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# Assess the potential of solar irrigation systems for sustaining pasture lands in arid regions – A case study in Northwestern China

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ABSTRACT

The combined impact of global climate change and increasing human activities has led to the severe deterioration of grasslands in China. Using the solar irrigation systems is an effective way for sustaining pasture lands in arid regions. A solar irrigation system is the device that uses the solar cell from the sun's radiation to generate electricity for driving the pump. And photovoltaic pump consists of an array of photovoltaic cells and pumps water from a well or reservoir for irrigation. Although ecologists and organizations constantly work and find ways to conserve grasslands through irrigation systems that use solar energy, issues on water resources are not yet thoroughly discussed. This paper takes into account the main factors in the study of water resources, including precipitation and groundwater, to analyze the feasibility of using a photovoltaic (PV) pumping irrigation. The appropriate area for such a PV pumping irrigation in Qinghai Province is also presented. The results show that the grasslands appropriate for PV pumping cover about 8.145 million ha, accounting for 22.3% of the grasslands in the entire province. Finally, the problems and countermeasures of PV pumping irrigation, including the impact on regional water balance, groundwater level and highland permafrost, are also considered.



## 1. Introduction

Grasslands in China have deteriorated severely in the past 30 years because of the impacts of global climate change along with excessive grazing. The application of renewable energy for grassland irrigation is necessary to protect the ecosystems and increase incomes in these pastoral areas. Solar powered irrigation systems are the most widely used tool for the pasture conservation. They usually consist of an array of solar cells, a power converter, a control unit, a pump and a well or reservoir. The photovoltaic pump is the key of the solar pump irrigation system. The operating principle is that the photovoltaic cells are capable of generating to electricity for driving the pump. The photovoltaic pumps have many advantages including they operate on freely available sunlight and therefore incur no fuel or electrical costs. They are also environmentally friendly, reliable and have a long working life. And photovoltaic technology has been one of the most promising and widely used technologies available today, considering the need for environmental restoration [1]. Bell Laboratory is a pioneer in efficient solar cell, as reported by the New York Times in a front page article entitled, "Vast power of the sun is tapped by battery using sand ingredient" [2–4]. Since then, solar energy has been applied in many different fields. PV pumping is now being applied for different uses in many regions of the world. For instance, a PV pumping project in South Morocco was begun in 1997, and by 2005, the project had already reached 18 villages, affecting 15,000 people [5]. PV-powered pumping is also used in Saudi Arabia in supplying sufficient quality water [6]. Nowadays, PV pumping irrigation is being applied for the conversation of pastures in many parts of the world. At the same time, solar energy is being used in grassland pumping for over 25 years in Namibia [7]. The results show that solar pumping can operate longer and more effectively compared with traditional irrigation measures. The system also directly improves quality of life and promotes socio-economic development in that area [8]. The application of this technology in Mexico and German also demonstrates that solar energy pumping produces more benefit and less pollution [7]. PV systems for the pumping of groundwater are also used in Upper Egypt, proving that the cost of the water unit pumped by PV systems is significantly lesser than that pumped by diesel systems [9]. Bhave [10] has discussed the potential for solar water-pumping systems in India and got the conclusion that solar photovoltaic systems are suitable in areas where cheaper sources of energy are not available. The research and application of solar irrigation system in China has not caused widespread concern. The application of solar powered irrigation has significant meanings in China, especially in Northwestern China. For the distribution of water resources is uneven and the precipitation is scare in that region. Using photovoltaic

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pump system for irrigating the grasslands is very necessary. Some specialists have applied solar energy for grassland pumping in small areas of the West for research purposes. The results show that there is a high potential for solar energy pumping and that the future of application is promising [11,12].

Nevertheless, although many specialists in solar energy have already carried out experiments in solar PV water pumping, the appropriate region for solar PV pumping in China has yet to be discussed at length. This study first discusses the appropriate indicators for solar irrigation. Qinghai Province is set as a research object. The most suitable geographic allocation for PV water pumping, based on the condition of local water resources and grasslands, is also presented. The geographic allocation of grasslands suitable for solar irrigation and the appropriate region for solar PV pumping in China are also discussed. Finally, the positive and the negative effects of solar water pumping and the appropriate countermeasures for the problems caused by solar PV pumping are given.

## 2. Background

Solar irrigation is an effective system that can contribute to grassland conservation. It can increase the livestock carrying capacity of grasslands and the income of the herdsmen. However, the application of solar irrigation is closely associated with the condition of local water resources and terrain. Thus, selecting appropriate factors that indicate the status of water resources and the geographic condition for research is very necessary. In this section, precipitation and the slope of the ground surface are selected as indicators when analyzing the viability of solar irrigation.

### *2.1. Appropriate indicators for solar irrigation systems*

#### *2.1.1. Suitable precipitation for solar irrigation*

Precipitation is associated with the water demand of plants closely. The receiving water of grasslands (in the process of grassland water cycle) comes mainly from precipitation and irrigation. The need for solar irrigation depends directly on precipitation, and the water demand of grasslands should be satisfied to ensure the steady growth of pastures. The amount of precipitation added to the irrigation norm must be higher than the water demand of grasslands. The effective precipitation which is the fraction of precipitation that can be effectively used by grasslands without irrigation measures is the main source of grasslands [13]. The relationship between precipitation and water demand can be described through Eq. (1), where *P* represents effective precipitation, *I* represents irrigation norm, and *W* represents the water demand of grasslands. The equation is set with month time scale to meet the water demand of grasslands especially in growing periods.

$$P + I > W \tag{1}$$

The water industry standard of China, the SL334-2005 Technical Specifications for Pastoral Grassland Irrigation and Drainage [14], states that the water demand of meadow grassland should be 525–600 mm in a normal year. The Water Use Norms of China states that the irrigation norm of natural grasslands in a normal year is around 1650–3000 $m^3$/ha, which is equivalent to a depth of 165–300 mm. Given that the normal water demand must be satisfied to maintain the normal growth of grasslands, there must be an appropriate amount of precipitation (about 300 mm, based on Eq. (1) considering the affect of deficit irrigation) aside from the supplement of irrigation water. Similarly, irrigation is no longer required if the annual precipitation is greater than the water demand of the normal growth of grasslands, and as such, developing water pumping irrigation is not significantly meaningful. The rainfall threshold in the area suitable for solar energy pumping irrigation in China is then generally between 300 and 600 mm annually. Solar energy pumping irrigation may still be considered even if the average annual total precipitation satisfies the water demand of grasslands in an area with a very uneven distribution of precipitation in a year. This is particularly applicable from March to May, when there is inadequate precipitation and large water demand in pasture lands.

#### *2.1.2. Suitable slope for solar irrigation*

Slope is related with the feasibility of solar irrigation closely. Although micro-spray irrigation is highly adaptable to the terrain, the flow rate of the nozzle is higher than that of drip irrigation so if the slope is high, runoff may be formed because of the restriction of infiltration, resulting in resource and energy wastage as well as soil erosion. The slope must not be more than 2–5% for furrow irrigation, while the slope must not be more than 0.2% for border irrigation. Micro-spray irrigation, which has better adaptability than the two irrigation methods, must also be applied to relatively flat terrains so it is usually applied to grasslands in interior basins, large valleys in mountains, river valley plains of the mainstream and tributaries of rivers, and other areas with a slope of not more than 5–9%.

#### *2.1.3. Suitable temperature for solar irrigation*

Temperature is another important indicator for the application of solar irrigation system. For one thing, the change in temperature can result in the change in evaportransation. And the evaportransation directly affect the water demand of plants. According to the Penman–Monteith equation, the temperature and evaportransation tend to be positive correlation. Higher temperature will increase the water demand of plants and add more pressure to the photovoltaic pump. So the suitable annual temperature for the solar irrigation should be less than 20 °C. For another, low temperature may affect the working efficiency of the solar irrigation system. Experiments show that the working efficiency of solar irrigation system is lower when the temperature is below minus 30 °C. The appropriate temperature for solar irrigation system should be more than minus 30 °C.

#### *2.1.4. Suitable solar radiation for solar irrigation*

Solar radiation repents the solar energy availability is one of the important indicators for the solar irrigation system. It is the original energy source of the photovoltaic pumping. So enough solar radiation is the assurance for the application of solar irrigation system. The annually amount of solar irrigation in a region should at least eloquent to 120 billion tons of standard coal. The annual sunshine should be more than 1400 h. The sunshine rate should be more than 30%.

### *2.2. The economic benefits analysis of solar irrigation*

The economic benefit is an important indicator in evaluating the feasibility of solar irrigation. Ould et al. [15] have evaluated the economic feasibility of the PV pumping system in comparison with systems that use diesel generators. The difficulty and economic benefit of applying solar irrigation vary significantly under different precipitation conditions. This study selected a water pump of type No. WQ15-26-1.5 to analyze the return on investment under different precipitation conditions. Prior inputs in the experiments include solar battery, controller, solar moving cart, water pump, hose of sprinkler irrigation, shallow well, and well shelter. The prices of the prior inputs are shown in Table 1. Considering the water consumption of the grasslands in Qinghai, the watering period was set at 16 days, and the solar battery pump working time was set 8 h and 20 min (8:50–17:10).

**Table 1**
Cost of the instruments used in the experiments.

| Instrument | Unit price (yuan) | Service life (year) |
|---|---|---|
| Solar battery | 38/watt | 25 |
| Controller | 5500 | 6 |
| Solar moving cart | 12,000 | 6 |
| Water pump | 500 | 10 |
| Hose of sprinkler irrigation | 3/m | 4 |
| Shallow well | 25,000 | 10 |
| Well shelter | 5000 | 10 |

Irrigation can increase the carrying capacity of grasslands for livestock. The carrying capacity of natural grasslands (around 80% of the total grasslands area) is different from those of man-planted forage grasslands (around 20% of the total). The annual incremental benefit of irrigation by unit pump can be calculated through the following equation:

$$W_{\text{Inc.}} = 0.8 \times W_0 \times \Delta W_0 \times A + 0.2 \times W_0 \times \Delta W_1 \times A \quad (2)$$

where $W_{\text{Inc.}}$ is the annual incremental benefit of irrigation by unit pump, $W_0$ is the value-added of a standard sheep, $\Delta W_0$ is the incremental number of standard sheep per mu of incremental irrigated natural grassland, and $\Delta W_1$ is the incremental number of standard sheep per mu of incremental irrigated man-planted forage grassland. Therefore, the rate of returns on investment can be estimated through the following equation:

$$W_R = W_{\text{Inc.}}/W_{\text{inv}} - 1 \quad (3)$$

$W_R$ represents rate on investment, and $W_{\text{inv}}$ represents the investment (derived by applying the above equations). From this, output per unit input under different precipitations can be calculated.

### 2.3. Groundwater sustainability and solar irrigation

It is important to keep the groundwater sustainable because solar lift irrigation may affect the groundwater cycle. This section defines the difference between groundwater recharge and effective irrigation norm as an indicator for the evaluation of groundwater sustainability with solar lift irrigation [16]. Groundwater recharge is calculated by multiplying the precipitation with the recharge coefficient, while the effective irrigation norm is calculated by multiplying the irrigation norm with effective irrigation coefficient. A positive indicator indicates sustainable exploitation of groundwater, while a negative indicator indicates water deficit resulting from higher exploitation than the recharge rate given as Eq. (4). Where $P$ is the precipitation, $\eta$ is the recharge coefficient, $M$ is the irrigation norm, and $\mu$ is the effective irrigation coefficient. The coefficient $\eta$ and $\mu$ are calculated by an empirical formula based on local irrigation experiments.

$$S = P \times \eta - M \times \mu, \quad (4)$$

## 3. Case study area – Qinghai Province

### 3.1. Climate

Qinghai Province was chosen as the research object of this study. Qinghai lies in the west of China the northeast of the Qinghai–Tibet plateau. It is located in the 31°39′–36°12′ north latitude and 89°45′–102°23′ east longitude. The Province is 1200 km from east to west and 800 km from south to north. The total area is 714,400 square kms. The terrain is complex and diverse, with the following trends: west high, east low, north and south high, and middle low. The complex terrain gives the region a unique plateau continental climate. The sunlight time is long, and the air is thin. The annual sunlight ratio is above 2500 h. Most of the region is 300–500 m above sea level. The mean temperature annually is between −5.7 and 8.5 °C. The mean temperature shows the following trends: north and south-low and middle high. The annual precipitation is 290 mm. The Yellow, Yangtze, and Lancang Rivers all originate from Qinghai Province.

### 3.2. Solar radiation resources

The atmosphere is relatively thin and the sunlight through rate is high because Qinghai is located in the high latitudes. The solar radiation resource is rich with the influence of the dry climate. The annual sunshine is in the range of 2323–3575 h, the second highest in China [17]. The sunshine rate is between 53% and 81%. The amount of solar energy being received is equivalent to 162.3 billion tons of standard coal. The spatial distribution exhibits a specific characteristic of "high west-low east." The "Cold Lake" area in the west has the largest solar radiation resources in the region.

### 3.3. Water resources condition

#### 3.3.1. Characters

Precipitation in Qinghai is lesser than those in other parts of east China because it is located in the interior continent, far from oceans and bordered by high mountains, such as the Tsinling Mountains. The water resource in Qinghai is uneven in the spatial and temporal distribution sense because of the impacts of the terrain and population. The characteristics of the water resources in Qinghai are described below.

Water resources are scarce. Qinghai Province, with an average annual precipitation of 290.5 mm, is located in the arid zone. Water resources in Qinghai are estimated to be at 62.93 $km^3$ or 2.2% of the total amount in China (equivalent to 88.1 mm or 30.1% of the national average). Moreover, the surface water yield in the province is 61.12 $km^3$ (equivalent to 85.6 mm or 30.4% of the total amount in China and only 27% of the global total).

There are uneven spatial and temporal distributions of water resources. The spatial and temporal distributions of the water resources are inconsistent vis-à-vis the distributions of land, natural resources and population, and the pattern of economic and social development. The seasonal distribution of water resources is uneven because runoff in the flood season of 4 months accounts for more than 50% of the annual total and even more than 70% in some rivers, resulting to difficulty in water use. Runoff in the irrigation season (March to May) only accounts for 15% of the annual total, and this cannot satisfy the irrigation requirement. The sharp inter-annual variation in the runoff is disadvantageous to the development and utilization of water resources. The uneven regional distribution of the water resources is also inconsistent vis-à-vis the trend in economic and social development. Huangshui, a tributary of the Yellow River with only 3.5% of the water resources in all of Qinghai, is utilized by 52% of the population, 52.3% of the cultivated areas, and contributes to 67% of the GDP of the Province.

There is a high potential in water resources development. The water use of 2.7 $km^3$ amounts to only 4.84% of the provincial gross water resources. Consumptive use accounts for only 11.9% of the provincial available water resources, indicating that Qinghai has a high potential in water resources development. However, the potential significantly differs between the regions. For instance, the consumptive use in the Huangshui River basin and the Qinghai Lake area has almost reached the limit of available water resources.

There is a stable trend in the change of water resources conditions. In general, precipitation, runoff, and gross water resources of the provincial total and major river basin basically remain unchanged for the past 50 years.

*3.3.2. Precipitation distribution*

The spatial distribution of precipitation is closely related to that of the grasslands in the Qinghai Province, except for the Qaidam Basin. This shows that the grasslands in the Province rely on precipitation as the main water resource, and the availability of precipitation is the dominant factor affecting the spatial distribution of the grasslands.

Qaidam Basin, as mentioned previously, lies within the northwest semi-arid region of Qinghai Province and receives considerably less rainfall than the other parts of the province. However, it is located in a basin area where there is direct contribution of groundwater; thus, there are patches of pastures distributed throughout. The main concentration of grasslands is located in areas where there are abundant groundwater resources.

*3.3.3. Runoff distribution*

The annual runoff depth varies from 0 to 410 mm, with maximum depth in the southeast and decreasing towards the northwest. The Qaidam Basin and Chaka-Shazhuyu Basin are areas of low runoff with annual depth of 50 mm; Yushu–Nangqian and Jiuzhi–Banma, both located in the southeast region and the east of Hexi inland river, are high runoff areas with annual runoff depths of over 300 mm. In contrast, the Qaidam Basin produces an average annual runoff of less than 5 mm.

*3.4. Water needs*

Qinghai is considered as a region suffering from scarcity in water resources and frequent occurrence of water-related disasters. Competitive use may be experienced in the near future owing to the inconsistent spatial and temporal distributions of water resources, demand distribution for other resources, the pattern of economic and social development, difficulty in water usage, and restricted availability of water resources. This may eventually constrain the further economic and social development of Qinghai. The rational development of scattered groundwater by considering the water resources conditions of Qinghai is thus recommended for future water resources development and utilization. This will serve the needs in industrial and agricultural production and increase the income of the herdsmen at the same time.

*3.5. Grasslands condition*

Qinghai Province is one of the five largest pastoral areas in China, covering a total area of natural pasture of 3.645 million ha, with 3.16 million ha (86.7%) of available pasture. The winter and spring pastures cover 1.586 million ha (49.9% of the total area), while the summer and autumn pastures cover 1.574 million ha (50.1% of the total area). The natural pasture in Qinghai Province occupies 10% of the total pastures in China, ranking fourth in the country. The national classification system categorizes nine main types of pastures, seven sub-types, 29 pastoral groups, and 173 pastoral types throughout Qinghai Province. The grass output from the pasture is 2533 kg/ha, and the total output is 79.6 billion kg.

The distribution of grasslands in Qinghai Province exhibits specific characteristics of "high east-low west; high south-low north." The Qaidam Basin located in the northwest is the lowest part of the Qinghai grassland; the pasture extends outward from the Qaidam Basin in the east, southeast, and southerly directions resembling three, long fan-shaped blades; the south part of the Qaidam Basin is a high-value grassland (Fig. 1). The compatible of grasslands and water resources can be seen in Fig. 2. And the compatible of grasslands and runoff are presented in Fig. 3. From the figure it can be seen that the location of the grasslands is associated with the runoff depth. Grasslands mainly occupy areas of abundant surface water resources and are distributed along strips where runoffs are located. Despite the relatively low runoff in the Qaidam Basin, there are grasslands interspersed in the area because of the supply of water from groundwater sources.

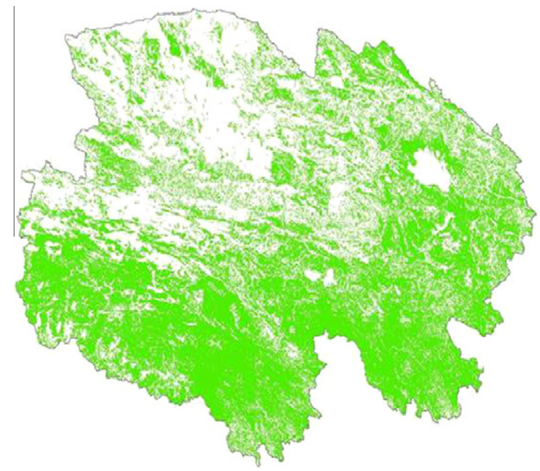

**Fig. 1.** The distribution of grasslands in Qinghai Province.

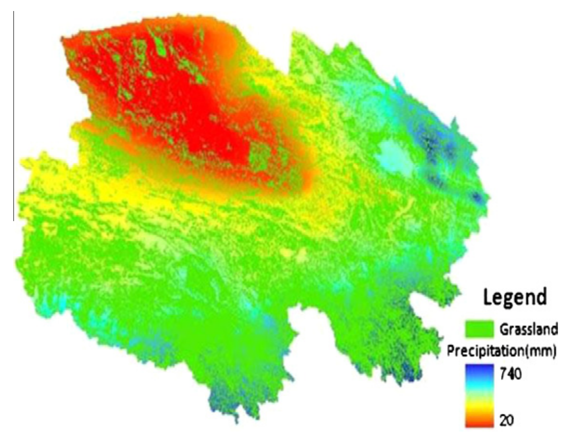


**Fig. 2.** Overlay map showing the precipitation and grasslands of Qinghai Province.

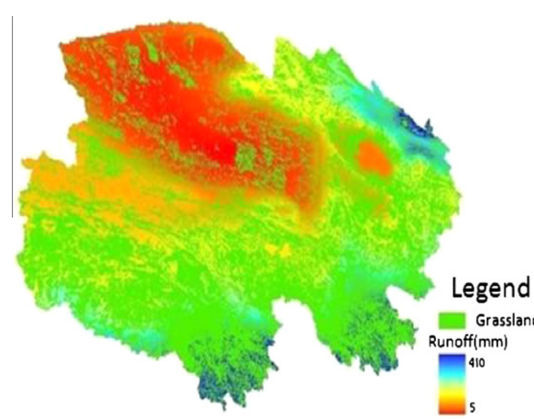


**Fig. 3.** Overlay map showing the runoff and grasslands of Qinghai Province.

*3.6. Economic benefits*

Applying the method mentioned above, the economic benefit under different precipitation condition can be seen in Fig. 4. It shows that solar lift irrigation is feasible in cases when the

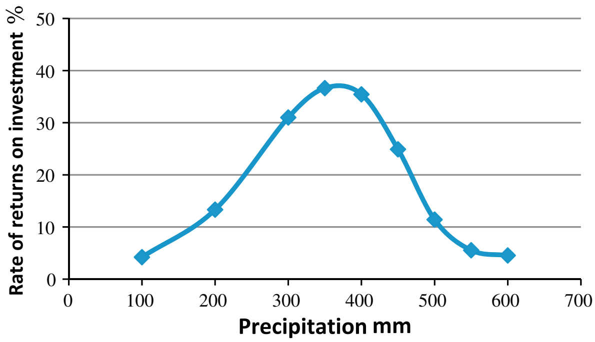


**Fig. 4.** Relationship of the return rate on investment (with precipitation).

precipitation is between 300 and 600 mm. The output per unit input reaches the maximum or the highest economic benefit of solar lift irrigation in areas with 350–400 mm of precipitation. Although the annual precipitation of Qinghai Province is less than 300 mm, the area where the precipitation is more than 300 mm accounts for a large proportion. The annual precipitation of Qinghai Lake area is just between 350 and 400 mm.

### 3.7. Groundwater sustainable evaluation

The calculation results show that a total area of 5.65 million ha is suitable for solar lift irrigation because of sustainable groundwater utilization. The areas with precipitation or 350–400 mm and without groundwater overdraft should be selected for lift irrigation, considering both the benefit of solar lift irrigation and groundwater sustainability. And the selected areas cover about 1.74 million ha. These areas can gain more benefits from the lift irrigation and groundwater sustainability.

## 4. Results

### 4.1. Appropriate area for solar irrigation in Qinghai Province

Based on a comprehensive consideration of all the factors previously described, the planned appropriate regional distribution and size of irrigated grasslands in Qinghai Province can be seen as Fig. 5. From this Figure, it can be seen that the appropriate area for solar irrigation mainly distribute in the southwest of Qinghai Province and the Qinghai Lake area. The area covers about 8.145 million ha, accounting for 22.3% of the grasslands in the entire province. Fig. 6 gives the best practice of grasslands and

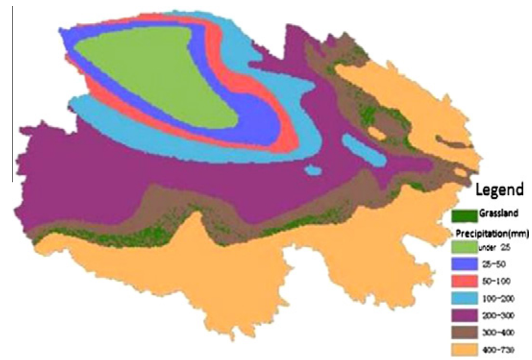


**Fig. 6.** Distribution of grasslands in different water resources conditions.

precipitation area. The area covers about 1.73 million ha, accounting for 22.3% of the grasslands in the entire province.

### 4.2. Appropriate area for solar irrigation in China

#### 4.2.1. Grasslands in China

China is one of the three largest pastoral countries in the world with a total area of natural pasture reaching 3928.32 million ha. The impact of precipitation and graphic characteristics has led to a distribution of grasslands exhibiting specific characteristics of "high west-low east." The Daxinganling-Yianshan Mountain-East Qinghai–Tibet Plateau line divides the grasslands with those in the east occupying 82%, while those in the west occupy only 18%. The grasslands are widely distributed in the west of China's northeast, Inner Mongolia, northwest of China and the Qinghai–Tibet Plateau. Fig. 7 shows the distribution of grasslands in China.

#### 4.2.2. The distribution of appropriate area for solar irrigation

The precipitation and slope of surface are selected as indicators for PV pumping. The precipitation should be between 300 and 600 mm, and the slope should be less than 5°. An analysis of the relationship among precipitation, grassland, and slope reveals that the area suitable for PV pumping irrigation is about 412.47 million ha, accounting for 10.5% of the total grasslands area. Fig. 8 shows the distribution of appropriate grasslands. The regions have the potential for PV pumping irrigation are mainly distributed in the south and northeast regions in China. The feasibility of solar water pumping is restricted by many other indicators. Whether it is feasible to carry out solar irrigation in all the potential areas should be discussed further.

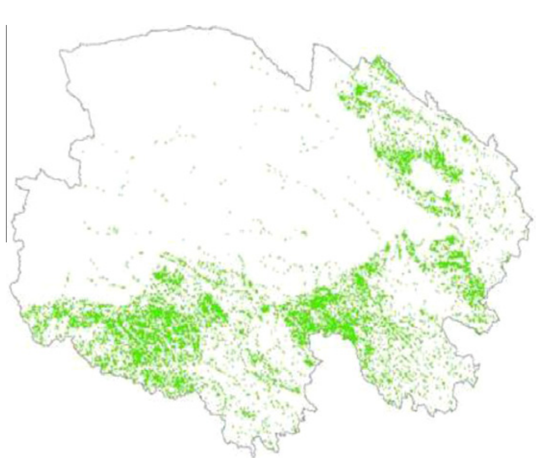

**Fig. 5.** Distribution of suitable irrigation areas in Qinghai Province.

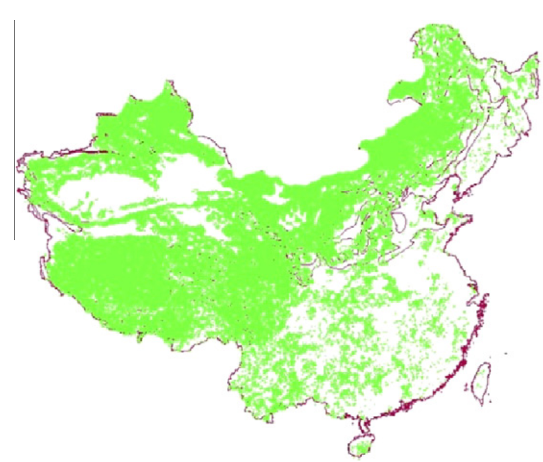

**Fig. 7.** Distribution of grasslands in China.

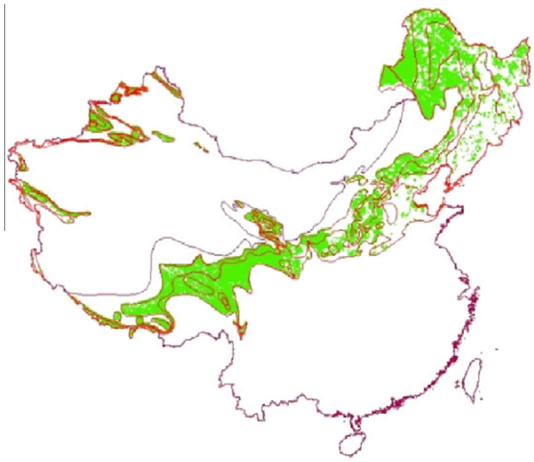

**Fig. 8.** Appropriate grasslands for PV pumping irrigation in China.

## 5. Discussions

Solar PV pumping is an effective system that can contribute to grassland conservation. However, it may also cause certain problems because it can decrease the groundwater level. This section discusses the positive and negative effects of solar PV pumping. The countermeasures for the problems arising from solar water pumping are also mentioned.

### *5.1. Impact on regional water balance*

The extraction of groundwater or surface water for irrigation in the water balance process causes a reduction in the amount of groundwater and surface water and an increase in evaporation and rainfall water infiltration, thus leading to the flux increase in local small cycles. The use of groundwater for irrigation not only reduces the availability of groundwater, which leads directly to decreasing water tables, it also affects the local hydrological cycle. Pumping groundwater to the surface for irrigation increases the surface soil moisture in irrigated areas, thereby increasing evapotranspiration and the flux of local hydrological cycles. Moreover, such modifications in the local hydrology may cause the formation of local micro-climate as groundwater from deeper zones is pumped to the surface.

### *5.2. Impact on groundwater level*

An underground water pumping project produces short-term decline in localized groundwater levels even though a part of the irrigation water replenishes groundwater loss through seepage. From the perspective of water balance, water pumping increases evapotranspiration, and as such, groundwater abstraction is greater than the replenishment. This can lead to a decline in groundwater levels in the long term. Past experiences have shown that groundwater over-exploitation has caused falling water tables and the formation of groundwater funnel, eventually leading to a range of adverse effects. Adequate pumping of groundwater should thus be allowed within tolerable levels. The current design of solar water pumping for irrigation facilities has a life span of 25 years. The peak of population increase in China is predicted to be over in 25 years, so the pressure of grazing on pastures may be reduced by that time. The plan is to replenish the natural recharge from rainfall and restore grassland ecology and groundwater supply.

### *5.3. Impact on highland permafrost*

The use of groundwater for crop irrigation affects the localized water cycle process, leading to changes in the dynamic equilibrium of permafrost (e.g., thinning). On one hand, water pumping for irrigation affects the water table, resulting to land subsidence; on the other hand, it affects the permafrost (causing a wide range of ecological problems) as well as the stability of structural foundations. These changes are likely to affect the buildings on the plateau, railways, and other infrastructures. These impacts on permafrost must be avoided; hence solar energy projects for underground water must avoid areas with dense buildings as well as rail systems and major roads.

### *5.4. Research on countermeasures*

There is abundant solar energy resource in Northwestern China. Solar energy water-pumping systems provide local residents with convenient access to water and can also improve their living standards significantly. The impact of pumping water to the entire water cycle must also be recognized. The measures listed below should be considered to ensure regional water balance.

– *Rationalizing the structure of vegetation.* There is a need to analyze the performance of the water consumption of vegetation on the plateau area to selectively breed drought-resistant vegetation cover with low water needs. Appropriate vegetation can reduce the amount of water supply, increase output, and improve the living standards of farmers and herdsmen in Qinghai Province.
– *Improving the efficiency and rationale of water use.* There is a need to ensure the rational use of water resources and provide effective means in safeguarding the ecological environment. The control of total water consumption to ensure that more water can be left in the soil layer is also necessary. Effective water consumption management can reduce evaporation and minimize the amount of bare soil evaporation as well as minimize the selection of optimal planting structure.
– *Establishing ecological monitoring and early warning systems.* The water intake process requires the regulation and control of groundwater level while considering the minimum limit of the water table. This must be done so that groundwater extraction is managed within a certain range. It is necessary to establish a real-time monitoring system of groundwater levels through monitoring stations. The authorities should be alerted so the water abstraction rate can be adjusted accordingly when the water level drops below that level. There is also a need to improve ecological monitoring capabilities. Numerous regional developments show that ecosystem health is essential in maintaining regional socio-economic sustainable development.
– *Limiting the abstraction of groundwater around major civil engineering works.* The abstraction of groundwater may cause land subsidence and geological problems, such as permafrost destruction, that can lead to damages to building structures. As such, solar energy water pumping irrigation projects must be at least 5 km away from major railway lines, highways, water conservancy, civil engineering projects, and other key hubs.

## 6. Conclusions

Solar PV powered irrigation is an effective system that can contribute to grasslands conservation. This study looks at precipitation, slope, and water quality as controlling factors. The grasslands (in the research area) that meet the above requirements cover about 8.145 million $hm^2$, or 22.3% of the total grassland area of Qinghai Province, the chosen subject. An area of about 995,000 $hm^2$ is suitable for surface water irrigation, accounting for 12% of the total area considered suitable for irrigation; Another 7.15 million $hm^2$ is suitable for groundwater irrigation, accounting for 88% of the area suitable for irrigation. Therefore, groundwater irrigation is the main choice for the grasslands suitable for solar energy pumping irrigation. The areas most suitable for the pumping irrigation should be those with annual precipitation of 300–400 mm, considering both the benefit of solar energy pumping irrigation and groundwater sustainability. Those areas cover a total area of 1.73 million $hm^2$, and are mainly distributed in a zone (in a reversed ‘‘C’’ shape) on the two banks of the Qinghai Lake. Solar energy pumping irrigation should first be extended in those areas. The grasslands appropriate for PV pumping in China are also discussed. Such areas cover about 412.47 million ha, accounting for 10.5% of the grasslands in China.

Applying solar energy pumping irrigation can create considerable opportunities in promoting local development. First, the new irrigation systems can protect the grasslands from deteriorating. Second, they improve the quality of people's life directly by stimulating socio-economic development indirectly. However, it may also produce bad effects. Solar energy pumping irrigation may intensify the flux of water cycle in local areas and result in the decreased groundwater level that, in turn, can damage the plateau permafrost. Certain measures that can prevent the negative effects include rational adjustment of cropping structure and control of water demand, improvement of water efficiency, rational water use, establishment of an ecological monitoring and early warning system, and restriction of groundwater abstraction in the vicinity of important civil engineering projects and facilities. At the same time, monitoring mechanism on the development of solar irrigation should be set up.

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