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Research Article

Evaluation of Potential Sites for Solar Powered Irrigation System in Gilgit-Baltistan for Sustainable Agriculture

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Abstract: The depletion of glaciers and frequent occurrence of glacial floods and landslide hazards typically affect the irrigation channels, resulting in disruption of water supplies for irrigation and domestic use in the Upper Indus Basin (UIB). The cultivated and arable land requires sustainable and alternative irrigation sources, such as using river/stream water through solar-powered irrigation system (SPIS), to ensure food security in the region. An effort has been made to assess the potential of SPIS in Gilgit-Baltistan (GB) province, lying in the UIB of Pakistan, based on the climate and topographic indexing approach. The SPIS potential was found to be high over 2153 km² and moderate over 3786 km² (collectively over 5939 km²) of the GB based on the slope-aspect (SLA) suitability. The high and moderate SLA suitability areas for SPIS were observed collectively over 22.9% of the Diamer, 16.9% of the Gilgit, and 8.8% of the Astore District. The SLA suitability was observed high over 11.2% and moderate over 19.2% area of the cropping zone below 3500 m elevation in the GB. The SPIS system may be adopted through coupling with some storage facility (water tanks, ponds, or reservoirs) and high efficient irrigation system (drip, sprinkler, and bubbler) for raising high value crops and multipurpose plant species, while reducing water consumption, fuel and labor cost. Integrated water resources management strategies need to be developed and implemented to cultivate unused lands in the valleys to ensure food security and economic development in the region in future.

Keywords: Climate Change, Drip Irrigation, Glacial Retreat, Indus Basin, Solar Radiation.

1. INTRODUCTION

Water demand is increasing rapidly in wake of growing urbanization, agriculture land use, change in social worth and climate change [1]. Moreover, adequate and economical availability of energy sources is crucial for meeting energy demand for agricultural water management. Climate change is causing serious glacial retreat/surging, avalanche, landslide and glacial lakes outburst flood (GLOF) hazards impacting the social and physical infrastructure in the Upper Indus Basin (UIB) [2]. As a result of increased warming, i.e., more than the world average temperature, most of the glaciers exhibit varying degree of retreat in the Himalayan region [3-5], except the Karakoram where most of the glaciers indicate stable behavior likely because of conducive environment [6-9]. The changing behavior of cryosphere would ultimately affect stream flow, irrigation potential and food production system. Water is crucial in bringing new area under cultivation in this region. The meltwater flows nurturing vast cryosphere-fed irrigation network are frequently disrupted by glacier retreat and lowering of the glacial surface in the region [10, 11]. The irrigation channels were also damaged many times owing to severe GLOF/flash flood and landslide events, consequently affecting crop farming and agricultural livelihoods [12-15]. Solar energy has become a highly valuable resource owing to intense global interest in climate change mitigation [16]. Pakistan is facing an unprecedented energy crisis owing to the increasing cost of diesel and electricity and frequent shutdowns of electricity. The growing population in GB, i.e., 0.56 million in 1981 to over 1.7 million in 2022, needs efficient energy sources for sustainable agriculture and livelihood improvement. Solar energy is available for over 300 days a year in Pakistan [17] and over 95% of the country's area receives solar radiation incident

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within a range of 5-7 kWh/m²/day with a persistence factor of over 85% [18]. Photovoltaic (PV)-based water pumping systems have become increasingly important because they use the clean, renewable energy of the sun, which accounts for the high cost of diesel and the limited supply of electricity. In a solar-powered water pump system, a bore/surface pump is driven by an electric motor that is powered by electricity produced by one or more solar panels. The pumped water is generally stored in a tank to make possible gravity-fed irrigation. The National Water Policy 2018 of Pakistan emphasized promoting measures for the long-term sustainability of the irrigation system to support food security in the country. Solar-powered irrigation system (SPIS) can be adopted to utilize the river/stream water for sustaining agriculture and livelihoods in the region [19, 20]. When compared to traditional fuel-based pumping systems, the versatile SPIS system has a longer operational life and lower maintenance cost. SPIS offers a promising substitute to diesel pumps, which contribute to carbon emissions and climate change.

The majority of arable land alongside the rivers, such as the Indus, Gilgit, Hunza, Shigar, Shyok, and Astore, and the perennial streams, remain fallow because of limited access to water supplies. There is a need to adopt irrigation system that could ensure water and food security and improve the livelihoods of a number of communities residing along the riverbanks under changing climate and cryosphere. It is hypothesized that considerable potential exists for establishing the SPIS to sustain agriculture and livelihoods in this region. This paper is aimed at assessing the potential of SPIS in the valley areas of Gilgit-Baltistan (GB), Pakistan, based on the climate and topographic indexing approach.

2. MATERIALS AND METHODS

2.1. Geographical Setup

The study area of GB (about 72,971 km^2) lies within elevation range from < 1000 m to > 8000 m in the northern Pakistan (Figure 1). Climate is predominantly warm continental/mediterranean continental to humid sub-tropical and arctic/ cold desert with mean minimum temperature about 7 °C and maximum about 21 °C per annum. Annual rainfall ranges between 125 and 600 mm, which generally occurs from the westerly during winters and the monsoon during summers, besides a small amount from the local thunderstorms [10]. Majority of the households in the GB are engaged in subsistence agriculture. On an average, the land holding for cultivation is 0.2 hectare per household in the region. In the lower arid valleys below 1900 m, crops are grown in both summer and winter seasons (typically wheat is grown during winters and maize during summers). In the highlands, only single crop is cultivated during summers, and between 1900 and 2300 m, marginal single crop cultivation is practiced which can be transformed into double cropping using early maturing barley and wheat types [10]. Water supply is mainly managed through channels fed by springs, snow/glacier melt and river/stream water, which occasionally become disrupt due to climate induced disasters like floods, landslides and snow avalanches occurred during mid-summers.

The highlands are characterized by rugged and difficult mountainous terrain consisting of gravelly fans and terraces. The land use/land cover includes rangeland (grazing areas) over 33%, bare ground over 39%, snow cover and glaciers over 25%, and, agricultural land over < 2% area, besides other classes (Figure 1). Agriculture is generally practiced in the valleys and some sloppy areas in the region. The main crops grown include wheat, barley, maize, potatoes, buckwheat, millet, vegetables and fruits [21]. The major vegetables consist of tomatoes, potatoes, peas, onions, beans, carrots, turnips, spinach, while fresh and dry fruits include apples, apricots, cherries, pears, mulberries, grapes, plums, almonds and walnuts. The sowing season generally starts in early February and continues till second week of April in the highlands. The

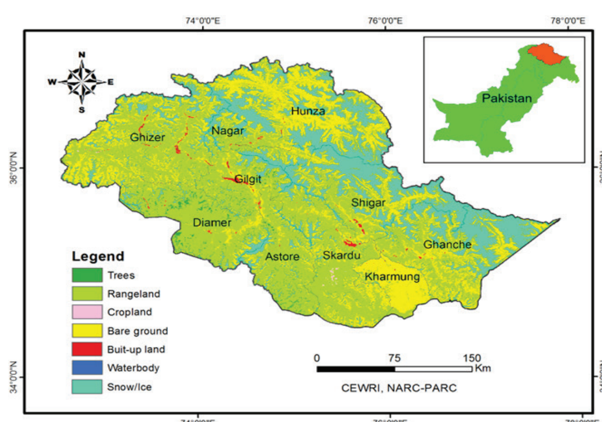

Fig. 1. Location of Gilgit-Baltistan study area in northern Pakistan.

harvesting season begins in mid-July in the lower regions and continues till the end of October in the upper reaches of the region.

2.2. Data Source

Thematic data of topography, land forms, land use, hydrology (drainage network, river discharges) and climate were acquired from source departments like Survey of Pakistan, Soil Survey Water and Power Development Authority, and Pakistan Meteorological Department (PMD). The monthly climate data (i.e., temperature and rainfall) of the selected meteorological stations, i.e., Gilgit, Gupis, Bunji, Astore, and Skardu (1990-2019 period), were acquired from PMD for variability and spatial trend analysis. The Sentinel-2 based global land use/land cover map (2022) available at ESRI site (https://livingatlas.arcgis.com) was used for land use/land cover analyze of the study area. The Shuttle Radar Topography Mission SRTM-DEM data of 90 m resolution was downloaded from the National Aeronautics and Space Administration (NASA) site (www.jpl.nasa.gov/) for developing elevation, slope and aspect maps of the study area. Field surveys were carried out to gather information of landforms, land use, agriculture, water resources and socioeconomics from various locations of the study region.

2.3. Determination of SPIS Potential

SPIS potential was explored in the region through adopting a climate and topographic (slope, aspect, altitude) indexing approach [22]. The efficiency of the PV cell that transforms sunlight into useful energy is defined by the ratio of maximum power output to the power received by the cell [23]. The efficiency of panel increases as the temperature declines, while it falls as the voltage between the cells falls at high temperatures [24, 25]. Solar panels can operate most efficiently between 15 and 40°C; temperatures above this range will reduce solar cell efficiency [24]. Since solar radiation and sunshine length are crucial factors in evaluating the effectiveness of renewable energy systems, the effects of slope and aspect on solar energy are especially important in mountainous terrain [26]. According to Kereush and Perovych [25], sites above 1500 m elevation are also suitable for setting up the solar-powered systems, so it is presumed that all altitudes in this region are equally effective at gathering solar energy. A slope map was generated using the DEM and reclassified into two classes, i.e., < 35° and > 35°. The slope < 35° was considered suitable and assigned value 1 as allowing more perpendicular light and receiving higher solar radiations than other slope class feasible for the system's operation [27, 28].

The length of sunshine hours and the amount of solar energy available have been represented in this study by the aspect factor. Aspect classes, i.e., south, southeast, and east, were deemed appropriate for SPIS installation because they received more solar energy and retained more sunshine duration than other aspect classes, whereas shadow areas in mountainous terrain received the least amount of solar energy to harness [22]. The south aspect was given the maximum weight of 2 due to its higher aptness for receiving solar energy than other aspects in this area. The East-Southeast (E-SE) aspects were assigned weight 1 since they were deemed to be medium suitable for receiving solar radiation, whereas other aspect classes were allocated weight zero as inappropriate for harnessing solar radiation. A slope-aspect (SLA) index was developed to define three land suitability classes for establishing SPIS, i.e., High (< 35° slope at S aspect), Moderate (< 35° slope at E-SE aspects) and Low (>35° slope at all aspects excluding S, E and SE). A final SLA suitability map was prepared for the GB area based on the weighted overlay analysis, and spatial analysis was performed at district level in the ArcGIS software for planning and decision-making.

3. RESULTS AND DISCUSSION

3.1. Assessment of SPIS Potential

Mean maximum temperature indicated a decreasing trend towards the northeast in this region (Figure 2). The temperature range 10 - 20 °C appears dominant in most of the northwestern, central, and southeastern parts, while > 20 °C temperature seems prominent in the southern parts of the area. A mean minimum temperature range of 0 - 10 °C appears dominant in the NW-SE belt, while > 10 °C prevails in the southern valleys of the region. The temperature range below zero appears concentrated in the high mountainous region towards the northeast (Figure 2). Overall, the majority of the valleys and depressions have mean annual temperatures above 15 °C. Summers have high solar radiation, whereas winters have low solar radiation in this region [29]. The region contains an extensive network of perennial streams and rivers fed by rainwater, permanent snow, and numerous small and large glaciers residing at higher reaches (Figure 2). The stream/river flows are large during May to August, while the irrigation requirements are large from April to June. The slope class < 35° derived from the DEM was identified over 90% of the study area (Figure 3). Most of this slope class lies in the Ghizer, Hunza, Ghanche, and Skardu districts (Table 1). Over 13% of the area was found under the southern aspect class, the majority of

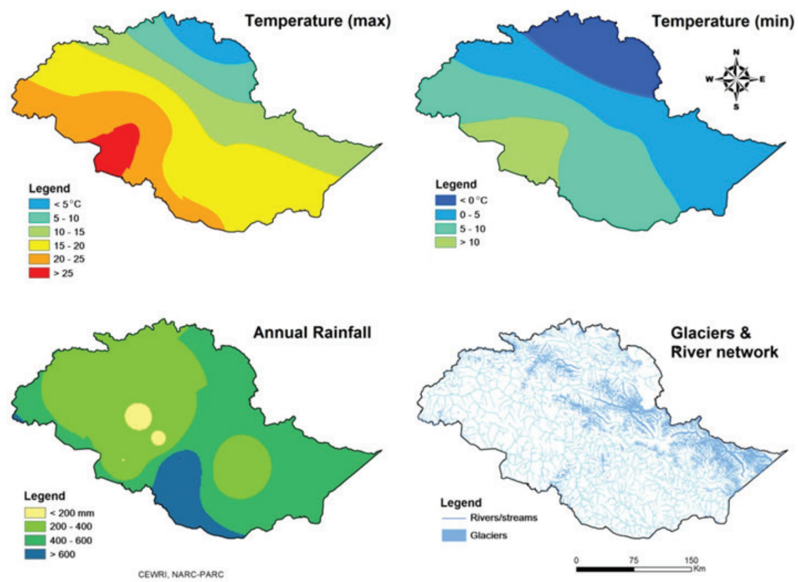

Fig. 2. Spatial analysis of hydro-climate in the GB area.

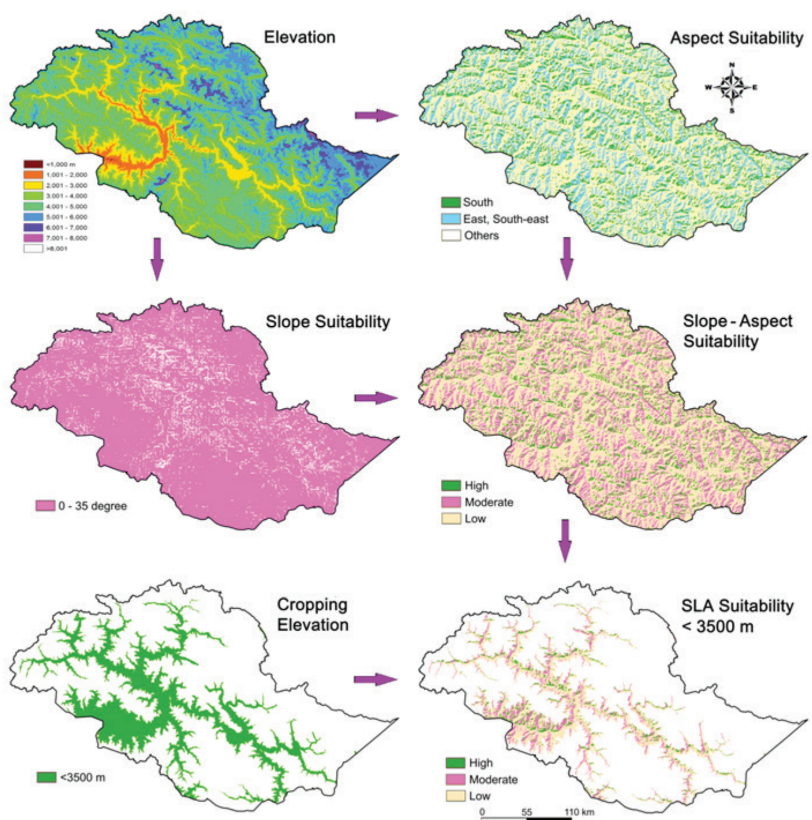

Fig. 3. Assessment of slope-aspect (SLA) suitability for establishing SPIS in the GB area.

Table 1. The slope and aspect suitability areas (in km^2) for SPIS in different districts of the study area.

District	Slope < 35°	South	E-SE
Ghizer	11404	1556	3134
Gilgit	3763	555	1089
Nagar	1958	291	575
Hunza	11134	1763	2931
Shigar	7455	1228	2009
Ghanche	8520	1311	2401
Kharmung	2566	314	595
Skardu	7710	969	2149
Diamer	6863	860	1778
Astore	4959	619	1280
Total	66331	9465	17940

which lies in the Hunza, Ghizer, Ghanche, and Shigar districts. This aspect was observed over a < 700 km^2 area in the Nagar, Kharmung, Gilgit, and Astore districts. The E-SE class covers about 24.6% of the area, predominantly in the Ghizer, Hunza, Ghanche, and Skardu districts (Table 1). The coverage of this class was observed within 500-600 km^2 in the Nagar and Kharmung districts. The SLA suitability was found to be high over 2153 km^2 and moderate over 3786 km^2 of the study area (Figure 3). Among various districts, the suitability was observed high over 532 km^2 area of the Diamer, 357 km^2 of the Ghizer, 252 km^2 of the Gilgit and 215 km^2 of the Hunza District (Figure 4). Similarly, the moderate suitability was found over 1128 km^2 area of the Diamer, 573 km^2 of the Ghizer, 483 km^2 of the Gilgit and 359 km^2 of the Skardu District. Collectively, high and moderate SLA suitability for SPIS was observed over 22.9% area of the Diamer, 16.9% of the Gilgit and 8.8% area of the Astore District (Figure 5).

3.2. SPIS Potential Below 3500 m Elevation

Agriculture is typically practiced in the valleys and some sloppy areas below 3500 m elevation. The climatic condition below 3500 m elevation is generally suitable for crop farming and livelihoods in the region [10]. About 22% of the GB area (i.e., 15975 km^2) lies below 3500 m elevation, in which major area lies in the Diamer, Ghizer and Gilgit districts (Table 2). The slope class < 35° covers about 14325 km^2 area, majority of which lies in the Diamer (3973 km^2), Ghizer (2176 km^2), Gilgit (1711 km^2), Astore (1333 km^2), Skardu (1307 km^2) and Hunza districts (1041 km^2). The least area of this class exists in the Nagar (445 km^2), Kharmung (594 km^2), Ghanche (856 km^2) and Shigar districts (889 km^2). The southern aspect stretches over 1979 km^2 and E-SE aspects over 3511 km^2 area, majority of which lie in the Diamer, Ghizer and Gilgit districts. The SLA suitability below 3500 m elevation was found to be high over 11.2% (1792 km^2) and moderate over 19.8% (3167 km^2) of the area. Diamer has the maximum of about 4216 km^2 area under 3500 m elevation, in which SLA suitability was found high over 11.7% and moderate over 24.6% area of the district (Table 2). According to a study by Ali *et al.* [29], Chilas in the Diamer District has a good solar profile with a maximum irradiance of about 7.981 kWh/m^2/day in July, while Khaplu in the Ghanche District has the least irradiance of about 1.783 kWh/m^2/day in December. The SLA suitability was identified high over 8 to 11% area in the five districts, i.e., Gilgit, Nagar, Kharmung, Skardu and Astore, and > 12% area in the Hunza and Shigar districts. The suitability was found to be moderate over 16 to 18% area in the Ghizer, Nagar, Hunza, Shigar and Ghanche districts. Overall, the SLA suitability for

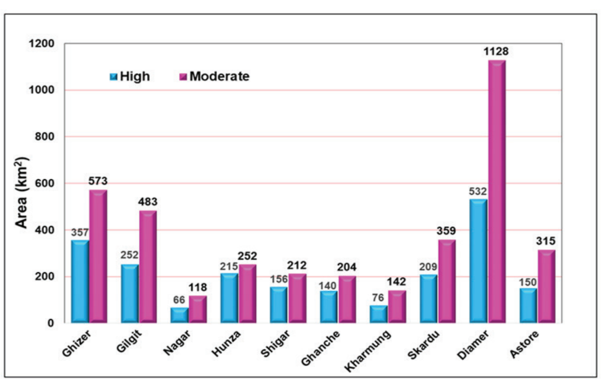

Fig. 4. The slope-aspect suitability for SPIS in different districts of the study area.

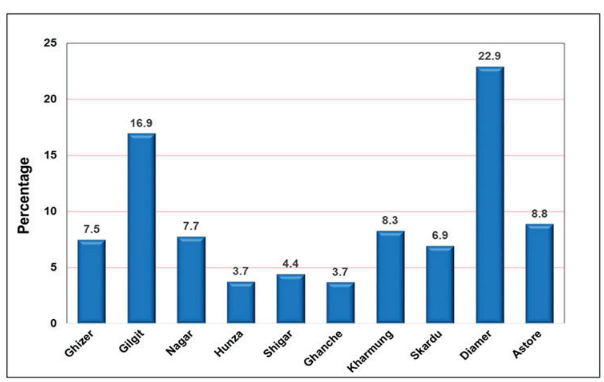

Fig. 5. Percentage coverage of collective high and moderate SLA suitability in different districts.

establishing SPIS was observed high over 11.2%, moderate over 19.2%, and low over 69% of the area below 3500 m elevation in the GB (Table 2 and Figure 3). The latter low suitability area of the SLA points toward the existence of > 35° slopes at other than S, E and SE aspects, assuming a non-promising area for establishing SPIS.

3.3. Adoption of SPIS for Sustainable Agriculture

SPIS can benefit farmlands in a number of ways, including less reliance on fossil fuels and electricity, lower operating costs, and less environmental impact [30]. Several researchers have thoroughly documented the potential impacts of various elements in the SPIS, including the design of the PV pumping system, water source characteristics, irrigation technique and local climate to achieve maximum efficiency [31, 32]. The system consists of equipment such as pumping units, pump controllers, and photovoltaic modules. The SPIS is generally implemented and promoted, especially in areas with little access to conventional irrigation supplies. It can be adopted for converting cultivable land into productive land in the valleys and to uplift meltwater from a lower water input point at a depleted glacier to an irrigation channel at an elevated area to sustain water supply in the channel. The solar-powered water pumps have the benefit of significantly lower labor and maintenance costs [33, 34], which is supportive for areas facing labor shortages owing to outmigration. When combined with efficient irrigation methods, the water-lifting mechanism can be used to grow high-value crops like fruits and vegetables in unused land alongside the perennial streams and rivers. The drip irrigation linked with solar-powered system has advantages for water conservation, fewer chances of soil erosion, and reduction in pest attacks/disease. Compared to other irrigation techniques, this method increases irrigation efficiency by up to 90%, making it the most appreciated innovation for water security. Pakistan Agricultural Research Council (PARC) and several other institutions have adopted the SPIS for growing high-value crops (vegetables and fruits) in various parts of the region.

Table 2. Percentage coverage of SLA suitability for SPIS below 3500 m elevation in different districts.

District	Area below 3500 m (km^2)	High (%)	Moderate (%)	Low (%)
Ghizer	2493	11.4	17.5	71.1
Gilgit	1971	10.6	19.5	69.9
Nagar	514	10.9	17.2	71.9
Hunza	1188	14.1	17.2	68.7
Shigar	1018	12.5	17.2	70.3
Ghanche	987	11.6	16.7	71.7
Kharmung	637	9.1	19.1	71.8
Skardu	1522	10.8	19.3	69.9
Diamer	4216	11.7	24.6	63.7
Astore	1429	8.1	18.4	73.5
Total	15975	11.2	19.8	69.0

Although solar pumps are initially more costly compared to diesel pumps, they require fewer operation and maintenance costs over time [35]. To help offset the high upfront costs, the local communities may be encouraged to adopt SPIS through the provision of subsidies and adequate financial incentives. In cases where the system may face power outages during prolonged cloud cover (due to a shortage of sunlight), integrated water resources management plans may be developed and implemented to sustain crop farming activities. Ali *et al.* [29] recommended appropriate hybrid systems to meet the energy demand at selected locations of the GB. Capacity building of the communities and institutions is necessary to address the SPIS challenges such as water delivery, storage, and system maintenance in the region. The male and female farmers need to be trained in water conservation, kitchen gardening, and raising fruit nurseries and orchards using SPIS-coupled efficient irrigation system to improve their livelihoods.

4. CONCLUSIONS

In this study, potential of SPIS has been assessed in the valley areas of GB, Pakistan, using the indexing approach. The SPIS potential was found to be high over 2153 km^2 and moderate over 3786 km^2 (collective over 5939 km^2) of the study area based on the slope and aspect suitability. It was observed high over 532 km^2 of the Diamer, 357 km^2 of the Ghizer, 252 km^2 of the Gilgit and 215 km^2 area of the Hunza District. The SLA suitability for SPIS was observed high over 11.2% and moderate over 19.2% area of the cropping zone below 3500 m elevation. Diamer has the maximum area under 3500 m elevation, where SLA suitability was determined to be high over 11.7% and moderate over 24.6% of the district. The suitability of SLA was found to be high across 8 to 11% areas of the Gilgit, Nagar, Kharmung, Skardu, and Astore districts, while it was > 12% in the Shigar and Hunza districts. The moderate suitability of SLA was observed over 16 to 18% areas of the Ghizer, Nagar, Hunza, Shigar, and Ghanche districts. The SPIS can be adopted through coupling with some storage facility and drip irrigation system for raising high value crops (vegetables and fruits) and multipurpose tree species in the arable land along major rivers and streams. Integrated water resources management plans may be developed and implemented in arable and unused lands to ensure food security, ecosystem health, and economic development in the region in future.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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