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Assessment of human-induced evapotranspiration with GRACE satellites in the catchment area of lake Baikal

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Abstract. Evapotranspiration is an integral part of the Earth system studies, but it is challenging to measure it on regional scales. One estimation technique is a terrestrial water budget, i.e., total precipitation minus the sum of evapotranspiration and net runoff equals the change in water storage. Gravity Recovery and Climate Experiment (GRACE) satellite gravity observations are now enabling the closure of this equation by providing information on the terrestrial water storage changes. The main objective of this study was to estimate human induced evapotranspiration (HET) using the water budget and Remote Sensing-Based Vegetation Interface Processes (VIP-RS) model. We compare VIP-RS model ET estimates with Gravity Recovery and Climate Experiment and Moderate Resolution Imaging Spectroradiometer satellite-based estimates in the intensively managed Lake Baikal basin. The GRACE-based ET (0,534–133,570 mm/yr.), considerably higher than VIP-RS ET (0–94,319 mm/yr.), agrees well with existing estimates found in the literature and indicates that human activities contribute to an increase in ET. The evaluated uncertainty of monthly precipitation, runoff, GRACE based terrestrial water storage, ET-GRACE, and VIP-RS is 1,56, 0,04, 1,3, 0,89, and 0,8 km^3 $month^{-1}$, respectively. The differences may be utilized as an indicator of water management impacts on ET. We argue that satellite-based ET should yield larger seasonal amplitudes in the lake basin due to the impacts of anthropogenic activities. To date, no such investigation has been available in the existing literature for the Lake Baikal basin. Therefore, the adopted approaches for HET and its result will be regarded as a new and honest contribution to the Lake Baikal basin.

Keywords: evapotranspiration, ET-GRACE, human-induced, precipitation, VIP-RS model ET, temperature

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Научная статья

Оценка антропогенного суммарного испарения с помощью спутников GRACE в водосборном бассейне озера Байкал

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Аннотация. Эвапотранспирация является неотъемлемой частью исследований земной системы, однако ее трудно измерить в региональном масштабе. Одним из методов оценки является водный баланс суши, т. е. общее количество осадков минус сумма суммарного испарения и чистого стока, равная изменению запасов воды. Спутниковые наблюдения за гравитационным восстановлением и климатом (GRACE) в настоящее время позволяют закрыть это уравнение, предоставляя информацию об изменениях в запасах воды на земле. Основная цель этого исследования – оценка суммарного испарения, вызванного деятельностью человека (HET), с использованием модели водного баланса и процессов взаимодействия растительности на основе дистанционного зондирования (VIP-RS). Мы сравниваем оценки ET по модели VIP-RS с результатами эксперимента по гравитационному восстановлению и климату, а также с оценками, полученными с помощью спутниковых спектрорадиометров среднего разрешения в интенсивно управляемом бассейне о. Байкал. Значение ET, основанное на GRACE (0,534–133,570 мм/год), значительно выше, чем значение ET, основанное на VIP-RS ET (0–94,319 мм/год), хорошо согласуется с существующими оценками, приведенными в литературе, и указывает на то, что деятельность человека способствует увеличению ET. Оцененная неопределенность месячных осадков, стока, наземных запасов воды на основе GRACE, ET-GRACE и VIP-RS составляет 1,56, 0,04, 1,3, 0,89 и 0,8 км^3 в месяц за один месяц соответственно. Эти различия могут быть использованы в качестве показателя воздействия управления водными ресурсами на ET. Мы утверждаем, что спутниковые наблюдения за погодой должны давать более высокие сезонные амплитуды в бассейне озера из-за воздействия антропогенной деятельности. На сегодняшний день в существующей литературе по бассейну о. Байкал нет данных о подобных исследованиях. Таким образом, принятые подходы к HET и его результат будут рассматриваться как новый и честный вклад в развитие бассейна о. Байкал.

Ключевые слова: эвапотранспирация, ET-GRACE, антропогенный, осадки, модель VIP-RS ET, температура

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INTRODUCTION

Understanding the regional water balance requires an understanding of evapotranspiration (ET). In contrast to other significant elements of the surface water balance (such as streamflow and precipitation), quantifying the effect of evapotranspiration on the role of water resource variability remains a significant challenge [1]. Furthermore, it is extremely difficult to accurately estimate regional ET with discernible spatial heterogeneity due to the interaction of the atmosphere, hydrology, energy, and human activity [1].

It is significant that a great deal of research has been done in recent years assimilating satellite remote sensing data to derive ET. Cleugh, Ray, Qiaozhen, Steven, [2] evaluated the abilities of the energy balance model and the Penman Monteith (P-M) model and demonstrated the potential of the P-M model for evaporation climatology; Zhang, Kimball, Nemani, and Running, [3] provided a long-term global ET with remote sensing NDVI.

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, combined with other auxiliary data, serves as an alternative to estimate the regional ET by water balance, either from natural and/or anthropogenic sources [4–7].

The water balance equation at the regional or watershed scale can be written as precipitation equals the sum of ET, runoff, and changes in total water storage components. Nowadays, reliable precipitation datasets across the globe are reasonably available with moderate spatial and temporal resolutions.

Parametric process-based ET models typically require intensive datasets such as soil, crop, and climatic data to derive ET at different spatial scales with reasonable accuracy [8]. But remote sensing-based methods have the advantage of estimating hydrological fluxes such as ET from routinely available weather parameters without actually integrating intensive and complex land use, crop, and soil parameters [9].

Continuous monitoring of current and past distributions of surface water, precipitation, and other variables in the basin can provide us in advance with the most probable variation of water storage in the river basin. Increasing temperatures increase evapotranspiration, which may shift the fraction of precipitation that runs off as surface water or infiltrates into the subsurface and also maintain lakes and other water bodies.

Long-term shifts in evapotranspiration can change the water availability and affect the ecosystem of the water bodies. Such human activities as groundwater exploration and land surface water resource assignment may induce a significant difference between satellite-based evapotranspiration and evapotranspiration land surface models, which are considered to be human-induced evapotranspiration. Different studies have presented that the annual evapotranspiration is contributed by human activities that lead to water resource variability [4].

These indicate that anthropogenic activities may substantially contribute to evapotranspiration changes, which could be evaluated by GRACE terrestrial water storage and the physically based evapotranspiration models.

Evapotranspiration is not only influenced by natural climate and vegetation factors but also by human activities such as irrigation or groundwater pumping. Such human influences are difficult to parameterize in hydrologic models due to the lack of data and understanding of their physical mechanisms and impacts.

Hence, most LSMs can only simulate ET under natural climate conditions. Yet studies using GRACE to detect human-induced ET (ETH) were rarely reported in the literature. It has been widely accepted that GRACE can detect changes of TWS (the sum of surface water storage (SWS), soil moisture storage (SMS), and groundwater storage (GWS)) caused by both natural and human factors [10].

Currently, no methodology exists to directly observe intra-annual evapotranspiration (ET) over a large region such as a river basin due to complex interactions among atmospheric, hydrologic, energy, and anthropogenic variables which complicate ET estimation at such scales.

But, given the unique capability of monitoring terrestrial water storage (TWS) variations from space, the gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) twin-satellite mission have been utilized along with other ancillary data to estimate regional evapotranspiration.

Most of these studies focused on comparing GRACE-based ET estimates from water budget analysis with other methods such as land surface model (LSM) simulations [11] or remote sensing-based approaches like Moderate Resolution Imaging Spectroradiometer (MODIS).

This method provides an independent constraint on higher-resolution satellite-based ET estimates that incorporate data from multispectral and thermal instruments.

This approach has been applied to observations from NASA’s Gravity Recovery and Climate Experiment (GRACE) mission [12].

GRACE provides monthly global terrestrial gravity anomalies that can be processed to create terrestrial water storage anomalies (TWSA) for regions larger than 200,000 km2 [13].

Previous work has compared GRACE-derived ET to estimates from LSMs, with the intent to validate each approach by comparison.

According to previous research on a global and regional scale, climate change and human activities are the two main drivers that affect hydrological processes [14] that also affect both potential and actual terrestrial ET rates. Remotely sensed ET rates have been used to diagnose the trends of hydrological cycles at regional and global scales [3]. Natural climate factors are commonly the main reason for the total TWS variations, which dominate the trends of water storage in large scale basins.

Human activities not only have direct impacts on TWS variations in basin scale but also have a magnifying effect on the changes caused by natural factors which affect evapotranspiration.

For instance, the increase in population leads to the expansion of agricultural land [1], and the expansion of agriculture and the increase in irrigative demand result in an increase in water utilization.

In recent decades, the consumption of water resources in the Lake Baikal basin has significantly increased due to the increase in Mongolia's population [15].

However, as the Lake Baikal basin is located in a sensitive area of global climate change, the TWS variations in this region may still be seriously affected by the natural climate changes which are the main cause for the variability of evapotranspiration.

Despite the numerous ET estimates are available it remains a challenge to quantify anthropogenic contributions to ET due to the dearth of information on anthropogenic activities.

Therefore, in this study, GRACE monthly terrestrial water storage from 2002-2016 are first estimated, and then used to estimate evapotranspiration as the residual of the water budget equation.

Additionally, human induced evapotranspiration (HET) is evaluated by the GRACE-TWS data and the predicted ET by Remote Sensing based Vegetation Interface Processes (VIP-RS) model, and then the variations, causes and uncertainties of HET in the Lake Baikal basin were evaluated.

The identification of HET is achieved through comparison between ET from GRACE and VIP-RS modeled ET. The differences may be utilized as an indicator of water management impacts on ET.

We argue that satellite-based ET should yield larger seasonal amplitudes in the lake basin due to the impacts of anthropogenic activities.

To date, no such investigation has been available in the existing literature for Lake Baikal basin. Therefore, the adopted approaches for HET and its result will be regarded as a new and honest contribution to the Lake Baikal basin.

MATERIALS AND METHOD

Study area

Lake Baikal is located in the southern part of eastern Siberia, in the Buryatia and Irkutsk oblasts (province) of Russia (Fig. 1). Lake Baikal has 336 rivers flowing into the lake, covering an area of 560,000 km^2.

The main ones draining directly into Baikal are the Selenga, the Barguzin, the Upper Angara, the Turka, the Sarma, and the Snezhnaya.

It is drained through a single outlet – the Angara River.

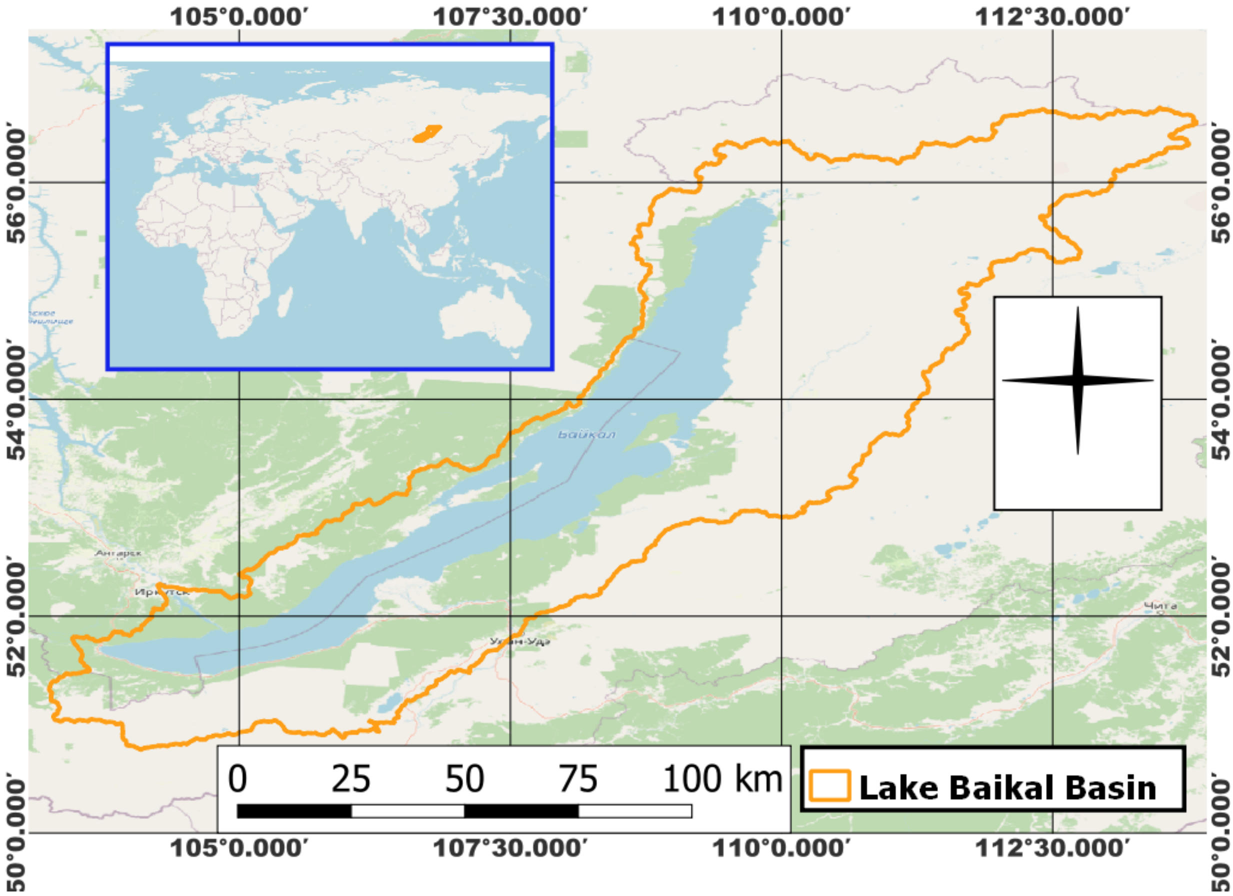


Fig. 1. The study area location map
Рис. 1. Карта расположения района исследования

Data source

The daily meteorological data was collected from the Russian hydrometeorological center in the Siberian Federal District of Russia.

The observed evapotranspiration for the model validation was obtained by R-Studio from 2001 to 2023.

Precise precipitation data is very essential for the closure of the surface water balance in the whole lake basin.

The forcing dataset of the TerraClimate data was used for this study. Indirect spatialized data for precipitation, and temperature were provided by TerraClimate: Monthly Climate data (https://support.climateengine.org/article/87-terraclimate), GRACE Monthly Mass Grids – Land data (https://grace.jpl.nasa.gov/data/get-data/), MODIS/061/MOD16A2: Terra Net Evapotranspiration Gap-Filled 8-Day Global 500m https://lpdaac.usgs.gov/products/mod16a2v061/) and others.

Water balance from GRACE-satellite dataset

In this analysis basin averaged surface mass anomalies from GRACE, equivalent to the column-integrated water stored on land, which includes soil water, groundwater, surface water, and snow water, are evaluated.

GRACE is the widely used satellite that can evaluate global water storage changes, launched in March 2002 [5–7].

The measurements of GRACE can produce spatiotemporal change in the Earth's gravity field, which shows the water mass change over the land surface [5, 6, 7, 16]. These products of the GRACE terrestrial water storage data set have undergone pre-processing, such as a de-striping filter, glacier isostatic adjustment, and Gaussian smoothing [3, 5, 6, 7].

Evapotranspiration and precipitation are key components of both atmospheric and terrestrial water storage [18]. The precipitation minus evapotranspiration shows the net water flux onto the earth's surface, and gives essential information regarding the interaction between the atmosphere and the land surface [16].

For each river basin, the relationship between terrestrial water, precipitation and evapotranspiration can be expressed as in equation 1:

$$\Delta LWE = RF - ET \quad (1)$$

ET is affected by both natural climate factors and anthropogenic factors such as irrigation or groundwater pumping [4]. But GLDAS only simulates EVT under natural climate conditions. RF-ET obtained from GLDAS was compared with TWS from GRACE, the former of which reflects TWS changes under natural climate conditions and the latter represents total terrestrial water storage (TWS) change, to evaluate the contribution of human activities to TWS changes. Moreover, to estimate the effects of human activities on the variations in ET, the ET calculated from GLDAS was compared with the total ET obtained from GRACE. The total ET can be estimated by equation 2.

$$ET_{GRACE} = RF - LWE_{GRACE} \quad (2)$$

Where ET_{GRACE} shows total ET and LWE_{GRACE} is liquid water equivalent obtained from GRACE

VIP-RS model

Based on the meteorological data and the remote sensing NDVI, the VIP-RS model was used to evaluate evapotranspiration. The evaluated evapotranspiration includes land surface water evaporation and natural vegetation evapotranspiration (ecological and agricultural water evaporation). The VIP-RS model evaluates evapotranspiration as vegetation transpiration (Ec), soil evaporation (Es) and rainfall interception (Ei), which can be written as:

$$E_c = (1 - f_{wet}) * f_t * f_m * \frac{0.408*\Delta*R_{nc} + f_{cover}*\gamma*\frac{900}{T+273}*U_2*VPD}{\Delta + r_{ccor}*\gamma*(1+0.3*U_2)} \quad 3$$

$$E_s = min([f_{wet} + f_{sm}(1 - f_{wet})]) * E_{ps}, E_{ex} \quad 4$$

$$E_{ps} = \frac{0.408*\Delta*(R_{nc} - G) + (1 - f_{cover})*\gamma*\frac{900}{T+273}*U_2*VPD}{\Delta + r_{ccor}*\gamma*(1+0.3*U_2)} \quad 5$$

Where Δ is the slope of saturation vapor pressure per temperature relationship in hectopascal per *degrees Celsius*, R_{nc} and R_{ns} are the net radiation absorbed by canopy and soil (MJ per day) respectively, f_{wet} is humidity of land surface, f_t is the temperature stress, f_m is water restriction of vegetation, f_{sm} is the limitation of soil moisture, f_{cover} is the fractional cover of vegetation, T is the air temperature in degree Celsius, G is the soil heat flux in MJ per day, γ is the psychrometric constant in hectopascal per *degrees Celsius, VPD is the saturated water vapour pressure deficit,* E_{ps} is the potential evapotranspiration of the surface and E_{ex} is the soil moisture exudation rate. The E_i is estimated as

$$E_i = \frac{1}{\lambda} * f_{wet} * 1.26 * \frac{\Delta}{\Delta+\gamma} * R_{nc} \quad 6$$

Where λ is the latent heat of vaporization of water in J/kg. According to [19], evaporation of water body ((E_{water}) was estimated by net radiation (R_n).

$$E_{water} = \frac{\Delta*\frac{0.75}{\lambda} + \gamma*2.6*(1+0.536*U_2)*VPD}{\Delta+\gamma} \quad 7$$

Accuracy evaluation method

The accuracy of the established model of community ET was evaluated using the evaluation indexes of mean square error (MSE)

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(X_i - y_i)^2 \quad 8$$

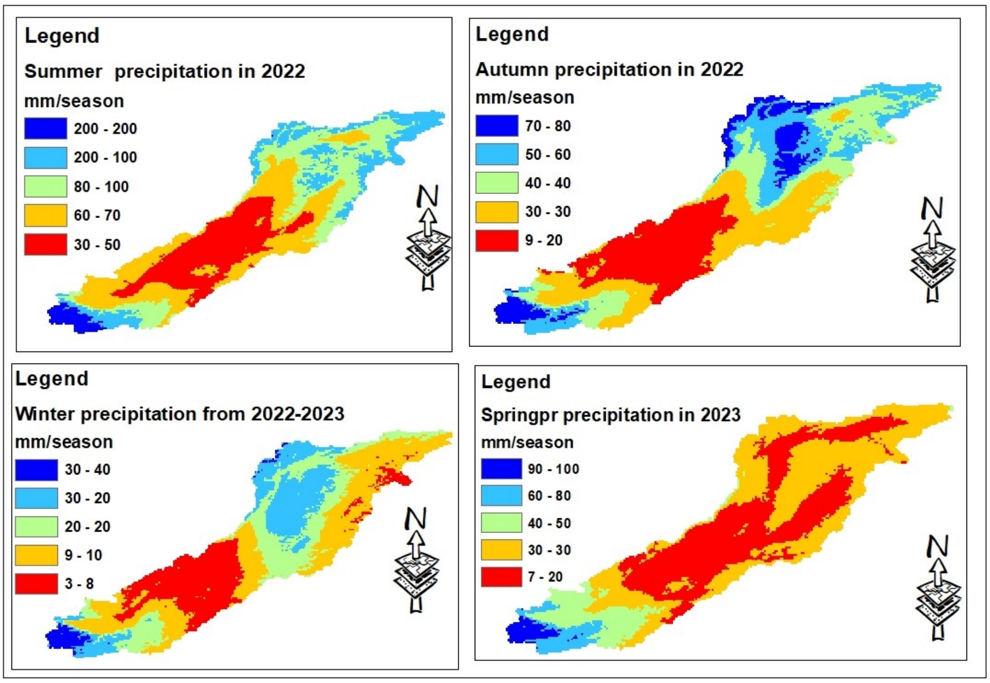
Result. Precipitation and temperature

The significant dynamic variability of precipitation and temperature has significant effects on evapotranspiration. The patterns of precipitation in Lake Baikal have undergone significant changes, with a distinct increase in precipitation in the summer followed by spring, autumn, and the smallest amount of precipitation observed in winter. As shown in Fig. 2a, the seasonal spatial distribution of precipitation in the Lake Baikal basin ranges for the year 06/01/2022 to 05/31/2023. The shift in precipitation distribution poses a serious threat to water resource availability.

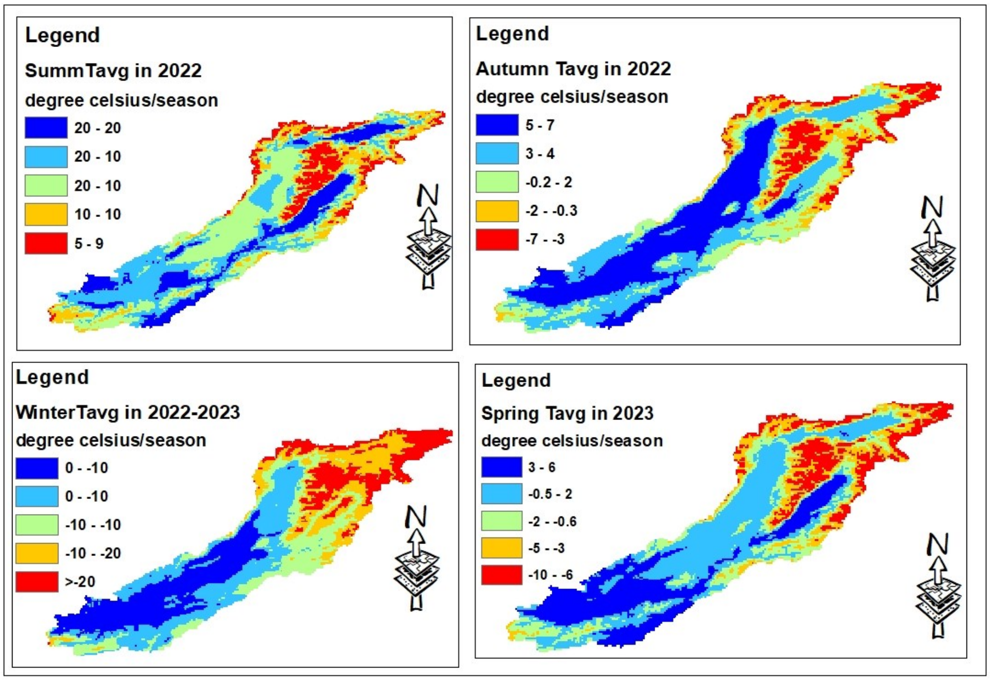
Our study suggests that water resource management should consider the decreasing trend in rainfall, particularly in the areas where a significant decreasing trend was identified (red color).

Additionally, the scarcity of rainfall in certain regions has a negative impact on domestic activities, industrial production, and declining groundwater levels. Temperature is one of the most essential climatic parameters that can affect the evapotranspiration rate. Higher temperatures lead to higher evapotranspiration. In this study area, the red color demonstrates a higher temperature, and the green color shows a lower temperature. Fig. 2b demonstrates the seasonal average temperature variation in the Lake Baikal basin, which ranges in degrees Celsius. The blue color shows the highest temperature, whereas the red color shows the lowest temperature during study period. ET was moderately correlated with precipitation (P), and only weakly correlated with net radiation or air temperature.

The strong correlation between ET and the Enhanced Vegetation Index (EVI), as opposed to the moderate correlation with rainfall, suggests that transpiration (T) is the dominant process controlling ET.



a) Seasonal precipitation from 06/2022 to 05/2023
а) Сезонные осадки с 06.2022 по 05.2023



b) Seasonal average temperature from 06/2022 to 05/2023
б) Средняя сезонная температура с 06.2022 по 05.2023

Fig. 2. Seasonal precipitation and average temperature in Lake Baikal
Рис. 2. Сезонные осадки и средняя температура на о. Байкал

RUNOFF

All the precipitation that comes to the earth's surface does not contribute to runoff, some part of it disappears. The loss is caused by evaporation, transpiration, interception, depression storage, and infiltration.

Fig. 3 shows the seasonal spatial distribution of runoff from 06/01/2022 to 05/31/2023 in the Lake Baikal basin.

Very high runoff was observed in spring season and no runoff was observed in winter for this study duration.

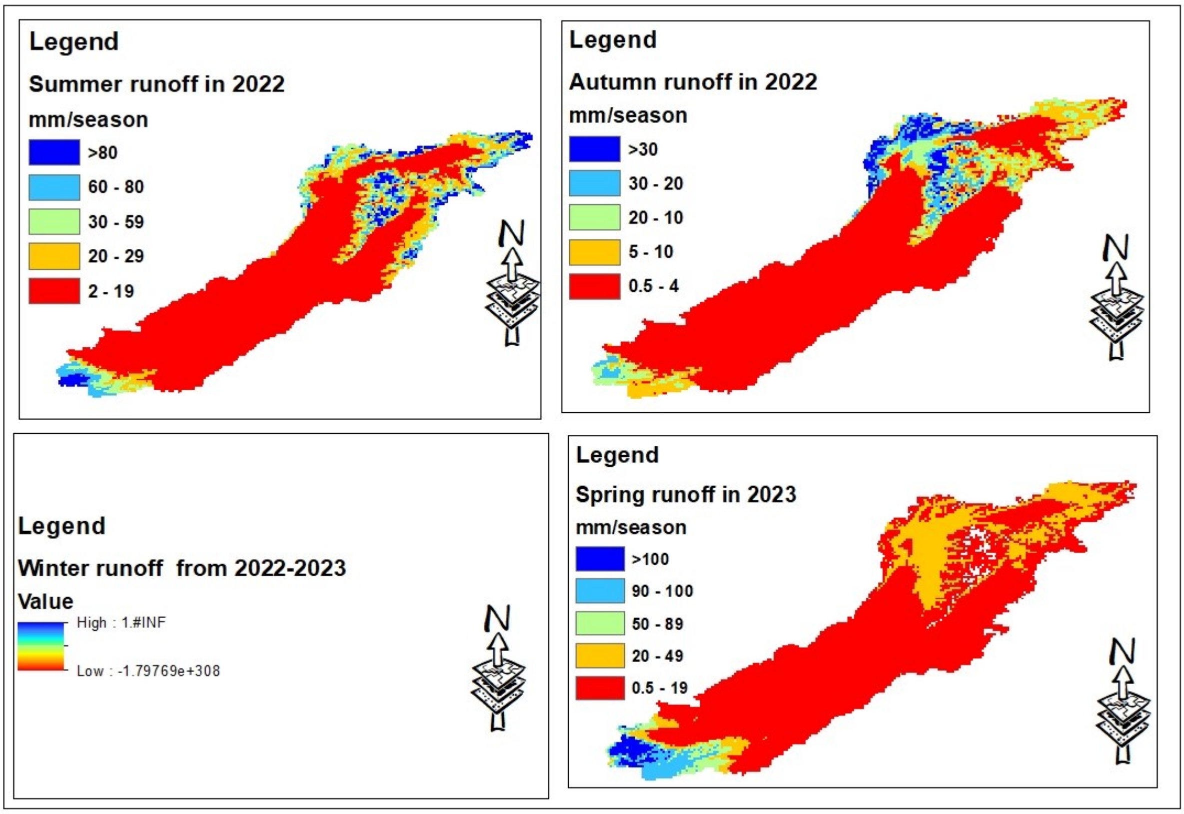


Fig. 3. Seasonal spatial distribution of runoff for 2022 to 2023

Рис. 3. Сезонное пространственное распределение стока в период с 2022 по 2023 г.

Terrestrial water storage variation in the Lake Baikal basin

The change in terrestrial water storage evaluated from the GRACE satellite dataset for the Lake Baikal basin for the period of April 2002 to January 2017. The anomalies in terrestrial water storage are relative to the mean storage value between 2004–2009. The annual trend indicates a significant decreasing trend during the study period, and the inter-anomalies of terrestrial water storage show continuous falling and rising trends in the Lake Baikal basin.

The variations in terrestrial water storage range from -12,134 to 4,312 cm per month. The change in terrestrial water storage is primarily caused by continuing human activities in the lake basin (like groundwater exploitation, increasing urbanization, mineral exploitation, etc.).

Estimation of evapotranspiration

Due to the availability of data on air temperature, the Thornthwaite method and Hargreaves model are frequently used because they are based on the measurement of air temperature, which is commonly recorded in many meteorological stations around the world.

The estimated value of daily ET by the Thornthwaite method was obtained by using the average daily temperature, effective daily temperature and corrected effective daily temperature in R-studio, whereas the estimated Hargreaves evapotranspiration was obtained by using average temperature with longitude and latitude of the meteorological stations in R-Studio. Figure 5a shows the yearly Thornthwaite method and Hargreaves model of ET presenting the higher ET value for Hargreaves model than that of the Thornthwaite method but followed similar trends. Temperature is the dominant variable that leads to the variation in evapotranspiration, as confirmed by other studies.

The estimates of mean daily ET based on the GRACE water balance approach are used, and yearly values are plotted in Fig. 4 for the study period from 2002 to 2016.

The estimation of GRACE-based evapotranspiration was based on precipitation and GRACE's terrestrial water storage dataset. The GRACE-based evapotranspiration also shows a significant variation during the study periods.

The VIP-RS model evapotranspiration was evaluated by using equations from 3 to 7. The estimated result shows the similar trends with previously estimated evapotranspiration but has the lowest value compared with other methods.

The GRACE based evapotranspiration falls in the middle of the Hargreaves and VIP-RS models and the Thornthwaite method. The estimated evapotranspiration using the Haregreves method produced a larger amplitude than other methods, followed by the Thornthwaite method of estimating evapotranspiration.

The monthly average evapotranspiration for Thornthwaite, Hargreaves, GRACE and VIP-RS models during the study period ranges from 0–131,613, 0–156,120, 0,534–133,570 and 0–94,319 mm respectively. The VIP-RS evapotranspiration was significantly lower than all the other evapotranspiration.

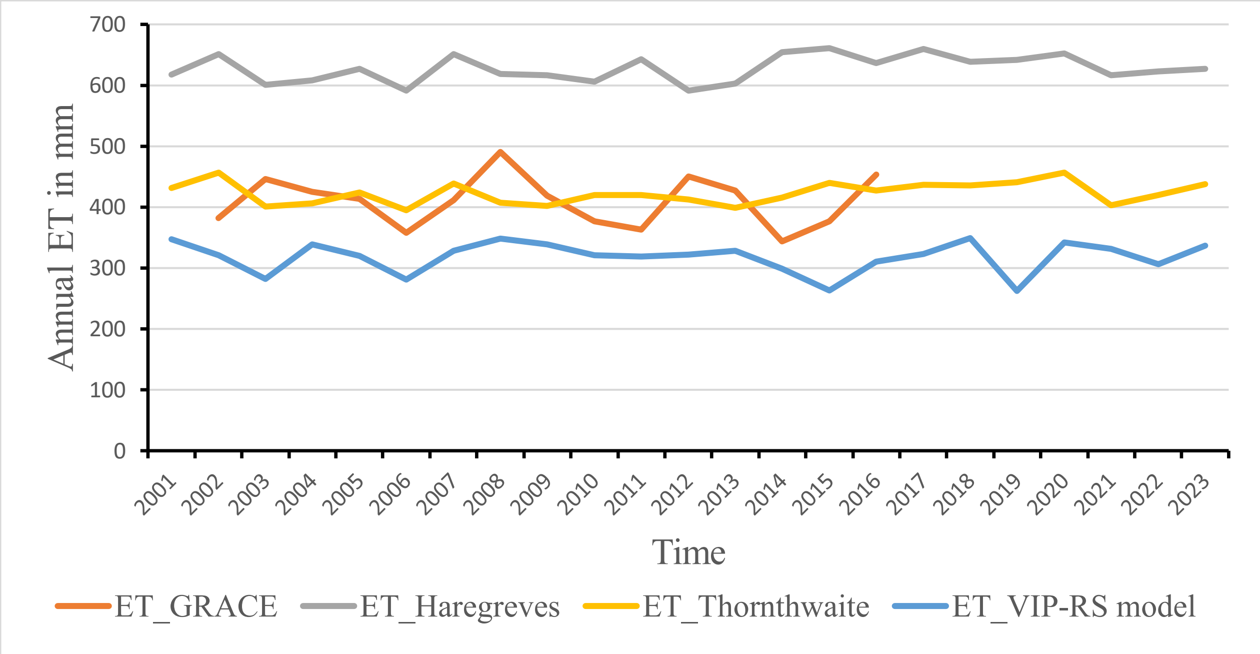


Fig. 4. Estimated annual evapotranspiration for the Lake Baikal basin
Рис. 4. Расчетное годовое суммарное испарение в бассейне о. Байкал

Seasonal spatial distribution of ET from Terra Net Evapotranspiration 8-Day Global 500m dataset

For this study the MODIS (MOD16A2.006) Terra Net Evapotranspiration 8-Day Global 500m datasets are used to evaluate the seasonal distributions of ET for the Lake Baikal basin.

Based on the estimate, higher ET was observed in the summer season followed by spring season ranging from 85–420 mm per season and 46–180 mm per season respectively, whereas the lowest ET was observed in winter season ranging from 12 to 55 mm per year.

The spatial distribution of MODIS evapotranspiration for the Lake Baikal basin was presented in Fig. 5 during study season from 06/01/2022 to 05/31/2023.

Model Validation

The estimated ET-VIP was compared with the Hargreaves and Thornthwaite methods of ET. The Hargreaves and Thornthwaite methods of ET were considered as observed ET. Overall, seasonal changes of ET-VIP were consistent with the Hargreaves and Thornthwaite methods of ET. The correlation coefficient between Thornthwaite and Hargreaves, Hargreaves and the VIP-RS model and Thornthwaite and the VIP-RS model were 0,949, 0,951 and 0,944 respectively.

The mean square error (MSE) between VIP-RS and GRACE-ET, Hargreaves and GRACE-ET, and Thornthwaite and GRACE-ET were 0,80, 1,48, and 0,90 mm/day, respectively, while the standard deviation of the three models averages 0,72 mm/day. The Thornthwaite method shows the best agreement with GRACE with a mean bias of -0,24 mm/day, whereas Hargreaves methods show an overestimate of ET with a mean bias of 0,65 mm/day, whereas the VIP-RS model shows an underestimate of ET with a mean bias of -0,55 mm/day. Although the uncertainties of meteorological data are unavoidable between different ET algorithms [20].

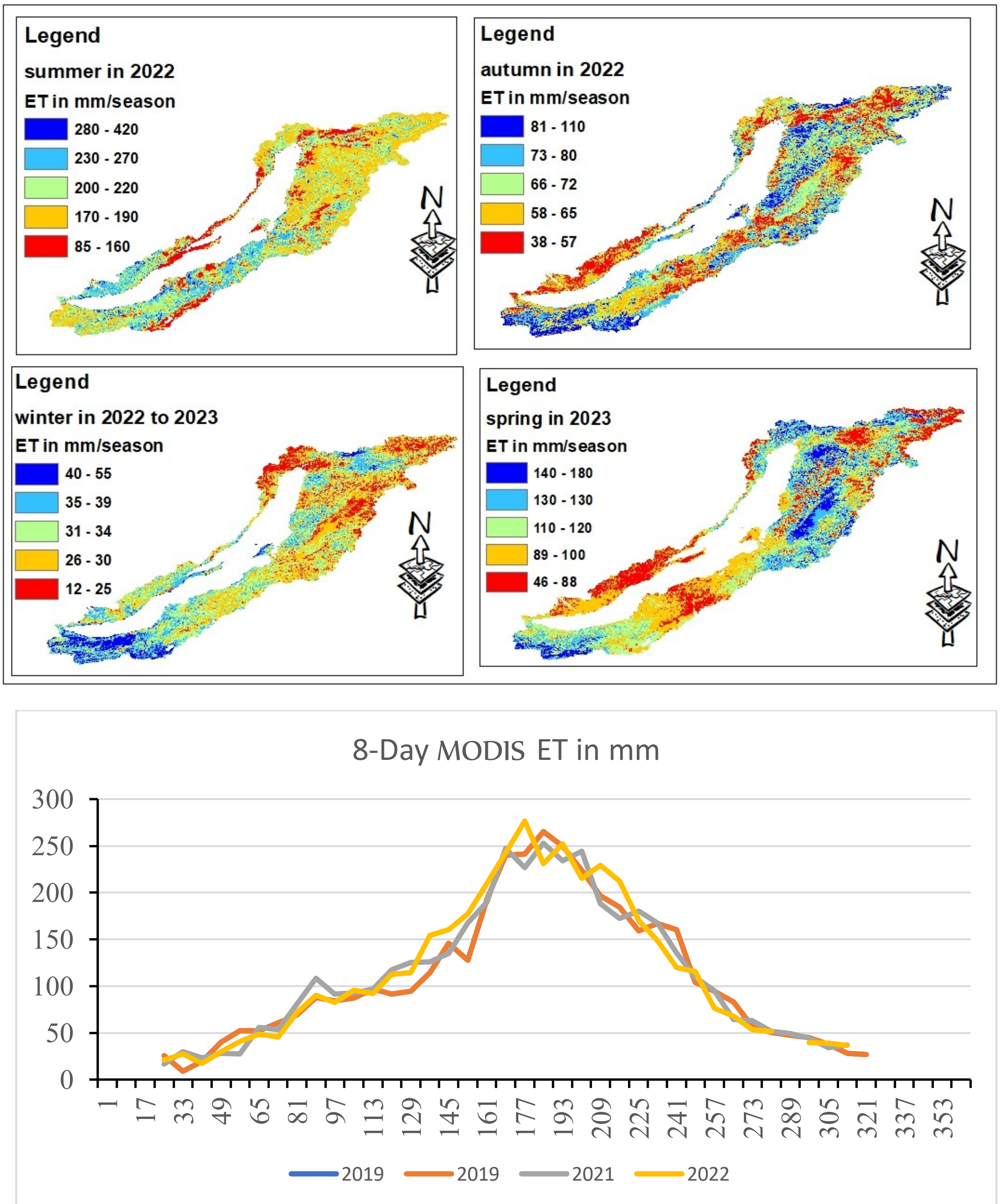


Fig. 5. Seasonal evapotranspiration for the lake Baikal basin from 2022 to 2023
Рис. 5. Сезонное суммарное испарение в бассейне о. Байкал с 2022 по 2023 г.

Evaluating the human-induced evapotranspiration during study period

The human-induced evapotranspiration was obtained by subtracting VIP-RS evapotranspiration from GRACE. The uncertainty of annual GRACE-ET, VIP-ET, and HET was 0,60, 0,86 and 0,95 km^3 year^{-1}, respectively. The uncertainty of monthly precipitation, runoff, GRACE based terrestrial water storage, ET-GRACE, and VIP-RS is 1,56, 0,04, 1,3, 0,89, and 0,8 km^3 month^{-1}, respectively.

The GRACE-ET showed larger amplitude than VIP-RS model ET due to lake of ET contribution by human activities in the VIP-RS model. The human-induced evapotranspiration obtained from the GRACE data set and VIP-RS model ranges from -50,9 to 61,0 mm. The uncertainty of runoff was lower than that of precipitation because annual runoff is lower than annual precipitation. The variation in terrestrial water storage showed large uncertainties, which could probably be attributed to heavy precipitation and high terrestrial water storage. The uncertainty of monthly ET mainly comes from terrestrial water storage variation, which agrees with the similar findings [4, 21]. The distribution of evapotranspiration in the lake basin was influenced by the increasing economic and population growth rates and various economic activities conducted in the lake basin.

CONCLUSION

This research investigates the human-induced evapotranspiration based on water budges from GRACE TWS in the Lake Baikal basin from 2002 to 2016. First GRACE terrestrial water storage for the lake basin was evaluated during this study. Evapotranspiration based on VIP-RS, GRACE, the Hargreaves and Thornthwaite methods was evaluated for this study during the study period. From the estimated ET, the Hargreaves method shows an overestimation of ET, whereas VIP-RS method shows an underestimation of ET. Based on the estimated results, they range from 490,6–343,7, 660,9–591,1, 456,6–394,84, and 349,11–262,3 mm per year for GRACE, the Hargreaves, Thornthwaite methods and VIP-RS model, respectively.

The human-induced evapotranspiration was evaluated during this study from GRACE and VIP-RS ET. The estimated human-induced ET ranges from 43,52-163,62 mm per year. The uncertainty of annual GRACE-ET, VIP-ET, and HET was 0,60, 0,86, and 0,95 km^3 year^{-1}, respectively. The uncertainty of monthly precipitation, runoff, GRACE based terrestrial water storage, ET-GRACE, and VIP-RS is 1,56, 0,04, 1,3, 0,89, and 0,8 km^3 month^{-1}, respectively.

In conclusion, this study emphasizes the unique ability of gravity satellites in monitoring water storage variations due to both climatic and human factors by comparing with VIP-RS model in the Lake Baikal basin with intensive human impacts such as groundwater exploitation, industrialization, increasing urbanization, mineral mining. It also addresses the potential and uncertainty of GRACE-based TWSC and ET for understanding hydrologic changes under multiple driving factors and it provides valuable information on isolating and quantifying human impacts.

The land surface model community may also benefit from this study for improving model parameterizations and simulations.

This study also presents and demonstrates the importance and cost-effectiveness of remote sensing and satellite datasets to identify the human induced evapotranspiration for engaged river basins.

This method is also important to access and manipulate large data coverages and inaccessible areas within limited time intervals.

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