthropogenic influences. When the study area and soil and water conditions change, the selection of models should be compared and selected according to the actual situation. In view of this actual situation, the exploration of theories and models of water and salt transport is still a hot research topic for saline land improvement. On the premise of the review of current research results and model applications, it is believed that the later research can be carried out in the following aspects:

(1). Models have their own advantages and disadvantages, but different models can be used in combination with each other, so as to improve the simulation efficiency and simulation accuracy, but also to cope with a larger range and more complex field conditions.

(2). Water and salt transport is a multi-way, and its complex process, not only by a single influence factors, irrigation quota, soil mechanical composition, the degree of salinization, soil combination, meteorological conditions, water table

depth, etc. often combined influence water and salt transport process, to filter out the influence factors as far as possible, to explore the influence of factors coupled with the water and salt transport process.

(3). Hydrus model has a root uptake module, which can be combined with crop growth, so remote sensing can be used in combination with hydrus model to explore the water and salt transport characteristics of long time series. At the same time, the research on the coupling of crop growth and water and salt transport processes should be strengthened to improve saline lands while saving resources and increasing yields.

(4). The scale of water and salt transport research should be enlarged to link the transport process in the field with atmospheric and hydrological processes to provide a basis for scientific water allocation and prevention of salinization, while improving the prediction accuracy of the model.

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