

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)

**NEWS OF THE NATIONAL ACADEMY
OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF
GEOLOGY AND TECHNICAL SCIENCES**

№5

2026

ISSN 2518-170X (Online)

ISSN 2224-5278 (Print)



N E W S
OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN,
SERIES OF GEOLOGY AND TECHNICAL
SCIENCES

5 (479)

September – Oktober 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Owner: «Central Asian Academic Research Center» LLP (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.

<http://www.geolog-technical.kz/index.php/en/>

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).

Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

<http://www.geolog-technical.kz/index.php/en/>

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

ISSN 2224-5278

Volume 5.

Number 479 (2026), 256–272

<https://doi.org/10.32014/2026.2518-170X.702>

UDC: 528.87

IRSTI: 38.01.85

©Mukaliyev Zh.K.^{1*}, Zhumatayeva Zh.M.¹, Turganaliyev S.R.², 2026.

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GIS-BASED GEOMORPHOMETRIC ASSESSMENT OF TOPOGRAPHIC EROSION POTENTIAL AT THE SEMIPALATINSK TEST SITE

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Abstract. Introduction. Water erosion contributes to soil degradation and surface-material redistribution in the arid and semi-arid landscapes of the Semipalatinsk Test Site (STS), Kazakhstan, where natural relief processes interact with a technogenic legacy. This study evaluates only the topographic component of erosion potential and does not estimate radionuclide transport or radiological risk. The aim was to map and quantify the RUSLE LS factor as the first geomorphometric stage of a broader erosion assessment. Materials and methods. A 30 m ALOS World 3D (AW3D30) elevation model (JAXA) was processed in Google Earth Engine; slope and LS-factor calculations and cartographic visualization were performed in ArcGIS 10.8. D8 flow direction and upstream drainage area were obtained from the ~90 m MERIT Hydro product. The S factor was calculated using McCool et al. (1987), with slope capped at 26.6° (50%), and the L factor from specific catchment area following Moore and Burch (1986) and Mitasova et al. (1996). No local calibration or field validation was applied. Results. Across 18,367 km², mean slope was 2.5° ± 2.6°, and 91.3% of the territory had slopes below 5°. LS values ranged from 0.07 to 5784.10 (mean 3.25); extreme values occurred at isolated channel

confluences because contributing flow length was not capped. Very low and low LS classes occupied 65.2% of the territory, whereas high and very high classes ($LS > 5$) covered 11.9%, mainly in the Degelen and Murzhik massifs and along the principal ephemeral drainage network. Conclusions. The LS map shows relative spatial contrasts in topographically controlled erosion potential and provides a basis for field verification and subsequent full RUSLE modeling. Absolute values should be interpreted cautiously because the equations were not recalibrated for local arid conditions, the workflow combines 30 m terrain and ~90 m hydrography data, and small technogenic landforms are not resolved. Linking these patterns to ^{137}Cs , Pu and other radionuclides requires contamination-density and soil-loss data and remains a separate stage of future research.

Keywords: LS factor, RUSLE, topographic erosion potential, digital elevation model, GIS analysis, Semipalatinsk Test Site, relief morphometry

***For citations:** Mukaliyev Zh.K., Zhumatayeva Zh.M., Turganaliyev S.R. GIS-Based Geomorphometric Assessment of Topographic Erosion Potential at the Semipalatinsk Test Site. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. 2026. No.5. Pp. 256–272. DOI: <https://doi.org/10.32014/2026.2518-170X.702>*

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СЕМЕЙ СЫНАҚ ПОЛИГОНЫНЫҢ ТОПОГРАФИЯЛЫҚ ЭРОЗИЯЛЫҚ ӘЛЕУЕТІН ГЕОАҚПАРАТТЫҚ ГЕОМОРФОМЕТРИЯЛЫҚ БАҒАЛАУ

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Аннотация. *Өзектілігі.* Су эрозиясы Семей сынақ полигонының (ССП) аридті және семиаридті ландшафтарында топырақ деградациясы мен жер беті материалының қайта бөлінуіне ықпал етеді, мұнда табиғи жер бедері үдерістері ұзақ мерзімді техногендік әсермен ұштасады. Бұл жұмыста эрозиялық әлеуеттің тек топографиялық құрамдас бөлігі бағаланады;

радионуклидтердің тасымалдануы мен радиологиялық қауіп тікелей модельденбейді. Зерттеудің мақсаты - RUSLE моделінің LS-факторын кең ауқымды эрозиялық бағалаудың алғашқы геоморфометриялық кезеңі ретінде картаға түсіру және сандық бағалау. *Материалдар мен әдістер.* Кеңістіктік ажыратымдылығы 30 м ALOS World 3D (AW3D30) биіктік моделі (JAXA) Google Earth Engine ортасында өңделді; еңіс пен LS-факторды есептеу және картографиялық визуализация ArcGIS 10.8. бағдарламасында орындалды. D8 ағын бағыты мен жоғары орналасқан су жинау ауданы шамамен 90 м ажыратымдылықтағы MERIT Hydro деректерінен алынды. S-фактор McCool et al. (1987) бойынша еңісті $26,6^\circ$ -қа (50%) дейін шектеу арқылы, ал L-фактор Moore and Burch (1986) және Mitasova et al. (1996) бойынша үлестік су жинау ауданы негізінде есептелді. Жергілікті калибрлеу мен далалық валидация жүргізілген жоқ. *Нәтижелер.* 18 367 км² аумақта орташа еңіс $2,5^\circ \pm 2,6^\circ$ болды, ал аумақтың 91,3%-ында еңіс 5° -тан төмен. LS мәндері 0,07-ден 5784,10-ға дейін өзгерді, орташа мәні 3,25; экстремалды мәндер ағын ұзындығына жоғарғы шек қойылмағандықтан су арналары тоғысатын жекелеген пикселдерде байқалды. Өте төмен және төмен LS кластары аумақтың 65,2%-ын, жоғары және өте жоғары кластары ($LS > 5$) 11,9%-ын қамтиды; олар негізінен Дегелең және Мұржық массивтерінде және негізгі уақытша су арналары бойында шоғырланған. *Қорытынды.* LS картасы топографиямен анықталатын эрозиялық әлеуеттің салыстырмалы кеңістіктік айырмашылықтарын көрсетіп, далалық тексеру мен кейінгі толық RUSLE модельдеуіне негіз болады. Абсолюттік мәндерді жергілікті калибрлеудің болмауына, 30 м және шамамен 90 м деректердің бірлесіп қолданылуына және ұсақ техногендік жер бедері нысандарының көрінбеуіне байланысты сақтықпен түсіндіру қажет. Анықталған заңдылықтарды ¹³⁷Cs, Pu және басқа радионуклидтермен байланыстыру үшін ластану тығыздығы мен топырақ жоғалуы туралы деректер қажет және бұл кейінгі зерттеулердің жеке кезеңі болып табылады.

Түйін сөздер: LS-фактор, RUSLE, топографиялық эрозиялық әлеует, цифрлық биіктік моделі, ГАЗ-талдау, Семей сынақ полигоны, жер бедері морфометриясы

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ГЕОИНФОРМАЦИОННАЯ ГЕОМОРФОМЕТРИЧЕСКАЯ ОЦЕНКА ТОПОГРАФИЧЕСКОГО ЭРОЗИОННОГО ПОТЕНЦИАЛА СЕМИПАЛАТИНСКОГО ИСПЫТАТЕЛЬНОГО ПОЛИГОНА

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Аннотация. *Введение.* Водная эрозия является одним из факторов деградации почвенного покрова и перераспределения поверхностного материала в аридных и семиаридных ландшафтах Семипалатинского испытательного полигона (СИП), где естественные процессы рельефообразования сочетаются с последствиями длительного техногенного воздействия. Оценка пространственной изменчивости топографического эрозионного потенциала представляет особую значимость для выявления территорий, потенциально подверженных эрозионным процессам. Настоящее исследование ограничивается анализом топографической составляющей эрозионного потенциала и не предусматривает непосредственного моделирования переноса радионуклидов и оценки радиологического риска. *Цель.* Выполнить картографирование и количественную оценку топографического фактора LS модели RUSLE как предварительного геоморфометрического этапа комплексной оценки эрозионных процессов на территории Семипалатинского испытательного полигона. *Материалы и методы.* В качестве основного источника пространственных данных использована цифровая модель высот ALOS World 3D (AW3D30), разработанная Японским агентством аэрокосмических исследований (JAXA), с пространственным разрешением 30 м. Предварительная обработка данных выполнена в облачной платформе Google Earth Engine. Расчет уклонов, топографического фактора LS и картографическая визуализация результатов осуществлялись в программной среде ArcGIS 10.8. Для определения направлений поверхностного стока по алгоритму D8 и площади вышележащего водосбора использованы данные MERIT Hydro

с пространственным разрешением около 90 м. Расчет фактора крутизны склонов (S) проводился по методике McCool et al. (1987) с ограничением уклона до $26,6^\circ$ (50 %), а фактора длины склонов (L) — на основе удельной площади водосбора в соответствии с подходами Moore and Burch (1986) и Mitasova et al. (1996). Локальная калибровка модели и полевая проверка полученных результатов не проводились. *Результаты.* Установлено, что на исследуемой территории площадью 18 367 км² средний уклон поверхности составляет $2,5 \pm 2,6^\circ$, при этом 91,3 % территории характеризуется уклонами менее 5° . Значения топографического фактора LS варьируются от 0,07 до 5784,10 при среднем значении 3,25. Экстремально высокие значения приурочены к отдельным пикселям в местах слияния водотоков, что связано с отсутствием ограничения максимальной длины стока в расчетной модели. Очень низкий и низкий классы значений LS охватывают 65,2 % исследуемой территории, тогда как на долю высокого и очень высокого классов ($LS > 5$) приходится 11,9 %. Участки с повышенными значениями топографического фактора преимущественно сосредоточены в массивах Дегелен и Мурджик, а также вдоль основных временных водотоков. *Выводы.* Разработанная карта пространственного распределения топографического фактора LS отражает относительные различия эрозионного потенциала, обусловленные особенностями рельефа, и может служить основой для последующей полевой проверки и комплексного моделирования водной эрозии с использованием модели RUSLE. Интерпретация абсолютных значений LS требует осторожности вследствие отсутствия локальной калибровки, использования пространственных данных с различным разрешением (30 и около 90 м), а также ограниченных возможностей выявления мелкомасштабных техногенных форм рельефа. Оценка возможной связи выявленных пространственных закономерностей с перераспределением ¹³⁷Cs, изотопов Pu и других радионуклидов требует привлечения дополнительных данных о плотности радиоактивного загрязнения и величинах потерь почвы. Данное направление рассматривается как самостоятельный этап дальнейших исследований.

Ключевые слова: LS-фактор, RUSLE, топографический эрозионный потенциал, цифровая модель высот, ГИС-анализ, Семипалатинский испытательный полигон, морфометрия рельефа.

Introduction. According to contemporary approaches to erosion process modeling, the Revised Universal Soil Loss Equation (RUSLE) remains one of the most widely applied empirical models for estimating soil loss caused by water erosion (Renard et al., 1997). Within the RUSLE framework, the topographic factor LS (slope length and steepness factor) plays a fundamental role in determining erosion potential, as it reflects the influence of terrain morphology on runoff accumulation and flow velocity (Panagos et al., 2015; Mitasova et al., 1996).

The LS factor integrates two components: slope length (L factor), which represents the distance from the point of surface runoff initiation to the location of

deposition or channelized flow, and slope steepness (S factor), which characterizes the inclination angle of the terrain surface (Renard et al., 1997; McCool et al., 1987). An increase in slope length promotes the accumulation of surface runoff and enhances flow velocity, thereby significantly increasing the erosive capacity of overland flow (Liu et al., 2000).

Recent studies have demonstrated the effectiveness of using digital elevation models (DEMs) in combination with geographic information systems (GIS) for calculating the LS factor at various spatial scales (Michalopoulou et al., 2022). The spatial resolution of a DEM has a substantial impact on the accuracy of morphometric parameter extraction and, consequently, on the resulting LS-factor values (Wu et al., 2005; Konyrbekov, 2015; Fijalkowska, 2021). Higher-resolution DEMs enable a more detailed representation of terrain variability and improve the identification of erosion-prone areas, particularly in landscapes characterized by complex topography (Zhang et al., 2017). Previous studies in Kazakhstan have also confirmed the effectiveness of remote sensing and GIS approaches for environmental assessment and land degradation analysis (Rafikov et al., 2024).

A variety of methodological approaches to LS-factor calculation have been proposed in the scientific literature. Among the most widely applied are the GIS-based procedures developed by Desmet and Govers (1996), as well as the two-dimensional approach introduced by Mitsova et al. (1996), which accounts for upslope contributing area and flow accumulation. Comparative analyses indicate that although different computational algorithms may influence absolute LS values, the overall spatial patterns of erosion susceptibility remain consistent (Seitkazy et al., 2024; Kazybayeva et al., 2014; Panagos et al., 2015).

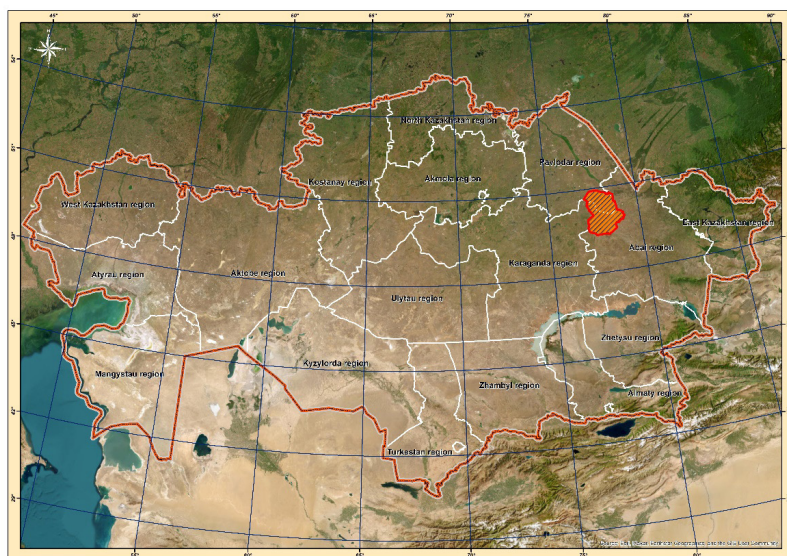


Figure 1. Location of the Semipalatinsk Test Site and Its Main Experimental Areas.

The LS factor is only one component of the RUSLE model ($A = R \times K \times LS \times C \times P$). Accordingly, the present study is deliberately limited to the topographic control on erosion potential as the first geomorphometric stage of a broader assessment. Throughout this paper, “erosion potential” refers to relative topographic susceptibility inferred from LS, not to measured soil loss or radiological risk. Estimating soil loss and radionuclide redistribution requires the remaining RUSLE factors (R, K, C, P), contamination-density data and field validation, which are outside the scope of the present work (Renard et al., 1997).

The aim of this study is to quantify and map the topographic component of erosion potential (LS factor) across the Semipalatinsk Test Site and to identify areas requiring subsequent field verification and integration with complete RUSLE and contamination datasets

Materials and Methods. The Semipalatinsk Test Site (STS) is located in the northeastern part of the Republic of Kazakhstan. The study area is characterized by a highly dissected terrain with elevation values ranging from 200 to 600 m above sea level. Regional climatic conditions promote the development of water erosion processes: a continental climate with uneven annual precipitation distribution, intensive spring snowmelt, and convective summer rainfall create favorable conditions for surface runoff generation (Zhang et al., 2023).

The territory is subdivided by a dense network of temporary watercourses and shallow depressions through which meltwater and rainfall runoff are transported. A well-developed gully–ravine system represents one of the major challenges for sustainable land use in the region. Rugged relief, pronounced elevation differences, and the predominance of sloping surfaces contribute to the active formation and expansion of the erosion network.

The primary elevation dataset was the ALOS World 3D-30m (AW3D30) global digital surface model (JAXA), with an approximate spatial resolution of 30 m (Fig. 1). The elevation data were processed in the Google Earth Engine cloud platform (Gorelick et al., 2017). AW3D30 is derived from ALOS PRISM stereo imagery (Tadono et al., 2014). Alternative global DEMs, such as ALOS PALSAR, have also been used for morphometric assessments in post-nuclear landscapes (Mukaliyev et al., 2026). The 30 m resolution provided complete coverage of the 18,367 km² STS territory while retaining regional-scale terrain detail.

DEM spatial resolution is a critical factor in LS-factor estimation, as the level of terrain detail directly affects the accuracy of slope length and slope steepness calculations (Wu et al., 2005). The use of high-resolution DEMs enables more precise identification of geomorphological features and improves the assessment of erosion potential, particularly in areas with complex relief (Fijalkowska, 2021; Michalopoulou et al., 2022).

The workflow combined Google Earth Engine and ArcGIS 10.8. Elevation-data preparation was performed in Google Earth Engine, whereas slope calculation, integration with the MERIT Hydro layers, LS-factor computation and final cartographic visualization were performed in ArcGIS 10.8.

Step 1. Hydrographic Data Preparation.

Flow direction and flow accumulation were obtained from the MERIT Hydro global hydrography product (Yamazaki et al., 2019; ~90 m / 3 arc-second resolution), which is hydrologically conditioned at the global scale. Slope was computed independently from the 30 m AW3D30 elevation data. The use of 30 m terrain data together with ~90 m hydrography constitutes a mixed-resolution workflow and is treated as a source of uncertainty in the Discussion.

Step 2. Slope Calculation.

Slope gradients were calculated using the Spatial Analyst Tools module, resulting in a slope map expressed in degrees (Fig. 2). Surface slope is a key parameter controlling runoff velocity and represents the main input for the S-factor component of the RUSLE model. According to RUSLE methodology, the influence of slope steepness on erosion intensity is described by different equations depending on slope magnitude (McCool et al., 1987; Renard et al., 1997).

Step 3. Flow Direction Analysis.

Flow direction was obtained from the MERIT Hydro D8 flow-direction layer (Yamazaki et al., 2019), in which the direction of water movement from each cell to one of its eight neighboring cells (Fig. 3) has already been determined from a hydrologically corrected DEM. The D8 approach is widely applied in hydrological modeling and LS-factor estimation within GIS environments (Desmet & Govers, 1996; Panagos et al., 2015).

Step 4. Flow Accumulation Calculation.

Flow accumulation, expressed as the upslope drainage area contributing to each cell, was likewise obtained from the MERIT Hydro upstream-drainage-area layer and converted from km² to m². Flow accumulation is directly related to slope length and serves as the fundamental input for calculating the specific catchment area used in the L-factor of the RUSLE model (Foster & Wischmeier, 1974; Desmet & Govers, 1996; Mitsova et al., 1996).

Step 5. LS-Factor Computation.

The S-factor was calculated from the 30 m slope raster using the two-branch equation of McCool et al. (1987), after capping slope at a maximum of 26.6° (50%) to keep the calculation within the range adopted in regional RUSLE implementations (Panagos et al., 2015). The L-factor was calculated from the specific catchment area following Mitsova et al. (1996) and Moore and Burch (1986):

$$\begin{aligned} S &= 10.8 \cdot \sin\beta + 0.03 \quad (\tan\beta < 0.09); \\ S &= 16.8 \cdot \sin\beta - 0.5 \quad (\tan\beta \geq 0.09) \end{aligned} \quad (1a)$$

$$L = (A_s / 22.13)^{0.4} \quad (1b)$$

$$LS = L \times S \quad (1c)$$

where: A_s (specific catchment area, m^2 per m of contour width) is the MERIT Hydro flow accumulation divided by the cell size (30 m);

0.4 is the fixed L-factor exponent following Moore and Burch (1986) and Mitasova et al. (1996);

β is the slope angle, capped at a maximum of 26.6° (50%) to stay within the empirically validated range of the McCool et al. (1987) equation;

22.13 m represents the standard slope length adopted in the USLE/RUSLE framework (Renard et al., 1997);

0.09 is the $\tan\beta$ threshold separating the two branches of the McCool et al. (1987) S-factor equation.

This formulation combines the specific-catchment-area approach to slope length (Mitasova et al., 1996; Moore & Burch, 1986) with the empirically validated S-factor of McCool et al. (1987), and is applicable to landscapes with converging flow paths and complex topography (Zhang et al., 2017).

Results. Morphometric Characteristics of the Relief. Analysis of the 30 m AW3D30 elevation data shows that the Semipalatinsk Test Site is predominantly a gently undulating steppe plain, punctuated by several isolated low-mountain massifs - most notably Degelen and Murzhik - where local relief and slope steepness are markedly higher than in the surrounding terrain. Absolute elevations across the territory range from approximately 200 to 600 m a.s.l., with local elevation contrasts of up to 300–350 m within and around these massifs. These massifs, historically associated with underground nuclear testing at the STS, form the principal loci of topographically driven erosion potential identified in this study.

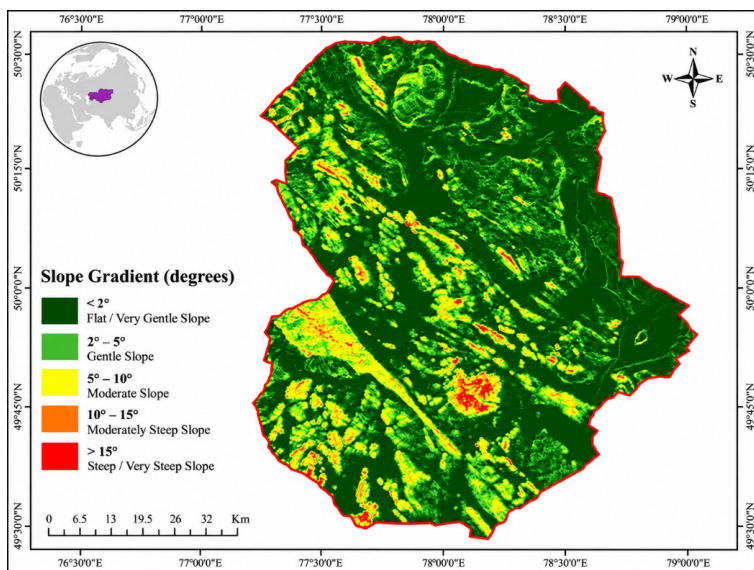


Figure 2. Slope map.

The slope map (Fig. 2) shows that the study area is overwhelmingly flat to gently sloping: the mean slope is $2.5^\circ \pm 2.6^\circ$ (range 0 - 56.5°), and 91.3% of the territory has a gradient below 5° . Only 2.2% of the territory exceeds 10° , and these steeper gradients are spatially concentrated within the Degelen and Murzhik massifs and along a small number of dissected valley systems, rather than being broadly distributed across the polygon (McCool et al., 1987; Liu et al., 2000).

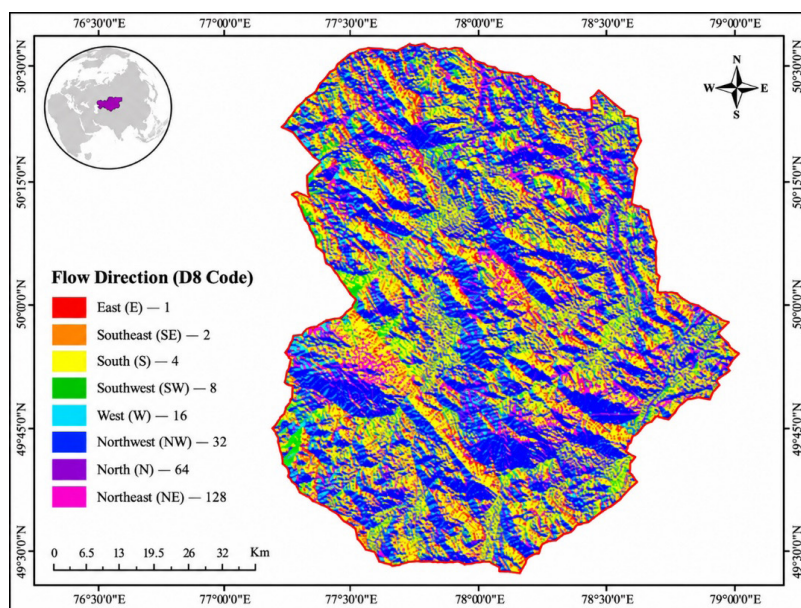


Figure 3. Flow direction.

The flow direction map (Fig. 3), derived from the MERIT Hydro D8 layer (Yamazaki et al., 2019), reveals a well-organized runoff pattern controlled by relief morphology. Dominant flow pathways follow the orientation of major erosional depressions and the low-mountain massifs, indicating structural control of surface runoff organization. Zones of flow convergence spatially coincide with areas of increased erosion potential, which is consistent with, but does not by itself validate, the relationship between terrain configuration and runoff concentration processes (Panagos et al., 2015).

The calculated LS-factor values range from 0.07 to 5784.10, with a mean value of 3.25 (Fig. 4). Although the mean is modest, the distribution is strongly right-skewed (SD = 14.24): extreme values are confined to isolated pixels at the confluence of ephemeral drainage channels, where flow accumulation was not truncated at a maximum contributing length.

For visualization and relative spatial ranking, LS values were grouped into five LS classes. These classes describe the topographic component only and should not be interpreted as absolute erosion-rate or radiological-risk categories:

- Very low ($LS < 1.0$) - 36.6% of the territory (6,713.6 km²), corresponding to the flat interfluvial areas of the steppe plain;
- Low ($LS = 1.0\text{--}2.0$) - 28.6% (5,256.7 km²), gently sloping terrain adjoining the plain;
- Moderate ($LS = 2.0\text{--}5.0$) - 22.9% (4,214.0 km²), transitional zones bordering the low-mountain massifs and larger drainage lines;
- High and very high ($LS = 5.0\text{--}10.0$ and $LS > 10.0$) - a combined 11.9% (2,182.5 km²), concentrated within the Degelen and Murzhik massifs and along the principal channels of the ephemeral drainage network, where slope length and steepness jointly maximize runoff energy.

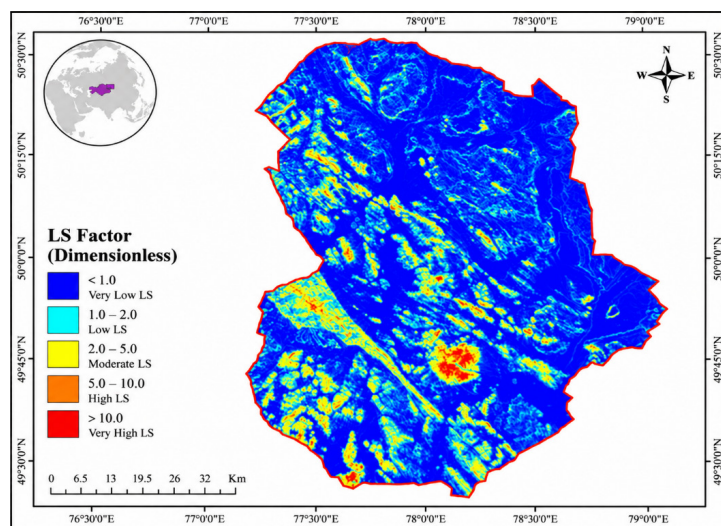


Figure 4. Spatial distribution of the LS factor (relative topographic erosion-potential classes).

Extreme LS values (>100), confined to a small number of pixels at major channel confluences, reflect the unconstrained growth of flow accumulation with drainage area rather than typical hillslope conditions; they should not be interpreted as representative erosion rates but as markers of major concentrated-flow pathways requiring targeted field verification.

The mean LS value (3.25) exceeds the European average of 1.63 reported by Panagos et al. (2015), but the difference is far less pronounced than a simple comparison of maxima would suggest. This moderate excess reflects the concentration of steep, high-relief terrain within the Degelen and Murzhik massifs against an otherwise flat steppe background, together with the effect of an uncapped flow-accumulation term on local maxima.

Comparative analysis with previous studies conducted for Western Kazakhstan (Seitkazy et al., 2024), based on a 30 m elevation model, indicates broadly similar orders of magnitude for typical (non-confluence) LS values, although

direct numerical comparison is limited by differences in flow-routing algorithms and in whether a maximum contributing length was imposed. Methodological comparisons indicate that different computational approaches may change absolute LS magnitudes, whereas the main spatial pattern - concentration of high-LS areas in steeper massifs and major drainage pathways rather than uniform distribution across the plain - remains comparatively stable (Desmet & Govers, 1996; Mitsova et al., 1996).

The reliability of LS estimation is controlled by elevation/hydrography resolution and by the flow-routing method. In this study, slope was derived from 30 m AW3D30 elevation data, while flow direction and upstream drainage area were obtained from the coarser (~90 m) MERIT Hydro product. This mixed-resolution approach enabled full-territory coverage but is a source of uncertainty and should be refined in future work using a single, locally processed, hydrologically corrected elevation model (Wu et al., 2005).

Although the D8 algorithm provides stable and reproducible results, it simplifies multidirectional runoff processes. Nevertheless, its application remains widely accepted for regional LS-factor assessment (Panagos et al., 2015).

The generated cartographic database provides a geospatial framework for:

- prioritizing field verification in the high and very high LS classes ($LS > 5$);
- integrating LS-based topographic zoning with site-specific technogenic and contamination datasets;
- subsequent full RUSLE-based soil-loss modeling;
- targeting areas for long-term monitoring of erosion and landscape-degradation processes.

Discussion. The LS-factor values obtained in this study (0.07–5784.10; mean = 3.25) exceed those reported for most European territories on average, though the comparison is sensitive to how extreme, channel-confluence values are treated. According to the pan-European assessment by Panagos et al. (2015), the mean LS-factor value for the European Union is 1.63, with maximum values reaching up to 99 under a capped flow-length approach. Even in mountainous regions such as the Alps and Pyrenees, average LS values rarely exceed 3.0. The Semipalatinsk Test Site (STS) therefore shows a moderately elevated, spatially concentrated topographic erosion potential rather than a uniformly high one. Similar GIS-based studies at the Semipalatinsk Test Site have demonstrated the applicability of DEM-derived morphometric indicators for assessing erosion-related landscape characteristics (Mukaliyev et al., 2026).

Comparable LS ranges have been reported for Western Kazakhstan (0–244) using a 30 m elevation model (Seitkazy et al., 2024). The much higher maximum obtained here (5784.10) is attributable to the absence of a maximum flow-length threshold in the present workflow, which allows LS to increase strongly at major channel confluences. Applying a maximum contributing-length threshold, as used in regional-scale LS implementations (Panagos et al., 2015), should be tested in future work to reduce this artifact and improve comparability of absolute values.

The influence of DEM spatial resolution on LS-factor estimation has been widely documented. Wu et al. (2005) demonstrated that coarser DEMs tend to smooth slope gradients and enlarge contributing areas, resulting in systematic distortions of LS values. Similarly, Fijalkowska (2021) showed that high-resolution datasets significantly improve the identification of microtopographic variations and localized erosion hotspots, and improve the representation of drainage networks in complex terrain. In the present study, the mixed-resolution combination of 30 m elevation data and ~90 m hydrography likely smooths part of the local variability. Future work should therefore use a single, locally processed, higher-resolution and hydrologically corrected elevation model where feasible.

The selection of the LS-factor calculation method critically influences model outcomes. In this study, the L-factor was calculated from the specific catchment area following the approach of Moore and Burch (1986) and Mitsova et al. (1996), combined with the empirically validated S-factor equation of McCool et al. (1987) applied within its valid range (slope capped at 26.6°). Alternative GIS-based approaches, such as the fully two-dimensional method of Desmet and Govers (1996), which explicitly incorporates flow-direction geometry, are also widely used and may better capture flow convergence in complex terrain.

Although absolute LS magnitudes may vary with algorithm choice and flow-length treatment, previous comparative studies indicate that the broad spatial pattern of topographic erosion potential can remain relatively stable (Desmet & Govers, 1996; Seitkazy et al., 2024). For the STS, the specific-catchment-area approach highlights the Degelen and Murzhik massifs and the main drainage pathways as areas of elevated LS; these areas require field verification rather than direct interpretation as measured erosion rates.

The high LS-factor values observed within the STS are primarily controlled by several key morphometric parameters:

Slope steepness. Although steep slopes (exceeding $15 - 20^\circ$) occupy only a small fraction of the STS (about 2.2% of the territory has slopes above 10°), they are precisely the areas, mainly within the Degelen and Murzhik massifs, where LS values peak. According to McCool et al. (1987), increasing slope steepness from 9% to 20% can result in a 2–3-fold increase in erosion intensity, consistent with the concentration of high-LS pixels in these massifs.

Slope length. Extended slope segments (locally exceeding several kilometers) promote runoff accumulation and energy concentration. The relationship between slope length and soil loss has been theoretically established within the RUSLE framework (Renard et al., 1997), and the present results confirm that the highest LS values coincide with zones combining long slopes and steep gradients.

Vertical relief dissection. Elevation differences of up to 300–350 m within and around the Degelen and Murzhik massifs create significant gravitational potential energy, enhancing runoff acceleration and erosive capacity. Similar relationships between relief dissection and erosion intensity have been reported for mountainous environments (Liu et al., 2000).

Hydrological connectivity. Dense networks of ephemeral watercourses enhance flow convergence and linear erosion development, particularly under storm-driven precipitation events.

The continental climate of the region may further amplify relief-controlled runoff processes. Seasonal snowmelt and high-intensity convective rainfall create conditions favorable for rapid surface runoff generation (Zhang et al., 2023). Therefore, areas with elevated LS values should be treated as priorities for subsequent field-based erosion assessment under high-runoff conditions rather than as direct estimates of soil degradation.

The study has several limitations.

First, flow direction and upstream drainage area were obtained from the ~90 m MERIT Hydro global product rather than derived locally from the 30 m AW3D30 elevation data. This mixed-resolution approach does not explicitly represent microrelief elements such as anthropogenic barriers or small-scale runoff interruptions, which may locally modify effective slope length (Panagos et al., 2015).

Second, the D8 algorithm simplifies multidirectional flow processes. Although widely accepted for regional LS modeling, alternative multi-flow algorithms may improve hydrological realism (Panagos et al., 2015).

Third, LS-factor modeling provides a static representation of topographic erosion potential and does not incorporate temporal variability in rainfall erosivity or vegetation cover.

Fourth, the absence of field-based erosion measurements limits direct validation of modeled LS values. Future integration with RUSLE factors R, K, C, and P would allow for quantitative soil loss estimation.

Fifth, flow accumulation was not truncated at a maximum contributing length, so LS values at major channel confluences reach extreme and likely non-representative magnitudes (up to 5784.10). Testing a maximum contributing-length threshold, consistent with regional-scale LS implementations such as Panagos et al. (2015), is required in the next iteration of the model.

Site-specific factors and radionuclides. The LS factor describes only the topographic component of water-erosion potential and does not by itself characterize the redistribution of radionuclides (^{137}Cs , $^{239+240}\text{Pu}$ and others) within the site. Lateral transfer of radionuclides depends on soil loss (R, K, C and P factors), on the distribution of contamination density across the test areas and on zones of deposition; these data were not used here. The present LS map is therefore regarded as the first, geomorphometric stage of a wider assessment, and its link to radionuclide transport should be examined in further work by combining LS/soil-loss maps with contamination-density data. Technogenic landforms of the site (nuclear explosion craters, spoil heaps and embankments, roads and infrastructure of test areas) were also not mapped separately. At the resolution used here (30 m DEM / ~90 m hydrography), smaller features are not resolved, and closed depressions such as craters may be masked or removed by the pre-conditioning of

the hydrography product, which can distort flow paths and effective slope length. Vectorizing these features and masking them or incorporating them into a locally processed DEM is a necessary next step.

Equation calibration. The S-factor (McCool et al., 1987) was applied with slope capped at 26.6° (50%) to keep the calculation within the range used in regional RUSLE applications (Panagos et al., 2015); slopes exceeding this threshold occur on less than 1% of the territory. The L-factor exponent ($m = 0.4$), taken from Moore and Burch (1986) and Mitsova et al. (1996), was applied without local recalibration for the arid and semi-arid conditions of the STS, and no maximum flow-length threshold was imposed. Because the L-factor exponent is sensitive to the balance between rill and interrill erosion and because flow accumulation was left uncapped, absolute LS values - particularly extremes at channel confluences - are less reliable than the overall spatial pattern. They should therefore be interpreted as relative indices of topographic erosion potential, not as absolute soil-loss estimates. Local calibration against field evidence, including erosion features or ^{137}Cs -derived soil redistribution, together with a flow-length cap and comparison with alternative formulations (Desmet & Govers, 1996), is required for further refinement.

From a land-management perspective, areas with $LS > 5$ - concentrated in the Degelen and Murzhik massifs and along the main drainage pathways - should be treated as priority zones for field verification and subsequent integrated erosion assessment. The LS layer can support environmental planning only when interpreted together with the remaining RUSLE factors, site-specific technogenic features and, where relevant, contamination data.

Conclusion. This study provides a spatially explicit assessment of the topographic component of erosion potential (LS factor) for the Semipalatinsk Test Site using 30 m AW3D30 elevation data and ~90 m MERIT Hydro flow-routing information. Elevation-data processing was performed in Google Earth Engine, while slope and LS-factor calculations and final map preparation were carried out in ArcGIS 10.8. The workflow combines the McCool et al. (1987) S-factor with the specific-catchment-area L-factor of Mitsova et al. (1996) and Moore and Burch (1986), providing a reproducible regional-scale geomorphometric framework while retaining the limitations described above.

The calculated LS values (0.07 - 5784.10; mean = 3.25) show a strongly spatially concentrated pattern. The highest values occur in the Degelen and Murzhik low-mountain massifs and at confluences of the ephemeral drainage network, where flow accumulation was not capped at a maximum contributing length. Accordingly, extreme LS values are interpreted as indicators of concentrated topographic flow pathways rather than direct measures of erosion rate.

Approximately 11.9% of the territory falls within the high and very high LS classes ($LS > 5$). These zones should be prioritized for field verification and for integration with the remaining RUSLE factors before soil-loss estimates or management measures are derived. The mixed-resolution workflow (30 m

elevation data and ~90 m hydrography) remains an important source of uncertainty to be reduced in follow-up work.

The thematic maps of slope, flow direction, flow accumulation and LS factor establish a geospatial basis for subsequent full RUSLE modeling and for comparison with site-specific technogenic and contamination datasets. The present results therefore represent a geomorphometric screening stage rather than a complete assessment of soil loss or radionuclide redistribution.

Overall, the results demonstrate the usefulness of combined cloud and desktop GIS processing for regional-scale morphometric assessment across a large and partially inaccessible territory, while emphasizing the need for locally calibrated, higher-resolution data to refine absolute LS values and to resolve the technogenic landforms of the Semipalatinsk Test Site.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)**

Managing Editor: *T. Apendiyev*
Editors: *D.S. Alenov, A.Shormakova*
Computer layout: *G.D. Zhadyranova*

Signed for print: Oktober 14, 2026
Format: 70×90 1/16. 26.5 printed sheets. Order No. 5.

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