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ASSESSING WATER LEVEL VARIABILITY IN THE ZHAIYK (URAL) RIVER BASIN USING GRACE SATELLITE GRAVIMETRY AND HYDROLOGICAL OBSERVATIONS

Precise monitoring of surface water storage dynamics is crucial for effective water resource management and comprehension of local hydrological processes. This study examines the correlation between fluctuations in water levels in the Zhaiyk River Basin (Ural) and anomalies in overland water storage derived from the Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry.

We assess the degree of the satellite-in situ measurement correlation using long-term hydrological observations and GRACE equivalent water thickness data. With a coefficient of determination (R^2) of 0.7459, the results show a noteworthy positive correlation, indicating that GRACE data capture regional large-scale hydrological changes. Nevertheless, the study also highlights the coarse spatial resolution of GRACE, which limits its ability to detect local water level fluctuations. GRACE continues to be an invaluable instrument for evaluating the dynamics of long-term water storage and its underlying factors, such as precipitation, evapotranspiration, and anthropogenic influences.

Future research should investigate the feasibility of integrating GRACE with hydrological models and higher-resolution remote sensing products to enhance the precision of monitoring and broaden the scope of satellite gravity's application in regional water resources assessment.

Key words: gravimetry, water level, Zhaiyk, Ural, Kazakhstan, GRACE, Kazhydromet, gauging station.

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Грейс спутниктік гравиметриясын және гидрологиялық бақылауларды пайдалана отырып, Жайық (Орал) өзені бассейніндегі су деңгейінің өзгермелілігін бағалау

Су ресурстарын тиімді басқару және жергілікті гидрологиялық процестерді түсіну үшін жер үсті суларын сақтау динамикасын нақты бақылау өте маңызды. Бұл зерттеу Жайық өзені алабындағы (Жайық) су деңгейінің ауытқуы мен Гравитацияны қалпына келтіру және климаттық эксперимент (GRACE) спутниктік гравиметриясынан алынған жер үсті су қоймаларындағы ауытқулар арасындағы корреляцияны зерттейді. Біз ұзақ мерзімді гидрологиялық бақылаулар мен GRACE эквивалентті су қалыңдығы деректерін пайдалана отырып, жерсеріктік жердегі өлшеу корреляциясының дәрежесін бағалаймыз.

Детерминация коэффициентімен (R^2) 0,7459, нәтижелер GRACE деректері аймақтық ауқымды гидрологиялық өзгерістерді қамтитынын көрсететін назар аударарлық оң корреляцияны көрсетеді. Дегенмен, зерттеу сонымен қатар GRACE-тің дөрекі кеңістіктік рұқсатын көрсетеді, бұл оның су деңгейінің жергілікті ауытқуларын анықтау мүмкіндігін шектейді. GRACE ұзақ мерзімді суды сақтау динамикасын және жауын-шашын, булану және антропогендік әсерлер сияқты оның негізгі факторларын бағалаудың баға жетпес құралы болып қала береді.

Болашақ зерттеулер мониторинг дәлдігін арттыру және аймақтық су ресурстарын бағалауда жерсеріктік тартылыс күшін қолдану аясын кеңейту үшін гидрологиялық модельдермен және жоғары ажыратымдылығы бар қашықтықтан зондтау өнімдерімен GRACE интеграциясының орындылығын зерттеуі керек.

Түйін сөздер: гравиметрия, су деңгейі, Жайық, Орал, GRACE, өлшеу станциясы.

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Оценка изменчивости уровня воды в бассейне реки Жайык (Урал) с использованием данных спутниковой гравиметрии GRACE и гидрологических наблюдений

Точный мониторинг динамики запасов поверхностных вод имеет решающее значение для эффективного управления водными ресурсами и понимания локальных гидрологических процессов. В этом исследовании изучается корреляция между колебаниями уровня воды в бассейне реки Жайык (Урал) и аномалиями в запасах воды на суше, полученными с помощью спутниковой гравиметрии Gravity Recovery and Climate Experiment (GRACE). Мы оцениваем степень корреляции спутниковых и натурных измерений, используя долгосрочные гидрологические наблюдения и данные об эквивалентной толщине воды GRACE.

При коэффициенте детерминации (R^2) 0,7459 результаты показывают заслуживающую внимания положительную корреляцию, что указывает на то, что данные GRACE фиксируют региональные крупномасштабные гидрологические изменения. Тем не менее, исследование также подчеркивает грубое пространственное разрешение GRACE, что ограничивает его способность обнаруживать локальные колебания уровня воды. GRACE остаётся бесценным инструментом для оценки динамики долгосрочного запаса воды и его основных факторов, таких как осадки, эвапотранспирация и антропогенные влияния.

В будущих исследованиях следует изучить возможность интеграции GRACE с гидрологическими моделями и продуктами дистанционного зондирования с более высоким разрешением для повышения точности мониторинга и расширения сферы применения спутниковой гравитации при оценке региональных водных ресурсов.

Ключевые слова: гравиметрия, уровень воды, Жайык, Урал, GRACE, Казгидромет, гидропост.

Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite mission has transformed remote sensing of the Earth's gravitational field, providing unparalleled capabilities for monitoring global water supplies. The Gravity Recovery and Climate Experiment (GRACE) satellite mission offers invaluable information about the Earth's water resources (Hasan et al., 2019). Currently, the GRACE Follow-on (GRACE-FO), which began in 2018, continues the legacy of its predecessor (2002-2017). GRACE-FO monitors the movement of water (groundwater, large lakes and rivers, soil moisture, ice, and sea level) on the planet (Landerer et al., 2020). The mission measures changes in the Earth's gravitational field and produces monthly gravity maps containing information about changes in water supplies (Gyawali et al., 2022). Measurements of the Earth's gravitational field can reveal anomalies in the distribution of water masses (Hasan & Tarhule, 2021; Lopez et al., 2020). GRACE terrestrial water storage (TWS) data have been extensively utilized to evaluate groundwater depletion, significant hydrological alterations, and variations in water balance.

Nevertheless, regional and local hydrological investigations are restricted by the coarse spatial resolution of GRACE data (~55-111 km). To overcome this limitation, the spatial resolution of GRACE-based water storage estimates is being enhanced by the application of statistical downscaling methods and machine learning approaches. In hydrological research, it is crucial to evaluate the attributes of different satellite platforms utilized for water resource monitoring. The following table compares GRACE, GRACE-FO, and alternative satellite missions in terms of their spatial and temporal resolution, as well as their suitability for water balance and localized monitoring (Tab. 1).

Evaluation of regional and global changes in water storage depends on GRACE and GRACE-FO, particularly with relation to large-scale water balance. Nevertheless, especially in small and medium-sized basins, their spatial resolution limits their usefulness for tracking local changes. Therefore, it is relevant to integrate GRACE data with results from other satellite missions as SWOT, SMAP, and Sentinel-1 since they offer improved geographical resolution. Furthermore, combining satellite data with in situ hydrological observations and machine learning approaches could increase the accuracy and forecasting capacity of assessments of water resources.

Table 1 – Comparison of GRACE, GRACE-FO and other satellite missions for water monitoring

Platform	Spatial Resolution	Temporal Resolution	Primary Purpose	Advantages / Limitations
GRACE	~100–300 km	30 days	Total water storage	Coarse resolution, global coverage, sensitive to significant anomalies (Abegeja, 2024)
GRACE-FO	~100–300 km	30 days	GRACE continuation	Modern instruments, higher accuracy, data continuity (Gyawali et al., 2022)
SWOT	10–100 m	10 days	Water level, surface area	High resolution, suitable for small rivers and lakes, detailed monitoring (Nair et al., 2021)
SMAP	10 km (soil), 1–3 km (SAR)	2–3 days	Soil moisture, surface water	Fast revisit time, high detail in soil moisture (Colliander et al., 2017)
Sentinel-1	10–20 m	6–12 days	Water height, surface area	SAR data, high resolution, effective for small water bodies (Slimani, 2022)

According to publications, using GRACE satellites to assess hydrological changes in river basins is an established methodology. Thus, in the Colorado Basin, GRACE was utilized to analyze long-term changes in water storage, encompassing both groundwater and reservoirs (Scanlon et al., 2015). GRACE was used to estimate river runoff and forecast floods in the Amazon and Ganges (Blue Water Intelligence, 2024). In the CONUS (USA), GRACE data were integrated with hydrological models for water management (Mohanasundaram et al., 2021).

GRACE has been effectively utilized in multiple studies to evaluate groundwater variations in arid and semi-arid regions of Iran. In West Azerbaijan Province, analyses of groundwater storage changes using GRACE and CHIRPS have indicated a consistent decrease in water levels since 2008, attributed to reduced precipitation and increased water extraction (Mehdi et al., 2021). The correlation between satellite and groundwater data was 86–97%, confirming the effectiveness of GRACE even for basins smaller than 200,000 km².

Northern China: In the Hai River Basin (318,866 km²), GRACE data showed good agreement with groundwater measurements (R=0.82), especially in the seasonal cycle (Moiwo et al., 2009). This confirms the suitability of GRACE for monitoring water resources in medium-sized semi-arid basins. India: In the northern states of India (Radjastan, Punjab, Haryana), GRACE has been used to detect groundwater depletion caused by both climate and anthropogenic factors. Other studies have found high correlations between GRACE data and groundwater observations even in conditions of a limited hydrological network. Morocco and North Africa: In Morocco, where drought is a significant issue, GRACE has been utilized to evaluate changes in water storage in basins smaller than 150,000 km² (Hamou-Ali et al., 2025). The use of downscaling techniques has allowed the spatial resolution of the data to be increased to 1 km, which is critical for small and medium-sized basins.

Several studies on the application of GRACE to major river basins, including the Amazon (Cui et al., 2020), Mississippi (Ren et al., 2023), and the Ganges (Ahi & Cekim, 2021), have been conducted. However, little is known about its applicability for medium-sized, semi-arid basins such as the Zhaiyk (Ural). Moreover, earlier studies have primarily focused on total water storage anomalies (TWSA) rather than establishing clear connections between GRACE-derived changes and in situ hydrological data. Using an analysis of the relationship between GRACE-derived water equivalent thickness (WET) and in situ water level measurements, the present work attempts to close this disparity (Awange et al., 2008).

The authors of the Zhaiyk paper adapted this methodology to a new region, highlighting its limitations (low spatial resolution), which is consistent with the findings of other studies. Their contribution is applying the approach to a specific region (Kazakhstan) and assessing the correlation between satellite and ground-based data for local conditions. River Zhaiyk is a vital source of drinking water, supporting agricultural and industrial potential and maintaining the balance of the ecosystem in the adjacent areas. In recent decades, climate change, increased anthropogenic load, and water resource shortages have been observed, necessitating the development of modern methods for monitoring and managing these resources. The observed climate fluctuations and uneven changes make it difficult to predict the river's water content and manage water-related consequences.

The distribution of water mass is directly affected by climate, and an increase in surface temperature impacts the amount of precipitation in liquid form, and in mountains, the area and period of solid precipitation are reduced (Казгидромет, 2023). In recent years, extreme changes in water level have been observed in the Republic of Kazakhstan. Maximum water levels are recorded in the valleys of large and medium-sized rivers of the Zhaiyk (Ural), Tobol, Torgai, Yesil, and Yertis, their tributaries (Plekhanov P.A. et al., 2019). For a long time, the situation has been complicated along the Zhaiyk (Ural) river in West Kazakhstan and Atyrau regions (Плеханов, 2017).

The main objective of this study is to evaluate the relationship of in-situ water level data in the Zhaiyk River Basin with GRACE-derived water storage variations.

A study conducted by Kazakhstani scientists during the period of spring ice processes on the Zhaiyk River (Ural) based on long-term observations (1937–2020) revealed significant changes in the ice regime caused by climate change and anthropogenic factors. It was found that the river breakup and the onset of ice drift shifted towards earlier dates by 13–18 and 9–12 days, respectively, especially in the southern sections of the channel, while the duration of spring ice phenomena increased from 4–6 to 10 days. The increase in the frequency of ice jams observed since the end of the 20th century indicates an increase in hydrological risks caused by a longer and more unstable period of ice breakup. The results obtained emphasize the need to consider the changing ice regime in regional water resources management and emergency response planning (Kisebaev et al., 2022).

Methods

The Ural (Zhaiyk), the third longest in Europe (2428 km), is a transboundary river (Fig. 1). The upper and middle parts of the basin are located on the territory of the Russian Federation, and the lower, 1084 km long, passes through the Republic of Kazakhstan, discharging into the Caspian Sea in the surroundings of the Atyrau city (Abiev et al., 2021). The river meanders through flat, semi-desert landscapes until it reaches the Caspian Sea (Eremkina & Yarushina, 2022).

The Zhaiyk River basin (Ural) is characterized by a height difference of about 600 meters (from 637 m above sea level at the source to 26 m at the downstream). The average height of the catchment is 186 m. The valley of the ancient river is filled with loose alluvial sediments, the thickness of which reaches tens of meters in some areas. The Zhaiyk (Ural) River basin has a continental climate. The average annual air temperature fluctuates around 4.9°C, and in the delta, it drops to -9.1°C. Seasonal and daily temperature fluctuations are significant.

The Zhaiyk (Ural) River is unique for its length, making it one of the longest rivers in the world, and for its high intra- and inter-annual flow variability (Magrickij et al., 2018). In the 20th century, the flow of the Zhaiyk (Ural) River was altered due to the construction of artificial reservoirs and water intakes for industrial and domestic purposes. Currently, there are seven reservoirs in the basin. Along the main channel of the Urals, there are the Verkhneuralskoye, Magnitogorskoye, and Iriklinskoye reservoirs, and on the tributaries – Aktobe (Ilek River), Verkhne-Kumak (Bolshoi Kumak), Kargalinskoye in Dzhaksiya (Kargala River), and Chernovsky (Chernaya River) (Tab. 2).

Water intake and regulation resulted in a decrease in flow of 1.2-1.3 km^3 per year. In dry years, the annual decline in flow reaches 2.2 km^3. The highest water level associated with the Zhaiyk (Ural) River basin within Kazakhstan was observed in 1942 (945 cm), 1957 (932 cm), and 1994 (853 cm). In 1993, the dam of the Aktobe reservoir burst, affecting the Atyrau, West Kazakhstan, and Aktobe regions. Excess water levels caused significant damage in the West Kazakhstan region, as well as in the city of Oral (Uralsk). The city of Uralsk is located on the right bank of the middle reaches of the Zhaiyk (Ural) River. A steppe plain and steep coastal ledges characterize the territory. The territory in the area between the city and the river is described as flat, with heights from 19 to 93 m (an average of 34 m). The Zhaiyk River turns south toward the Caspian Lowland.

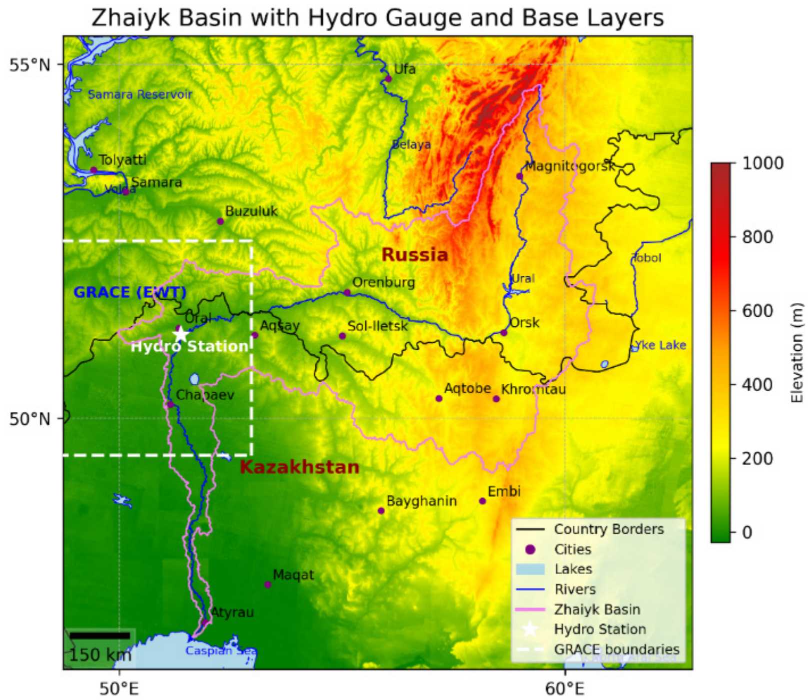

Figure 1 – Study location: Zhaiyk (Ural) River basin

Table 2 – Basic information on the reservoirs

Reservoir Name	Surface Area (km²)	Year of Commissioning	Country
Iriklinskoye	260	1966	Russia
Verkhneuralskoye	72	1960	Russia
Magnitogorskoye (Zavodskoy Pond)	33.4	1931	Russia
Kargalinskoye	28.5	1975	Kazakhstan
Verkhne-Kumak (Bolshoi Kumak)	12.7	1967	Russia
Chernovsky (Chernaya River)	4.55	1953	Russia

The study workflow illustrates the process of analyzing the relationship between water level data and GRACE satellite data (Gravity Recovery and Climate Experiment) to assess hydrological variations in the Zhaiyk (Ural) River basin (Fig. 2).

Stage 1 – Data Preparation involves two types of input data: daily water level data and GRACE data. The daily water level values were extracted from the Kazhydromet website for the Oral (Ural'sk) gauging station (RGP «Kazgidromet», 2021). Daily water level data (cm) are combined into monthly averages to produce an aggregated water level and GRACE data set (TCE). Water equivalent thickness (cm) describes monthly average values from GRACE satellite gravimetric measurements. Data is recorded at irregular intervals, usually ranging from one to three months. The data series in this article covers the period from April 2002 to December 2021 to ensure equal coverage of the two measurement methods specified. To obtain a homogeneous time series, rows with missing values in water levels were removed. Its monthly averages were also calculated to align the period with the GRACE time series, anomalous values were removed, resulting in aggregated data (57 records) for analysis. WET, measured in centimeters (cm), reflects the amount of water stored in the ground compared to a reference period.

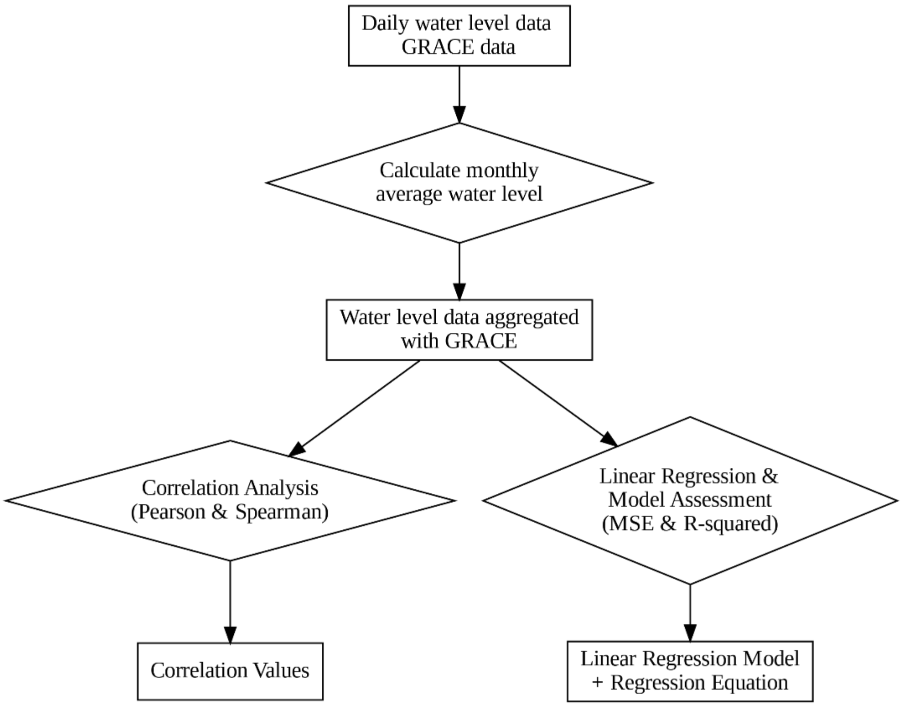

Figure 2 – Research Methodology
The research methodology consists of three main stages:

Stage 2 – correlation analysis combined set of water levels and GRACE using Pearson and Spearman methods to assess potential relationships. Correlation characteristics were obtained, indicating the strength and direction of the relationship between the two variables. Correlation analysis helps understand the relationship between these variables, and the linear regression model provides a quantitative tool for validating satellite data.

Stage 3 – development and evaluation of the model. A linear regression model was constructed using water level as the independent variable and GRACE data as the dependent variable. Model performance is assessed using the coefficient of determination R^2.

Results

To analyze the water level change, a time series of data points was obtained from the GRACE satellite gravimetry pixel covering the city of Oral (NASA JPL, 2024). Data on the water level (in centimeters) of the Oral (Ural'sk) gauging station were selected for comparative analysis (RGP «Kazgidromet», 2021). The data series covers the period from April 2002 to December 2021. Based on the aggregated data, diagrams were constructed showing changes in water levels in the study area (Fig. 3).

Figure 3 shows the water equivalent thickness (WET), consisting of data from the GRACE and GRACE-FO satellites. The data cover the area designated by coordinates 51.0N, 51.0E – 52.0N, 52.0E. Positive WET values indicate more water than average, while negative values indicate less.

Main observational results from the WET time series:

- in WET over 20 years, ranging from +14 cm to -10 cm;
- there is a cyclical pattern of highs and lows every 2-3 years;
- by 2010, WET values declined, with relatively low values thereafter.

The water level in the Zhaiyk River (Ural) during the observation period fluctuated between 8 cm and 533 cm.

A seasonal pattern is evident in the time series, with maximums occurring in the spring (March-May) and minimums in the summer and autumn months. This schedule corresponds to the hydrological regime of water bodies, which has a direct dependence on snowmelt, evaporation, and water consumption.

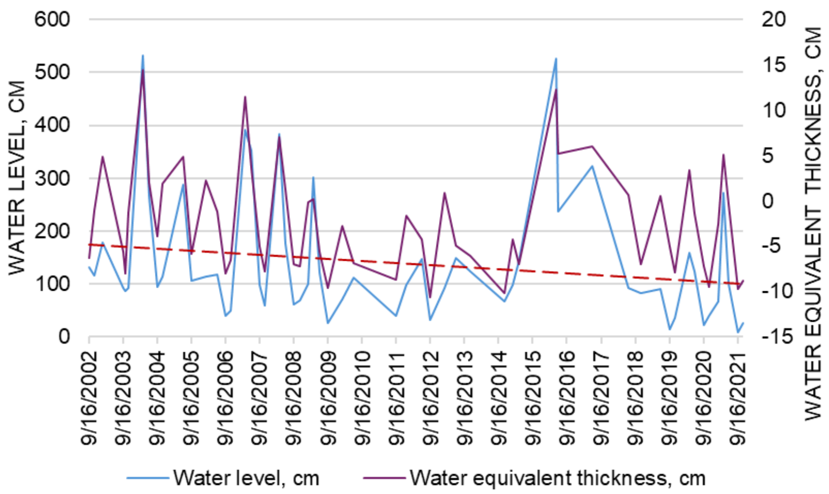

Figure 3 – Time series of water level (with trend line) and equivalent thickness

As a result of the analysis, we found a positive correlation between water level and WET. This shows that an increase in water equivalent thickness (positive WET values) generally coincides with an increase in water level in the Zhaiyk River (Ural). A Pearson coefficient of 0.864 shows a strong positive linear correlation between river water levels and GRACE data.

The Spearman coefficient of 0.806 also indicates a strong positive correlation between river water level and WET. A positive value confirms the tendency for water levels to rise as GRACE water equivalent thickness increases. A regression model was constructed, and its metrics were calculated (Fig. 4). According to the obtained model, for every 1 cm increase in the water equivalent thickness, the water level in the Zhaiyk River (Ural) increases by an average of 178.73 cm.

The equation of the regression model is (1):

$$Y = 17.324 * x + 178.73 \quad (1)$$

Where Y – water level (cm), x – water equivalent thickness, intercept is at 178.73 cm. The determination coefficient R^2 equals 0.7459. This linear regression model can be used to predict water levels from GRACE data.

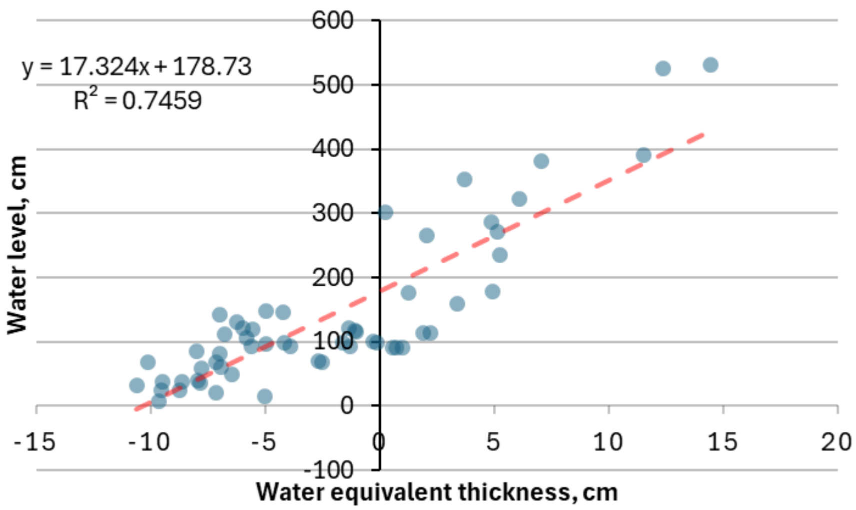

Figure 4 – Scatterplot of water level data in the Zhaiyk River (Ural) and WET

Figure 4 is a scatter plot that shows how the water level in the Zhaiyk River changed over time, compared to GRACE satellite gravity data (shown as equivalent water thickness, WET) from 2002 to 2021. For a specific period (a month), each point displays the water level and the corresponding WET value. With a coefficient of determination of 0.7459, changes in the equivalent water thickness from GRACE measurements can explain about 74.6% of the changes in water level. This indicates that measurements made from space and those made on the ground are closely linked in a straight line. However, some deviations from the regression line, especially at high WET values, show that other things may be at play, such as local rainfall, runoff, economic activity, or GRACE's limited spatial resolution.

Discussion

One of the main limitations of the study is the minimal geographic resolution of the GRACE data, which limits its ability to capture localized hydrological variations. GRACE is not suitable for high-resolution monitoring of specific water bodies, small streams, or local groundwater changes, although it provides detailed information on changes in large-scale water storage. To enhance the geographic specificity of hydrological assessments, this limitation underscores the need to integrate GRACE data with in situ observations or higher-resolution remote sensing products. Despite these limitations, the analysis of the equivalent water thickness time series revealed long-term patterns and changes in surface water storage in the Zhaiyk (Ural) River Basin over the past 20 years.

Among the causes of seasonal and interannual oscillations in precipitation, evapotranspiration dynamics, human impacts, including agricultural water extraction, and climate-induced changes in hydrological cycles are those that interact with one another. Improving regional water management planning depends on understanding these components.

With an R-squared value of 0.7459, the regression model revealed a clear positive correlation between water levels and GRACE data. This information suggests that about 74.59% of the fluctuation in river water levels is attributable to GRACE-derived water storage anomalies. Still, the remaining 25.41% of the variance indicates a range of hydrological processes generating water-level variations, including short-term rainfall, uncontrolled water abstraction, and snowmelt dynamics. This work demonstrates the capabilities and limitations of satellite gravimetry in hydrological evaluations, offering significant insights into the correlation between river levels and GRACE-induced storage anomalies. Future research should focus on multi-sensor data fusion and advanced modeling techniques, including auxiliary datasets such as machine learning approaches, climate reanalysis products, or ground-based hydrological observations to improve the accuracy of validating satellite data in the Zhaiyk River Basin (Ural) and related areas.

While the primary motivation for this work was to assess the potential relationship between GRACE data and hydrological station data, it is vital to acknowledge the limits in the temporal resolution of GRACE observations.

Conclusion

This research demonstrated the potential of GRACE satellite gravimetry data for monitoring and assessing the relationship between satellite data and water level in the Zhaiyk River basin (Ural). The strong positive correlation between river water level and water equivalent thickness (WET) demonstrates the value of satellite gravimetry for understanding hydrological processes.

The linear regression model obtained during the study explains a significant part of the water level variability. It also indicates the presence of other factors such as precipitation, evaporation, and human activities. This is important considering several reservoirs are in the upper part of the Zhaiyk River basin (Ural).

The study's analysis showed a significant relationship between river water levels and water equivalent thickness (WET) parameters. It shows that changes in water reserves, as measured by GRACE satellite data, are interconnected with fluctuations in water levels observed at the gauging station in Oral (Ural'sk) city.

The study results have important implications for water resource management in the Zhaiyk River basin (Ural). Further integration of GRACE data with ground-based observations will enable the development of more accurate models incorporating water levels and satellite data. However, given the study's limitations, further research is needed to refine the model parameters and include other variables to analyze water level variability in the Zhaiyk River basin (Ural). Also, machine learning methods can contribute to validating satellite data for aggregating water levels.

The results showed that GRACE has the potential to predict river water levels. They emphasize the importance of integrating diverse data sources and modeling techniques to enhance the understanding of hydrological processes and mitigate flood risks.

In this study, it is necessary to critically examine several factors that may affect the reliability and interpretation of the obtained results.

One of the key factors that can distort the relationship between satellite and ground-based measurements is the presence of large and medium-sized reservoirs, as well as intensive economic activity in the river basin. Flow regulation, water withdrawals for agricultural and industrial needs, and the construction of dams and canals change the natural hydrological regime. This makes it challenging to distinguish between climate and natural signals in GRACE data and ground-based observations. In addition, evaporation from the surface of reservoirs, especially in dry years, can significantly reduce the amount of available water.

Comparable effects have been observed in research carried out in other semi-arid regions.

A significant source of uncertainty arises from the discrepancy in time intervals between GRACE satellite data, which is presented as monthly averages, and ground-based hydrological observations, typically recorded daily.

Even when reducing to a standard time step, discrepancies may remain due to the different sensitivities of the methods, delays in the river system's response to precipitation, water abstraction, or snowmelt. These discrepancies can affect the magnitude of the correlation coefficients and reduce the accuracy of the constructed regression models.

The spatial resolution of GRACE (~100–300 km) itself limits the ability to assess local hydrological processes. The use of one or more ground stations (gauging posts) does not reflect the full spatial heterogeneity of the basin. In addition, data aggregation in time and space can smooth out extreme values and hide significant local anomalies. The GRACE processing method is also subject to the "leakage effect", in which the signal from neighboring areas can distort the estimates within the analyzed basin, which increases the overall uncertainty of the results.

These constraints, taken together, necessitate a careful and critically confirmed method for interpreting the acquired results. The integration of GRACE with high-resolution hydrological models is recommended to enhance dependability and scientific rigor. The network of ground-based observations should be expanded, and techniques to adjust for temporal and spatial mismatches between different data sources should be employed. Such actions will ensure more consistent regional management decisions and significantly enhance the accuracy of water resource evaluations.

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References

Abegeja, D. (2024). The application of satellite sensors, current state of utilization, and sources of remote sensing dataset in hydrology for water resource management. *Journal of Water and Health*, *22*(7), 1162–1179.

Abiev, S., Darbayeva, T., & Sarsenova, A. (2021). Possible pathways for the formation of flora and macromycetes of floodplain forests of the Ural River within Western Kazakhstan. *BULLETIN of the L.N. Gumilyov Eurasian National University. BIOSCIENCE Series*, *135*(2), 18–27. https://doi.org/10.32523/2616-7034-2021-135-2-18-27

Ahi, G. O., & Cekim, H. O. (2021). Long-term temporal prediction of terrestrial water storage changes over global basins using GRACE and limited GRACE-FO data. *Acta Geodaetica et Geophysica*, *56*(2). https://doi.org/10.1007/s40328-021-00338-4

Awange, J. L., Sharifi, M. A., Ogonda, G., Wickert, J., Grafarend, E. W., & Omulo, M. A. (2008). The falling lake Victoria water level: GRACE, TRIMM and CHAMP satellite analysis of the lake basin. *Water Resources Management*, *22*(7). https://doi.org/10.1007/s11269-007-9191-y

Blue Water Intelligence. (2024). *NASA's GRACE Satellites: Measuring Aquifer Dynamics and River Discharge from Space*. https://bwi.earth/nasas-grace-satellites-measuring-aquifer-dynamics-and-river-discharge-from-space/

Colliander, A., Fisher, J. B., Halverson, G., Merlin, O., Misra, S., Bindlish, R., Jackson, T. J., & Yueh, S. (2017). Spatial Downscaling of SMAP Soil Moisture Using MODIS Land Surface Temperature and NDVI during SMAPVEX15. *IEEE Geoscience and Remote Sensing Letters*, *14*(11), 2107–2111. https://doi.org/10.1109/LGRS.2017.2753203

Cui, L., Song, Z., Luo, Z., Zhong, B., Wang, X., & Zou, Z. (2020). Comparison of terrestrial water storage changes derived from grace/grace-fo and swarm: A case study in the amazon river basin. *Water (Switzerland)*, *12*(11). https://doi.org/10.3390/w12113128

Eremkina, T. V, & Yarushina, M. I. (2022). Ural River Basin. In *Rivers of Europe* (pp. 883–899). Elsevier. https://doi.org/10.1016/B978-0-08-102612-0.00022-5

Gyawali, B., Ahmed, M., Murgulet, D., & Wiese, D. N. (2022). Filling Temporal Gaps within and between GRACE and GRACE-FO Terrestrial Water Storage Records: An Innovative Approach. *Remote Sensing*, *14*(7), 1565. https://doi.org/10.3390/rs14071565

Hamou-Ali, Y., Karmouda, N., Mohsine, I., Bouramtane, T., Kacimi, I., Tweed, S., Tahiri, M., Kassou, N., El Bilali, A., Chafki, O., & others. (2025). Downscaling GRACE total water storage data using random forest: a three-round validation approach under drought conditions. *Frontiers in Water*, *7*, 1545821.

Hasan, E., & Tarhule, A. (2021). Comparison of decadal water storage trends from common GRACE releases (RL05, RL06) using spatial diagnostics and a modified triple collocation approach. *Journal of Hydrology X*, *13*, 100108. https://doi.org/10.1016/j.hydroa.2021.100108

Hasan, E., Tarhule, A., Hong, Y., & Moore, B. (2019). Assessment of Physical Water Scarcity in Africa Using GRACE and TRMM Satellite Data. *Remote Sensing*, *11*(8), 904. https://doi.org/10.3390/rs11080904

Kisebaev, D., Musralinova, G., & Marchenko, S. (2022). Vesennie ledovye processy na r. Zhaiyk (Ural) [Spring ice processes on the Zhaiyk (Ural) River]. *Vestnik KazNU. Seriya geograficheskaya*, *66*(3), 42–52. https://doi.org/10.26577/JGEM.2022.v66.i3.04

Landerer, F. W., Flechtner, F. M., Save, H., Webb, F. H., Bandikova, T., Bertiger, W. I., Bettadpur, S. V, Byun, S. H., Dahle, C., Dobslaw, H., Fahnestock, E., Harvey, N., Kang, Z., Kruizinga, G. L. H., Loomis, B. D., McCullough, C., Murböck, M., Nagel, P., Paik, M., … Yuan, D. (2020). Extending the Global Mass Change Data Record: GRACE Follow□On Instrument and Science Data Performance. *Geophysical Research Letters*, *47*(12). https://doi.org/10.1029/2020GL088306

Lopez, T., Al Bitar, A., Biancamaria, S., Güntner, A., & Jäggi, A. (2020). On the Use of Satellite Remote Sensing to Detect Floods and Droughts at Large Scales. In *Surveys in Geophysics* (Vol. 41, Issue 6). https://doi.org/10.1007/s10712-020-09618-0

Magrickij, D., Evstigneev, V., Jumina, N., Toropov, P., Kenzhebaeva, A., & & Ermakova, G. (2018). Izmenenija stoka v bassejne r. Ural. *Vestnik Moskovskogo Universiteta*, *№ 1*, 90–99.

Mehdi, A., Mobin, E., Mohammad, A., Elyasi, A. H., & Zahra, N. (2021). Application assessment of GRACE and CHIRPS data in the Google Earth Engine to investigate their relation with groundwater resource changes (Northwestern region of Iran). *Journal of Groundwater Science and Engineering*, *9*(2). https://doi.org/10.19637/j.cnki.2305-7068.2021.02.002

Mohanasundaram, S., Mekonnen, M. M., Haacker, E., Ray, C., Lim, S., & Shrestha, S. (2021). An application of GRACE mission datasets for streamflow and baseflow estimation in the Conterminous United States basins. *Journal of Hydrology*, *601*. https://doi.org/10.1016/j.jhydrol.2021.126622

Moiwo, J. P., Yang, Y., Li, H., Han, S., & Hu, Y. (2009). Comparison of GRACE with in situ hydrological measurement data shows storage depletion in Hai River Basin, Northern China. *Water SA*, *35*(5). https://doi.org/10.4314/wsa.v35i5.49192

Nair, A. S., Kumar, N., Indu, J., & Vivek, B. (2021). Monitoring Lake Levels From Space: Preliminary Analysis With SWOT. *Frontiers in Water*, *3*. https://doi.org/10.3389/frwa.2021.717852

NASA JPL. (2024). *GRACE Data Analysis Tool*.

Plekhanov P.A., Medeu N.N., & Skufin P. (2019). Hydrological risks and their prevention in Kazakhstan. *International Journal of Hydrology*, *3*(1). https://doi.org/10.15406/ijh.2019.03.00154

Ren, D., Pan, Y., Liu, L., Huang, L., Zhou, L., Jiao, J., & Li, J. (2023). Interannual hydrological variability in the Mississippi River Basin based on contemporary geodetic measurements and land surface models. *Journal of Hydrology*, *626*, 130232.

RGP «Kazgidromet». (2021). *METEOROLOGICHESKAJA BAZA DANNYH*.

Scanlon, B. R., Zhang, Z., Reedy, R. C., Pool, D. R., Save, H., Long, D., Chen, J., Wolock, D. M., Conway, B. D., & Winester, D. (2015). Hydrologic implications of GRACE satellite data in the Colorado River Basin. *Water Resources Research*, *51*(12). https://doi.org/10.1002/2015WR018090

Slimani, M. (2022). Creating a DEM Using Sentinel-1 Data. *Hydrology and Earth System Sciences*. https://doi.org/10.5194/hess-26-4013-2022

Казгидромет. (2023). Ежегодный бюллетень мониторинга состояния и изменения климата Казахстана: 2022 год. In *Министерство экологии и природных ресурсов Республики Казахстан* (pp. 1–72).

Плеханов, П. А. (2017). Гидрологические риски природного характера и их предупреждение в Казахстане. *Центральноазиатский Журнал Исследований Водных Ресурсов*, *3*(1), 19–25.

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