Water in Loess

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Glossary

Available water capacity is the soil water content within a range between field capacity and wilting point. It is the soil water content that can be retained in the soil and is available for plants.

Confined groundwater is the counterpart of phreatic groundwater or unconfined groundwater. It refers to the groundwater stored in confined aquifers, which are overlain by a confining layer made up of low permeability materials such as clay.

Ecological civilization is a term that describes a new stage of the development of human civilization. It represents a new stage of civilization following industrial civilization and is the final goal of an environmental reform within a given society. Ecological civilization can be described as the sum of all material and ideological achievements obtained by employing strategies for a harmonious development of the human society and the environment. It involves a synthesis of economic, educational, political, agricultural, and other societal reforms toward sustainability.

Available water capacity

Field capacity

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retained in the soil after the drainage of excess water by gravity.

**Loess Plateau**
The Loess Plateau is one of the four highlands of China and one of the birthplaces of the ancient Chinese civilization. It was and still is an important center of the Silk Road and is the most concentrated and largest area on earth in terms of loess accumulation, covering 630,000 km². It spreads across the seven Chinese provinces Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, and Henan and is mainly composed by the Shanxi Plateau, the Shaanxi-Gansu- Shanxi Plateau, the Longzhong (mid-Gansu) Plateau, the Ordos Plateau, and the Hetao Plain.

**Loess**
Loess refers to the predominantly silt-sized sediment formed by the accumulation of windblown dust under dry climatic conditions. It is usually homogeneous, porous, slightly coherent, and non-stratified. The loess grains are angular and composed of crystals of quartz, feldspar, mica, and other minerals.

**Phreatic groundwater**
Phreatic groundwater refers to the groundwater stored in phreatic aquifers. Phreatic aquifers are also referred to as unconfined aquifers whose upper boundaries are provided by the phreatic surface where the pore water pressure is under atmospheric conditions.

**Water resources vulnerability**
Water resources vulnerability is the sensitivity and capability of a water resource system to adapt to the changes of water system structures, the decrease of water quantity, and the deterioration of water quality in the context of climate change and human activities as well as the consequent changes in water supply, water demand, and water management and the occurrence of water-related hazards. It involves the sensitivity of water resources to internal and external changes and the adaptability to these changes.

**Wilting point**
Wilting point is defined as the minimal soil moisture that the plant requires to avoid wilting. If moisture decreases to this point or below, a plant will wilt and can no longer recover its turgidity.

**Definition of the Subject**
Loess is a fine-grained windblown (aeolian) sediment which is homogeneous, porous, friable, pale yellow or buff, slightly coherent, typically non-stratified, and often calcareous [1, 2]. It is widely distributed in China, Argentina, Europe, the United States, and Middle Asia and mainly occurs in arid and semiarid regions with severe water resource shortages and fragile ecological environments. Mineral resources such as oil, gas, and coal, however, are rich in these areas.

The Loess Plateau of China is the most typical loess distribution area in the world. However, as a result of increasing human activities such as urbanization, industrialization, and energy exploitation, water demands are high, resulting in soil and water pollution [3]. The Loess Plateau is currently facing serious challenges in water resources development and environmental protection. It is therefore crucial to understand the characteristics of loess and the status of water resources in the Loess Plateau area.

This entry reviews the concept/origin of loess and its universal distribution, introduces its physicochemical and geotechnical characteristics, summarizes the problems associated with water resources development in the Loess Plateau of China, and discusses the importance of surface water, groundwater, and soil water in this region.
Introduction

Loess is a fine-grained windblown (aeolian) sediment which is widely distributed. Loss deposits contain buried evidence of Paleolithic occupations [4]. Along the Rhine Valley in Germany, where the deposit was first recognized, local residents named the widely distributed soil “Löss,” and this German word is the origin of the English term loess [2].

As early as 3000 years ago, there were some brief descriptions about loess in the ancient Chinese book “Yu Gong.” However, modern scientific research on loess began only after the publication of the book Principles of Geology by the English geologist Charles Lyell in the 1830s [5, 6]. Charles Lyell proposed that “the present is the key to the past,” suggesting the study of the past based on present characteristics of geological formations. Today, this proposal is still canonized by many researchers. Sun [5], however, thought that such an approach should be expressed as “the past is the key to the future,” because predicting the future from the past records is more meaningful to modern citizens. Nowadays, with an increasing awareness of ecological issues, people are much more concerned about the development of the geological and natural environment in the context of economic development, population growth, and environmental problems. However, the research conducted by Charles Lyell on loess marks the beginning of modern loess research, and the history of modern loess research in China can be divided into the following three phases [6–8]:

Phase I: From the 1840s to the 1940s

During this period, loess research has moved away from the fields of soil science and geography toward geology. At the same time, research on loess gradually changed from considering general problems to loess genesis, stratigraphy, and other specific studies. The research approach in this period was simple and relied mainly on fossils. International loess research was dominant in this period, and many internationally recognized geologists conducted their studies in China. For example, Pumpelly [9], Richthofen [10], and Willis et al. [11] carried out investigations on loess and published their results in books or journals. Representative publications in this period include the five-volume German book by Richthofen China: Ergebnisse eigener Reisen und darauf gegründeter Studien and the book Research in China by Willis. These publications show that research in this period was focused on the genesis of loess.

Phase II: From the 1950s to the 1970s

A large number of studies on the chemical, mineral, and grain composition as well as on the physical and mechanical properties of loess were carried out in this period. Due to massive geotechnical engineering projects in the loess areas of China, Chinese scholars became the leading loess research community, especially in the field of loess collapsibility and construction techniques on loess basement. Some Chinese monographs on loess were also published in this period, including Composition and Structure of the Loess, Loess in the Middle Reaches of the Yellow River, Chinese Loess Accumulation, Research on the Basic Nature of the Loess, and Chinese Loess and Loess Rock. In particular, Zhu [12] proved that the dark layer imbedded in the loess layers is paleosol, which is beneficial for the stratigraphic division of the loess strata and the recovery of the paleoclimate.

Phase III: From the 1980s to the Present

In this period, the latest technical methods such as paleomagnetism, isotopic chronology, and 14C dating became available, providing the possibility to determine loess age and for stratigraphic division of the loess strata [13]. In addition, environmental geochemistry, paleoclimatology, and microstructure analysis were also applied in loess research and enriched the scope of loess studies. Numerous scientific contributions were published in this period, such as Loess and the Environment, Soil and Agriculture in the Loess Plateau, and Loessology. Research efforts in this period have significantly enhanced our understanding of the formation and development history of the Chinese loess strata and the paleoclimate. Studies on the collapsibility of
loess, the mechanical constitutive of loess, the dynamic characteristics of loess, and the engineering of geological and geo-environmental issues in loess areas have also achieved great progress [6].

In the past two decades, many ecological and environmental studies have been carried out on the Loess Plateau. Loess water erosion constitutes a great threat for environmental safety and local residents in loess areas. Wang et al. [14] investigated the impacts of water erosion on a gas pipeline in the loess area through aerial photo interpretation. They suggested an approach of controlling loess water erosion using soil solidified material that could improve the mechanical properties and anti-erosion ability of loess. Research also showed that land use has significant effects on soil moisture and soil water storage [15]. Climate change significantly affects the water budget balance in loess areas [16, 17], and the total annual imbalance of the land-surface water budget could reach 20.6% across the Loess Plateau of China [17]. Such studies provide a significant contribution to the ecological preservation and the environmental restoration of loess areas.

However, due to the current rapid population growth and fast urbanization in loess areas of China, many land creation projects have been implemented on the Loess Plateau [18]. These projects may produce potentially negative effects on the local ecology and water resources, although they provide more land for urbanization and agriculture. Such projects should therefore be carried out with caution to sustain the results of ecological civilization construction, which took several decades to achieve.

**Loess and Its Distribution**

Loess is a wind-transported sediment formed mainly during the Quaternary and sometimes recorded in older geologic intervals [2, 5, 19]. It is mainly composed of fine sand and clay, with grain sizes ranging from 0.005 to 0.05 mm. The loess is loose and porous with well-developed vertical joints, which enables vertical water flow rather than horizontal flow. In addition, loess contains a variety of soluble substances, which facilitate the formation of eroded valleys and cause subsidence and collapse. The porosity of loess sediments generally ranges from 42% to 55% [5]. The mineral compositions of loess include three categories: clastic minerals, clay minerals, and authigenic minerals. Clastic and clay minerals are dominant, while authigenic minerals are minimal in loess. The clastic minerals mainly include quartz, feldspar, and mica, which account for 80% of the clastic minerals, followed by pyroxene, amphibole, chlorite, and magnetite. In addition, loess is rich in carbonates such as calcite. The clay minerals in loess are mainly illite, montmorillonite, kaolinite, goethite, and aqueous hematite. The chemical composition of loess is dominated by SiO$_2$, Al$_2$O$_3$, and CaO, followed by Fe$_2$O$_3$, MgO, K$_2$O, Na$_2$O, and FeO. The contents of TiO$_2$ and MnO in loess, however, are small. It should be noted that the mineral contents and the chemical composition of loess of different regions may vary with depth, age, and forming environment of the loess (Fig. 1).

Loess is extremely unstable and may collapse when wetted, seismically shaken, or disturbed by human activities [18]. The most significant feature of the loess is its great collapsibility. Worldwide, about half of the loess sustains collapsibility, and collapsible loess in China accounts for 60% of the total loess [20]. Collapsibility refers to the effect or ability of soil, under deadweight or additional load, to produce a sharp sinking and cause ground deformation in the case of constant pressure under the influence of moisture content changes [20]. The collapsibility of loess depends on multiple factors such as particle composition, porosity, depth, changes in atmospheric precipitation and temperature, and anthropogenic effects. The regional variation of loess collapsibility in China is controlled by climate and particle composition [20]. In northwestern China, the climate is dry and cool and becomes wet and hot in southeastern China, which corresponds to the regional loess collapsibility variation trend in China (high loess collapsibility in northwestern China to no collapsibility in southeastern China). Loess particle size also shows a descending trend from northwestern to southeastern China; the increase of clay
minerals in loess decreases soil porosity, thereby reducing loess collapsibility.

Loess is widely distributed over the world, accounting for 10% of the world land area [19]. It is mainly distributed in the mid-latitude arid and semiarid areas of the northern hemisphere. In the southern hemisphere, loess is mainly distributed in some countries of South America and in New Zealand (Fig. 2). Particularly in Europe and North America, the northern boundary of the area covered by loess is roughly connected to the Pleistocene glaciers, and the loess areas are mainly distributed in the United States, Canada, Germany, France, Belgium, the Netherlands, Central and Eastern Europe, and the Ukraine. In Asia and South America, the loess areas are adjacent to the desert and the Gobi and are mainly found in China, Iran, the Central Asian part of the Russia, and in Argentina [5]. China has the largest and thickest loess cover of the world (Fig. 3). Here, loess covers an estimated area of 630,000 km² and accounts for approximately 7% of the total territorial area [6]. The Loess Plateau, the main loess distribution area in China, is well known for its highest loess thickness and most complete loess stratigraphy and has become the center of world loess research.

Water Resources Development on the Loess Plateau

Water is the key element for economic development and ecological conservation in the Loess Plateau of China. Drought and water shortage are the most serious eco-environmental problems on the Loess Plateau and severely constrain ecological civilization and economic development [23]. On the Loess Plateau, river water and groundwater are the most widely used water
resources and are applied in a variety of uses. According to the literature [23], river water accounts for 77.3% of the total water supply in the Loess Plateau, while groundwater represents 22.7%. River water, which is mainly derived from the Yellow River and its tributaries, is predominantly used for agricultural irrigation and industrial production, while the domestic water supply relies mainly on groundwater. As shown in Fig. 4, agriculture is the largest sector in terms of water use, and each year, around 87% of the total water supplies are used for irrigation, while industrial and urban domestic uses account for 10% and rural domestic use accounts for 3% of the total water supply [23]. These numbers indicate that agriculture has the largest water-saving potential.

For the development of sustainable water resources on the Loess Plateau, it is crucial to adopt water-saving irrigation techniques and to implement vegetation structure adjustments. According to the national allocation of the Yellow River water [23], the total amount of available surface water resources for the Loess Plateau is only $224.2 \times 10^8$ m$^3$, of which about 80% are used for irrigation, leaving only $44.84 \times 10^8$ m$^3$ for other uses such as ecological maintenance. In terms of groundwater, only water resources stored underneath the alluvial plains on the Loess Plateau are available for development. There are several large irrigation districts on the Loess Plateau, and extensive irrigation has induced groundwater level rise, causing secondary soil salinization [24, 25]. There are also several irrigation districts experiencing groundwater level declines due to intense groundwater abstraction for multiple uses, causing damages to wells and pumps. Considering the severe situation of water resources, some Chinese scholars have proposed integrated water resources management for maintaining the sustainability of water resources [26]. It should be noted that groundwater is far more important on the Loess Plateau than other water resources, and thus, the scientific and sustainable development of groundwater is critical for the local economy and society. Soil water is also important for the sustainable development of the Loess Plateau. In the Loess Plateau area, the loess deposit is thick and porous, favoring the storage and occurrence of soil water. It has been estimated that the total soil water amount stored in a 2 m loess layer over the Loess Plateau can reach up to $1785.5 \times 10^8$ m$^3$ [23]. However, due to intensive evaporation in this area, the loess layers are usually in the state of water deficit.
In addition to drought and water shortage, another serious water-related problem associated with the development of economy and society on the Loess Plateau is water pollution. The Yellow River is the largest surface water source on the Loess Plateau, and its water quality has been significantly degraded because of human activities and natural environmental changes. The main stream and the tributaries of the Yellow River have been subject to contamination of different degrees. In addition, the groundwater on the Loess Plateau is undergoing severe quality deterioration. Various researches have shown that nitrate, fluoride, sulfate, and trace metals, due to agriculture/industry and natural release from soil, are major groundwater pollutants in the Loess Plateau area [27–30]. Issues related to water pollution cause dramatic economic losses each year and pose potential risks to residents and the environment [31, 32]. A study by Wu and Sun [32] has shown that health risks of local residents are mainly a result of ingestion of contaminants, with children being more vulnerable than adults. Ma et al. [33] reported a rapid decline in both surface water and groundwater quality during the past 20 years in

**Water in Loess, Fig. 3** Loess distribution in China (Modified after Wu [6])

**Water in Loess, Fig. 4** The use of water resources on the Loess Plateau
the Malian River Basin of the Longdong Loess Plateau; petroleum contamination caused by the oil industry in the Longdong oil field is the largest source of pollution and affects surface water and groundwater quality. In addition, some studies have shown that agriculture on the Loess Plateau is the main contributor to nonpoint source pollution [34, 35]. Tourism in the Loess Plateau area, which is the economic basis of a number of cities, should also be adequately regulated. The fast development of tourism in many parts of the Loess Plateau has caused significant water pollution and environmental degradation [36].

For the sustainable development and protection of water resources in the Loess Plateau, it is required to allocate all water resources conjunctively, including surface water, groundwater, and soil water. To achieve this goal, it is mandatory to obtain a full understanding of the quality and quantity state of these water resources.

**Surface Water on the Loess Plateau**

The uneven distribution of rainfall causes the deficiency of annual surface water resources, hampering vegetation restoration and ecological conservation on the Loess Plateau [37]. The Yellow River and its tributaries are the main surface water resources on the Loess Plateau. In this area, surface water is characterized by three factors: First, it is scarce, and such scarcity is not in harmony with the local population and land resources. The average annual runoff in this area is only 71.1 mm per year, which is less than one third of the average runoff in China. The per capita water resource in this area is only 546 m³, which is only 30% of the national per capita water resource, and the average water resource per hectare is only 2625 m³, less than 10% of the national water resource per hectare [23]. Second, surface water in this area is spatiotemporally uneven. Local surface water on the Loess Plateau is mainly recharged by precipitation. Precipitation, however, decreases gradually from south to north and from east to west, making the northwestern part of the area more arid than the southeastern part. Heavy rains are relatively more common in north Shaanxi, west Shanxi, and Inner Mongolia on the Loess Plateau and less common in Western Gansu and Ningxia. In addition, as the Loess Plateau is characterized by a continental monsoon climate, the temporal rainfall distribution in the area is highly uneven, and the amount of precipitation in July to September (summer season) occupies 50–70% of the annual total rainfall [38]. The Yellow River is the largest river flowing through the Loess Plateau and provides a large volume of surface water for irrigation and industrial uses. However, the spatiotemporal distribution of the Yellow River is also uneven. The Yellow River drainage can be divided into four zones: water abundance zone, transition zone, water shortage zone, and drought zone. The Loess Plateau mostly belongs to the transition and the water shortage zones, and the area of the Loess Plateau accounts for approximately 62% of the Yellow River drainage, but the volume of river water accounts for only 30% of the total Yellow River runoff [23], indicating an unevenness of spatial surface water distribution. Third, the surface water in the Loess Plateau contains large volumes of sediment. It has been estimated that the annual sediment load of the Yellow River reached $16 \times 10^8$ tons each year in the 1990s. In recent years, a variety of engineering and biological measures for water and soil conservation have been implemented on the Loess Plateau; as a result, the annual sediment load of the Yellow River is declining and soil erosion is alleviated in some areas [39]. However, due to the rapid economic development and urbanization, some local governments now neglect soil and water conservation, and many cities on the Loess Plateau focus on urban expansion, resulting in severe damage to vegetation planted 20 years ago [18, 40, 41]. Such an approach is likely to impede water and soil conservation achievements obtained by local governments. Shi and Shao [39] and Sun et al. [40] state that soil and water loss in the Loess Plateau region are caused by natural erosion and accelerated erosion. Cultivation, uncontrolled development, overgrazing, mining, road construction, and urbanization are important anthropogenic factors accelerating erosion. To maintain the soil and water conservation
achievements on the Loess Plateau, it is important and compulsory to strictly control human activities in this region.

The annual surface water resource in the Loess Plateau was $321.5 \times 10^8$ m$^3$ from 1950 to 1989 [23]. However, the amount of surface water varies from year to year and is influenced by recharge source, land cover/land use, and drainage size. The river runoffs measured at the main stations of the Loess Plateau from 1919 to 1979 are shown in Table 1 [23]. Annual runoff varies from year to year and from station to station. For the Sanmenxia station located in the downstream of the Loess Plateau, the average annual runoff is $504 \times 10^8$ m$^3$, with a maximum annual runoff of $823 \times 10^8$ m$^3$ and a minimum annual runoff of $242 \times 10^8$ m$^3$. The minimum annual runoff is less than half of the average annual runoff, while the maximum annual runoff is 3.5 times that of the minimum annual runoff. For the Lanzhou station in the upstream, the average annual runoff is $326 \times 10^8$ m$^3$, which is 64.7% of that at the Sanmenxia station. The maximum and minimum annual runoffs are also lower than those at the downstream stations, except for Hekou station, which indicates that local surface water joins the main Yellow River. The ratios between the maximum and minimum annual runoff at all four stations are larger than 3.0, suggesting significant interannual variation of the Yellow River runoff.

The overall water quality of the surface water on the Loess Plateau is not a reason for optimism, although water quality protection measures have been launched and some local improvements have been witnessed. Water quality is classified into five grades according to the Chinese water quality standards. Grades 1 and 2 represent excellent and good quality water which can be used for various purposes. Water falling into grade 3 is of fair quality and acceptable for domestic uses, while grade 4 water is of poor quality but can be used for irrigation. Grade 5 represents very-poor-quality water that cannot be used for any purpose [42, 43].

The river water quality assessment results for the Yellow River drainage from 1998 to 2007 are shown in Table 2 [44, 45]. The assessment was performed according to the surface water quality standard released by the Bureau of Quality and Technical Supervision of China [43]. As shown in Table 2, more than half of the rivers were characterized by very poor water quality (grade 5), and almost 80% of the river water was of poor and very poor water quality (grades 4 and 5) and therefore unsuitable for domestic uses in the first several years of the twenty-first century, indicating serious water pollution because of rapid economic development without adequate consideration of ecological issues. Particularly, in 2002, only less than 20% of the river water was acceptable for domestic purposes, and excellent and good quality water accounted for only about 5% of the total river length. This is, in fact, a poor condition for residents living in this area. In 2004, the river length with excellent and good quality exceeded 10% for the first time, and since then, the river water quality has gradually improved. In addition, since 2005, the total river length monitored and assessed has been accounting for over 10,000 km and since 2012, for more than 20,000 km, indicating a development in monitoring techniques and increasing investment in water quality protection. Most importantly, the river length with acceptable water quality for domestic uses (grades 1 to 3) has been over 50%
of the total river length monitored and assessed since 2012, which is regarded as a great success in river water pollution remediation.

The river water quality trend from 2002 to 2015 on the Loess Plateau is shown in Fig. 5. The percentage of very-poor-quality river water has been generally decreasing since 2002, while that of grades 1–2 water has been increasing, clearly demonstrating an improvement of river water quality. The percentages of fair-quality water and poor-quality water are also slightly decreasing. In particular, the water quality improvement since 2012 is significant probably because of the national strategy on ecological civilization construction.

The significant water quality improvement achieved in the past 10 years is encouraging. However, ecological civilization construction still needs to be further developed. As shown in Table 4, in 2015, over 30% of the rivers were still contaminated, and recovering these rivers requires long-term efforts and large amounts of
investments as well as endeavor from all parts including governments, scientists, and the public.

**Groundwater on the Loess Plateau**

As surface water on the Loess Plateau is scarce and mostly of poor quality, groundwater has long been the most important source of water in many parts of the arid and semiarid Loess Plateau [26, 42]. The occurrence, flow, and spatial distribution of groundwater on the Loess Plateau are controlled by geological and hydrogeological settings. Climate and geomorphological and hydrological conditions are also vital factors influencing its occurrence, distribution, and transformation. Groundwater on the Loess Plateau can be divided into four main types according to aquifer properties: pore water in loose rocks, karst water in carbonate rocks, pore-fracture water in clastic rocks, and fissure water in crystalline rocks [23], with pore water in loose rocks being the most abundant type. The estimated amount of total natural groundwater resources on the Loess Plateau is $333.45 \times 10^8$ m$^3$ (Table 3) [46]. Precipitation is the main source of groundwater recharge for groundwater in the region, and in some areas, it is the only recharge source. However, soil conservation measures on the Loess Plateau can alter the hydrologic cycle and change the water fluxes through the land surface to groundwater [47]. Influenced by climate zoning, groundwater is abundant in the south and scarce in the north of the Loess Plateau. The loess pores and fissures are the main sites for the storage and transportation of loess groundwater. Among these pores and fissures, small but uniform pores and microfractures represent the main water storage spaces in the loess layers, while large, nonuniform, but well-connected fissures and voids are the dominant migration channels for groundwater in loess layers [48].

There are several large basins (alluvial plains) on the Loess Plateau, such as the Yinchuan Basin in Ningxia, the Guanzhong Basin in Shaanxi, the Hetao Plain in Inner Mongolia, and the Fenhe Plain in Shanxi. These basins are densely populated, and groundwater is the most important water source for domestic water supply. The groundwater in these basins is mainly pore water, and the aquifers are usually thick and characterized by multilayer structures. The groundwater modulus in these basins is high, indicating abundant groundwater resources. For example, the groundwater modulus in the Yinchuan Basin ranges from $43.3 \times 10^4$ m$^3$/km$^2$ per year to $55.7 \times 10^4$ m$^3$/km$^2$ per year, being higher than the average groundwater modulus of pore water in loose rocks (Table 3). Typically, precipitation is an important recharge source for groundwater underneath the basins. However, irrigation infiltration and percolation from irrigation channels are major recharge sources for groundwater in some basins. Irrigation infiltration and percolation from irrigation channels account for over 70% of the total recharge for groundwater in both the Yinchuan Basin and the Weining Plain [49, 50], and in the Guanzhong Basin, irrigation is also one of the major recharge sources for groundwater [29, 31]. According to Li et al. [23], the total natural groundwater resources of the Loess Plateau amount up to $177 \times 10^8$ m$^3$ per year.

Groundwater in the loess tablelands and hilly-gully regions shows different characteristics from that in the basins. In these areas, the rocks underlying loess develop large numbers of fissures, facilitating water seepage. As such, the loess and underlying rocks usually form a unified aquifer characterized by a dual structure with pore water in the upper loess and fissure water in the underlying rocks. Phreatic groundwater underneath the tablelands usually flows from the center of the tablelands to the edges and outcrops as springs in the foot of the loess slope. Much of the phreatic groundwater with great abundance in the tablelands has been exploited for multiple uses. In the hilly-gully regions of the Loess Plateau, the terrain is strongly cut by gullies, enabling groundwater discharge. Most of the fissure water outcrops and is discharged as springs in the slopes, forming seasonal surface water in the valleys. The groundwater modulus in the arid hilly-gully regions of the Loess Plateau is usually smaller than $1.0 \times 10^4$ m$^3$/km$^2$ per year, while that in the semiarid and semi-humid hilly-gully regions of the Loess Plateau ranges from
1.0 × 10^4 to 5.0 × 10^4 m³/km² per year, indicating that groundwater recharge in the loess tablelands and the hilly-gully regions is limited. According to the literature [23], the amount of total natural groundwater resources in the loess tablelands and the hilly-gully regions of the Loess Plateau is only 63 × 10^8 m³ per year.

Groundwater in the mountainous parts of the Loess Plateau is mainly fissure water and karst water. Fissure water is widely distributed on the Ordos Plateau, in the Guide and Qinshui Basins, and in the water division zones of the Taihang, Lvliang, and Liupan mountains. Karst water is mainly found in the Taihang, Lvliang, and Beishan mountains [48]. Vertical infiltration of precipitation is the most important recharge source for groundwater in the mountainous regions [49]. Groundwater in the mountainous regions is more abundant than in the loess tablelands and the hilly-gully regions, and the groundwater modulus in the mountainous regions ranges from 5.0 × 10^4 to 15.0 × 10^4 m³/km² per year [23]. The amount of total natural groundwater resources in the mountainous regions of the Loess Plateau is approximately 94 × 10^8 m³ per year.

Compared to surface water, groundwater can be protected by the upper unsaturated zone and therefore is usually less contaminated and of better quality than surface water. In general, groundwater in the Loess Plateau is mainly freshwater with a salinity below 1000 mg/L. Brackish water with a salinity higher than 1000 mg/L is mainly distributed in northern Yinchuan, Western Gansu, and the Xihaigu region of Ningxia (including Xiji, Haiyuan, and Guyuan). The freshwater resource accounts for about 86% of the total natural groundwater resources, while brackish water accounts for 10% and saline water with a salinity higher than 3000 mg/L for about 4% [46, 48]. Natural groundwater quality anomalies and anthropogenic groundwater pollution are two main issues occupying local decision-makers and scientists. In many parts of the Loess Plateau, the natural background contents of harmful elements such as fluoride, arsenic, Mn, and Cr⁶⁺ are abnormally high. For example, abnormally high concentrations of fluoride have been reported in the Yinchuan Plain [30, 50, 51], southern Ningxia [52, 53], the Guanzhong Basin [29], and the Datong Basin [54, 55]. High arsenic levels in groundwater are also common in the northern Yinchuan Plain [51], the Datong Basin [56], and the Hetao Plain [57]. These groundwater quality anomalies are most likely the results of specific geological and hydrogeological conditions and water-rock interactions [58].

Anthropogenic groundwater contamination has also been widely reported in many parts of the Loess Plateau and has gradually become the most serious risk for human health. Common anthropogenic factors affecting groundwater quality include agricultural activities, industrial effluents, coal and oil mining activities, tourism, and wastes from livestock. Agriculture is an important factor influencing shallow groundwater quality and is mainly responsible for groundwater nitrate pollution in many agricultural production

**Water in Loess, Table 3** Natural groundwater resources of different types on the Loess Plateau [46]

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Area (10⁴ km²)</th>
<th>Groundwater amount (10⁸ m³ per year)</th>
<th>Percentage (%)</th>
<th>Groundwater modulus (10⁴ m³/km² per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore water in loose rocks</td>
<td>16.59</td>
<td>195.64</td>
<td>58.67</td>
<td>11.79</td>
</tr>
<tr>
<td>Fissure water in crystalline rocks</td>
<td>10.43</td>
<td>48.63</td>
<td>14.58</td>
<td>4.66</td>
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<td>Karst water in carbonate rocks</td>
<td>4.51</td>
<td>44.98</td>
<td>13.49</td>
<td>9.97</td>
</tr>
<tr>
<td>Pore-fissure water in elastic rocks</td>
<td>9.94</td>
<td>25.59</td>
<td>7.67</td>
<td>2.57</td>
</tr>
<tr>
<td>Pore-fissure water in loess and underlying rocks</td>
<td>20.00</td>
<td>18.61</td>
<td>5.58</td>
<td>0.93</td>
</tr>
<tr>
<td>Total</td>
<td>61.47</td>
<td>333.45</td>
<td>100.00</td>
<td>5.42</td>
</tr>
</tbody>
</table>

Water in Loess
regions of the Loess Plateau. Guo et al. [59] studied the impacts of fertilization practices on environmental risks of nitrate in semiarid farmlands of the Chinese Loess Plateau by analyzing soil profiles. Wu and Sun [31] reported shallow groundwater pollution in an agricultural and industrial region of the Guanzhong Basin and concluded that agricultural and industrial activities are important factors affecting nitrate pollution of shallow groundwater. As the Loess Plateau is rich in coal and oil resources, the exploitation of these resources has entailed serious groundwater pollution. Pan et al. [60] and Ma et al. [33] have reported petroleum pollution in both loess and groundwater underneath the loess. They concluded that petroleum contamination caused by the oil industry is the largest source of pollution, leading to the deterioration of the water quality.

Considering the significance of groundwater pollution in the loess areas, groundwater quality research to alleviate water pollution in northwest China is crucial. Li [61] and Li et al. [62] raised concerns about groundwater quality research in Western China and proposed to enhance groundwater monitoring networks, increase research investments from central and local governments, improve basic environmental education, and strengthen the collaboration among different organizations and parties.

**Soil Water on the Loess Plateau**

In addition to surface water and groundwater, soil water is another important and valuable water resource for agriculture on the Loess Plateau, especially in semiarid and semi-humid areas. It is a bond between surface water and groundwater conversion [63]. Because the unsaturated zone on the Loess Plateau is thick, only a small portion of precipitation can flow into rivers or infiltrate into aquifers, recharging groundwater. Most of the precipitation on the Loess Plateau is stored in the unsaturated zone as soil water. Soil water is an important component of water resources and a direct source and key element for vegetation growth and, therefore, highly important for ecological civilization construction. As such, research on soil water resources has become a hot topic in hydrogeological and ecological communities [64, 65].

The thick loess cover on the Loess Plateau has created a unique condition for the conversion of rainwater resources into soil water. Loess soil is thick and porous, and its effective porosity can reach 25–30% [23]. The soil water capacity for a 200 cm soil layer can reach 551.1–847.4 mm, that is, the theoretical soil water amount can reach $55.1 \times 10^8$ m$^3$–$84.7 \times 10^8$ m$^3$ for each 10,000 km$^2$ of loess land. However, the time of soil water retention is relatively short due to gravity and strong evaporation, and therefore, not all soil water can be used by vegetation. When the water content is larger than a threshold, soil water will infiltrate into groundwater. This threshold is called field capacity or field moisture capacity and represents the highest amount of water content that can be retained in the soil under field conditions. The water content under which plants cannot liberate the remaining moisture from the soil particles is called wilting point. Water available for vegetation growth is defined as available water capacity, the soil water within the range between field capacity and wilting point [66]. On the Loess Plateau, the total amount of the available soil water resources is $1785.54 \times 10^8$ m$^3$ [23]. It should be noted that the soil water storage capacity considerably varies under different land cover/land use types [67], and soil water content also changes with soil depth [68].

Overall, the total amount of regional water resources in the loess areas is controlled by precipitation. Surface water and groundwater are both derived from precipitation and readily available for multiple uses. Soil water is also derived from precipitation but cannot be used directly by humans. Due to the thick loess layer on the Loess Plateau, where surface water and groundwater are either limited or contaminated, soil water resources provide a supply for the majority of rain-fed agriculture and forestry. Such resources must therefore be protected as surface water and groundwater and should be considered in regional water resources allocation.
**Future Directions**

The Loess Plateau is a significant part of the Belt and Road Initiative, which acts as a bridge between Asia and Europe [3]. The water resources problems along the road have always been the concern of international scholars [69, 70], as the Belt and Road Initiative will increase the demand for water resources and the intensified human activities negatively impact the environment. However, based on the Belt and Road Initiative, many national and international organizations and institutes are involved in various scientific research projects to minimize the negative effects. Today, the Loess Plateau, as the most important Chinese part of the Belt and Road Initiative, draws much more attention from scholars than ever.

Water is the key to the success of the initiative and of the ecological civilization construction. A number of significant results have been achieved regarding water resources allocation, water conservation, and water quality protection on the Loess Plateau. However, the water-related issues in the loess areas of China still need to be evaluated in detail. The following issues or research fields are important and should be seriously considered:

- **Spatiotemporal evolution and drought history of the Loess Plateau.** This topic is of great value to track the water environment when loess was deposited and the cause of drought. Such research will require a long record of historical climate data and geochemical data.
- **Impacts of climate change on water resources and water resources vulnerability on the Loess Plateau.** Based on the analysis on the impacts of climate change on the water demand and water supply, this research topic should help to establish a new balance between water demand and water supply and assess water resources vulnerability.
- **Relationship between human activities and drought on the Loess Plateau.** This research field focuses on the impacts of land use/land cover changes on hydrological processes at different scales. It links human activities and climate change, which is quite complex and therefore requires international collaboration.
- **Impacts of human activities on the permeability of loess.** Large-scale human activities will completely change the physical properties of loess, affecting loess permeability and soil water dynamic. Research on this topic, via experiments and numerical modeling, seeks answers to reduce these negative impacts.
- **Groundwater research on the Loess Plateau.** The thick soil layer and the diverse and complex geological structures and geomorphology on the Loess Plateau impede groundwater research. It is therefore necessary to find ways to accelerate groundwater research on the Loess Plateau by proposing key groundwater research topics and introducing international collaborations and advanced technologies.

**Bibliography**

**Primary Literature**

9. Pumpelly R (1866) Geological researches in China, Mongolia and Japan during the years 1862 to 1865. Smithsonian Contributions to Knowledge, Washington


64. Liu X, He B, Yi X, Zhang L, Han F (2016) The soil water dynamics and hydraulic processes of crops with plastic film mulching in terraced dryland fields on the


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