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Necessity and feasibility for an ET-based modern water resources management strategy: A case study of soil water resources in the Yellow River Basin

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The necessity and feasibility of an ET-based modern water resources management was analyzed to improve assessment of critical water resources scarcity in the region/basin. This analysis was based on the whole water cycle process and its analysis object is evapotranspiration (ET), a main consumption component in the water resources dynamic transformation process. A case study was undertaken by selecting soil water resources in the Yellow River Basin and employing the WEP-L distributed hydrological model with physics mechanisms. This paper discusses the amount and consumption efficiency of soil-water resources according to completely simulated results of water cycle elements throughout the basin. Results indicate that it is important for the ET-based modern water resources management strategy to alleviate water resources scarcity because it may not only avoid unused water wasting but also improve water use efficiency. Therefore, an ET-based modern water resources management scheme is a good complement to the traditional water resources demand management system.

ET-based management, evapotranspiration, water resources management, soil-water resources, Yellow River Basin

1 Introduction

The basin water resources management (BWRM) is a coordinated project focused on the relationship between water supply and demand, which involves a united regulation and coordinated management process to maximize the benefits of available water resources, to improve the relationship between humans and water, and to develop economic systems and ecosystems. However, a water resources management system stresses different content depending on supply requirements, economic development and eco-environment protection policies in different social stages. Before the 1960s, the BWRM mainly focused on the management of water supply. It emphasized the development of water sources, to allocate water resources based on the principle that “water demands decide water supplies”. Following this period, there was a rapid increase in economic development and also a serious shortage of water resources. In addition, there has been a growing awareness that increasing water demands cannot be resolved by solely finding more water sources. Water conservation needs to go hand in hand with the development of new water sources. Thus, the BWRM system highlights the importance of managing the demand rather than the supply. Unfortunately, a lack of imperative requirements and corresponding technological supporting methods has led to the situation that water resources demand management utilizes simple

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linkages in the water cycle process, and falls short of investigation into the essence of water demand——water consumption. As a result, in-depth studies are needed to understand water demands, and especially water consumption in the entire cycle process because water is consumed in every step of the water cycle process, including the "withdrawal-deliver-use(consume)-drainage" process in the entire region/basin, and dissipated water, through evapotranspiration, accounts for high water losses, which leaves only a small portion of water in production. Consequently, there should be in-depth studies to apply the ET-based modern water resources management strategy throughout the water cycle process. The new management mode will be needed to improve the efficiency of water resources utilization, and to reduce the serious water scarcity problem. It also will not only improve the traditional management of water resources, but also become a necessary approach for the future.

2 The need for an ET-based modern water resources management mode

2.1 The role of evapotranspiration (ET) in the water and energy cycles process

Evapotranspiration (ET) is a general term that refers to evaporation and transpiration, including vegetation interception evaporation and vegetation transpiration, soil evaporation, and water surface evaporation. These processes incorporate physical, chemical, and biological reactions. ET is involved in the water, energy, and material cycle processes. On the one hand, ET directly affects rainfall-runoff by changing the quantity and composition of water in different aquifer sub-systems, thereby further affecting the precipitation re-distribution on land surfaces. On the other hand, ET impacts on the water conditions of regional ecological and geographical environments by affecting the allocation ratio of the net radiation arriving at the land surface. This is mainly apparent in the distribution relationship among soil heat flux, sensible heat flux returning to the atmosphere and latent heat flux into the atmosphere through evaporation. Thus, ET is a major component in the regional water and energy balance, and it not only plays an extremely important role in the water and energy cycle processes, but also works as an important link between the ecological and hydrological processes. Therefore, it is critical that an ET-based modern water resources management mode is used to improve the relationship between water and humans in the region. The role of ET in the water and energy cycle processes is shown in Figure 1. The figure is modified based on the Bonan[1]. That symbols in the figure indicate: In the energy cycle process, Rn, H, λE and G are regional/basin average net radiation, sensible heat flux, latent heat flux and soil heat flux, respectively. In the water cycle process, P, E, R and ΔS are regional/basin multi-annually average precipitation, evapotranspiration, runoff and water storage variations, respectively.

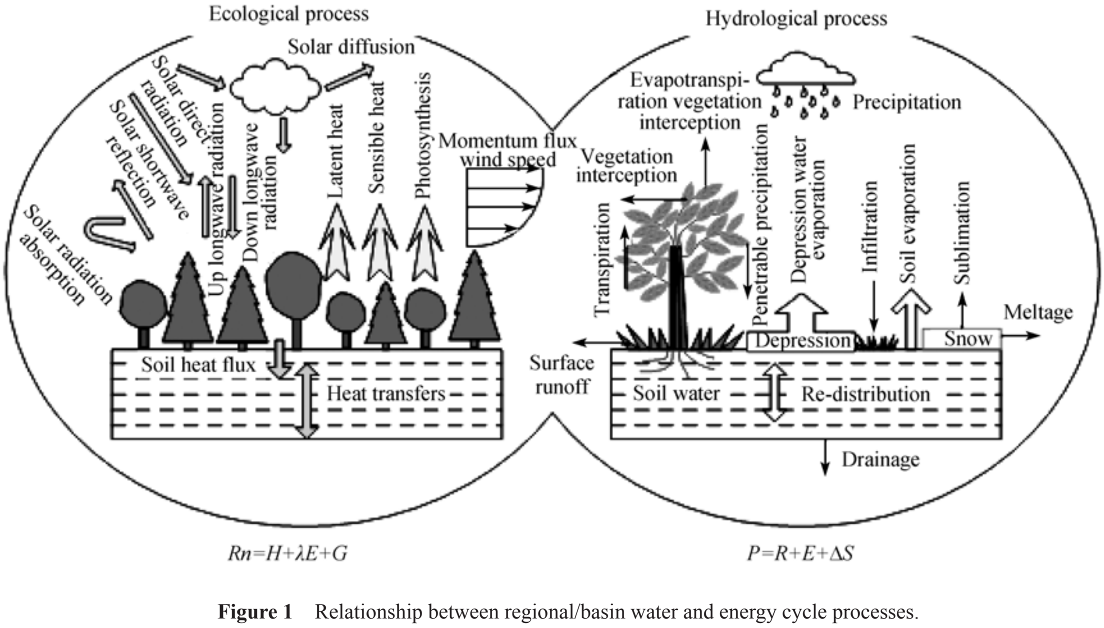

Figure 1 Relationship between regional/basin water and energy cycle processes.

2.2 Research status, function and significance of the ET-based modern water resources management mode

2.2.1 Research status of ET. There are many studies on ET at present, which mostly focus on three aspects: 1) Physiological process of moisture absorption and dissipation by vegetation at a micro-level[2−4]; 2) quantitative study of ET influence of vegetation within living environments in the farmland micro-meteorological area[5−7]; 3) ET reversed by remote sensing and simulated by distributed hydrological models at the macro-regional level[8,9]. Past studies have established the foundation for understanding the evapotranspiration mechanism. Furthermore, studies in the areas of farmland micro-meteorology and macro-regional levels are mainly used for regional/basin water resources demand management.

In recent years, numerous researchers throughout the world have developed water-saving irrigation modes based on vegetation micro-transpiration mechanisms associated with farmland micro-meteorological conditions. Some of these modes include deficit irrigation (also called limited water irrigation), regulated deficit irrigation (RDI), and controlled root divided irrigation[10−13]. In essence, all irrigation modes aim at reducing water supply and improving water use efficiency under the condition of no yield reduction or less reduction through adjusting farmland ET. To a certain extent, these modes also incorporate an ET-based management concept in the management of farmland water resources. However, these approaches only focus on reducing the irrigation water supply without further analysis of the utilization of precipitation. In addition, they also do not reflect the consumption efficiency of precipitation and irrigation water in farmlands. Nevertheless, these studies at the farmland micro-meteorological level make an exploratory contribution to the regulation of ET in production practices, and also build a foundation for further research at the macro-level.

At the macro level (namely basin/regional scale), ET studies are very limited due to the complexities of the natural land surface, and the great temporal and spatial variability at this scale. Only in recent years, with the development of remote sensing (RS) technology and distributed hydrological models, studies on ET reversion[14−18] and its simulation[9,19] have been possible at the regional level. In the 1950s and 1960s, studies focused on ET monitoring and calculation, which incorporated vegetation diversity with changing climatic conditions[20,21]. In the 1980s, the accuracy of ET observations and calculations was improved with near Earth atmospheric observation technology, and a better understanding of energy and matter exchange between land and atmosphere was achieved[22,23]. However, these observational and computational methods were applied only to ground monitoring stations, and not available for larger regions that have great temporal and spatial variability. The main reasons for this problem were limited labor force and material resources, point values instead of area values, and partial results. In the mid-late 20th century, the limitations of point values were overcome[24] with the appearance of “3S” including GIS, RS and ES, especially RS techniques, and ET studies gradually expanded into larger areas. This improvement made it possible for large-scale ET studies, which combined ground observations with remote sensing techniques. Furthermore, the regional ET reversed method with remote sensing techniques may obtain ET values at different times by using the energy balance equation, and by adequately considering the main ET driving factors—solar radiation, obeying the energy balance principle, comprehensive net radiation flux (Rn), soil heat flux (G), and sensible heat flux (H). Multi-band satellite remote-sensing can monitor or reverse some basic ground parameters, which are required by hydrological and weather models. This type of remote-sensing also can prescribe precisely the ET spatial distribution. The features and abilities of ET remote-sensing reversion can provide reliable tools for ET monitoring and computation at the macro-level. Nevertheless, because the ET remote-sensing reversion is mainly based on the energy balance in the energy system, it is difficult to involve the ET function to keep the water quantity balanced in the water cycle system.

Newly developed distributed hydrological models, especially models with physical mechanisms (herein termed distributed physical hydrology model), can reflect external change in climate and underlay factors, and can divide a study area into sub-units according to the underlay conditions. These models also can simulate all the elements in the water cycle process to identify the hydrology response at different spatial scales. Thus, results for the entire water cycle process simulation can be achieved by incorporating all water cycle elements. ET simulation results also can be obtained with aerodynamic and energy balance principles. In the process, the soil-water heat transposition, vegetation leaf area intercept, and leaf pore vapor diffusion, as well as root water absorbing capacity are considered. In addition, with the combination of the model simulation technique and remote-sensing reversion technique, ET simulation accuracy under complex underlay conditions can be improved by using underlay reversed parameters and assimilating related hydrological reversed elements through remote sensing. However, at present, most of the studies in this discipline are isolated investigations, which mainly focus on runoff and conflux processes, and hardly touch on the ET process. Thus ET studies are rare that are based on the region's water and energy cycle systems, and practical applications are absent.

The main reasons for the absence of macro-level ET studies are outlined as follows. ET is as important as any other hydrological factors (i.e., precipitation, runoff) in the water cycle system. However, ET is the most difficult parameter to measure in the "four-water" transfer process, especially at large scales. This is because ET is affected by many factors with meteorological conditions, including sunlight, wind speed, atmospheric humidity, and soil moisture condition, as well as regional underlay conditions. Otherwise, during periods of relatively abundant water resources, and when natural water cycle predominates in the hydrological cycle, the total amount of regional water resources consumption may be obtained with the multi-annual average water balance equation, $ET=P+I-O$ (where ET is evapotranspiration, P is precipitation, I is the input amount of water resources, and O is the output amount of water resources), which describes ET as the main component of consumption. Thus ground-truth ET observations and regulations at the macro-level have been ignored previously in water resources management, owing to the difficulties in obtaining first-hand large-scale ET data and the lack of practical applications. In addition, at present, the ET remote sensing reversion accuracy under complex regional underlay conditions cannot meet practice requirements because of the difficulties in being able to accurately distinguish between sensible heat flux and latent heat flux (evaporation) in the energy cycle process[23], which challenges the application of macro-level ET results based on the energy cycle process. According to the statistics, relative accuracy of ET RS reversion is currently about 85%[25,26].

Based on the studies mentioned above, all proposed methods for ET have established the foundation of understanding ET transferring mechanisms and supported the implementation of an ET-based modern water resources management mode. However, with increasing interference from human activities, the regional/basin water cycle takes on a dual characteristic ("natural-artificial"). Furthermore, the regional/basin ET consumption becomes more complex, including not only ET from the natural water cycle process (i.e. vegetation transpiration, soil and water surface evaporation), but also the artificial water cycle process ("withdrawal-deliver-use-consume-drainage" sub-processes). Hence, in the modern dualistic water cycle process, ET based on the regional water balance does not fully explain or regulate ET consumption in the water cycle process. In addition, with global climate warming, the energy conditions also have changed dramatically[27,28], which will also affect the energy cycle process, and also change effect between it and the water cycle process. This coupled relationship will become more complex in the current climate conditions[29], which makes it difficult to objectively identify the real ET change only based on the energy balance principle. Therefore, faced with today's water resources shortage conditions, improved efficiencies in water resources dynamic transfer processes are difficult to achieve by only stressing development of water sources to increase water inputs into land-water systems and water savings at the end of the usage process. Only if consumption at every step of the water cycle process is concerned, and adequately considered in every sub-process (atmosphere, land surface, soil and underground sub-processes), will the target of "real water-saving" be realized[30]. In the water cycle process, ET plays a decisive role in water use efficiency. Therefore, the ET-based water resources management concept in regional/basin water resources utilization has been accepted by the project of the Global Environment Fund (GEF), the Integrated Planning and Management for Water Resources and the Water Environment in the Haihe River Basin. The ET-based water resources management concept will make great improvements to the regional/basin water resources exploitation and utilization plan.

2.2.2 The function and significance of developing an ET-based modern water resources management mode.

It is necessary and beneficial to complement traditional water resources management with an ET-based modern water resources management mode. This transformation is also inevitable.

Traditional water resources management is based on the balance between supply and demand. That is, under the conditions of a limited water supply, the regional water resources demand would be met as much as possible by the adoption of engineering and non-engineering measurements (e.g. change in crop mixing, readjustment of industrial structure and improvement of management instruments). However, the ET-based modern water resources management is based on the relationship between regional water resources supply and consumption. That is, the approach considers the consumable water amount as the upper limit. This process applies under the premise that the farmers' basic benefits will be guaranteed. In this manner, the efficient utilization of water resources is eventually realized by the adoption of engineering and non-engineering measures. Having the same target of improving water resources utilization efficiency and increasing economic product, the water saving concepts and management objects of the traditional water resources management and the ET-based water resources management are entirely different.

The concept of "water-saving" in the traditional water resources management with balance of supply and demand usually aims at improving water use efficiency with scientifically rational hydraulic engineering and water resources management projects. Its assessment indicators mainly concentrate on the variability of water quantity between water withdrawal from water sources and water use at the end of the process, before and after implementation of different measures (i.e. the amount of water savings). There is no further difference consumption efficiency in the consumption amounts taken by the water cycle process including natural and artificial water cycle processes. That is, there is less concern about whether the consumption is useful or not. Thus the water savings in the traditional water resources management mainly emphasize water quantity, and ignore the practical water consumption efficiency, which is clearly indicated in the delivering sub-process. Thus, although the concept of improving consumption efficiency through ET management is reflected in different irrigation rules (i.e. practical agricultural irrigation processes), its management content and breadth are neither in-depth nor systemic. Furthermore, the concept does not make water resources consumption the foundation of water resources rational allocation.

Based on water resources consumption efficiency, the "water-savings" in the ET-based modern water resources management not only places importance on water-saving amounts at the end of water cycle process, but also further divides the consumption efficiency of water utilization in every sub-process into productive and non-productive consumptions. The difference between productive and non-productive consumptions is based on whether the sub-process takes part in the production. Productive consumption is also called efficient consumption because it highlights the component of ET that participates directly or indirectly in production, otherwise regarded as non-productive consumption. Productive consumption is further categorized into high efficiency and low efficiency consumptions, according to the degree of involvement of ET in the vegetation biomass production process. High efficiency consumption usually refers to the transpiration contributed to the production, while the rest refers to low efficiency consumption (i.e. luxurious transpiration, soil evaporation among plants used to adjust the farm micro-climate). It is generally difficult to readily identify the entire transpiration amount. This problem stems from the fact that luxurious transpiration closely relates to many elements of plant biological characteristics, life surroundings, etc. Thus all transpiration is considered as highly efficient consumption. Low efficiency consumption from soil evaporation changes with the vegetation closing degree. Usually, the higher the vegetation closing degree, the lower the total evaporation efficient consumption. Non-productive consumption is composed of the part of the evaporation amount among plants and unusable land (i.e. bare land, desert and salinization land). Although this part of evaporation can regulate the surrounding eco-environment system, the usable portion is lower when human activity is low. In these cases, this part of evaporation is termed inefficient consumption. Therefore, the consumption efficiency and structure of the entire water cycle should be clarified in order to reduce inefficient consumption and improve efficiency in consumption. Thus, it is important to clarify the net water shortage under the efficient water consumption condition, and the amount of "real water-savings" between water supply and water consumption. Consequently, it is significant for implementing an ET-based modern water resources management mode to reasonably utilize regional water resources.

The runoff amount in the water cycle process is the main management objective in the traditional water resources management, centering on the balance of supply and demand. That is, the traditional water resources management mainly focuses on the utilization and management of narrow-sense water resources, and does not consider non-runoff water resources, such as soil water resources which play an important role in agricultural production and environmental protection. By contrast, the main management objective of the ET-based modern water resources management approach is to categorize the entire vapor flux component throughout the whole water cycle process.

To sum up, water-saving in the traditional water resources management chiefly stresses the water amount saved at the end of the water cycle process, while water-saving in the ET-based modern water resources management is the amount of the regional/basin water resources saving. The latter is a beneficial supplement to the former in both water-saving and improvement of water resources utilization efficiency. The essence of the ET-based modern water resources management mode is to achieve in-depth control and management for the water demand side of the traditional water resources management system. The modern approach is also a management strategy for water consumption course. Therefore, under the condition of daily serious water resources scarcity, implementation of the ET-based modern water resources management mode based on the water cycle process is critical if we are to improve narrow-sense water resources utilization efficiency, develop water sources and fully use no-runoff water resources.

3 Feasibility analysis of the ET-based modern water resources management mode

It is expected that rational adjustment for the regional/basin ET in the water cycle process, based on the limiting water resources condition, might realize “real water-saving” by improving water resources utilization efficiency and decreasing water resources demand. But, because ET, as a process variable in the water cycle process, is affected by numerous natural and human activity factors, its structure and efficiency become more complex, and difficulty in its identification is also raised. In order to realize the ET-based modern water resources management and to provide practical guidance for more efficient utilization of water resources, it is necessary to precisely assess the complex ET structure and its efficiency. However, satisfactory results cannot be obtained by depending only on field-level study techniques, or macro-level remote sensing reversion techniques, or distributed hydrological simulation models. Thus monitoring for regional/basin ET and its hierarchical assessment introduce new difficulties. In fact, although there are many indefinite factors and complicated relations among these factors in the analysis and utilization process, the development of modern technical methods, especially “3S” technology and the distributed hydrological simulation model provide extremely important technical support for the ET-based modern water resources management.

Associated with the above description of studies on ET, the ET accuracy reversed by RS can be improved by further development of remote sensing technology and reversion models. In addition, the distributed hydrological simulation model developed in recent years, especially the model with physical mechanism, can also rectify the lack of remote sensing reversion without considering the water cycle process. Moreover, the accuracy of ET simulation under complex underlay conditions can also be improved by multi-kind data combination (e.g. data assimilation technology, underlay parameter reversion, etc.) associated with the two methods. Therefore, combined with remote sensing, the distributed hydrological simulation model provides a new technological support to carry out the ET-based modern water resources management. Selecting the distributed hydrological simulation model: WEP (water and energy transfer process)[31] as an example, the following section briefly explains the calculation of ET simulated by the distributed simulation model with physical mechanism.

The WEP model is a distributed hydrological model with physical mechanism. Besides the common characters of many distributed models, the WEP model may also simulate all elements in the “natural-artificial” dualistic water cycle process, and may calculate in detail all types of ET in the natural water cycle processes and the artificial lateral water processes based on water and energy balance. At the same time, in the simulation of the basin water cycle process, it is important to consider the asymmetry of land use in computed units, adopting a “mosaic” method. Hence, the model further classifies the computed units into several sorts according to land use, generally classified into five types, including bare-vegetation area, irrigated cropland, non-irrigated cropland, water area and impervious area. The bare-vegetation area can be further divided to three kinds: bare land, grass land and forest land. The impervious area can be divided into urban ground and city construction. The irrigated cropland can also be divided further according to the kinds of typical crops. In addition, to conveniently describe soil evaporation and vegetation root absorption at different rooting depths, the topsoil in the pervious area is divided into three layers to reflect change in soil moisture content with soil depth.

For the ET calculation, according to different underlay conditions and simulated processes above, the WEP model can simulate different kinds of ET and integrated ET in computed units. Simultaneously, according to the water consumption mechanism, the WEP model elaborately divides evapotranspiration into the following parts: vegetation transpiration, soil evaporation, and soil evaporation among plants, as well as canopy interception evaporation and depression storage evaporation. The ET consumption efficiency also can be continuously analyzed in terms of the ET classification above, and can consider functions of different kinds of ET for human activities. As for the simulation accuracy of the model, the accuracy of ET calculation can be ensured because the WEP distributed physical hydrological model is implemented based on extensive information from primary observation, such as precipitation, runoff and variables of regional/basin water storage, etc. Therefore, ET in any period of time can be determined robustly by precipitation, runoff, and regional/basin water storage variables according to the water balance principle. In this approach, monitoring precision is maintained above 95% of precipitation and runoff, following the national standards. The precision of measurement and calculation of the regional/basin water storage variable can be obtained based on the surface water storage variable, comprising rivers, lakes and so on. The groundwater storage variable is acquired by determining the fluctuation of the unconfined groundwater level and that of the confined groundwater head. In conclusion, the simulation error of the regional/basin ET may be within 5%. Furthermore, taking advantage of remote sensing to produce basin/regional underlay parameters, the simulation of ET including its spatial distribution and amount will be improved by data assimilation and parameter calibration in smaller areas, based on results monitored by remote sensing of the concrete time stage, and runoff observation data, as well as true ground observation values. All of these considered factors further assure the accuracy of the ET simulation by improving estimation of the water amount balance. Therefore, combined with remote sensing reversion technology, the WEP model can elaborately describe the complex ET consumption structure and its consumption efficiency based on the energy and water balance, which provides technologically advanced conditions for implementing an ET-based modern regional water resources management mode with the modern principle of “reducing inefficient consumption and raising efficient consumption”.

In addition, the WEP model can offer ET simulation results for different scenarios including water resources use, industrial structures and engineering measures by coupling the model with regional decision analysis model for multi-objective system and water resources allocation simulation models. Thus the distributed hydrological model with physical mechanism based on the energy and water balance would establish an important technical foundation for developing the ET-based modern water resources management mode.

Generally, the accuracy of ET monitoring and simulation can be further improved by an organic combination of the remote sensing reversion method and the distributed hydrological model with physical mechanism, as their functions complement each other. Thus they both would be able to provide strong technical support to systematic analysis of macro-level ET based on the energy and water cycle processes. This robust approach would also provide a reliable technological measurement for the ET-based modern water resources management mode once implemented.

In conclusion, when confronted with a serious water resources shortage situation, the ET-based modern water resources management mode, implemented with analysis of the consumption structure of all sorts of water resources based on the water cycle process, is not only a requirement of current water resources conditions and economic development, but also an inevitable choice in the world of modern water development. Moreover, the entire approach also sits upon a strong technological foundation by combining the advanced remote sensing reversion method with the distributed hydrological simulation model. In addition, with the rapid development of science and technology, this overall approach to water resources management will be further improved by simultaneously utilizing the remote sensing reversion technique, the distributed hydrological simulation technique, and ground truth data observation, as well as assimilating data at appropriate spatial scales. Thus, the feasibility of implementation of the ET-based modern water resources management mode is increased through improvement of the ET calculation accuracy at the macro-level under the complex underlay condition. Hence, it is not only necessary but also feasible to develop and implement the ET-based modern water resources management mode.

4 Case study

As an important element in the water cycle process and direct water source to the vegetation growth process, soil water resources have played an important role in agricultural product and eco-environment protection through ET for a long time. However, soil water resources have not been studied well enough and nor can be incorporated into the traditional water resources management plans because of complexities of natural properties with an over-dependency on precipitation and liability to consuming and dissipation. However, under the condition of increasingly serious water resources scarcity and eco-environment degradation, the function of soil water resources becomes much more obvious through ET via their dynamic transferring process. For example, multi-annual average soil water resources can become completely consumed by ET, namely its value becomes equal to the ET amount at the multi-annual average scale. Moreover, soil water resources are immense, as demonstrated by the statistics that the amount of soil water resources is above 50 percent of the amount of precipitation, and the soil water storage amount is 16 500 km^3, or 7.8 times the amount of runoff for the whole Earth[32]. In North China, 55% of the multi-annual average precipitation was transferred into soil water resources from 1956 to 1979[33]. If soil water resources can be rationally used by regulating ET, it will be helpful to alleviate the shortage of runoff water resources. Therefore, selecting assessment of soil water resources in the Yellow River basin as a case study, and employing the WEP-L distributed hydrological simulation model with physical mechanism, this research indicates the importance of the ET-based modern water resources management approach based on a complete analysis of the water cycle elements for the basin.

4.1 Overview of the Yellow River Basin

The Yellow River, the second longest river in China, runs from west to east through nine provinces, Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shanxi, Henan and Shandong, and terminates into the Bohai Sea. The length of the river is 5 464 km. The entire basin lies at 96° E to 119° E and from 32° N to 42° N. The area of the whole basin is 794 712 km^2, including the Erdos closing flow area of 42 269 km^2. A map of the Yellow River Basin is shown in Figure 2.

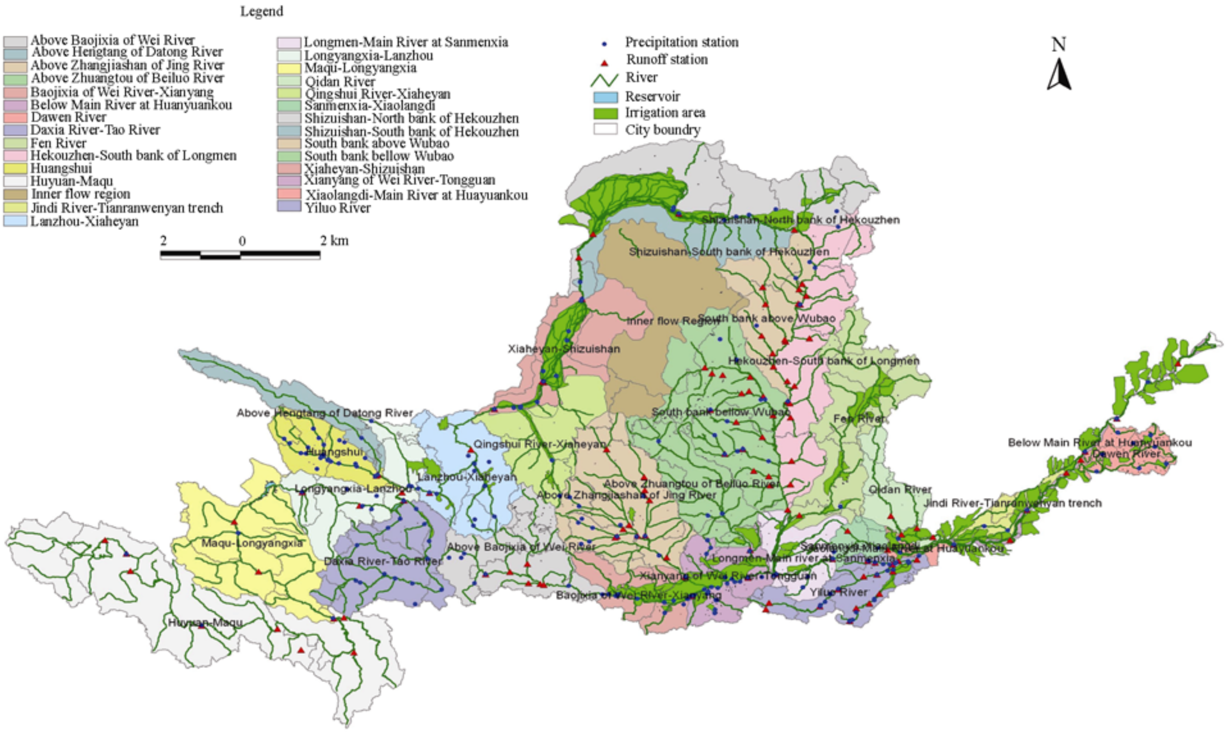

Figure 2 Outline map of the Yellow River Basin.

The Yellow River Basin spans three climatic zones, and has abundant soil and heat resources, but scarce water resources. The multi-annual average precipitation is only 466 mm, the amount of surface water resources is 58.0 km^3, and non-overlapping groundwater resources are 14.8 km^3. Per capita and per mu water resources are 633 and 277 m^3, respectively. The Yellow River Basin is confronted with severe water resources shortages. In addition, three-quarters of the entire area lies within arid or semi-arid zones, which forces agricultural development in the Yellow River Basin to rely heavily on soil water resources. Hence, facilitation of use and management of soil water resources is of great importance.

4.2 Brief introduction to soil water simulation and soil water resources assessment

In the simulation of the water cycle process in the Yellow River Basin, the paper uses the WEP-L distributed hydrological model, which is further developed based on some improvements to the model with respect to particular characteristics of the Yellow River Basin. In the simulation process, to adequately show underlay conditions and to improve computation efficiency, “contour bands inside small sub-watersheds” are used as the computation unit, and land use heterogeneity inside a computation unit is taken into account by adopting the mosaic method. Firstly, the Yellow River Basin is divided into 8485 sub-watersheds and 38720 contour bands by the method, and then a 45 a continuous simulation is carried out from 1956 to 2000 for the natural water cycle process without considering water use under historic series underlay conditions. Finally, based on the simulation results, soil water resources amounts are analyzed, and its consumption efficiency of the whole basin is assessed. In this approach, the soil water resources determined will be the maximum possibly usable soil water within the whole aeration zone, from surface to unconfined water table. In other words, this approach characterized the whole soil water reservoir. The amount of multi-annual average soil water resources equals the amount of ET in the whole aeration zone under the condition without irrigation water use. This methodology will avoid a repeat calculation between soil water resources and surface water. In addition, to avoid repetition within the groundwater resources variable, the latent water evaporation amount is subtracted in the calculation process. More detailed contents of the WEP-L structure, parameter calibration, and the amount and efficiency assessment of soil water resources are shown in ref. [32].

4.3 Analysis of soil water resources in the Yellow River Basin

4.3.1 Analysis of soil water resources amount. According to the simulation results shown in Table 1 and Figure 3, the amount of multi-annual average soil water resources is 207.898 km^3, and that of runoff water resources is 69.133 km^3 after precipitation moves through the water cycle process via interception, infiltration, runoff and conflux sub-processes operating throughout the whole basin. The amount of soil water resources and that of runoff are 58.35% and 19.4% of the precipitation, 356.302 km^3, over the Yellow River Basin, respectively. These results indicate that more than half of the precipitation in the whole basin transfers into soil water resources, and the amount of soil water resources is three times that of the runoff amount. The level-2 water resources regions have similar characterisic to the whole

Table 1 Soil water resources under historic series underlay conditions in Yellow River Basin

Level-2 water resources region	Area	Precipitation		Runoff		Soil water resources		Soil water resources /precipitation	Soil water resources /runoff
	(km^2)	(mm)	(km^3)	(mm)	(km^3)	(mm)	(km^3)	(%)	(times)
The whole basin	794284	448.58	356.302	87.04	69.133	261.74	207.898	58.35	3.01
Upstream Longyangxia	130323	485.15	63.227	180.77	23.558	198.77	25.905	40.97	1.10
Longyangxia-Lanzhou	90386	479.00	43.295	144.88	13.095	205.11	18.539	42.82	1.42
Lanzhou-Hekouzhen	161155	265.37	42.765	13.08	2.108	197.44	31.819	74.40	15.09
Hekouzhen-Longmen	110911	432.98	48.022	44.38	4.923	319.75	35.464	73.85	7.20
Longmen-Sanmenxia	191577	542.30	103.893	84.14	16.119	333.63	63.916	61.52	3.97
Sanmenxia-Huayuankou	41773	657.50	27.466	139.37	5.822	384.80	16.074	58.52	2.76
Downstream of Huayuankou	24524	643.40	15.779	121.45	2.978	315.62	7.740	49.05	2.60
Neiliuqu	43635	271.70	11.856	12.14	0.530	193.44	8.441	71.20	15.94

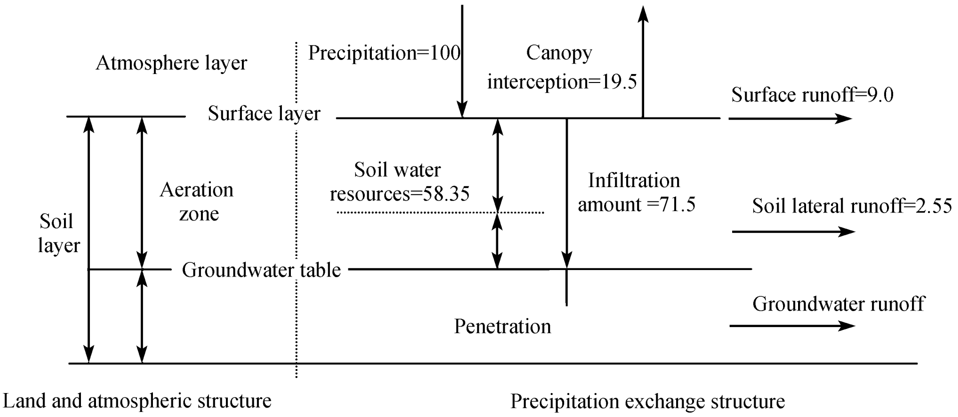

Figure 3 Precipitation transferring structure in the "four-water" transferring process in the Yellow River Basin.

basin. Thus, it is clear that the amount of soil water resources is immense, especially in arid and semi-arid zones to the northwest, where the soil water resources are much more important as compared to the runoff amount. Therefore, it is beneficial to enforce rational utilization of soil water resources to alleviate the shortage in regional runoff water resources.

4.3.2 Analysis of consumption efficiency of soil water resources. Although the soil water resources are immense in the Yellow River Basin, the consumption structure and consumption efficiency vary greatly through ET. In Table 2, the amount of vegetation transpiration consumption is listed as 38.189 km^3, which is 18.4 % of the 45 a average soil water resources amount for the entire basin. While the evaporation amount from difficultly usable land and among plants is 169.709 km^3, or 81.6% of the soil water resources amount. The transpiration amount is only 22.5% of the evaporation amount. Combined with the identification principle of vegetation transpiration efficiency[9,32], the results of consumption efficiency of soil water resources in the ET process shown in Table 3 indicate that the efficient consumption amount of soil water resources is 92.011 km^3 over the whole basin, or 44.3% of the soil water resources amount including a high efficiency consumption amount of 38.189 km^3 and a low efficiency consumption amount of 53.822 km^3. The amount of the high efficiency consumption and that of low efficiency consumption are 18.4% and 25.9% of the soil water resources amount, respectively, and the remaining 55.7% is the inefficient consumption amount of 115.886 km^3, comprising 97.605 km^3 from bare land, 15.759 km^3 from grassland and 2.522 km^3 from forest land, or 84.22%, 13.60% and 2.18% of the total inefficient evaporation amount, respectively (shown in Table 4). The changes in soil water resources consumptions in the level-2 water resources regions are similar to the whole basin.

In spite of the great amount of soil water resources in the Yellow River Basin, the efficiently used amount is quite low, over 55% of the total soil water resources amount is inefficiently consumed mainly in lands with low vegetation closing degree. If the soil water resources

Table 2 The consumption relationship of soil water resources under historic series underlay conditions in the Yellow River Basin

Level-2 water resources region	Soil water resources (km^3)	Vegetation transpiration consumption (km^3)	Soil evaporation consumption (km^3)	Transpiration/soil water resources (%)	Evaporation/soil water resources (%)
The whole basin	207.898	38.189	169.709	18.37	81.63
Upstream Longyangxia	25.905	2.094	23.811	8.08	91.92
Longyangxia-Lanzhou	18.539	3.525	15.014	19.01	80.99
Lanzhou-Hekouzhen	31.819	5.504	26.315	17.30	82.70
Hekouzhen-Longmen	35.464	6.832	28.632	19.26	80.74
Longmen-Sanmenxia	63.916	13.775	50.141	21.55	78.45
Sanmenxia-Huayuankou	16.074	4.621	11.453	28.75	71.25
Downstream of Huayuankou	7.740	1.485	6.255	19.19	80.81
Neiliuqu	8.441	0.353	8.088	4.18	95.82

Table 3 Consumption efficiency of soil water resources under historic series underlay conditions in the Yellow River Basin

Level-2 water resources region	Soil water resources (km^3)	Efficient consumption (km^3)			Inefficient consumption (km^3)	Efficiency consumption /soil water resources (%)			Inefficiency consumption /soil water resources (%)
		(1)$^{a)}$	(2)$^{a)}$	(3)$^{a)}$		(1)$^{a)}$	(2)$^{a)}$	(3)$^{a)}$	
The whole basin	207.898	92.011	38.189	53.822	115.886	44.26	18.37	25.88	55.73
Upstream of Longyangxia	25.905	9.537	2.094	7.443	16.368	36.81	8.08	28.73	63.19
Longyangxia-Lanzhou	18.539	10.352	3.525	6.827	8.187	55.84	19.01	36.83	44.16
Lanzhou-Hekouzhen	31.819	11.154	5.504	5.650	20.665	35.05	17.30	17.76	64.95
Hekouzhen-Longmen	35.464	11.440	6.832	4.608	24.024	32.26	19.26	12.99	67.74
Longmen-Sanmenxia	63.915	31.892	13.775	18.117	32.023	49.90	21.55	28.34	50.10
Sanmenxia-Huayuankou	16.074	9.876	4.621	5.255	6.198	61.44	28.75	32.70	38.56
Downstream of Huayuankou	7.740	5.860	1.485	4.375	1.880	75.70	19.20	56.51	24.30
Neiliuqu	8.441	1.900	0.353	1.547	6.541	22.51	4.18	18.33	77.49

a) (1) Total amount; (2) high efficient consumption; (3) low efficient consumption.

Table 4 Inefficient consumption of soil water resources under historic series underlay conditions in the Yellow River Basin

Level-2 water resources region	Inefficient consumption (km^3)				Ratio to the total (%)		
	Total	Forest land	Grass-land	Bare land	Forest land	Grass-land	Bare land
The whole basin	115.886	2.522	15.759	97.605	2.18	13.60	84.22
Upstream Longyangxia	16.368	0.283	6.215	9.870	1.73	37.97	60.30
Longyangxia-Lanzhou	8.187	0.551	3.367	4.269	6.73	41.13	52.14
Lanzhou-Hekouzhen	20.665	0.034	1.493	19.138	0.16	7.22	92.61
Hekouzhen-Longmen	24.024	0.338	0.999	22.687	1.41	4.16	94.43
Longmen-Sanmenxia	32.023	0.788	2.044	29.191	2.46	6.38	91.16
Sanmenxia-Huayuankou	6.197	0.445	0.422	5.330	7.18	6.81	86.01
Downstream of Huayuankou	1.880	0.080	0.112	1.688	4.26	5.96	89.79
Neiliuqu	6.541	0.003	1.107	5.431	0.05	16.92	83.03

can be rationally used by reducing the amount of inefficient and low efficiency consumption among plants by applying such measures as increasing vegetation closing degree, decreasing difficultly usable land area and adjusting crop mixing, there may be alleviation in the lack of regional/basin water resources. However, the rational usage of soil water resources is only through regulation for ET because it cannot be drawn and/or transported. Therefore, carrying out the ET-based modern water resources management strategy in the basin will not only avoid leaving water resources unused, but also alleviate the scarcity of the regional/basin water resources.

Moreover, Figure 3 shows that in the regional/basin water resources transferring process, besides soil water resources as a larger portion of precipitation, most of the other portions (mainly canopy interception and runoff water resources being in different media) are also consumed through direct evaporation or indirect ET in artificial “withdrawal-deliver-use-drainage” sub-processes. However, their consumption efficiency in all sub-processes is still not defined, which causes most of the inefficient use of water resources. If these water resources could be rationally utilized, they would alleviate the condition of water resources scarcity and eco-environment deterioration.

Consequently, as shown in Yellow River Basin case study, an ET-based water resources management strategy considering a regional/basin water cycle process will likely minimize water resources shortages by avoiding disuse of water resources and increasing water resources utilization efficiency in view of “real water-saving”.

5 Discussion and conclusion

5.1 Discussion

Employing the combined approach of theory and a case study, this paper systematically prescribes the importance of an ET-based modern water resources management strategy and its implementation process. However, an ET-based modern water resources management strategy is still primarily in the concept phase, and many difficulties still exist in both monitoring and calculation of regional/basin-scale water resources consumption through mainly ET, especially for complex underlay conditions. Hence, the uncertain factors affecting ET accuracy continue to reside in the data assimilation linkage between the remote sensing reversion technique and use of the distributed hydrological model. Therefore, considering restriction in the accuracy of ET simulation and calculation, more in-depth studies are needed in order to apply scientifically and rationally the ET-based modern water resources management strategy in practice.

Moreover, employing the dynamic transfer process of soil water resources in the Yellow River Basin, this paper explains the function and meaning of implementing the ET-based modern water resources management strategy. However, water resources consumption appears in any other water cycle sub-process. Therefore, other water resources consumption still needs detailed study because the ET-based modern water resources management mode is an integrated management mode for all water resources consumption amounts, and takes into consideration the whole "natural-artificial" dualistic water cycle process.

5.2 Conclusion

In evaluating the relation between water resources supply and demand in regional/basin water resources management, this paper constitutes the first in-depth analysis of the problem in water demand management. Given the general problems associated with water resources shortages and the actual water cycle condition disturbed by intensifying human activities, the necessity of implementing the ET-based modern water resources management strategy is becoming more urgent. A focus is strongly placed herein on evapotranspiration, the greatest proportion of regional/basin-scale water resources consumption over the whole water cycle process. Furthermore, the feasibility of implementing the ET-based modern water resources management strategy is discussed by combining regional/basin-scale advanced "3S" technology with the distributed hydrological model. On the basis of theoretical discussions herein, the importance of ET management by soil water resources amount and consumption efficiency in the Yellow River Basin is stressed via more accurate simulation of the water cycle process employing both the WEP-L distributed hydrological model with physical mechanism and the remote sensing reversion technique.

In conclusion, when confronted with increasingly water resources scarcity today, and from the viewpoint of water resources supply and consumption, it is both necessary and feasible to develop the ET-based modern water resources management strategy that based on the water cycle process and combined with advanced remote sensing technique and distributed hydrological model.

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