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ARTICLE

InVEST model-based estimation of water yield in the Upper Tuul river basin

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Abstract: The estimation and mapping of water yield are of significant importance to the effective planning and management of water resources in Mongolia. In this study, we quantified and assessed the water yield of the Upper Tuul River basin using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Water yield model. The study aimed to test whether it is possible to estimate the water yield of the selected research area using the model. The required input data included land use and land cover, mean annual precipitation and potential evapotranspiration, soil depth, and plant available water content. In addition, those data were obtained from Landsat 8, Climate Hazards Group Infrared Precipitation with Station data (CHIRPS), MODIS Global Terrestrial Evapotranspiration Product (MOD16), and International Soil Reference and Information Centre (ISRIC) database. Finally, we generated spatial distribution maps, namely, mean actual evapotranspiration (mm), mean water yield (mm), and the volume of water yield (km^3) by pixel within the research area. According to the modelling results, the estimated value for mean annual precipitation was 295.08 mm, and 827.09 mm respectively for potential evapotranspiration, 229.13 mm for average actual evapotranspiration, 55.89 mm and 0.43 km^3 for water yield within the study area. The result was slightly higher (15.1 mm) in terms of mean actual evapotranspiration compared to the results of previous studies, conducted in the same research area, and it was found that the potential water yield in the study area has also been impacted. However, the InVEST (Water Yield) model can be used for future research studies concerning water yield and resource in river basins as it is possible to further improve the model results by using in-situ measurement data and satellite products with high spatial accuracy as input data.

Keywords: *Water yield; Actual evapotranspiration; Ecosystem service; Upper Tuul River basin;*

INTRODUCTION

The annual water yield is the difference between the precipitation that falls in that watershed and total evapotranspiration, assuming that there is no net storage in vegetation or soils over the course of the year [1], and this is a key ecosystem function index [2] as it is instrumental in balancing socio-economic development and ecological security [3].

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Therefore, water yield calculation and mapping are critical for infrastructure and planning issues, such as water resource management and hydropower plant construction. However, researches on runoff, water yield, and resource are fairly complex because the runoff process in any basin tends to depend not only on a single factor, but also on many natural factors, namely, rainfall intensity, water absorption capacity in soil type, infiltration, surface slope, direction, vegetation and land use type.

Nonetheless, some hydrological models such as SWAT (Soil and Water Assessment Tool) [4] and PRMS (Precipitation Runoff Modeling System) [5], which are based on modern geographic information systems and remote sensing technology, make it possible to comprehensively approximate and map hydrological processes at the basin and sub-basin levels, and to assess the impact and intensity of changes of land use and climate change in the basin.

Studies have been conducted to estimate water resources using the long-term discharge data and flow measurements, as well as, some specific models, such as SWAT, RIBASIM, HBV, and HEC-Geo HMS in the Tuul River basin. For instance, in recent years many national hydrologists tried to apply Soil Water Assessment Tool (SWAT) in simulating ecohydrological process and climate change impact in the Tuul River basin [6]–[8]. They concluded that the hydrological model has performed well in simulating hydrological processes in watersheds and emphasized that data availability, monitoring information for the calibration and validation of the simulation model, were major limitations of those research works. Furthermore, developing and incorporating new datasets in the region is highly recommended for future research.

Accordingly, this study aims to simulate annual water yield and actual evapotranspiration in the Upper Tuul River basin with InVEST (Water Yield) model in order to improve the identified research limitations and to seek new possibilities by introducing internationally recognized modern research method in water resources research. On the other hand, InVEST (Water Yield) model is a relatively new method that has not been applied in hydrological studies in Mongolia, especially in the Tuul River basin where natural and anthrophogenic impacts had been significantly high for a number of years.

The model was developed in 2007 by the Natural Capital Project of Stanford University, the World Wide Fund for Nature, the Wildlife Conservation Fund, and the Nature Conservancy to support environmental decision-making and assess the value of ecosystem services. The model is a set of free and open-source software, and the InVEST model comprises of many sub-models, of which the Annual Water Yield model used in this study is a fundamental model used for evaluating the provisioning, supporting, and regulating services of water-related ecosystems [9]. What's more, the outcome results also can possibly become the underlying foundation for further ecosystem service evaluation studies.

MATERIALS AND METHODS

Study area

The study area covers the upper part of the Tuul River basin with a geographical coordination of $106^0$15'-$108^0$18'E, $47^0$23'-$48^0$33'N (Figure 1). The area of the upper part of the Tuul River basin is located in a mountainous area with semi-arid and sub-arctic conditions and it is also seen as an important area for generating surface runoff [10]. The annual mean air temperature in the area is around -2.0^{0}C at Buyant Ukhaa, 0.4^{0}C in Ulaanbaatar, -3.3^{0}C in Terelj, while the annual mean precipitation is about 252.90 mm in Buyant Ukhaa, 275.0 mm in Ulaanbaatar, and 225.3 mm in Terelj [11].

According to the long-term measurement data of the Tuul-Ulaanbaatar hydrological gauge, the amount of precipitation in the area is 335 mm per annum, of which about 214 mm is lost in the form of evaporation, and 68% of the total flow (layer 82 mm) consists of surface runoff [12].

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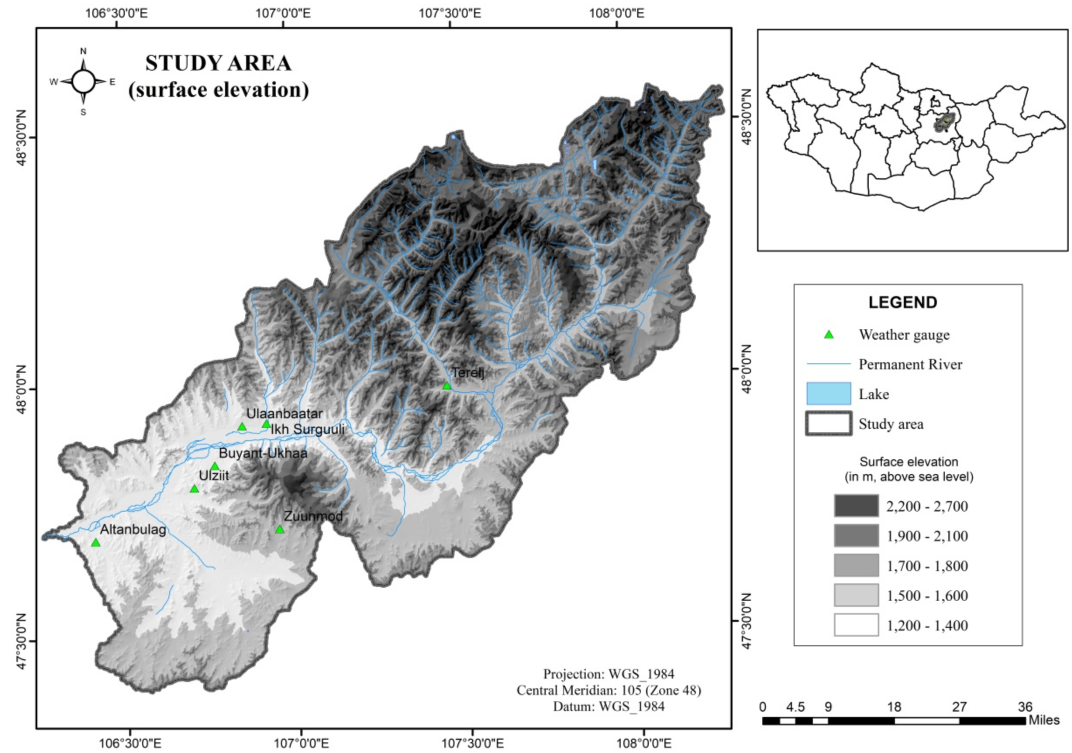

Figure 1. Location map of the study area

Water yield model

The water yield model is based on the Budyko curve and annual precipitation [13]. Annual water yield $Y(x)$ for each pixel on the landscape x was defined as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) * P(x) \qquad (1)$$

Where, AET*(x)* is the annual actual evapotranspiration for pixel x, and P*(x)* is the annual precipitation on pixel x; for vegetated land use/land cover (LULC) type, the evapotranspiration portion of the water balance, $\frac{AET(x)}{P(x)}$, based on the expression of the Budyko curve can be estimated by Zhang (2001) [14]:

$$\frac{AET\ (x)}{P\ (x)} = 1 + \frac{PET\ (x)}{P\ (x)} - \left[1 + \left(\frac{PET\ (x)}{P\ (x)}\right)^{w}\right]^{1/w} \qquad (2)$$

Where, PET*(x)* is the reference evapotranspiration and w*(x)* is a non-physical parameter that characterizes the climatic-soil properties, both of which are detailed below. Potential evapotranspiration PET*(x)* is defined as:

$$PET(x) = K_c(l_x) * ET_0(x) \qquad (3)$$

Where, $ET_0(x)$ is the reference evapotranspiration from pixel x and, $K_c\ (l_x)$ is the plant (vegetation) evapotranspiration coefficient associated with the LULC l_x on pixel x. $ET_0(x)$ reflects the local climatic conditions, based on the evapotranspiration of a reference vegetation, such as grass or alfalfa growing at that location. $K_c(l_x)$ is largely determined by the vegetative characteristics of the land use/land cover found on that pixel [15]. K_c adjusts the ET_0 values to the crop or vegetation type in each pixel of the land use/land cover map. *w(x)* is an empirical parameter that can be expressed as linear function of $\frac{AWC*N}{P}$, where N s the number of rain events per year, and AWC is the volumetric plant available water content. While further research is being conducted to determine the function that best describes global data, we used the expression proposed by [16] in the InVEST model, and thus define:

$$w_x = Z\frac{AWC\ (x)}{P(x)} + 1.25 \tag{4}$$

Where, *AWC(x)* is the volumetric (mm) plant available water content. The soil texture and effective rooting depth define *AWC(x)* which establishes the amount of water that can be held and released in the soil for use by a plant. It is estimated as the product of the plant available water capacity (PAWC) and the minimum of root restricting layer depth and vegetation rooting depth:

$$AWC(x) = (Rest.lay.dep, root.dep) \cdot PAWC \tag{5}$$

Z is an empirical constant, sometimes referred to as “seasonality factor”, which captures the local precipitation pattern and additional hydrogeological characteristics. It is positively correlated with N, the number of rain events per year. The 1.25 term is the minimum value of *w(x)*, which can be seen as a value for bare soil (when root depth is 0), as explained by Donohue et al. (2012) [16]. Following the literature [16]–[19], values of *w(x)* are capped to a value of 5. For other LULC types (open water, urban, wetland), actual evapotranspiration is directly computed from reference evapotranspiration $ET_0(x)$ and has an upper limit defined by precipitation.

Data requirement and preparation

The water yield model requires the raster of land use and land cover, precipitation, average annual potential evapotranspiration, root restricting layer depth, plant available water content, watersheds, and sub-watersheds [20]. In addition, the biophysical table with values of biophysical parameters defined for each type of land use and land cover are also included.

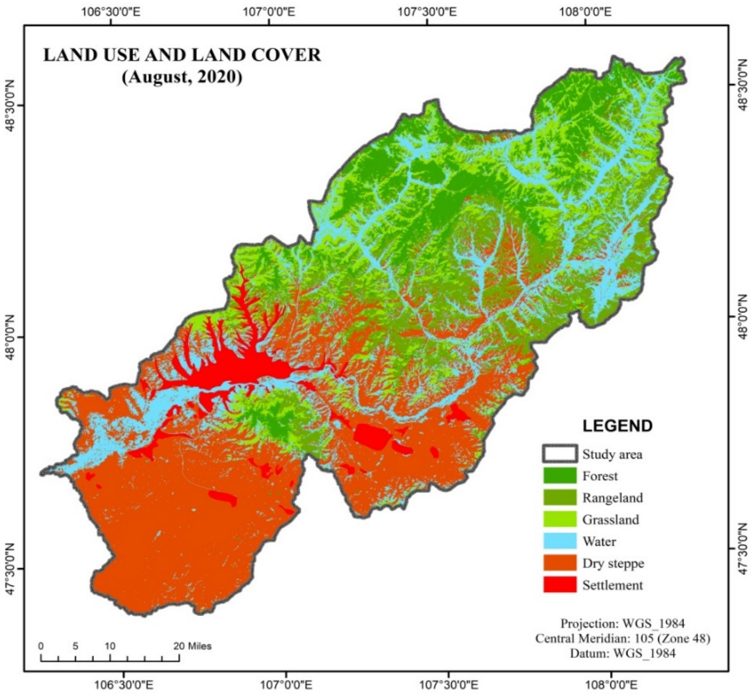

Figure 2. LULC type (Landsat 8 OLI)

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Land use/land cover data

Supervised classification was used to retrieve Landsat 8 satellite data (2020.08.26) for preparing LULC raster data. In the study area, six LULC types were identified: forest, rangeland, grassland, dry steppe, water, and settlement (Figure 2).

Precipitation

CHIRPS data (Climate Hazards Group Infrared Precipitation with Station data), processed by USDA, NOAA, FEWS NET, NASA, USGS, and Climate Hazards Center UC Santa Barbara, were applied to obtain the annual mean precipitation of 2009-2020 within the study area.

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 35+ year quasi-global rainfall data set. Spanning 50°S-50°N (and all longitudes) and ranging from 1981 to near-present, CHIRPS incorporates our in-house climatology, CHPclim, 0.05° resolution satellite imagery, and in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring.

The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset builds on previous approaches to 'smart' interpolation techniques and high resolution, long period of record precipitation estimates based on infrared Cold Cloud Duration (CCD) observations. [21].

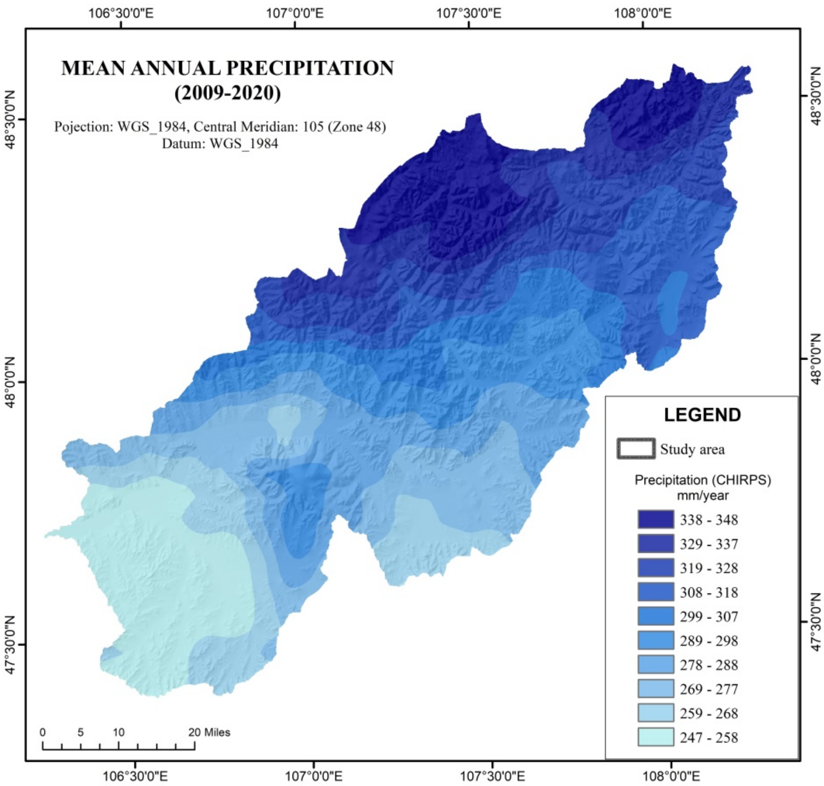

Figure 3. Mean annual precipitation, mm (CHIRPS)

Potential evapotranspiration

Potential evapotranspiration (ETo) is the most important indicator in hydrological research, water resources and irrigation management.

The Penman-Monteith method is a commonly accepted standard method for calculating potential evapotranspiration, but requires the values of several meteorological parameters. The Food and Agriculture Organization of the United Nations recommends the Penman-Monteith method for estimating potential evapotranspiration [15], but the method requires the values of several meteorological parameters, such as solar radiation, air temperature, wind speed, and relative humidity [22], [23].

Determining the values of the above parameters and compiling measurement data is costly, so calculating ET using this method is complicated. Therefore, for this study, input data was prepared by performing the requisite

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processing on Potential Evaporation (PET) layer data of MOD16 [24], [25] satellite products.

The MOD16 global evapotranspiration (ET), latent heat flux (LE), potential ET (PET), and potential LE (PLE) datasets are regular 1km^2 land surface ET datasets for the 109.03 million km^2 global vegetated land areas at 8-day, monthly and annual intervals.

MOD16 product basic method is [25], [26] the Penman-Monteith, and is characterized by combining remote sensing data with weather measurement data and reanalyzing the results.

Table 1. MOD16 product [20]

Product	MOD16A3GF.006
Temporal extent	2000-02-18 to present
Spatial extent	Global
Coordinate system	Sinusoidal
Geographic dimension	1200km x 1200km
Number of SDS layers	5
Pixel size	500 m
PET_500 m	0.1 (Scale factor)

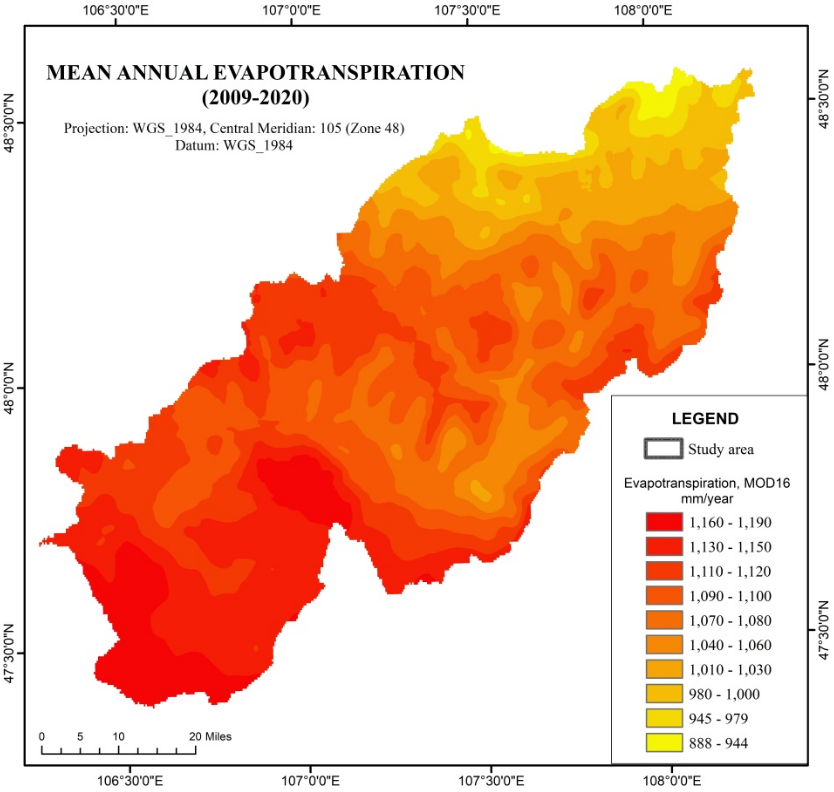

Figure 4. Mean annual evapotranspiration, mm (MOD16)

In this study, the MOD16 product was used for generating annual mean evapotranspiration data for the study area from 2009 to 2020 (Figure 4). The product was processed using MODIS reprojection tools (MRT), and Arc GIS 10.5, including projection, extension, and removal of unnecessary pixel values.

Root restricting layer depth and Plant available water content

The root restricting layer depth is defined by the soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics, while plant available water content is the fraction of water that can be stored in the soil profile that is available to plants. In other words, PAWC is defined as the difference between the fraction of volumetric field capacity and the permanent wilting point.

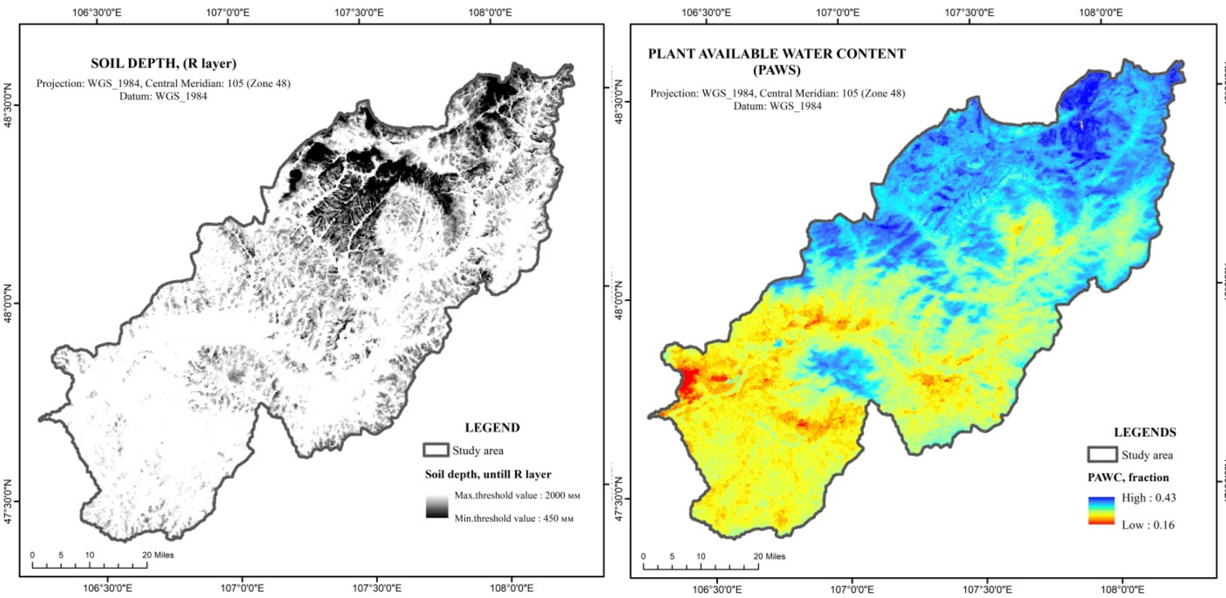

Figure 5a. Soil depth, till R layer (ISRIC), 5b. Plant available water content (ISRIC)

Due to the lack of detailed research results and information materials defining these parameters for each type of soil occurring in the study area, a) soil depth to R layer (Figure 5a), b) potential soil water capacity at 10 cm soil layer (Figure 5b) in the database of ISRIC (International Soil Reference and Information Center) with 250-meter spatial resolution data were processed and used as input data.

Biophysical parameters

In order to run the water yield model, a biophysical table is required reflecting the attributes of each land use and land cover type (LULC), containing LULC code, descriptive name of LULC, the maximum root depth for vegetated land use classes in millimeters (non-vegetated LULCs should be given a value of minimal root depth, but a zero value should not be used) and the plant evapotranspiration coefficient for each LULC class. We estimated the evapotranspiration coefficient of each LULC type based on Allen et al. (1998) [15], and the InVEST user guide. The values of parameters Kc (crop evapotranspiration coefficient) and Root_depth (maximum root depth for the plants) relevant for the determined types of land use and land cover of the study area are shown in Table 2.

Table 2. Biophysical parameters

№	Description	Root_depth	Kc	LULC_veg
1	Forest	3500	1.055	1
2	Grassland	2000	0.865	1
3	Rangeland	3500	1.008	1
4	Water	10	1.05	0
5	Dry steppe	1000	0.58	1
6	Settlement	500	0.2	0

Watershed delineation

Based on a digital elevation model (DEM), the watershed and sub-watersheds were generated using ArcSWAT and required shapefile formats. Each sub-watershed was given only one identification number. The watershed was delineated to 6 sub-watersheds. (Figure 6, Table 3).

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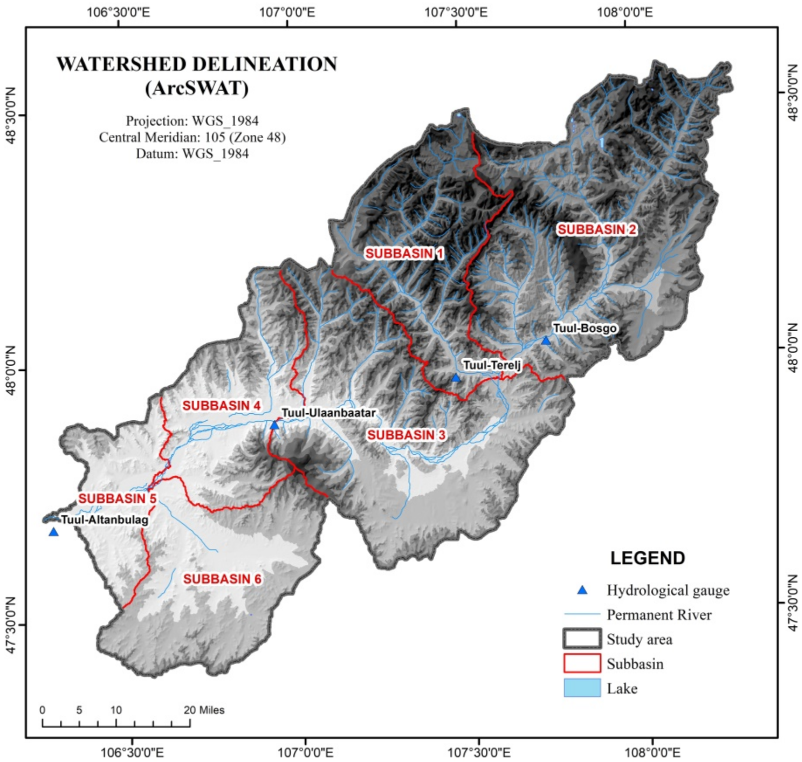

Figure 6. Watershed delineation (Arc SWAT model)

RESULTS AND DISCUSSION

InVEST (Water Yield) model was calibrated by altering the value of Z and biophysical parameters based on input data, including LULC, precipitation, potential evapotranspiration, soil depth, plant available water content, and root restricting layer depth. The results of the modeling, the average values for water yield by volume (m^3) and layer (mm) for six subbasins, which are obtained from Arc SWAT modeling, were estimated and shown in Table 4.

Table 3. Sub watersheds, by area

№	Sub watersheds	Area, km^2
1	Terelj	1309.49
2	Tuul River, headwater	2695.23
3	Selbe-Uliastai	2272.96
4		1053.25
5	Tuul-Altanbulag	591.72
6	Bukheg-Turgen	1343.13
The total area of the basin		9265.78

Table 4. The model result, by sub watersheds

Sub watershed	P, mm	PET, mm	AET, mm	Runoff layer, mm	Water Yield, km^3
1	326.4	1022.3	300.8	25.51	0.03
2	317.8	989.8	289.3	28.42	0.08
3	284.6	811.6	229.1	55.43	0.13
4	283.6	752.5	236.2	47.31	0.05
5	258.6	805.4	199.3	59.14	0.03
6	261.5	679.8	183.8	77.73	0.10

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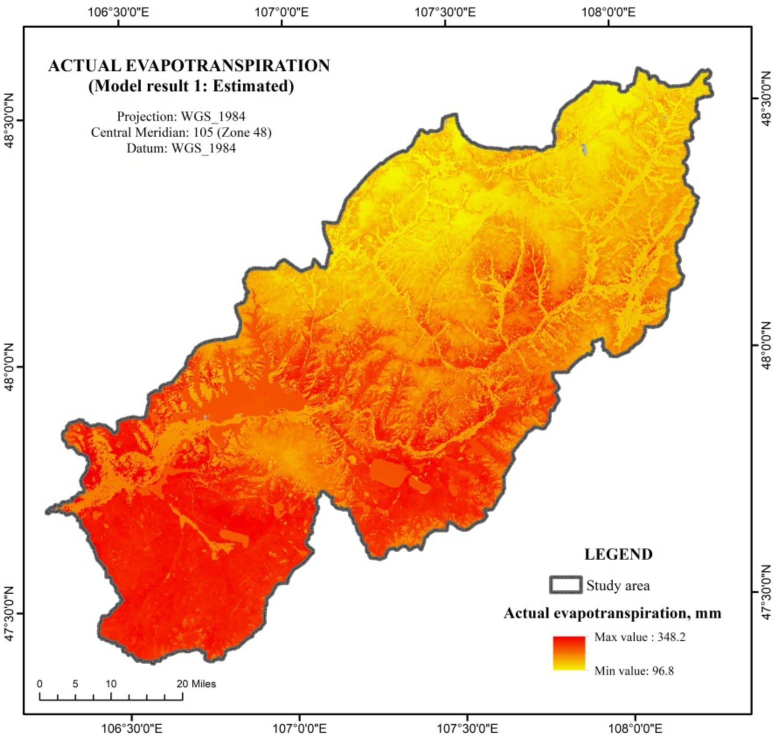

Figure 7. Actual evapotranspiration (estimated value)

According to the results of the model, the mean annual precipitation is 295.08 mm, the potential evapotranspiration is 827.09 mm, the actual evapotranspiration is 229.13 mm, the surface runoff layer that can be formed is 55.89 mm, and the water yield is 0.43 km^3 in the Upper Tuul River basin.

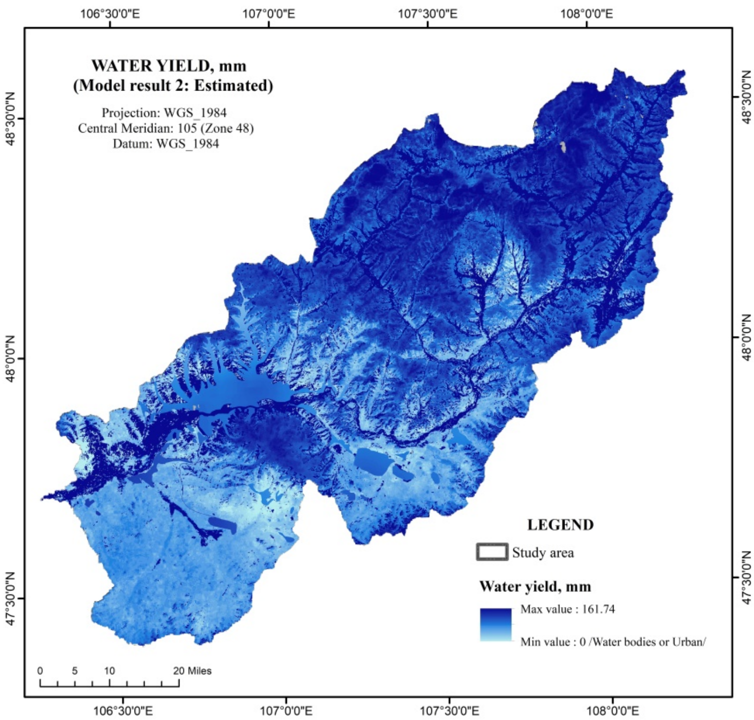

Figure 8. Water yield (Estimated value)

According to the research results of researcher G. Davaa and others [27] based on the long-term measurement data of the Tuul-Ulaanbaatar water gauging station, 335 mm of precipitation falls in the basin and 214 mm evaporates.

The surface runoff is 82 mm (accounting for 68 percent of the total runoff), and the baseflow is 39 mm (accounting for 32 percent of the total runoff). In addition, according to the results of studies carried out by G.Davaa, D.Oyunbaatar, S.Tumurchudur, Z.Munkhtsetseg [28] it was determined that 62.1-403.6 mm of annual precipitation falls in the basin, of which 48.4% (30.05-195.34 mm) is total evaporation and 51.6% (32.04-208.26 mm) is surface and groundwater supply. Also, the researchers formulated the water balance of the main part of the basin just above the Tuul River as follows.

$$Q\ 127.5\ mm = P\ 246.7\ mm - ET\ 119.3\ mm\ [28]$$

In terms of water resources and yield, although there is a lack of detailed research data within the Tuul River basin and its sub-basins, in 2008, the Public Utilities and Services Organization (PUS) reported that the water resources and yield of Ulaanbaatar city was 0.77 km^3, which for provinces were 3.21 km^3 [28]. Moreover, the water resources of Mongolia's rivers are 34.6 km^3/year (34,600.0 million.m^3) [12] from which 16.9 km^3 (16,900.0 million.m^3) of this resource is in the Arctic Ocean basin, and 3.80 km^3 (3,800.0 million.m^3) is in the Pacific Ocean basin, and 13.9 km^3 (13,900.0 million.m^3) are formed by the flow of rivers of Central Asian Internal Drainage basin without outflow. The results of the InVEST WaterYield model are compared with the results of related researchers' studies, as shown in Table 5.

Table 5. Comparison of research results

Parameters	Results (InVEST)	Ref [27]	*	Ref [28]	*	Ref [28]
P, mm	295.08	335	-39.9	246.7	+48.4	*
PET, mm	827.09	*	*	*	*	*
ET, mm	229.13	214	+15.1	119.3	+110	*
Q, mm	55.89	82	-26.1	127.5	-71.6	*
Q, km^3	0.43	*	*	*	*	0.7

The results of the research calculated by the InVEST model showed that the amount of annual precipitation is 39.9 mm lower, the evapotranspiration is 15.1 mm higher, and the runoff layer is 26.1 mm lower than the results of the studies carried out by G. Davaa.

However, compared to the research by G. Davaa, D. Oyunbaatar, S. Tumurchudur, and Z. Munkhtsetseg, the annual precipitation is 48.4 mm higher and the evapotranspiration is 110 mm higher. This is due to the fact that Ulaanbaatar city and the neighbouring urban areas are included in the research area. This amount of evapotranspiration from urban areas and paved roads will be relatively higher than the amount of evapotranspiration from areas covered with vegetation, and consequently, the amount of evapotranspiration calculated by the InVEST model can be higher.

The difference of 71.6 mm less in the runoff layer was also compared to the total runoff calculated by the above researchers (surface and baseflow were calculated together), and the difference was significant. The parameter that had the greatest impact on the results of water resources, yield and layer was the Z parameter, and when the value of this parameter was reduced, the value of the above parameters increased. In addition, Budyko's curve, which is based on the calculation of water resources within the model, is often used for territories with large areas and not for spatially small areas, where the results of the InVEST model are obtained. Therefore, during the preparation of the input data of the InVEST model, it is important to use spatially accurate data that can represent the climate and natural conditions of the region, which can impact the model results to be much more accurate.

CONCLUSIONS

In the framework of this research, the water yield and actual evapotranspiration of the Upper Tuul River basin were estimated with the InVEST (Water Yield) model. Required input data of the model, such as land use and land cover, precipitation, annual mean potential evaporation, soil depth, plant available water content, and watershed and sub-watersheds data were prepared and processed.

Landsat 8 satellite data used for processing land use and land cover type of the study area, CHIRPS data for annual mean precipitation, and MOD16 satellite product for potential evaporation data, were processed and input data were prepared. In addition, information on determining the depth of the soil layer and plant available water content in the study area, a) the soil depth up to the R layer, and b) potential soil water capacity in the 10 cm layer of the soil data in the ISRIC database was used. Moreover, the ArcSWAT model delineated the watershed and sub-watersheds.

According to the modeling results, the annual mean precipitation is 295.08 mm, the average surface runoff layer that can be generated is 55.89 mm, and the water yield (by volume) is 0.43 km^3, while the potential and actual evapotranspiration are 827.09 mm and 229.13 mm respectively in the study area. Compared to the results of related studies by other researchers, the annual mean evapotranspiration was slightly higher (by around 15.1 mm), which can be contributed to the reduction of the potential runoff layer in the watersheds.

The results and maps of the InVEST (Water Yield) model have the advantage of being gridded, they can be flexible in terms of spatial coverage, and do not require many years of flow measurement data to develop the primary results. The results may vary significantly depending on the model, and the requirements for preparing and processing input data with good spatial accuracy may be the weaknesses of the model. Moreover, validating the model spatial-based results with the gauging-station-based measured data can be one of the possible limitations of the model. Thus, empirical validation of model outputs at a selected local scale should be conducted in future research. We firstly recommend that, where empirical data are available, models should be validated for locations in the region of interest and the effect of alternative parameter values or input data should be explored. Secondly, we recommend the application of sensitivity analysis to understand how model outputs vary across the region of interest, either in tandem with validation or, if validation data are not available, to understand uncertainty in model predictions. Finally, if no validation data are available, we advise exercising caution when interpreting model output values.

In conclusion, it can be considered “possible” to use the InVEST water yield model in future research to estimate the water yield based on multi-year measured data as input data or by calibrating the model using data with high spatial accuracy. Furthermore, it is suggested that the modeling outcomes will be enhanced by calibrating the results with long-term flow measurement data in-situ and validating empirically, as well as increasing the spatial resolution of some raster data, namely, root restricting layer and plant available water content in soil types.

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