# A review of soil water resource research and application in China

**JUN XIA[1,2], XINGYAO PAN[1,3], XIYUN CHEN[1] & YU LIU[1,3]**

1 *Key Laboratory of Water Cycle & Related Surface Process, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China*
jxia_mail@263.net

2 *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China*

3 *Graduate School of the Chinese Academy of Sciences, Beijing 100039, China*

**Abstract** With the rapid development of the economy, the conflict between agriculture and other water users becomes serious, especially in the water shortage regions. Soil water is the connection of surface water and groundwater. It is of great significance in the formation, transformation and consumption of water resources, and has a close relationship with agriculture, hydrology and the environment. Thus, research on soil water resources have drawn more and more attention and made great progress. This article reviews the research on the concepts, and characteristics of the soil water resource, as well as the relevant theories and methodologies for soil water resource quantification, through which the importance of soil water resource research is illustrated. It suggests that soil water should be a significant component of integrated water resources management in China. It also indicates that, currently, soil water resource study focuses on interdisciplinary characteristics, estimation of soil water resource heterogeneity, and the development of a soil water prediction model. In future, it is essential to develop a distributed land surface model based on remote sensing and GIS, on a large scale.

**Key words** China; research review; soil water resource

## INTRODUCTION

Water resources, as a kind of natural resource, are one of the most precious on Earth. It is essential for human survival and development. However, the contradiction between limited water resources and increasing demand caused by rapid economic development and population growth, has resulted in water crises in many countries and regions all over the world since the 20th century. How to satisfy the water requirement under the water shortage situation is a key point for sustainable water usage. At present, water resource assessment only included visible, directly useable and renewable surface and groundwater (Shiklomanov, 2000). Accordingly, the total volume of soil water resource on the Earth is 16 500 × $10^9$ $m^3$, 7.8 times the surface water (USSR, 1978). Though soil water has been used by land vegetation (including crops) and has been given great attention by agronomists and farmers, common ideas on the issues as to whether soil water belongs to the category of water resource and how to quantify it, have not been well documented.

As the biggest developing country, China has severe problems relating to water resource availability and utilization (Xia *et al*., 2001, 2004, 2005). In China, the annual averaged precipitation is 6188.9 × $10^9$ $m^3$ (648 mm), from which surface runoff accounts for 2711.5 × $10^9$ $m^3$ (213 mm), underground water 828.8 × $10^9$ $m^3$ (87 mm) and evapotranspiration 3326.6 × $10^9$ $m^3$ (348 mm) (Liu, 2001). A large proportion is lost through evapotranspiration from the land surface, which accounts for 56% of the total precipitation, indicating that soil water resource development and utilization is one of the important countermeasures to ensure the sustainability of agriculture, and to resolve water resources scarcity problems in China.

## CONCEPTION AND ITS FORMATION

The importance of soil water was recognized at the beginning of the 19th century. At the very beginning, research mostly focused on the morphology of soil water. In the 1960s, the concept of Soil–Plant–Atmosphere Continuum (SPAC) was proposed (Philip, 1966). SPAC reveals the dynamic relationship of water and energy transmission and transformation within the integrated continuum of soil, plant and atmosphere. In recent years, much effort had been made in the quantification of soil water movement and great achievements have been made. In the meantime, extensive progress in quantitative simulation was made with the use of computer techniques in soil water research.

The concept of soil water resource was introduced by M. Nputotulu in 1974 (Liu, 1988; Zhang, 1999; Wang, 2006). He suggested that soil water resource was the amount of water difference between precipitation and surface runoff, which regarded soil humidity as the soil water resource. Due to extensiveness, diversity and complexity, there is still no clear definition of soil water resource accepted globally (Liu, 1988; Wang, 2006).

The connotation and application of soil water resource are much wider in China than elsewhere due to the more severe water resource problem caused by the huge population. Shi *et al.* (1983) gave the term: soil water reservoir, and considered soil water as a resource, which is different from groundwater. In 1988, Liu (1988) gave the formula to estimate the annual soil water and defined the variation of soil water storage in unsaturated soil layers as soil water resource. Shen *et al.* (1992) defined soil water resource as the effective recharge capacity of soil under field conditions, which equals to ET minus irrigation recharge. Generally, the soil water resource can be expressed as the regional water suspended in the aeration zone. The soil water resource would be directly or indirectly used for producing a living for mankind, and the volume of water used for maintaining and recovering the eco-environment (Meng & Xia, 2004; Wang, 2006).

In 1995, Flakenmark (1995) proposed "Green Water" to represent the flows of water vapour in the form of transpiration, interception and evaporation from the soil and vegetation. The "Green Water" concept has attracted much interest in recent years, particularly in arid and semi-arid regions where it dominates the hydrological cycle. Falkenmark (2005) renewed the connotation and meaning of green water and regarded soil water as the core of terrestrial ecosystems. Liu & Li (2006) suggested that soil water resource has the same meaning as green water, which plays an important role in water and food security in China.

## CHARACTERISTICS

The soil water resource has many special characteristics, mainly the following:

(a) Soil water is the connection for surface water, groundwater and atmospheric water. It is of great significance in the formation, transformation and consumption of the water resources. The soil water resource has the same characteristic as other water resources, i.e. circulation, regeneration and regulation.

(b) Soil water is the main source of soil moisture, which maintains crop growth, and ecological cycles. Crops meet most of their water demand by root uptake. All the water should be transferred into soil water before it can be used by crops. The water that the crop needs to grow and develop is taken from the soil by the root system. Other water turns into soil water, and then the soil water is absorbed by the crop. The quantity and quality of soil water will directly influence the growth of the crop. Growing of crops is a key link to maintaining the normal operation of the ecological environment benign cycle.

(c) Due to the remarkable geographic diversity in China, soil water resources vary widely in space and time as the distribution of soil properties, meteorological factors (rainfall distribution and groundwater) and human activities factors (e.g. crop distribution, irrigation pattern, etc.).

(d) The total volume of soil water resource is 16 500 × $10^9$ $m^3$ in the world, and it is 7.8 times the long-term water demand of all rivers in the world. In China, the soil water flux is 4200 × $10^9$ $m^3$, which accounts for 67% of precipitation (Liu, 2001). Generally in semi-arid and semi-humid plain districts, it is higher than this value.

(e) As a porous media, soil has very strong purifying capacity. In turn, soil water has an important function of changing the quality of surface and groundwater by means of circulation.

In conclusion, soil water is not a kind of simple water circulation in the unsaturated soil layer, but is an enormous “soil water reservoir” (Meng & Xia, 2004). The soil water resource has common characteristics with surface water and groundwater resources: (1) regenerating through circulation; (2) regulation by the reserves; (3) objective reality with enormous reserves.

## QUANTIFICATION OF SOIL WATER RESOURCE

Since the concept first appeared in the literature, many researchers have begun studying soil water resource. Moreover, most of the studies carried out to date have mainly concentrated on defining the concept from different points of view, quantitatively calculating the soil water resource. Compared with its scope in foreign countries, the connotation and application of soil water resource in China is much wider than elsewhere due to a more acute Chinese water problem. However, today there is still a lack of theoretical models and quantitative methods or methodologies for the calculation of soil water resource.

In 1988, Liu (1988) analysed and calculated soil water as a kind of resource system. He defined soil water resource as the variation of storage in unsaturated soil layers and calculated as:

$$W = ET + R_g \tag{1}$$

where $W$ is amount of soil water resource (mm); $ET$ is evapotranspiration (mm); $R_g$ is groundwater flow (mm).

Xia (2001) defined soil water resource as the total volume of $ET$ from land surface. He analysed components of the soil water resource with special emphasis on the part that can be easily renewed, developed and available. In addition, he defined two indices: utilization coefficient ($K_t$) and potential utilization coefficient of soil water resource ($K_e$):

$$K_t = E_t / ET \tag{2}$$

$$K_e = (E_s + E_{tk}) / ET \tag{3}$$

where $E_t$ is plant transpiration (mm); $E_s$ is soil evaporation (mm); $E_{tk}$ is ineffective evaporation (mm).

Based on the soil water balance theory, Meng & Xia (2004) regarded the soil as the soil reservoir, and studied the water storage of soil. They proposed that the soil water resource should be the volume that supported land water transpiration and transformation process, which was continuously imposed and consumed in the plant root zones, and different from the water storing ability of soil, water storage of soil, and available water of soil:

$$W = ET + W_{sr} \tag{4}$$

where $W_{sr}$ is a variable of water storage in soil (mm). According to the method, they discussed soil water storage in CangZhou District in North China Plain, and analysed seasonality of the soil water resource in order to utilize the soil water more efficiently.

Yang (2004) developed models to estimate soil water resource based on the eco-environment and agricultural utilization. Different models were used for plain and hill areas, respectively.

The model for plain areas is:

$$W = P - PE - R_s - P_g + E_g + W_a \tag{5}$$

where $P$ is precipitation (mm); $PE$ is plant diversion and evaporation during rainfall (mm); $R_s$ is surface runoff (mm); $P_g$ is groundwater recharge from precipitation (mm); $E_g$ soil water replenishment from groundwater, which is phreatic evaporation (mm); $W_a$ soil water replenishment from atmospheric vapour condensates (mm).

The model for mountain areas is:

$$W = P - PE - R_s - P_g - R_g - Q_m + W_a \tag{6}$$

where $R_g$ is subsurface-flow (mm); $Q_m$ is net consumption of groundwater manually (mm).

Furthermore, the models were used for the Hebei plain, and soil water resource in this area was estimated. Results showed that soil water resource accounts for 73.7% of rainfall, equalling 3960.2 $m^3$ $ha^{-1}$, which suggests that the soil water resource is very important in arid or semi-arid areas.

In view of the disadvantages of traditional water balance methods to assess soil water resource, Wang (2005) established HYDRUS-1D, a dynamic soil water model based on vegetation coverage conditions (Simunek *et al*., 1998). Then, the model was used to calculate recharge, drainage and consumption of soil water in a typical experiment area of Yanqi basin in Xinjiang province, where groundwater occurs at less than 2 m depth. Results show that groundwater resource and soil water resource transformation is quite frequent, and because the soil reservoir action is rather weak it results in the leakage of irrigation water in such a region. This suggests that the assessment of soil water resource should be under the integration of soil water and phreatic water in areas with shallow groundwater.

Wang (2006) defined soil water resource as the regional suspended water, which can be directly utilized for production and living by mankind. He also established the index system of soil water resource assessment, which includes four indexes: the amount of water which can be absorbed by plants, the maximum available water, the amount of water which can be used for developing the national economy, and the amount of water for recovering and maintaining the eco-environment. The methods for calculating these indexes were also proposed. The method offers much room for further studies on quantification of soil water resource.

## DISCUSSION AND PERSPECTIVES

Much work has been done on soil water resource assessment and estimation. However, there are still many ambiguous and unknown issues. The major topics for further study may exist in the following areas:

(a) Studies on the basic concept and theory of soil water resource should be strengthened. In order to establish a uniform and acceptable principle, the concept of soil water resource, including its connotation and extension, should be further studied. Furthermore, the temporal and spatial scales for the study of soil water resource should be defined as clearly as possible. The study of water quality is on the threshold of soil water resource research. Therefore, the combining of water quality and quantity, as of soil water resource, need to be further studied.

(b) Enforce the multidisciplinary research on soil water resource. The future research of soil water resource should contain the following aspects: theory and application research, water resource problem and sustainable development of a region, river basin water cycle, micro research of eco-hydrology and water consumption of vegetation, water resource and socio-economic and management science. In addition, we should use a distributed hydrological model, Remote Sensing (RS) and Geographic Information System (GIS) methods as the basic technique based on water circulation theory. Therefore, the combination of different subjects is urgent.

(c) New approach application. The biggest obstacle for soil water resource research is the difficulty of soil water data collection and processing. The research on soil water resource must break through the traditional methods of data collection, and make good use of new techniques; for instance, effective combination of Earth surface observation and RS, application of GIS for numerical analysis and simulation. GIS has great advantages in achieving the management, analysis, modelling and display of geographic data to solve complex hydrological problems. Integration of the modelling methods for soil water resource and GIS will be a breakthrough in soil water resource research.

(d) Extend the research field. Soil water resource should be more explicitly considered in water resource management and planning. It should include: (1) The measurement and management of soil water use by land based activity; (2) understanding and predicting the links among soil water, surface water and groundwater resource as well as the spatial and temporal responses of catchments; (3) managing soil water resource in the scope of water resource management legislation.

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