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Article

CHELSA and WorldClim agree on the direction of warming but differ in its magnitude and in precipitation at three mountain sites of the Tien Shan

Kanat Kulymbet ^{1*}, Zhassulan Smanov ²

¹ U.U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry, Almaty, Kazakhstan; (K.K.)

qulymbet.qanat@gmail.com, <https://orcid.org/0000-0003-1864-8166>

² Center of Geospatial Sciences "Farabi GIS", Farabi University, Almaty, Kazakhstan; (Z.S.) zhassulansmanov1307@gmail.com,

<https://orcid.org/0000-0002-8182-3978>

* Corresponding author: Kanat Kulymbet, Kazakhstan, Almaty 050060, 75B Al-Farabi Street, qulymbet.qanat@gmail.com, +77783858788

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Abstract: Mountain climate assessments in Central Asia are sensitive to the choice of gridded climate dataset, particularly in complex terrain where meteorological observations are sparse. This study compared annual air temperature (1980–2019) and precipitation (1980–2018) series extracted from CHELSA v2.1 and WorldClim 2.1 historical monthly data at three mountain sites of southeastern Kazakhstan and the Tien Shan: Kegen Pass, Tekeli Gorge and the Terskey Alatau–Saryzhaz site. Trends were assessed with the Mann–Kendall test with trend-free pre-whitening and Sen's slope, and the temperature series were extended to 2040 with ARIMA models. Both products indicated warming at all three sites, but its magnitude differed. WorldClim showed nearly uniform trends of 0.31–0.38 °C per decade ($p < 0.001$), with decadal means rising by 0.9–1.0 °C between 1980–1989 and 2010–2019, whereas CHELSA showed weaker and more variable trends of 0.14–0.23 °C per decade (0.3–0.7 °C between the same decades); at Kegen Pass the CHELSA trend was only marginally significant. WorldClim was 1.2–4.2 °C warmer than CHELSA in absolute terms. Divergence was greater for precipitation: at Tekeli Gorge CHELSA gave about twice the WorldClim amount (mean 94 vs 48 mm per month), and a significant increase was found only in CHELSA at the Terskey Alatau–Saryzhaz site (+8.6 mm per month per decade, $p < 0.001$) and, more weakly, at Kegen Pass. ARIMA forecasts for 2040 exceeded the 2010–2019 mean by 1.0–1.1 °C in the WorldClim series and by –0.1 to +0.6 °C in the CHELSA series, but the 95% prediction intervals (about ± 1 °C) overlapped, so the forecast differences are not statistically distinguishable. The direction of long-term warming is therefore robust to product choice, whereas absolute values, warming magnitude and precipitation remain product-dependent and should be treated as structural uncertainty in mountain-climate and environmental assessments.

* * * * *

1 Introduction

Mountains compress strong climatic gradients into short horizontal distances. Elevation, slope orientation, exposure, valley geometry, snow persistence and local circulation create contrasting thermal and moisture regimes within the same mountain system. Warming may intensify with elevation, although its magnitude varies among regions and seasons (Pepin et al., 2015), while observational coverage decreases with elevation, leaving many high-mountain areas poorly represented by long-term meteorological records (Thornton et al., 2022). These limitations are particularly important in Central Asia,

where mountain climates influence water supply, agriculture, rangelands and downstream socio-ecological systems (Saidaliyeva et al., 2024).

The Tien Shan is a clear example. Long-term observations show substantial climatic and hydrological change since the second half of the twentieth century (Aizen et al., 1997; Unger-Shayesteh et al., 2013), and glacier mass declined by about 27% between 1961 and 2012 (Farinotti et al., 2015), raising concern over the stability of the Central Asian “water tower” (Chen et al., 2016). The warming signal is not spatially uniform: temperature and precipitation responses vary with elevation and season (Deng et al., 2015), the overall warming rate was about 0.32 °C per decade during 1960–2016 (Xu et al., 2018), and precipitation trajectories are heterogeneous and difficult to characterize at high elevations because of sparse gauge coverage (Guan et al., 2022; Jin et al., 2024). In Kazakhstan, 74 meteorological stations indicate a median warming of about 0.30 °C per decade during 1981–2023, somewhat stronger above 1500 m (Duisebek et al., 2026).

Because direct observations are sparse, gridded climate products are widely used in studies of vegetation, hydrology, land degradation and climate risk. However, relatively little is known about whether alternative high-resolution products describe the same long-term climatic trajectory at specific mountain locations in southeastern Kazakhstan and the adjacent Tien Shan. Station-based studies quantify regional trends (Deng et al., 2015; Xu et al., 2018; Duisebek et al., 2026) but do not evaluate gridded products, and Kyrgyzbay et al. (2023) compared open climate products with ground observations in the Almaty region and found larger discrepancies in mountainous terrain than on the plains, but did not compare the time series of CHELSA and WorldClim at mountain sites. The present study addresses this gap: it compares the two most widely used kilometre-scale products at the same mountain localities, tests their trends formally and examines how their differences carry over into statistical forecasts.

WorldClim provides interpolated climate surfaces based on station observations and geographic covariates (Hijmans et al., 2005; Fick & Hijmans, 2017), whereas CHELSA uses a topographically informed downscaling of atmospheric reanalysis, including orographic effects on precipitation (Karger et al., 2017). Other products, including CRU TS, TerraClimate and ERA5, differ in resolution, interpolation, data assimilation and intended use (Abatzoglou et al., 2018; Harris et al., 2020; Hersbach et al., 2020). Nominal resolution should not be confused with climatic realism: a kilometre-scale raster inherits uncertainty from sparse observations and unresolved topoclimatic processes. Changing the climate input from WorldClim to CHELSA altered estimates of potential species distribution in the Himalayas (Bobrowski & Schickhoff, 2017), finer-resolution products are not superior for every variable or mountain region (Bobrowski et al., 2021), and streamflow-based evaluation revealed systematic biases in global precipitation climatologies (Beck et al., 2020). Precipitation is particularly sensitive: CHELSA and WorldClim gave similar temperature patterns but different precipitation-based classifications in northern Patagonia (Fierke et al., 2024), and both misrepresented precipitation maxima on tropical mountains (Hemp & Hemp, 2024; Newell et al., 2022). Climate-services and ecological-modelling studies therefore recommend that such uncertainty be characterized and propagated rather than removed by selecting a single dataset (Littell et al., 2011; Otto et al., 2016).

The study has three objectives: (1) to determine whether CHELSA and WorldClim indicate a consistent direction and a comparable magnitude of temperature and precipitation change during 1980–2019; (2) to evaluate whether inter-product disagreement differs among sites and is greater for precipitation than for temperature; and (3) to assess whether historical discrepancies are carried forward into ARIMA-based forecasts to 2040. We expected the direction of warming to be more robust than its local magnitude and precipitation to show the strongest product dependence. The three sites are localities of the rare species *Adonis tianschanica* (Kulymbet et al., 2023); they were chosen because gridded climate layers are routinely used as predictors in species-distribution and habitat models for such localities, so that differences between products translate directly into uncertainty in environmental assessments.

2 Materials and methods

2.1 Study sites

The study covered three mountain sites in southeastern Kazakhstan and the adjacent Tien Shan: Kegen Pass in the Ketmen Ridge (KP), Tekeli Gorge in the Zhetysu (Dzungarian) Alatau (TG) and the Terskey Alatau near Saryzhaz (TAS) (Figure 1). Field reference points were taken from Kulymbet et al. (2023): two points at Kegen Pass (43.143417° N, 79.196194° E and 43.143444° N, 79.189389° E), two in Tekeli Gorge (44.796444° N, 78.994694° E and 44.796167° N, 78.992778° E) and one in the Terskey Alatau (42.874194° N, 79.749556° E). The paired points at Kegen and Tekeli lie only 150–550 m apart, i.e. within one or two adjacent grid cells, and were therefore treated as a single site. The analysis is thus based on point extraction at three sites; the sites represent, but do not spatially sample, the surrounding mountain ranges.

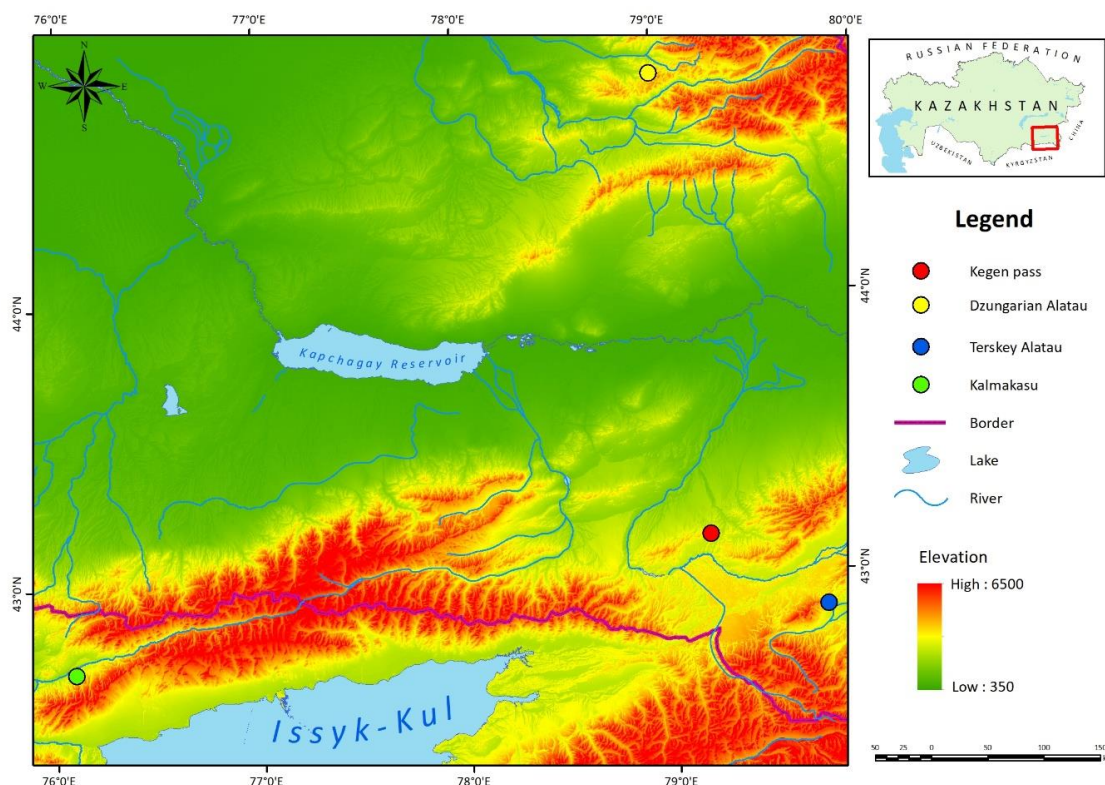


Figure 1. Location of the Kegen Pass, Tekeli Gorge (Dzungarian Alatau) and Terskey Alatau–Saryzhaz study sites. The Kalmakasu point shown in the legend was not used in this study. Background: digital elevation model (m a.s.l.)

The elevations of the reference points and of the surrounding terrain are given in Table 1. The points lie at about 1.950–2.160 m a.s.l. Kegen represents the southeastern part of the Northern Tien Shan in an intermontane setting adjoining the Ketmen Ridge, Tekeli lies farther north in the strongly dissected Zhetysu Alatau, and the Saryzhaz site represents a colder high-mountain environment of the Terskey Alatau.

Table 1. Elevation of the reference points and of the surrounding terrain

Site	Reference point(s), m a.s.l. (SRTM, 30 m)	Terrain at 1 arc-minute (ETOPO1), m	Terrain within the 2.5 arc-minute cell, m (range of four sampled values)
Kegen Pass (KP)	1.953; 2.034	1.892	1.706–1.932
Tekeli Gorge (TG)	2.063; 2.018	2.099	1.759–1.998
Terskey Alatau–Saryzhaz (TAS)	2.159	2.168	2.091–2.686

Source: compiled by the authors from SRTM and ETOPO1 elevation data (OpenTopoData).

2.2 Climate datasets

Candidate global and regional datasets (including CRU TS, TerraClimate, ERA5, CHELSA and WorldClim) were screened using three criteria: (i) availability of monthly temperature and precipitation; (ii) spatial resolution suitable for mountain-scale assessment; and (iii) temporal coverage of several decades. CHELSA and WorldClim were selected because they are the products most widely used as kilometre-scale climate predictors and are based on different temporal data sources.

CHELSA v2.1 monthly time series of mean, maximum and minimum near-surface air temperature (tas, tasmax, tasmin) and precipitation (pr) have a resolution of 30 arc-seconds (about 1 km) and are produced by topographic downscaling of the ERA5 reanalysis (Karger et al., 2017, 2021; Brun et al., 2022; Hersbach et al., 2020). The stored integer values were converted to physical units with the scale and offset given in the technical documentation (temperature: K/10 converted to °C; precipitation: kg m⁻² month⁻¹/100, i.e. mm per month). WorldClim 2.1 historical monthly weather data provide minimum and maximum temperature and precipitation at a resolution of 2.5 arc-minutes (about 4.6 km in latitude); they are produced by applying the monthly anomalies of the CRU TS dataset (0.5° resolution) to the WorldClim 2.1 climatology (Fick & Hijmans, 2017; Harris et al., 2020; WorldClim, 2020). The two products therefore differ in both spatial resolution and temporal source (ERA5 versus interpolated station anomalies of CRU TS), which is essential for interpreting their differences.

The comparison was not designed as a validation of either dataset. Because no independent station records were available for the three sites, differences between CHELSA and WorldClim were interpreted as inter-product divergence rather than as error, and neither product was treated as a reference. Station-based regional trends from the literature (Xu et al., 2018; Duisebek et al., 2026) were used as an external benchmark in the discussion.

2.3 Variables, periods and aggregation

Mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperature and precipitation (P) were analysed. For WorldClim, which does not supply mean temperature, Tmean was calculated as:

$$T_{mean} = (T_{max} + T_{min}) / 2 \quad (1)$$

For CHELSA, the supplied mean temperature (tas) was used. Monthly values were averaged to annual means. Temperature series cover 1980–2019 (40 years) and precipitation series cover 1980–2018 (39 years), the period for which monthly precipitation was available for both products. Precipitation is reported as the mean monthly amount of each year (mm per month), i.e. the annual total divided by 12; annual totals are given alongside for orientation. Decadal means were calculated for 1980–1989, 1990–1999, 2000–2009 and 2010–2019 (2010–2018 for precipitation and for the maps in Figure 2).

2.4 GIS processing

Spatial processing was performed in ArcGIS 10.4 with Spatial Analyst tools. Monthly raster layers were organized by variable, year, month and dataset and clipped to the study region, and the values of the grid cells containing the reference points were extracted (single-cell extraction). Decadal maps of mean temperature were produced for visual comparison (Figure 2). The same reference points and extent were used throughout so that differences between products reflect climatic representation rather than sampling location.

2.5 Trend analysis and inter-product comparison

The warming magnitude was defined in two ways: (i) the difference between the decadal means of 2010–2019 and 1980–1989, and (ii) the linear trend estimated with Sen's slope (Sen, 1968) and its 95% confidence interval, expressed per decade. The significance of monotonic trends was tested with the Mann–Kendall test (Mann, 1945; Kendall, 1975) after trend-free pre-whitening, which accounts for lag-1 autocorrelation (Yue et al., 2002); p-values of the unmodified test are reported where the two differ in

interpretation. The same tests were applied to precipitation. Products were compared by (a) the mean difference of the annual series (WorldClim minus CHELSA), (b) the Pearson correlation between the two annual series at each site, and (c) the agreement in the sign, magnitude and significance of trends. We distinguished signal agreement, where both products indicate change in the same direction, from magnitude agreement, where the size of the change is also comparable. Because only annual series were analysed, seasonal trends were not assessed.

2.6 ARIMA forecasting

To examine how differences between products propagate into near-term statistical forecasts, autoregressive integrated moving-average (ARIMA) models were fitted to each annual temperature series (Box et al., 2015). Because the series are annual, no seasonal component was included. The general model is:

$$\varphi(B)(1 - B)^d y_t = c + \theta(B) \varepsilon_t \quad (2)$$

where y_t is the annual mean temperature in year t , B is the backshift operator, $\varphi(B)$ and $\theta(B)$ are the autoregressive and moving-average polynomials of orders p and q , d is the order of differencing, c is a constant (a drift term when $d = 1$) and ε_t is the residual. Model orders were selected following the procedure of Hyndman and Khandakar (2008): d was determined with the KPSS test (Kwiatkowski et al., 1992) at the 5% level, and p and q (0–2) were chosen by minimizing the corrected Akaike information criterion (AICc). Residual autocorrelation was checked with the Ljung–Box test at lag 10 (Ljung & Box, 1978). Forecast skill was assessed by hold-out validation: models with the selected orders were fitted to 1980–2009 and used to predict 2010–2019, and the root-mean-square error (RMSE) and mean absolute error (MAE) were compared with a naive forecast equal to the 2000–2009 mean. Forecasts were then produced for 2020–2040 with 95% prediction intervals and compared with the 2010–2019 mean. Calculations were carried out in Python with the statsmodels (Seabold & Perktold, 2010) and py Mann-Kendall (Hussain & Mahmud, 2019) packages. The forecasts are statistical extrapolations of each series and not physically based climate scenarios.

3 Results

3.1 Temperature level and inter-product offset

WorldClim gave higher temperatures than CHELSA at all three sites (Table 2). The mean difference of the annual series was 4.19 °C at Kegen Pass, 1.21 °C at Tekeli Gorge and 2.08 °C at the Terskey Alatau–Saryzhaz site. The interannual variability of the two products was nevertheless positively correlated ($r = 0.80, 0.78$ and 0.83 , respectively). The decadal maps show the same general pattern in both products, with the warmest conditions in the lowlands and the coldest along the high ranges (Figure 2); because the two products are mapped with different class limits, the colours are not directly comparable between products.

3.2 Temperature trends

Both products indicated warming at all three sites (Figure 3, Table 2). In the WorldClim series, the decadal mean rose by +1.03 °C at Kegen Pass, +0.87 °C at Tekeli Gorge and +1.05 °C at the Terskey Alatau–Saryzhaz site between 1980–1989 and 2010–2019, and Sen's slopes were 0.37, 0.31 and 0.38 °C per decade, all highly significant ($p < 0.001$). In the CHELSA series the corresponding decadal differences were +0.33, +0.66 and +0.65 °C and the slopes were 0.14, 0.21 and 0.23 °C per decade. The CHELSA trends were significant at Tekeli Gorge ($p = 0.002$) and at the Terskey Alatau–Saryzhaz site ($p < 0.001$), whereas at Kegen Pass the trend was only marginal: $p = 0.024$ after pre-whitening and $p = 0.062$ with the unmodified test, and the confidence interval of the slope includes zero. In the WorldClim series, warming was concentrated between the 1990s and the 2000s, and the 2010–2019 mean was close to that of 2000–2009, whereas the CHELSA series at Tekeli Gorge and the Terskey Alatau–Saryzhaz site continued to rise in the last decade.

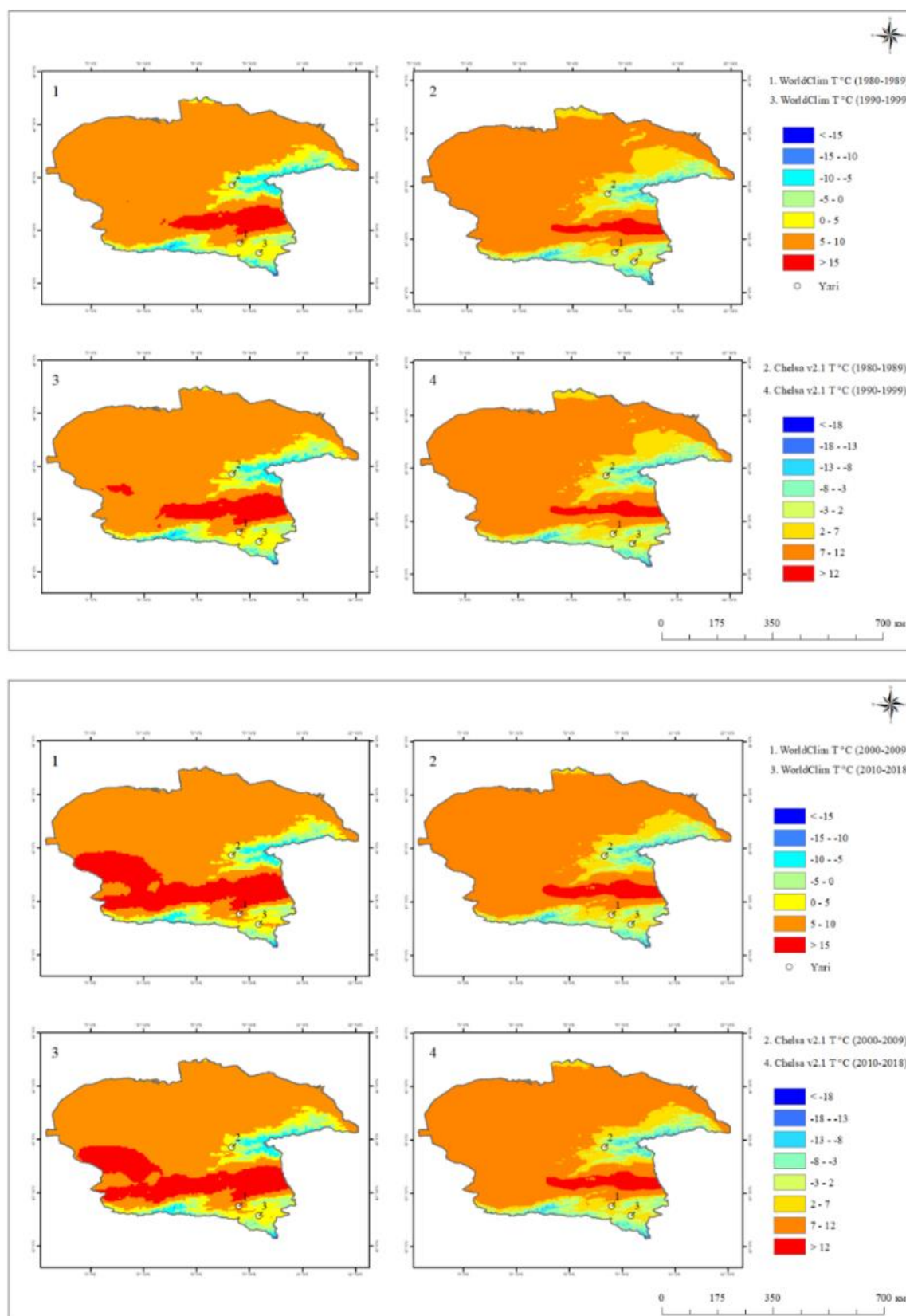


Figure 2. Decadal mean air temperature (°C) in the study region. Upper image: 1980–1989 (panels 1 and 2) and 1990–1999 (panels 3 and 4); lower image: 2000–2009 (panels 1 and 2) and 2010–2018 (panels 3 and 4). Panels 1 and 3 – WorldClim 2.1; panels 2 and 4 – CHELSA v2.1. Circles mark the study sites (1 – Kegen Pass, 2 – Tekeli Gorge, 3 – Terskey Alatau–Saryzhaz). Class limits differ between the two products

Source: compiled by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

Table 2. Decadal mean air temperature (°C) and trend statistics for 1980–2019

Site	Product	1980–1989	1990–1999	2000–2009	2010–2019	Δ , °C	Sen's slope, °C per decade (95% CI)	p
Kegen Pass	WorldClim	4.87	5.22	5.95	5.90	+1.03	+0.37 (0.19; 0.55)	< 0.001
	CHELSA	1.05	1.16	1.61	1.38	+0.33	+0.14 (−0.01; 0.28)	0.024
Tekeli Gorge	WorldClim	1.40	1.72	2.39	2.27	+0.87	+0.31 (0.14; 0.50)	< 0.001
	CHELSA	0.41	0.57	0.91	1.07	+0.66	+0.21 (0.08; 0.39)	0.002
Terskey Alatau–Saryzhaz	WorldClim	1.47	1.82	2.56	2.52	+1.05	+0.38 (0.20; 0.55)	< 0.001
	CHELSA	−0.32	−0.09	0.15	0.33	+0.65	+0.23 (0.09; 0.39)	< 0.001

Note: Δ – difference between the 2010–2019 and 1980–1989 means; p – Mann–Kendall test with trend-free pre-whitening. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

The two products therefore agree on the sign of the temperature change but not on its magnitude or on its spatial pattern. WorldClim shows strong and nearly uniform warming at all three sites (0.31–0.38 °C per decade), whereas CHELSA shows weaker warming that differs more among sites (0.14–0.23 °C per decade), with the smallest trend at Kegen Pass. The WorldClim series at Kegen Pass and at the Terskey Alatau–Saryzhaz site are almost identical apart from a constant offset of 3.39 °C ($r = 1.00$; standard deviation of the difference 0.03 °C), and the Tekeli series is also very similar ($r = 0.98$). The corresponding correlations between sites in CHELSA are lower ($r = 0.82$ and 0.65). The uniformity of the WorldClim trends thus reflects a shared coarse-scale anomaly signal rather than three independent estimates.

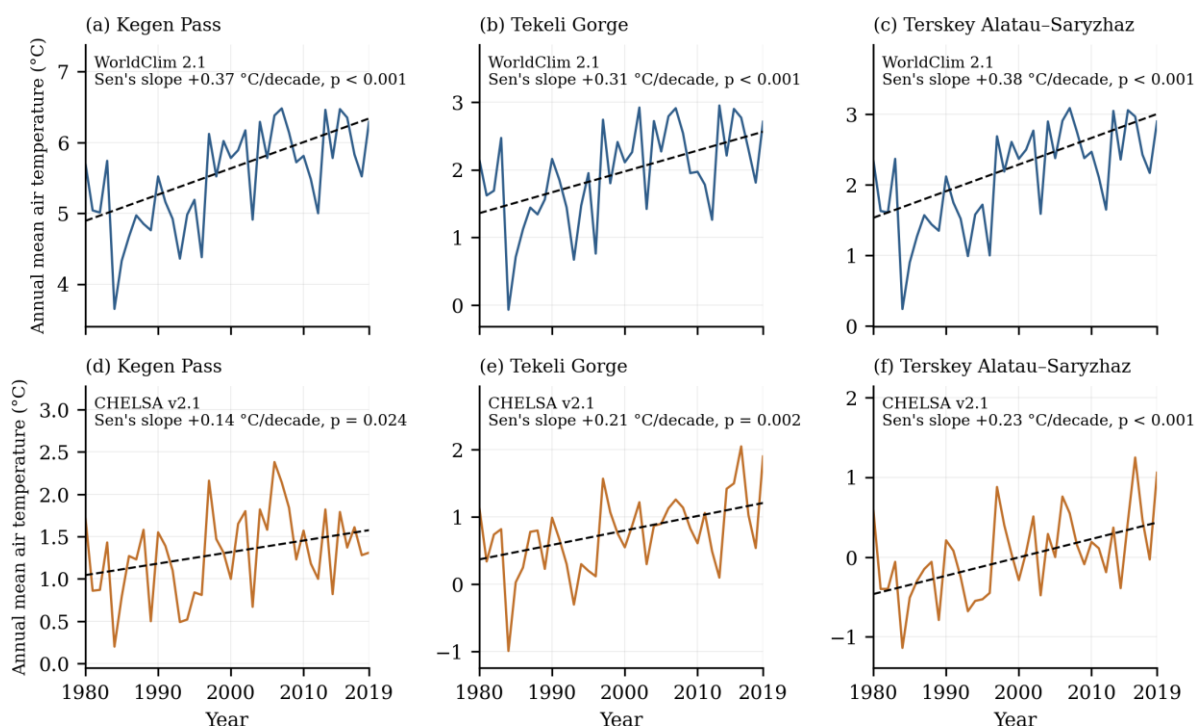


Figure 3. Annual mean air temperature at the three sites in 1980–2019: (a–c) WorldClim 2.1; (d–f) CHELSA v2.1. Dashed lines show the Sen's slope trend; p-values refer to the Mann–Kendall test with trend-free pre-whitening

Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

Maximum and minimum temperature also increased in both products (Table 3). In WorldClim, Tmax increased by 0.60–0.85 °C and Tmin by 0.86–1.00 °C between the earlier (1980–1999) and later (2000–2019) halves of the record, so that their average change (0.73–0.93 °C) is consistent with the change in Tmean between the same periods (0.77–0.89 °C). In CHELSA, Tmax increased by 0.48–0.87 °C and Tmin by 0.48–0.64 °C, compared with 0.39–0.50 °C for Tmean; the correspondence is less close because the CHELSA mean temperature is an independent variable and not the average of Tmax and Tmin. Both products thus indicate less severe low-temperature conditions at all three sites.

Table 3. Change in mean, maximum and minimum air temperature (°C) between 1980–1999 and 2000–2019

Site	Product	Tmean	Tmax	Tmin
Kegen Pass	WorldClim	5.04 → 5.93 (+0.89)	10.89 → 11.73 (+0.84)	−1.14 → −0.17 (+0.97)
	CHELSA	1.10 → 1.49 (+0.39)	6.94 → 7.42 (+0.48)	+0.48
Tekeli Gorge	WorldClim	1.56 → 2.33 (+0.77)	7.40 → 8.00 (+0.60)	−4.58 → −3.72 (+0.86)
	CHELSA	0.49 → 0.99 (+0.50)	5.42 → 6.29 (+0.87)	+0.56
Terskey Alatau–Saryzhaz	WorldClim	1.65 → 2.54 (+0.89)	7.81 → 8.66 (+0.85)	−4.84 → −3.84 (+1.00)
	CHELSA	−0.20 → 0.24 (+0.44)	5.21 → 5.95 (+0.74)	+0.64

Note: for CHELSA Tmin only the change is given. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

3.3 Precipitation

Inter-product divergence was greater for precipitation than for temperature (Figure 4, Table 4). At Kegen Pass the two products were of similar magnitude, with CHELSA about 18% lower than WorldClim (mean 44 vs 54 mm per month). The strongest divergence occurred at Tekeli Gorge, where CHELSA gave about twice the WorldClim amount in every decade (mean 94 vs 48 mm per month, i.e. roughly 1,100 vs 570 mm per year). At the Terskey Alatau–Saryzhaz site the long-term means were similar (48 vs 46 mm per month), but the temporal behaviour differed: CHELSA increased from 36.6 mm per month in 1980–1989 to 65.3 mm per month in 2010–2018, whereas WorldClim remained between 43.0 and 49.1 mm per month.

The trend tests confirm this contrast. None of the WorldClim precipitation series showed a significant trend ($p = 0.191$ – 0.379). In CHELSA, a strong and highly significant increase was found at the Terskey Alatau–Saryzhaz site ($+8.6$ mm per month per decade, $p < 0.001$), a weaker increase at Kegen Pass ($+2.1$ mm per month per decade, $p = 0.024$; $p = 0.057$ with the unmodified test) and no significant trend at Tekeli Gorge ($p = 0.083$). The interannual correlation between the two products was only moderate ($r = 0.54, 0.33$ and 0.41), much lower than for temperature. For precipitation, the products therefore differ in amount, in interannual variability and in the presence of a trend.

Table 4. Decadal mean monthly precipitation, mm per month (annual total, mm, in parentheses), and trend statistics for 1980–2018

Site	Product	1980–1989	1990–1999	2000–2009	2010–2018	Sen's slope, mm per month per decade (95% CI)	p
Kegen Pass	WorldClim	51.7 (620)	49.2 (590)	56.6 (680)	57.1 (690)	+1.6 (−1.0; 4.7)	0.191
	CHELSA	42.6 (510)	41.7 (500)	43.4 (520)	49.4 (590)	+2.1 (0.0; 4.6)	0.024
Tekeli Gorge	WorldClim	47.0 (560)	44.0 (530)	50.7 (610)	49.1 (590)	+1.2 (−1.1; 3.5)	0.379
	CHELSA	90.9 (1090)	91.6 (1100)	87.0 (1040)	107.3 (1290)	+4.7 (−1.4; 9.8)	0.083
Terskey Alatau–Saryzhaz	WorldClim	44.9 (540)	43.0 (520)	48.1 (580)	49.1 (590)	+1.3 (−1.2; 3.7)	0.269
	CHELSA	36.6 (440)	43.0 (520)	47.2 (570)	65.3 (780)	+8.6 (6.1; 10.8)	< 0.001

Note: annual totals are rounded to 10 mm; p – Mann–Kendall test with trend-free pre-whitening. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

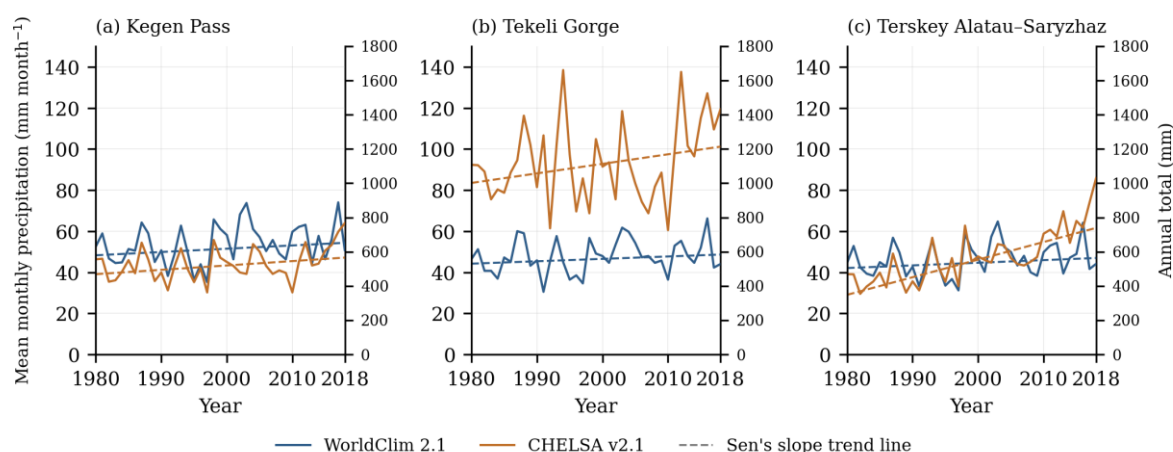


Figure 4. Mean monthly precipitation (left axis) and the corresponding annual total (right axis) at the three sites in 1980–2018 according to WorldClim 2.1 and CHELSA v2.1; dashed lines show the Sen's slope trend

Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

3.4 ARIMA forecasts to 2040

The selected models, diagnostics and forecasts are given in Table 5 and Figure 5. For five of the six series the KPSS test indicated non-stationarity and a model with one difference and a drift term was selected: ARIMA(0,1,1) for the three WorldClim series and for CHELSA at the Terskey Alatau–Saryzhaz site, and ARIMA(1,1,2) for CHELSA at Tekeli Gorge. For CHELSA at Kegen Pass, where the trend is weak, the series was classified as stationary and a constant-mean model, ARIMA(0,0,0), was selected. The Ljung–Box test did not indicate residual autocorrelation in any model ($p = 0.34$ – 0.89). In the hold-out validation for 2010–2019, the RMSE was 0.61 – 0.68 °C for WorldClim and 0.33 – 0.58 °C for CHELSA. The CHELSA models performed slightly better than the naive forecast, whereas the WorldClim models, which extrapolated the earlier warming, performed slightly worse because warming slowed in 2010–2019. Forecast skill at the decadal horizon is therefore limited.

Table 5. ARIMA models, diagnostics and forecasts of annual mean air temperature (°C)

Site	Product	ARIMA (p,d,q)	Ljung–Box Q (df); p	Hold-out RMSE / MAE / naive RMSE	Mean 2010–2019	Forecast mean 2020–2040	Forecast 2040 (95% PI)	2040 minus 2010–2019
Kegen Pass	WorldClim	(0,1,1)	9.9 (9); 0.36	0.62 / 0.50 / 0.47	5.90	6.62	7.00 (5.92; 8.08)	+1.10
	CHELSEA	(0,0,0)	10.4 (10); 0.41	0.33 / 0.27 / 0.39	1.38	1.30	1.30 (0.33; 2.27)	–0.08
Tekeli Gorge	WorldClim	(0,1,1)	7.0 (9); 0.64	0.68 / 0.55 / 0.55	2.27	2.92	3.23 (2.02; 4.44)	+0.97
	CHELSEA	(1,1,2)	7.9 (7); 0.34	0.58 / 0.49 / 0.63	1.07	1.47	1.71 (0.69; 2.72)	+0.64
Terskey Alatau–Saryzhaz	WorldClim	(0,1,1)	9.7 (9); 0.38	0.61 / 0.49 / 0.45	2.52	3.25	3.63 (2.56; 4.70)	+1.11
	CHELSEA	(0,1,1)	4.3 (9); 0.89	0.46 / 0.36 / 0.52	0.33	0.69	0.91 (0.03; 1.80)	+0.59

Note: models with $d = 1$ include a drift term; the model with $d = 0$ includes a constant. PI – prediction interval. Source: calculated by the authors.

In the WorldClim series, the forecast for 2040 exceeded the 2010–2019 mean by $+1.10$ °C at Kegen Pass, $+0.97$ °C at Tekeli Gorge and $+1.11$ °C at the Terskey Alatau–Saryzhaz site; the mean of the whole 2020–2040 forecast was $+0.73$, $+0.65$ and $+0.73$ °C above the 2010–2019 mean. In the CHELSA series, the corresponding changes by 2040 were $–0.08$, $+0.64$ and $+0.59$ °C. The forecasts thus preserve the historical difference between the products: stronger and nearly uniform warming in WorldClim and weaker, site-dependent warming in CHELSA. However, the 95% prediction intervals for 2040 are about ± 0.9 – 1.2 °C

wide and overlap between the products for the projected change at every site. The difference between the WorldClim and CHELSA forecasts (0.3–1.2 °C) is smaller than the forecast uncertainty and is therefore not statistically distinguishable.

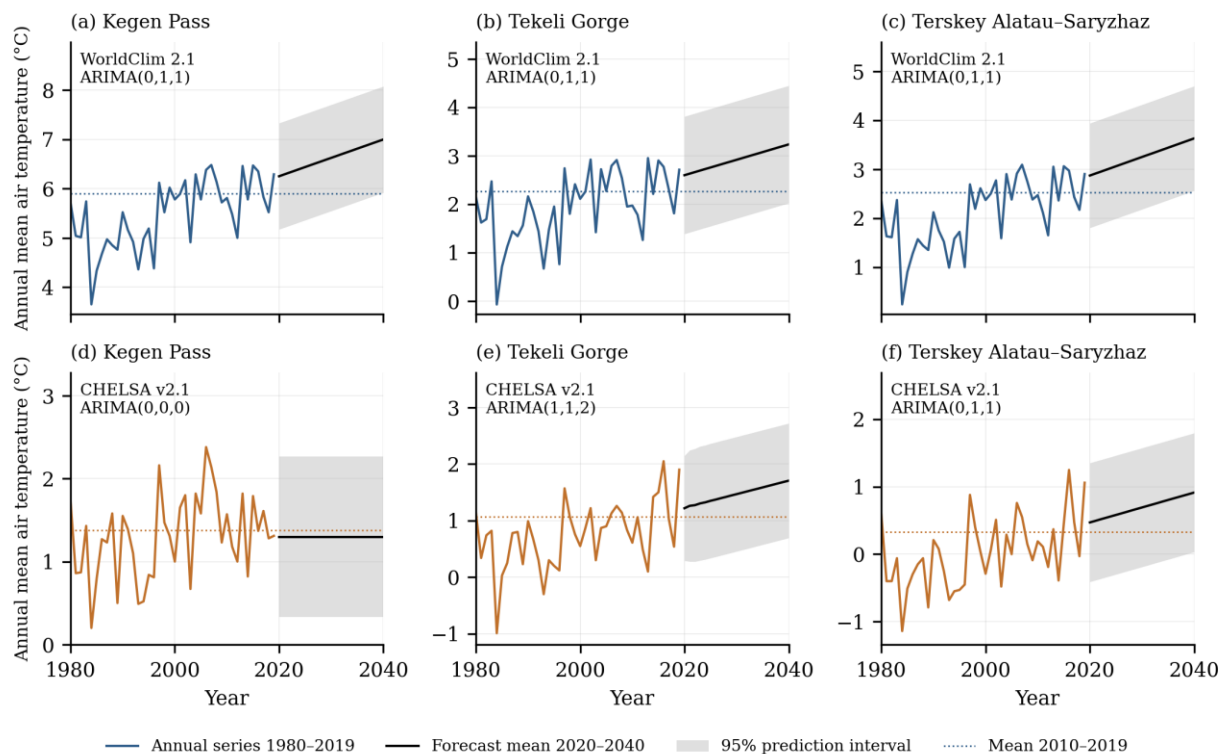


Figure 5. ARIMA forecasts of annual mean air temperature to 2040: (a–c) WorldClim 2.1; (d–f) CHELSA v2.1. Coloured lines – annual series for 1980–2019; black lines – forecast mean; shaded areas – 95% prediction intervals; dotted lines – mean of 2010–2019

Source: calculated by the authors.

4 Discussion

4.1 A robust warming signal with product-dependent magnitude

The most consistent result is the agreement of the two products on the direction of long-term temperature change: both indicate warming at all three sites, including higher minimum temperatures. The magnitude, however, differs by a factor of about two. The WorldClim trends (0.31–0.38 °C per decade) are close to station-based estimates for the region: about 0.32 °C per decade for the Tien Shan in 1960–2016 (Xu et al., 2018) and a median of about 0.30 °C per decade for Kazakhstan in 1981–2023, with somewhat stronger warming above 1500 m (Duissebek et al., 2026). The CHELSA trends (0.14–0.23 °C per decade) are lower than these benchmarks. This comparison does not validate either product at the study sites, but it indicates that the WorldClim series reproduce the regional station signal, whereas CHELSA yields a weaker local trend.

The local trajectories should not be interpreted as responses to elevation alone. Temperature evolution in the Tien Shan is linked to large-scale circulation (Ling et al., 2023), and elevation-dependent warming is not spatially universal; its magnitude and vertical structure depend on region, season, variable and data source (Pepin et al., 2022). The three sites lie within a narrow elevation range (about 1.950–2.160 m) and differ in several other characteristics, so the differences among them cannot be attributed to elevation-dependent warming. Demonstrating such a mechanism would require an elevation-stratified station network and seasonal analysis.

4.2 Why CHELSA and WorldClim differ

The differences between the products can be traced to three mechanisms. The first is the temporal data source. WorldClim historical monthly data take their interannual variability from CRU TS, which interpolates station anomalies onto a 0.5° grid using a large correlation decay distance (Harris et al., 2020). Neighbouring cells therefore carry almost the same anomaly, which explains why the WorldClim series at Kegen Pass and the Terskey Alatau are practically identical apart from a constant offset and why the WorldClim trends are uniform across the three sites. The WorldClim series thus describe the regional station signal shifted to the local climatological level, not independent local trajectories. CHELSA derives its variability from ERA5 (Hersbach et al., 2020; Brun et al., 2022), in which the three sites lie in different reanalysis cells and are downscaled separately; its trends are therefore more site-specific, but they also inherit any trend bias of the reanalysis in complex terrain.

The second mechanism is spatial resolution and grid-cell elevation. A 2.5 arc-minute WorldClim cell covers about 15 km² and averages over valley floors and slopes, whereas a 30 arc-second CHELSA cell covers less than 1 km². At Kegen Pass and Tekeli Gorge the terrain within the WorldClim cell is mostly lower than the reference points (Table 1), which contributes to the warmer WorldClim values. With a typical lapse rate of about 0.6 °C per 100 m, however, an elevation difference of 100–200 m accounts for only about 1 °C of the 4.19 °C offset at Kegen Pass, and at the Terskey Alatau–Saryzhaz site the terrain within the cell is mostly higher than the reference point, which would act in the opposite direction. Most of the offset must therefore arise from the third mechanism, the different climatologies and downscaling methods: WorldClim interpolates station normals with elevation and other covariates, whereas CHELSA applies reanalysis-based lapse rates, and the two approaches can differ by several degrees in intermontane basins and passes where stations are absent. Studies from other mountain systems confirm that such differences are systematic and propagate into environmental interpretations (Bobrowski & Schickhoff, 2017; Bobrowski et al., 2021), and in the Almaty region discrepancies between products and observations were larger in mountainous terrain than on the plains (Kyrgyzbay et al., 2023).

4.3 Precipitation as the principal source of inter-product uncertainty

The strongest divergence occurred for precipitation: a twofold difference in amount at Tekeli Gorge and a significant increasing trend in CHELSA at the Terskey Alatau–Saryzhaz site that is absent in WorldClim. Mountain precipitation is controlled by orographic uplift, exposure, rain-shadow effects and valley geometry, which are difficult to reconstruct from sparse station networks. High-elevation precipitation in the Tien Shan remains poorly constrained (Jin et al., 2024), in situ observations are disproportionately sparse in mountains worldwide (Thornton et al., 2022), and high-resolution precipitation climatologies, including WorldClim and CHELSA, contain systematic biases (Beck et al., 2020). Similar product disagreement has been reported from Patagonia, tropical mountains and the Andes (Fierke et al., 2024; Hemp & Hemp, 2024; Newell et al., 2022).

The higher CHELSA values at Tekeli are consistent with its orographic correction, which enhances precipitation on exposed slopes of the Zhetysu Alatau (Karger et al., 2017), whereas the WorldClim interpolation yields a smoother field and a station-based anomaly signal with little trend. The increase in CHELSA at the Terskey Alatau–Saryzhaz site may reflect a trend in ERA5 precipitation rather than an observed change. Without independent gauges, neither the higher CHELSA amounts nor the more stable WorldClim amounts can be regarded as more realistic; for hydrological, erosion, vegetation or habitat applications, the difference between them should be carried into the analysis as structural uncertainty.

4.4 Forecasts and their limitations

The ARIMA forecasts are statistical extensions of the respective series and are conditional on their historical properties. Models fitted to the strongly trending WorldClim series extrapolate a warming of about 1.0–1.1 °C by 2040 relative to 2010–2019, whereas the weaker CHELSA trends give –0.1 to +0.6 °C. Two qualifications are essential. First, the prediction intervals are wider than the differences between the

products, so the forecasts cannot be said to diverge in a statistical sense; what differs is the central estimate, which simply continues each product's historical trend. Second, hold-out validation showed limited skill at the decadal horizon, particularly for WorldClim, because warming slowed in 2010–2019. The forecasts do not represent greenhouse-gas pathways, land–atmosphere feedbacks or circulation changes and should not be used as climate scenarios. A physically based comparison would use the CMIP6-derived future climatologies available for both products (CHELSA for 2011–2040 and WorldClim for 2021–2040), which is a logical next step.

4.5 Implications for geographical and environmental applications

Environmental analyses commonly select one high-resolution climate dataset and treat its values as fixed predictors. For the localities of Adonis tianschanica examined here, the choice between the two products changes the mean annual temperature by 1.2–4.2 °C and, at Tekeli Gorge, the precipitation by a factor of two. Differences of this size are sufficient to shift bioclimatic predictors and therefore the output of species-distribution and habitat-suitability models (Bobrowski & Schickhoff, 2017; Fierke et al., 2024). Similar effects can be expected in modelling vegetation zones, erosion susceptibility, pasture productivity, snow conditions or hydrological response. A more defensible strategy is to distinguish conclusions that are stable across datasets – here, the occurrence of warming – from those that are product-dependent – absolute temperature, warming magnitude and precipitation – and to report results for more than one product.

4.6 Limitations

The study has several limitations. Values were extracted from single grid cells at three sites, so the results describe these localities and not whole mountain ranges; zonal statistics over elevation bands would give a more representative comparison. No station records or third product were available for independent validation. Only annual series were analysed, so seasonal trends and seasonal forecasting were not addressed. The decadal maps (Figure 2) use different class limits for the two products. Finally, the forecasts are univariate statistical extrapolations with limited skill.

5 Conclusion

CHELSA v2.1 and WorldClim 2.1 agree that the three Tien Shan sites warmed between 1980 and 2019, but they differ in how much. WorldClim indicates nearly uniform trends of 0.31–0.38 °C per decade (about 0.9–1.0 °C between 1980–1989 and 2010–2019), close to station-based regional estimates, whereas CHELSA indicates 0.14–0.23 °C per decade (0.3–0.7 °C), with only a marginal trend at Kegen Pass. WorldClim is 1.2–4.2 °C warmer than CHELSA in absolute terms. The uniform WorldClim trends reflect the coarse CRU TS anomaly signal shared by the sites, while the CHELSA trends reflect the downscaled ERA5 reanalysis.

Precipitation is considerably more product-dependent: CHELSA gives about twice the WorldClim amount at Tekeli Gorge (about 94 vs 48 mm per month), and a significant increase occurs only in CHELSA, most clearly at the Terskey Alatau–Saryzhaz site (+8.6 mm per month per decade). Spatial resolution should therefore not be equated with climatic certainty.

ARIMA forecasts continue the historical trend of each product (+1.0 to +1.1 °C by 2040 relative to 2010–2019 for WorldClim; –0.1 to +0.6 °C for CHELSA), but their 95% prediction intervals overlap, so the forecasts do not differ significantly and have limited skill.

The main limitations are single-cell extraction at three sites, the absence of independent validation and the univariate statistical nature of the forecasts. Future work should combine both products with Kazhydromet station records and a third product such as ERA5-Land or TerraClimate, use zonal statistics over elevation bands, analyse seasonal trends and compare the statistical forecasts with CMIP6-based projections. Until then, environmental studies in the Tien Shan should compare several climate products and separate conclusions that are stable across them from those that depend on the dataset.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kanat Kulymbet	✓	✓	✓	✓	✓				✓	✓	✓			
Zhassulan Smanov	✓				✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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Biographies of authors



Kanat Kulymbet

Ph.D., Senior-researcher of the Department of soil ecology, U.U. Usanov Kazakh Research Institute of Soil Science and Agrochemistry, Almaty, Kazakhstan
Soil Science, Irrigation and Water Management, Agronomy
kulymbet.qanat@gmail.com
<https://www.scopus.com/authid/detail.uri?authorId=58405375600>
<https://orcid.org/0000-0003-1864-8166>



Zhassulan Smanov

Senior researcher, Center of Geospatial Sciences “Farabi GIS”, Farabi University, Almaty, Kazakhstan
Environmental Science, Soil Science, Irrigation and Water Management
zhassulan.smanov@kaznu.edu.kz
<https://www.scopus.com/authid/detail.uri?authorId=57211743539>
<https://orcid.org/0000-0002-8182-3978>

Article

Strategic priorities for tourism industry development in the Almaty region

Lóránt Dénes Dávid^{1,2,3,4*} 

¹ John von Neumann University, Faculty of Economics and Business, Department of Tourism and Hospitality, Kecskemét, Hungary; (L.D.D.) dr.david.lorant@gmail.com, <https://orcid.org/0000-0001-7880-9860>

² Hungarian University of Agriculture and Life Sciences (MATE), Institute of Rural Development and Sustainable Economy, Department of Tourism and Hospitality, Gödöllő, Hungary

³ Eötvös Loránd University, Faculty of Social Sciences, Savaria Department of Business Economics, Savaria University Centre, Szombathely, Hungary

⁴ Széchenyi István University, Kautz Gyula Faculty of Business and Economics, Department of Tourism and Hospitality, Győr, Hungary

* **Corresponding author:** Lóránt Dénes Dávid, Hungary, Gödöllő, HU-2100, dr.david.lorant@gmail.com, +36 20 9722833

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Abstract: Tourism is an important instrument for diversifying regional economies and creating employment. Despite its diverse natural and cultural-historical resources, the Almaty region has not fully realized its tourism potential, while development priorities remain insufficiently examined from the perspectives of residents and tourists. This study aims to identify the main constraints on tourism development and formulate strategic priorities for the Almaty region. A mixed-methods design combined a review of scientific literature and national strategic documents with a structured online questionnaire of 15 closed-ended questions completed by 503 respondents. Data were analyzed using descriptive statistics, while SWOT analysis and a TOWS matrix were used to develop strategic directions. The main barriers were inadequate road and transport infrastructure (25.0%), low quality of tourist services (21.3%), and insufficient protection of natural resources (20.5%). Priority measures included improving service quality (23.1%), protecting natural monuments (21.3%), and implementing advertising campaigns (21.1%). Social media was the main source of tourism information (52.9%), while health and wellness tourism was the most demanded type (33.6%). Nearly half of respondents (48.5%) rated service quality as average or below average, and 60.5% considered staff training important or very important. Kolsai Lakes and Charyn Canyon accounted for 51.2% of reported tourism demand, indicating the need for visitor management at major natural attractions. Respondents primarily associated the role of government with attracting investment (40.4%), while Talgar district was identified as the main territorial priority (42.5%). The SWOT-TOWS analysis identified strategic priorities including infrastructure modernization, workforce development, digital marketing, investment attraction, and nature conservation. The findings provide an evidence base for regional tourism development programmes and management decisions.

* * * * *

1 Introduction

Tourism is regarded as an important instrument for diversifying regional economies, creating new jobs and preserving natural and cultural heritage (Baiburiev et al., 2018; Laut et al., 2021). In Kazakhstan, tourism development is one of the priority areas of state policy: the Concept for 2023–2029 sets the

objectives of increasing domestic and inbound tourism, developing tourism infrastructure and improving service quality (Government of the Republic of Kazakhstan, 2023).

The Almaty region is one of the country's regions with the highest tourism potential. Well-known sites such as Charyn Canyon, the Kolsai and Kaindy Lakes, Altyn-Emel National Park and the Kapshagay Reservoir, together with proximity to the Almaty agglomeration with more than a million inhabitants, ensure a steady tourist flow to the region (Zheldibayev et al., 2024; Moldagaliyeva et al., 2024). However, tourism development in the region is hindered by weak transport infrastructure, a shortage of qualified staff, insufficient marketing and institutional gaps in governance (Aktymbayeva et al., 2021; Sakypbek et al., 2025).

The theoretical basis for destination development is provided by R. Butler's tourist area life cycle concept, according to which a destination passes through stages of development and, without planned management, its resources deteriorate and its attractiveness declines (Butler, 1980). From the perspective of tourism geography, the spatial balance between tourism demand and supply, the accessibility of infrastructure and the pressure on the natural environment are considered key issues of regional planning (Hall & Page, 2014), while event tourism is viewed as an additional factor in enhancing destination competitiveness (Getz, 2008). Since small enterprises form the core of tourism supply, their management practices, competencies and access to state support determine the quality of regional tourism (Ateljevic, 2007; Thomas et al., 2011; Koens & Thomas, 2015).

Studies from Kazakhstan confirm these trends. Research on small tourism businesses in Almaty showed that most entrepreneurs lacked specialized tourism knowledge and a marketing plan (Issakov et al., 2023). Interviews with stakeholders in Almaty city and region identified institutional fragmentation, non-transparent permitting procedures and weak trust between the state and business as the main barriers (Sakypbek et al., 2025). A similar survey-based study in the Akmola region showed that, despite natural attractiveness, infrastructure deficits limit destination competitiveness (Dyussekeyeva et al., 2025), while a study of the Kazakhstan section of the Great Silk Road focused on the relationship between tourists' satisfaction with infrastructure and the socio-economic benefits of tourism (Moldagaliyeva et al., 2024). Work analysing the life cycle of ecotourism emphasizes the importance of managing the load on natural sites (Mukhambetov et al., 2014).

However, previous studies on the Almaty region have mostly focused on the city level, on individual types of tourism or on stakeholder interviews; comprehensive assessments that combine the broad opinions of local residents and tourists with strategic analysis tools (SWOT and TOWS) remain scarce. Accordingly, the aim of this study is to identify the strategic priorities for developing the tourism industry in the Almaty region on the basis of demand-side empirical data. To achieve this aim, the following objectives were set:

- to analyse the scientific literature and strategic documents on the tourism potential of the Almaty region and its development;
- to identify the needs and opinions of tourists and local residents through a questionnaire survey;
- to determine the main factors hindering tourism development in the region;
- to propose specific strategic directions for tourism development based on SWOT and TOWS analysis.

Thus, by combining demand-side empirical data with strategic analysis, the article provides an evidence base for regional-level tourism planning and contributes to filling this gap in regional tourism geography.

2 Materials and methods

2.1 Study area

The study area is the Almaty region, located in south-eastern Kazakhstan. The southern part of the region is occupied by the Ile Alatau, Kungey and Ketmen ranges, while the Ile River valley and the Kapshagay Reservoir lie in the north. This altitudinal zonation makes it possible to develop several types of tourism simultaneously, including mountain, ecological, health and wellness, cultural-historical and

rural tourism. In 2022, the Zhetysu region was established on the basis of the north-eastern part of the region. The study used the boundaries of the region prior to the 2022 administrative-territorial changes, because respondents traditionally perceive sites now belonging to the Zhetysu region, such as Altyn-Emel National Park and Panfilov district, as part of the Almaty tourism area.

2.2 Research design

The study followed a mixed-methods design combining quantitative survey data with qualitative strategic analysis and was conducted in four stages:

- Stage 1 – analysis of the scientific literature and strategic documents (to form the theoretical basis and the external factors of the SWOT analysis);
- Stage 2 – development of the questionnaire and its expert pilot testing;
- Stage 3 – collection of primary data through an online survey;
- Stage 4 – data processing, descriptive statistical analysis, SWOT analysis and formulation of strategic directions using a TOWS matrix.

2.3 Data sources

The primary data source was the survey conducted by the authors. Secondary data included peer-reviewed scientific publications and the Concept for the Development of the Tourism Industry of the Republic of Kazakhstan (Government of the Republic of Kazakhstan, 2023). The literature was retrieved from the Scopus, Web of Science and Google Scholar databases using the keywords "Almaty region tourism", "tourism development Kazakhstan", "small tourism firms" and "SWOT analysis tourism". The selection criteria were: (1) direct relevance to regional tourism development; (2) publication in a peer-reviewed outlet with a DOI or a stable link; and (3) priority for works published in 2018–2025, with earlier publications used only as foundational theoretical works (Butler, 1980; Ateljevic, 2007).

2.4 Data collection methods

The questionnaire consisted of 15 closed-ended questions divided into two blocks (Table 1). The first block (questions 1–3) covered the socio-demographic characteristics of respondents (age, gender, place of residence), while the second block (questions 4–15) assessed the current state of tourism in the region and its development priorities. A single answer option was allowed for each question.

Table 1. Structure of the questionnaire

Block	No.	Question	Figure
I. Socio-demographic	1	What is your age?	1(a)
	2	What is your gender?	1(b)
	3	Are you a resident of the Almaty region?	2
II. State of tourism and development priorities	4	What are the main barriers to the development of tourism in the Almaty region?	3
	5	Which tourist sites in the Almaty region do you prefer to visit most often?	5
	6	Which type of tourism should be prioritized in the Almaty region?	4
	7	What measures are needed to attract more tourists to the Almaty region?	6
	8	Where do you obtain information about the tourism potential of the Almaty region?	7
	9	How do you rate the quality of tourist services in the Almaty region?	8
	10	How should tourism infrastructure in the Almaty region be developed?	9
	11	Is training of tourism sector employees important?	10
	12	What role should the state play in developing tourism in the Almaty region?	11
	13	What measures should be taken to protect natural attractions?	12
	14	In which districts of the Almaty region should tourism be developed?	13
	15	Which foreign experience could be used to develop tourism in the Almaty region?	14

Source: compiled by the authors.

The questionnaire was created on the Google Forms platform (<https://docs.google.com>) and distributed through WhatsApp groups; that is, convenience and snowball sampling were applied. The survey was

conducted from October to December 2025 and yielded 503 fully completed responses. Participation was voluntary, the survey was anonymous, and no personally identifiable data were collected.

2.5 Data processing and analysis

Responses were exported from Google Forms to Microsoft Excel and checked for completeness. Relative frequencies (%) of answer options were calculated for each question and presented as bar or pie charts. To assess the statistical precision of the proportions, the margin of error (e) at the 95% confidence level was calculated as follows:

$$e = z \cdot \sqrt{p(1-p)/n} = 1.96 \cdot \sqrt{(0.25/503)} \approx 0.044 \quad (1)$$

where $z = 1.96$ is the value corresponding to the 95% confidence level, $p = 0.5$ is the proportion yielding maximum variance, and $n = 503$ is the sample size. Hence, the margin of error of the obtained proportions is approximately ± 4.4 percentage points. Because non-probability sampling was used, this figure is indicative.

The strategic analysis was carried out in two steps. First, a SWOT analysis was performed: internal factors (strengths and weaknesses) were derived from the survey results (barriers, service quality, infrastructure, staff) and the resource characteristics of the area, while external factors (opportunities and threats) were derived from strategic documents and the literature (Helms & Nixon, 2010). Second, internal and external factors were matched in a TOWS matrix to formulate SO, WO, ST and WT strategies.

2.6 Tools and software

Google Forms was used for data collection, WhatsApp for distribution, and Microsoft Excel for data processing, calculations and chart construction.

3 Results

3.1 Socio-demographic profile of respondents

A total of 503 people of different age and gender groups took part in the survey. The largest share of respondents (33.6%) were young people aged 18–24 (Figure 1a), which indicates young people's strong interest in travel and their role as one of the main consumer groups of the tourism industry. The 35–44 age group ranked second (24.9%); this group typically comprises middle-aged people travelling with family members or friends. The share of the 25–34 age group (20.5%) is also considerable, as this category includes economically active travellers. Respondents aged 45–54 accounted for 15.5%, and those over 55 for 5.6%; this may indicate that older people travel less or that existing tourist services are insufficiently adapted to their needs. Most respondents were women (72.6%), while men accounted for 27.4% (Figure 1b).

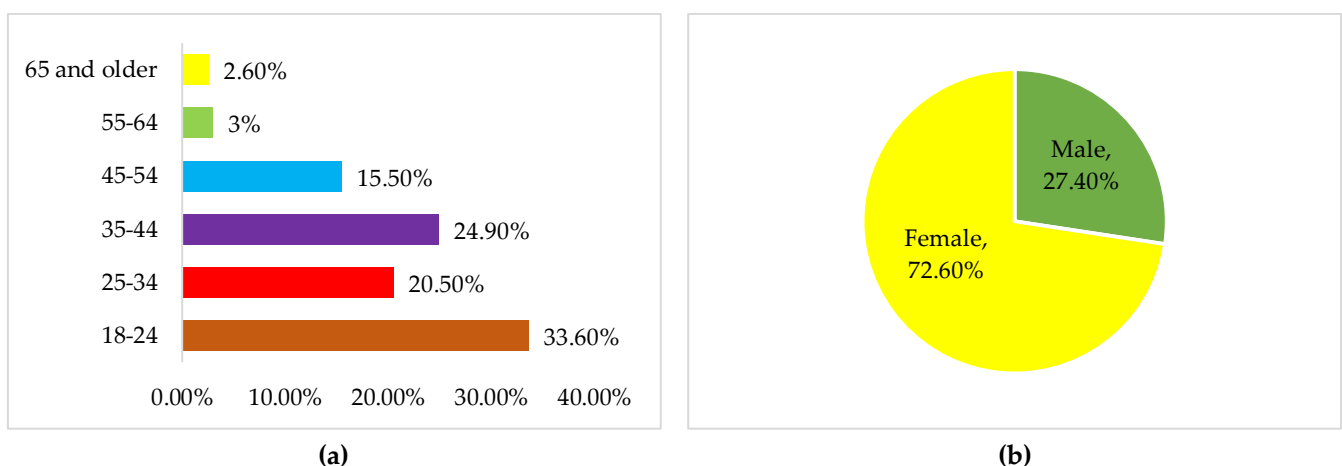


Figure 1. Socio-demographic structure of respondents: (a) distribution by age group; (b) distribution by gender

These data point to the need to develop differentiated tourism products that take into account the needs of different age groups: active tourism (hiking, adventure sports) for young people, family holidays for middle-aged groups, and comfortable leisure facilities for older people.

Of the respondents, 84.7% were residents of the Almaty region, while 15.3% came from other regions (Figure 2). This shows that the opinions of domestic tourists and local residents prevail; therefore, the results primarily reflect the needs of the region's domestic tourism market. The opinions of non-resident respondents partly capture the perspective of visitors to the region.

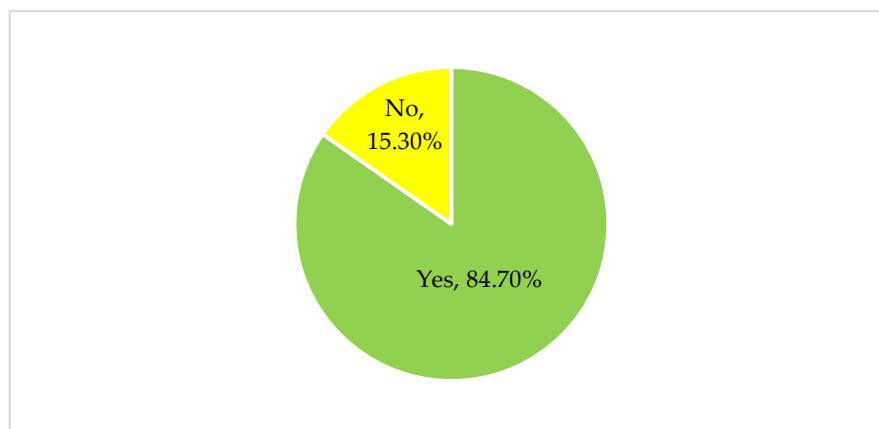


Figure 2. Distribution of respondents by place of residence (resident of the Almaty region: yes/no)

3.2 Barriers to tourism development

The survey identified several key factors hindering the development of tourism in the Almaty region (Figure 3). The largest share of responses referred to the lack of road and transport infrastructure (25.0%). Poor road quality and inconvenient transport connections make the region less attractive to tourists and reduce travel comfort. The low quality of tourist services (21.3%) was also rated as a significant problem, since service quality directly affects tourists' experience and their intention to return. Natural resource protection issues (20.5%) and insufficient information campaigns (19.5%) ranked third and fourth, while the shortage of qualified staff was mentioned by 13.7% of respondents.

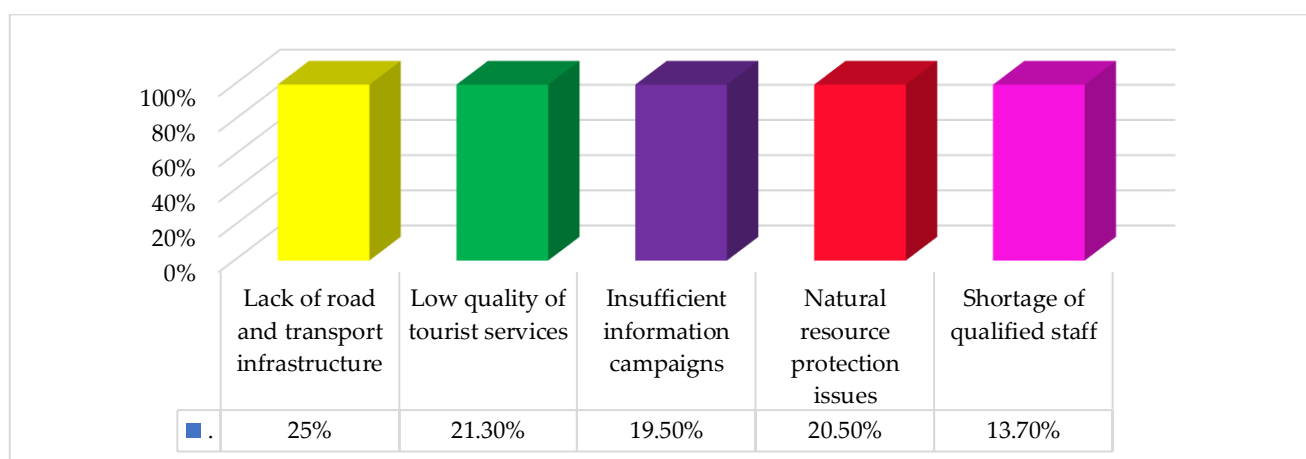


Figure 3. Factors hindering the development of tourism in the Almaty region

3.3 Tourism demand: priority types and sites

According to respondents, health and wellness tourism is the most demanded type of tourism in the Almaty region (33.6%) (Figure 4). The region's mountain climate, mineral waters and sanatoriums create favourable conditions for this type of tourism. Ecotourism (20.9%) and cultural-historical tourism (20.7%)

ranked second. Ecotourism makes it possible to combine nature conservation with tourism activities, while cultural-historical tourism can perform an educational function by introducing the region's history and traditions. Demand for adventure tourism (14.9%) and rural tourism (9.9%) is relatively low: adventure tourism targets a specific audience, whereas rural tourism requires dedicated infrastructure and support.

The sites most frequently chosen by tourists are the Kolsai Lakes (25.8%) and Charyn Canyon (25.4%) (Figure 5). Kaindy Lake (20.3%) and Kapshagay (19.1%) are also in high demand, while Altyn-Emel National Park was chosen by only 9.3% of respondents. The concentration of more than half of the demand (51.2%) on two sites may lead to increased recreational pressure; therefore, it is important to distribute the tourist flow more evenly across the territory through alternative routes.

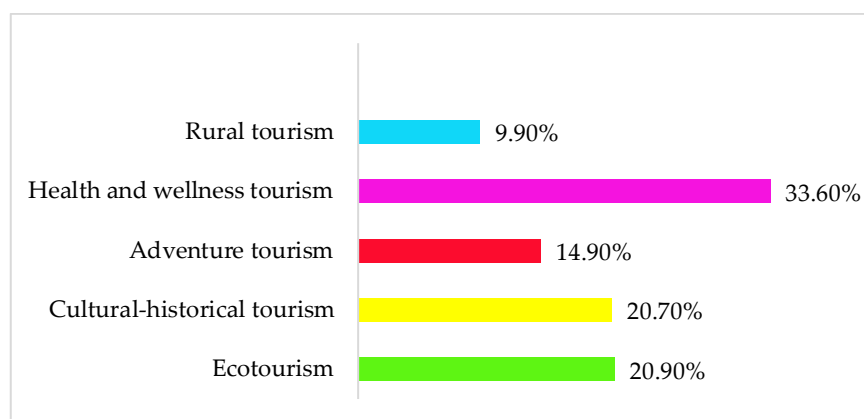


Figure 4. Types of tourism that should be prioritized in the Almaty region

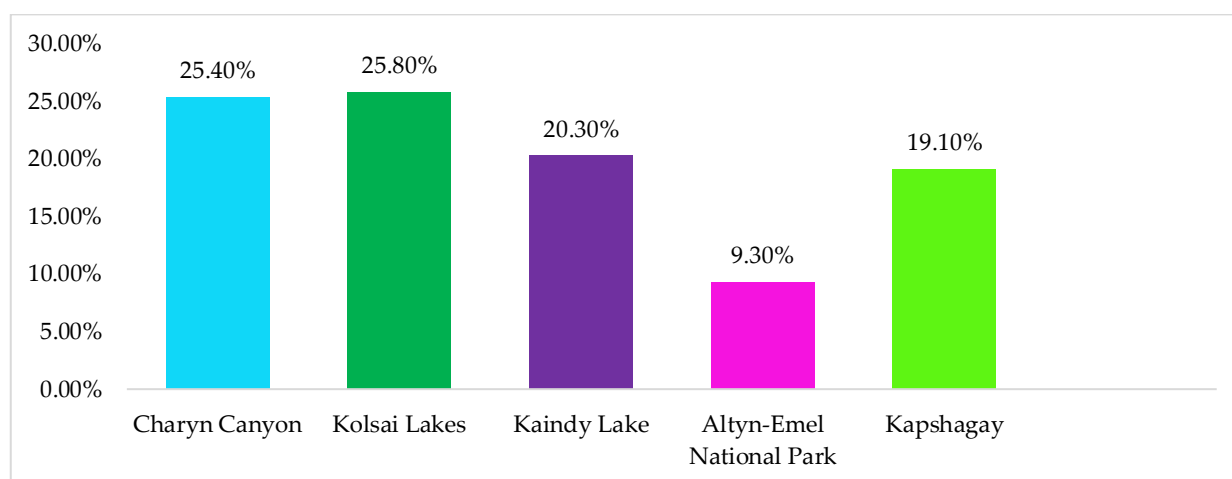


Figure 5. Tourist sites in the Almaty region most frequently visited by respondents

3.4 Measures to attract tourists and information sources

The most important measures for attracting more tourists to the region were improving service quality (23.1%), strengthening the protection of natural monuments (21.3%) and organizing advertising campaigns (21.1%) (Figure 6). Developing new tourist routes (20.9%) and improving roads (13.7%) were also rated as measures that facilitate tourist mobility and make access to the region more convenient.

Social media is the main source of information about the region's tourism potential (52.9%) (Figure 7). The shares of respondents using advertising posters and banners (18.1%), recommendations from friends and acquaintances (13.5%) and local travel agencies (12.5%) are considerably lower, while television and

radio were mentioned by only 3.0%. This highlights the decisive role of digital tools in promoting the region's tourism potential.

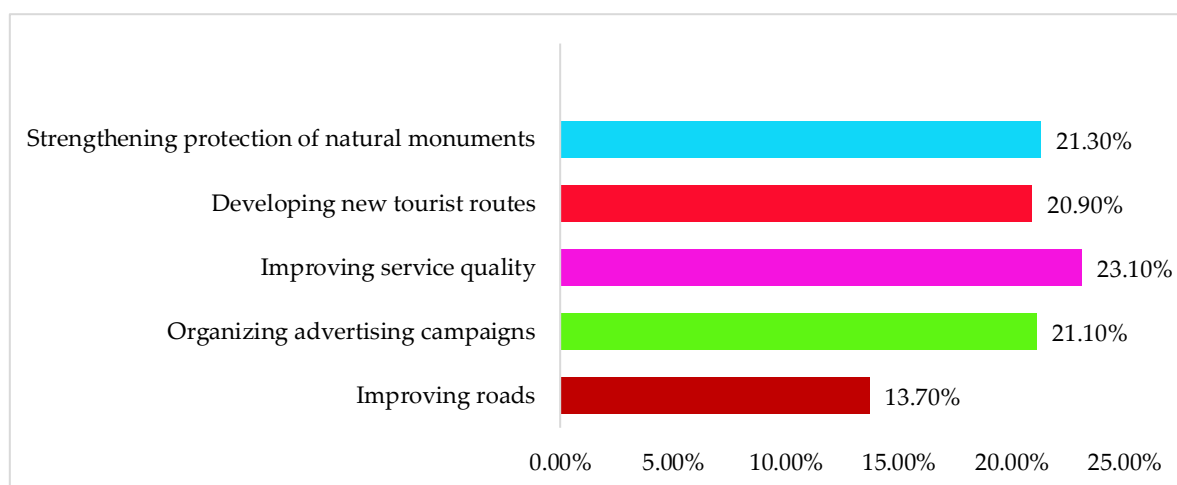


Figure 6. Measures needed to attract more tourists to the Almaty region

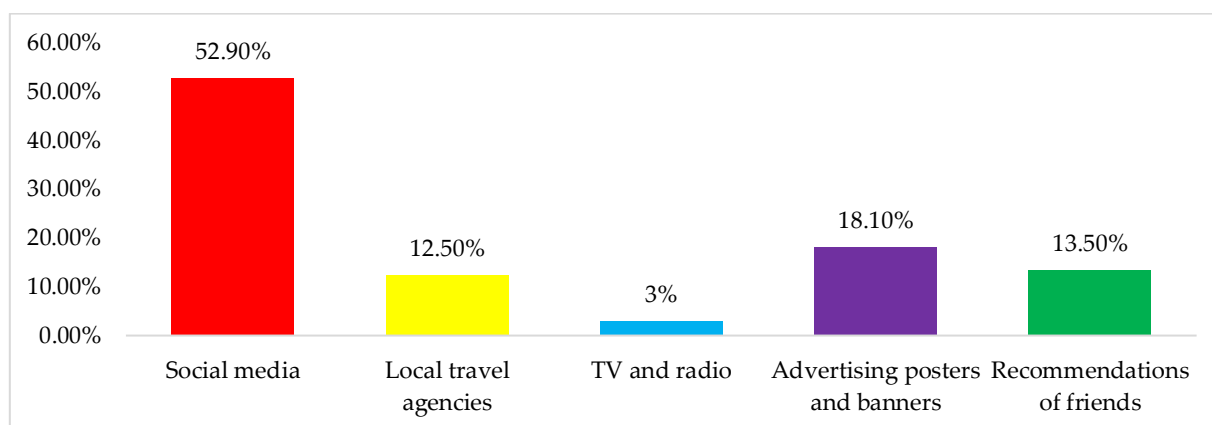


Figure 7. Sources of information about the tourism potential of the Almaty region

3.5 Service quality, infrastructure and staff

More than half of the respondents rated the quality of tourist services as "good" (31.0%) or "very good" (20.5%) (Figure 8). However, the combined share of "average" (19.7%), "poor" (15.7%) and "unsatisfactory" (13.1%) ratings (48.5%) indicates that service quality problems remain to be solved. Introducing quality standards and upgrading staff skills are important conditions for increasing the region's attractiveness.

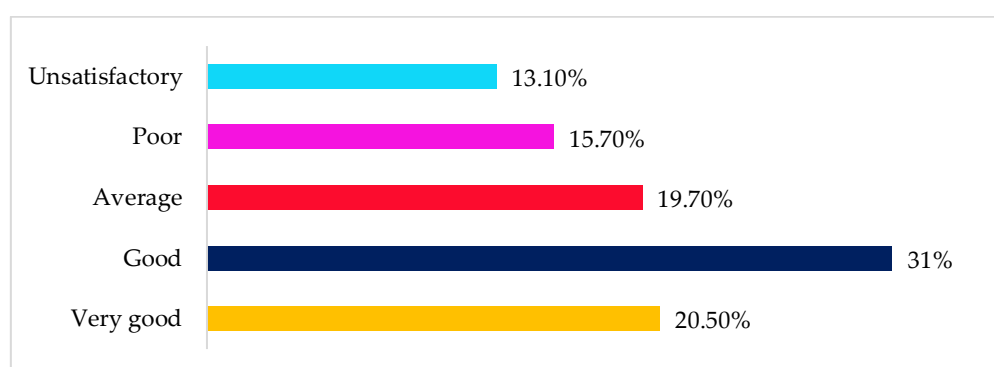


Figure 8. Assessment of the quality of tourist services in the Almaty region

Responses on priority directions for tourism infrastructure development were evenly distributed (Figure 9): increasing the number of tourist routes (21.5%), building new hotels (20.1%), opening information centres (19.7%), building public toilets and rest areas (19.5%) and improving transport (19.3%). This indicates the need to develop infrastructure comprehensively rather than along individual lines.

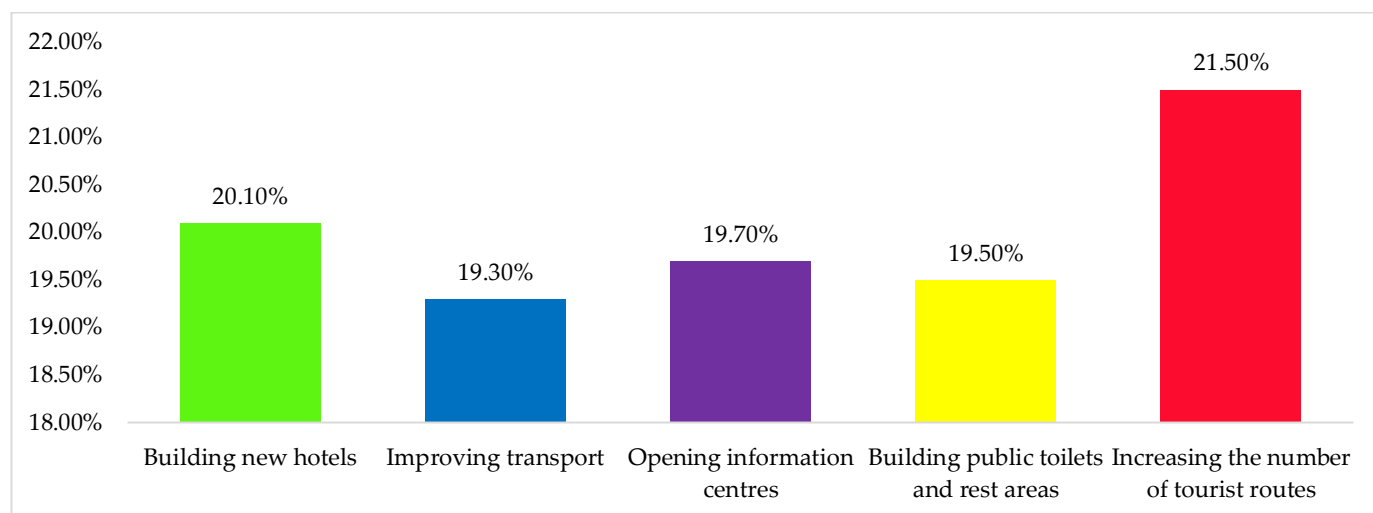


Figure 9. Priority directions for tourism infrastructure development in the Almaty region

Overall, 60.5% of respondents consider training of tourism employees "very important" (40.8%) or "important" (19.7%) (Figure 10). Those rating training as "moderately important" (13.7%), "not very important" (14.1%) or "not important" (11.7%) are in the minority. The results confirm that improving staff qualifications is one of the key tasks of tourism in the region.

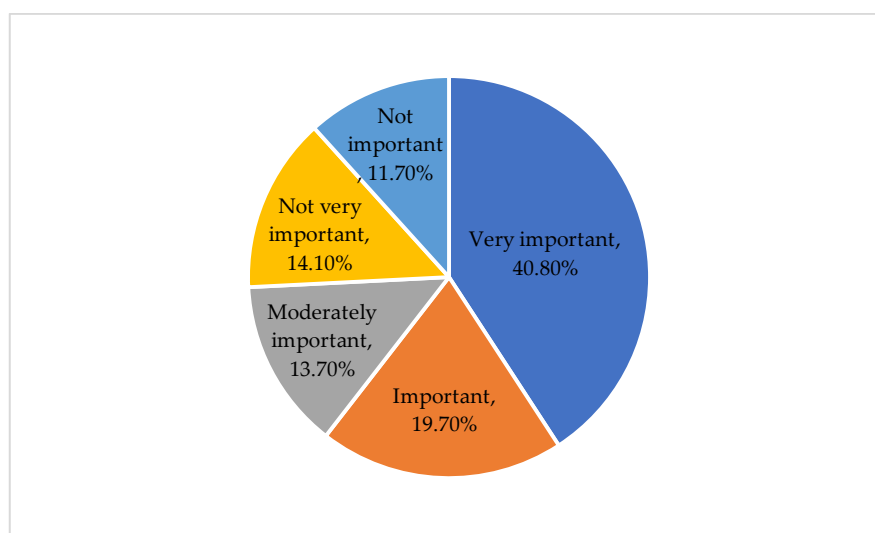


Figure 10. Assessment of the importance of training tourism sector employees

3.6 The role of the state and nature conservation

According to respondents, the state should prioritize attracting investment in tourism (40.4%) (Figure 11). Developing infrastructure (25.0%) and improving legislation (18.7%) were also named as important directions, while increasing tourism funding (9.5%) and providing marketing support (6.4%) were seen as supplementary measures.

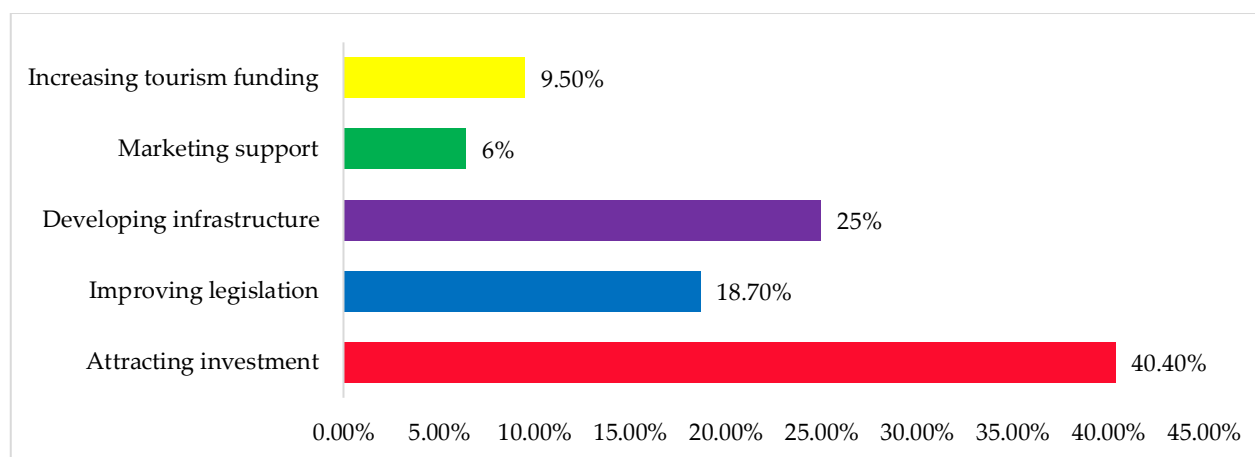


Figure 11. The priority role of the state in developing tourism in the Almaty region

Engaging local communities (21.9%) and introducing restrictions for tourists (21.7%) were named the most effective measures for protecting natural attractions (Figure 12). Developing ecotourism (21.1%), organizing educational programmes (19.7%) and establishing nature reserves (15.7%) are also among the important measures. The even distribution of responses shows that nature conservation requires a comprehensive approach rather than a single instrument.

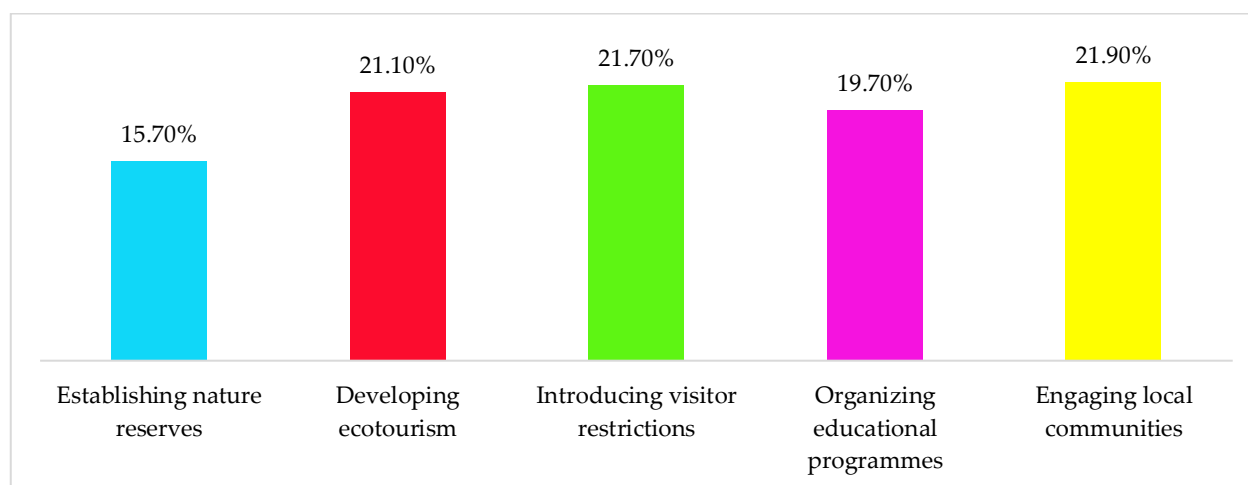


Figure 12. Effective measures for protecting natural attractions in the Almaty region

3.7 Territorial priorities and foreign experience

Talgar district was chosen by 42.5% of respondents as the district that should be prioritized for tourism development (Figure 13). Enbekshikazakh (19.5%) and Raiymbek (18.7%) districts were also rated as areas with considerable tourism opportunities, while demand for Uighur (13.7%) and Panfilov (5.6%) districts was low. The priority of Talgar district can be explained by its proximity to Almaty city and its abundance of mountain recreation sites. The results point to the need for a comprehensive development plan covering various districts of the region.

Regarding foreign experience, the largest share of respondents chose Japan's ecotourism experience (21.1%) (Figure 14). European cultural tourism models (20.3%), Swiss mountain tourism and US marketing technologies (19.9% each), and the luxury tourism strategies of Arab countries (18.9%) received similar shares. This indicates the need to adapt international experience comprehensively rather than relying on a single model.

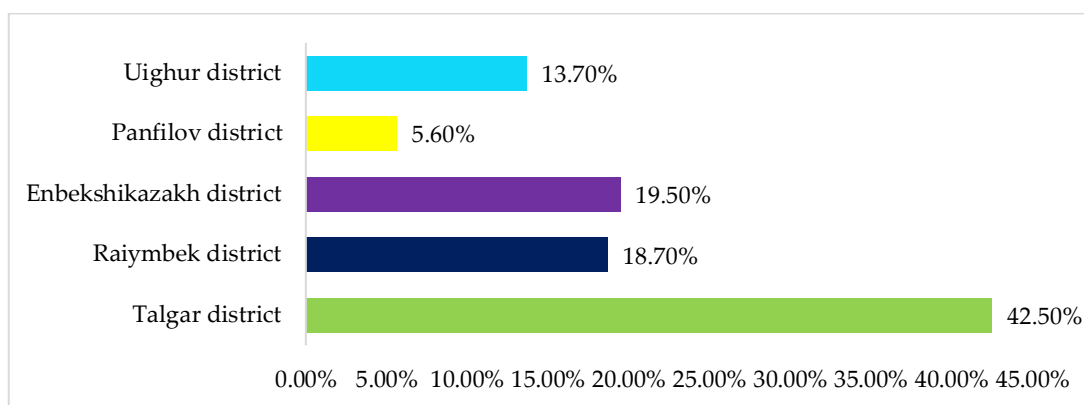


Figure 13. Districts of the Almaty region that should be prioritized for tourism development

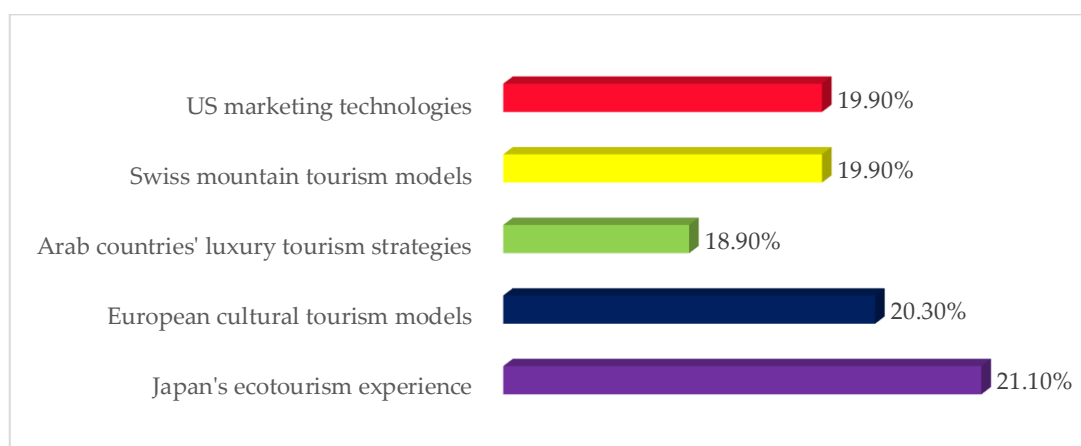


Figure 14. Foreign experience that could be used to develop tourism in the Almaty region

3.8 SWOT analysis and strategic directions

Based on the survey results and the literature review, a SWOT analysis of the tourism industry of the Almaty region was conducted (Table 2).

Table 2. SWOT analysis of tourism industry development in the Almaty region

Strengths	Weaknesses
– Abundance of natural attractions: Kolsai, Kaindy, Charyn Canyon, Altyn-Emel National Park; – Favourable geographical location close to the Almaty agglomeration; – Diverse natural and climatic conditions enabling several types of tourism; – Historical and cultural monuments (Tamgaly petroglyphs, Koilyk ancient settlement); – High demand for health and wellness tourism (33.6%).	– Insufficient road and transport infrastructure (25.0%); – Uneven service quality (48.5% rated it average or lower); – Shortage of qualified specialists; – Insufficient information and advertising about tourist routes; – Concentration of tourist demand on a few sites (51.2% – Kolsai and Charyn).
Opportunities	Threats
– State support under the Concept for the Development of the Tourism Industry for 2023–2029; – Modernization of infrastructure by attracting investment; – Development of new tourist routes and ecotourism; – Development of online marketing through digital technologies and social media; – Adaptation of international experience (ecotourism, mountain tourism).	– Degradation of natural resources and growing recreational pressure at popular sites; – Increasing competition from neighbouring countries and regions; – Insufficient involvement of local communities in tourism development; – Impact of natural hazards and climate change; – Limited investment due to budget constraints.

Source: compiled by the author based on the survey results and the literature.

The results of the SWOT analysis were translated into specific strategic directions using a TOWS matrix (Table 3).

Table 3. Strategic directions for tourism industry development in the Almaty region (TOWS matrix)

Strategy type	Strategic direction and key measures	Survey evidence
SO (strengths + opportunities)	Develop ecotourism and health and wellness tours based on unique natural sites; promote them through social media and digital platforms; offer short weekend routes from Almaty city.	Figures 4, 5, 7
WO (weaknesses + opportunities)	Modernize road, sanitary and recreational infrastructure through public-private partnerships and investment; introduce training programmes for tourism employees; adopt service quality standards.	Figures 3, 8, 9, 10, 11
ST (strengths + threats)	Involve local communities in tourism; regulate visitor numbers at popular sites (online booking, permit system); organize environmental education programmes.	Figure 12
WT (weaknesses + threats)	Distribute the tourist flow evenly across the territory by developing new routes in Enbekshikazakh, Raiymbek and Uighur districts; establish a system for monitoring natural and climate risks and ensuring tourist safety.	Figures 5, 13

Source: compiled by the authors.

4 Discussion

The results are largely consistent with previous studies on regional tourism in Kazakhstan. The lack of infrastructure, especially transport accessibility, was also identified as the main constraint on destination development in the Akmola region (Dyussekeyeva et al., 2025), while in Almaty city the growth of tourist flows has made improving infrastructure and service quality a priority (Zheldibayev et al., 2024). The uneven service quality and the high importance attached to staff training (60.5%) in our study complement the findings on the lack of specialized knowledge and marketing planning in small tourism businesses in Almaty (Issakov et al., 2023). This is also consistent with international evidence that the management capacity of small enterprises determines the quality of the regional tourism product (Ateljevic, 2007; Thomas et al., 2011).

Respondents' association of the role of the state primarily with attracting investment and improving legislation is consistent with stakeholders' views on institutional barriers in the Almaty region (Sakypbek et al., 2025). At the same time, the finding that the contribution of small enterprises to local economic development is limited without state support (Koens & Thomas, 2015) substantiates the importance of the proposed WO strategy.

From the perspective of Butler's life cycle model, the concentration of demand on Kolsai and Charyn indicates that these sites are in the development or consolidation stage and risk losing their attractiveness without load management (Butler, 1980). Respondents' support for restricting visitors and engaging local communities is in line with findings on the need to ensure a sustainable life cycle of ecotourism (Mukhambetov et al., 2014). The dominance of social media among information sources (52.9%) shows the need to shift tourism marketing to digital channels, while the high demand for health and wellness tourism suggests an opportunity to turn the region's balneological and mountain-climatic resources into new tourism products. The fact that the positive economic effect of tourism is fully realized only when infrastructure and service quality are ensured (Baiburiev et al., 2018; Laut et al., 2021) also confirms that the proposed strategies should be implemented in an integrated manner.

5 Conclusion

The results show that the Almaty region has great potential for tourism development owing to its abundant natural attractions, cultural-historical heritage and proximity to the Almaty agglomeration. The survey of 503 respondents identified the lack of road and transport infrastructure, uneven service quality

and natural resource protection issues as the main barriers to tourism development. Improving service quality, protecting natural monuments, organizing advertising campaigns through digital marketing and developing new routes were rated as priority measures.

Based on the SWOT and TOWS analysis, four strategic directions for developing the region's tourism industry were proposed: (1) promoting ecotourism and health and wellness products based on unique natural sites through digital channels; (2) modernizing infrastructure and training staff through public-private partnerships; (3) engaging local communities and managing visitor pressure at popular sites; and (4) distributing the tourist flow evenly across districts and managing natural and climate risks. These results can be used in the development of regional tourism programmes.

The study has several limitations. First, since the survey used a convenience sample distributed via WhatsApp, the results cannot be fully generalized to all residents and tourists of the region. Second, women (72.6%), young people aged 18–24 (33.6%) and residents of the region (84.7%) predominate in the sample, and foreign tourists were not considered as a separate group. Third, the analysis was limited to descriptive statistics and was based on cross-sectional data. In addition, the study did not directly capture the views of tourism businesses and government bodies.

Future research should use stratified probability sampling, include foreign tourists and tourism business representatives, and apply multivariate statistical methods such as factor and regression analysis to assess the relationship between barriers and tourist satisfaction. Furthermore, GIS-based assessment of the transport accessibility of tourist sites and of the recreational carrying capacity of popular sites such as Kolsai and Charyn is a relevant direction for further research.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Lóránt Dénes Dávid	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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Biographies of Authors



Lóránt Dénes Dávid

Dr., Professor, John von Neumann University, Kecskemét; Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő; Eötvös Loránd University, Szombathely; Széchenyi István University, Győr, Hungary
dr.david.lorant@gmail.com
<https://orcid.org/0000-0001-7880-9860>
<https://www.scopus.com/authid/detail.uri?authorId=23034044700>

Article

The impact of project-based learning on the development of ninth-grade students' research skills in geography: a quasi-experimental study

Gulzira Aksanbayeva^{1*}, Duman Aliaskarov¹, Evren Atış²

¹ Abai Kazakh National Pedagogical University, Faculty of Natural Sciences and Geography, Department of Geography and Ecology, Almaty, Kazakhstan; (G.A.) gulziraaksanbaeva454@gmail.com, <https://orcid.org/0009-0007-0973-0439>; (D.A.) d.aliaskarov@abaiuniversity.edu.kz, <https://orcid.org/0000-0002-7628-1246>

² Kastamonu University, Faculty of Arts and Science, Kastaamonu, Turkey; (E.A.) evrencografya@gmail.com, <https://orcid.org/0000-0002-5686-3169>

* **Corresponding author:** Gulzira Aksanbayeva, Kazakhstan, Almaty, 13 Dostyk Avenue, gulziraaksanbaeva454@gmail.com, +77473554379

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Abstract: Modern geography education requires students to develop not only subject-specific knowledge but also the ability to independently set research problems, work with various information sources, analyze data, and formulate well-founded conclusions. The purpose of this study was to determine the impact of Project-Based Learning (PjBL) on the development of ninth-grade students' research skills in studying geography. A pedagogical experiment was conducted at Secondary School No. 43 in the Talgar district of the Almaty region. Forty-seven students from two ninth-grade classes, divided into experimental ($n = 23$) and control ($n = 24$) groups, participated in the study. A quasi-experimental pre-test/post-test control group design was used. Research skills were assessed with a nine-criterion analytic rubric including problem definition, formulation of a research question, study planning, searching for and collecting geographic data, analyzing and interpreting it, formulating conclusions, and presenting and justifying the results. The pre-test showed that the experimental and control groups were comparable. After the formative stage, students in the experimental group demonstrated a more pronounced development of research skills compared to the control group, and the post-test between-group differences were statistically significant with a large effect size ($t(45) = 7.99$, $p < 0.001$, Cohen's $d = 2.33$). The most significant changes were observed in the ability to define a research problem, interpret cartographic, statistical, and graphical materials, and formulate well-founded conclusions. The results indicate that the systematic use of PjBL facilitates a transition from primarily searching for and retrieving information to its independent analysis and use to solve research problems. Project-based learning can be effectively integrated into the school geography curriculum as a means of organizing consistent research activities and developing relevant skills in students.

* * * * *

1 Introduction

Modern school education focuses not only on the acquisition of subject-specific knowledge but also on developing students' ability to independently ask questions, work with various sources of information, analyze data, and present their findings logically. In geography education, developing these skills is particularly important, as the subject involves the study of natural and socioeconomic processes, working with cartographic and statistical materials, comparing territorial data, and explaining spatial patterns. Therefore, finding teaching methods that engage students in independent research and connect the material they are learning to the solution of specific geographic problems is a pressing task.

One such approach is Project-Based Learning (PjBL), in which content acquisition occurs through consistent problem-solving and the creation of a final product. Unlike completing individual project assignments, PjBL involves a longer cycle of activity, including problem formulation, work planning, information search and collection, data analysis, decision making, and presentation of results. In the classical synthesis by Thomas (2000), PjBL is characterized by projects that are central to the curriculum, organized around a driving question, involve constructive investigation, give students considerable autonomy, and are realistic rather than school-like. From a learning-sciences perspective, Krajcik and Blumenfeld (2006) identify its key features as a driving question, situated inquiry, collaboration, the use of cognitive tools, and the creation of tangible artifacts. A meta-analysis of 66 experimental and quasi-experimental studies demonstrated the positive impact of PjBL on students' academic achievement, thinking skills, and attitudes toward learning activities; however, the effectiveness of the method depends on the duration of its implementation, the subject area, and the organization of group work (Zhang & Ma, 2023). A more recent review of meta-analyses also confirms the generally positive impact of PjBL on academic and cognitive outcomes, while also highlighting the heterogeneity of methodological approaches and the need for more carefully designed studies (Farshad & Fortin, 2026).

Project-based learning is of particular interest in geographic education due to its ability to combine subject content with direct research activities. When completing projects, students can use maps, statistics, and spatial data, conduct observations, identify territorial differences, and draw conclusions based on these. A study by Grobelski et al. (2023) demonstrates that project-based learning engages students in the practice of geographic research and promotes the acquisition of methods for obtaining and interpreting geographic information. In turn, the use of PjBL in geographic education has demonstrated positive results in the development of geographic literacy (Sekarrini et al., 2024), creative thinking, and student independence (Aliman et al., 2025), as well as in enhancing student engagement and geography learning outcomes (Marpaung et al., 2025). Contemporary research also demonstrates the potential of inquiry-oriented PjBL, which directly combines project activities with the collection and analysis of empirical data and the development of critical thinking (Musyawarah et al., 2026).

In the Kazakhstani context, Laiskhanov and Barat (2024) also demonstrated the potential of project-based learning in school geography, showing that its implementation can support students' learning activity and create opportunities for research-oriented work. Project activities have also been applied to the investigation of real geographical and territorial problems, demonstrating their potential to connect geographical knowledge with practical analysis (Kholina et al., 2024).

However, existing studies often evaluate the effectiveness of PjBL through academic achievement, geographic literacy, and creative or critical thinking. The development of students' comprehensive research skills has been studied considerably less. This issue is also relevant in the Kazakhstani educational context. Sadykova et al. (2023) emphasized that geographic inquiry involves a set of interconnected process skills and highlighted the importance of their systematic assessment in geography education. Testing the effectiveness of this approach in school geography education using data from a specific region is particularly relevant. The purpose of this study is to experimentally determine the impact of Project-Based Learning on the development of ninth-grade students' research skills in geography. To achieve this purpose, the following objectives were set: (1) to determine the baseline level of research skills in the experimental and control groups and verify their comparability; (2) to design and implement a sequence of research-oriented geography projects within the regular 9th-grade curriculum; and (3) to compare pre-test and post-test changes in the overall research skills score and in each of its nine components within and between the groups.

Accordingly, the following hypotheses were tested. H1: after the formative stage, students taught using PjBL (experimental group) will achieve a significantly higher overall research skills score than students taught in the traditional format (control group), given comparable baseline levels. H2: the gains in the experimental group will not be limited to information retrieval but will also cover the analytical stages of

the research cycle, namely problem definition, interpretation of geographic data, and formulation of conclusions.

2 Materials and methods

The study aimed to evaluate the impact of Project-Based Learning (PjBL) on the development of students' research skills in geography. A quasi-experimental design with control and experimental groups and a pre-test/post-test was used. This design was chosen due to the school educational context, where the study participants were members of established classes and were not randomly assigned to groups (Creswell & Creswell, 2018; Cohen et al., 2018).

2.1 Research base and participants

The pedagogical experiment was conducted at Secondary School No. 43 in the Talgar district of the Almaty region. Forty-seven 9th-grade students participated in the study: Grade 9A (n=23) served as the experimental group, whereas Grade 9B (n=24) served as the control group. The educational process in both groups was carried out within the framework of the 9th-grade geography curriculum. Both groups were taught by the same geography teacher (one of the authors / a teacher with N years of experience) — please confirm, which reduced the influence of differences in teaching style on the results.

Ethical considerations. The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by (name of the ethics committee / the pedagogical council and administration of Secondary School No. 43), protocol No. __ dated __. Because the participants were minors, written informed consent was obtained from their parents or legal guardians, and the students gave oral assent. Participation was voluntary, the results did not affect students' grades, and all data were anonymized by assigning codes before analysis. After the study, the project materials were also made available to the control class.

The study included three sequential stages: pre-test, formative, and post-test. During the pre-test stage, the initial level of students' research skills was determined in both groups. The formative stage involved the systematic application of Project-Based Learning elements in the experimental group, while the control group received instruction in accordance with the traditional educational process. During the post-test stage, a repeat assessment was conducted using uniform assessment criteria, after which changes in the indicators in both groups were compared.

2.2 Organization of Project-Based Learning

The formative stage of the study lasted six weeks (N geography lessons of 45 minutes, i.e., N academic hours in total) and was implemented within the curriculum-based geography lessons of the 9th-grade class. During this period, students in the experimental group completed three research projects. The project-based activities were integrated into the topics covered and did not require additional lessons outside of the curriculum. In the control group, the corresponding topics were studied in a traditional format during the same number of lessons, while in the experimental group, instruction was organized using Project-Based Learning (PjBL).

The projects focused on the study of Kazakhstan's geographic processes and issues at the regional and local levels. When developing the assignments, consideration was given to their relevance to the curriculum, the availability of information sources for students, the ability to use cartographic and statistical data, and the presence of a problem that allowed for independent analysis. Three projects were implemented during the formative stage: "Changes in the size and spatial distribution of the Almaty region population," "Water resources of the Almaty region: Use and challenges of rational water management," and "Anthropogenic pressure on the natural complexes of the Talgar district." The content of the project-research activities is presented in Table 1.

Table 1. Contents of Project-Research Activities for students in the experimental group during the formative stage.

Project Topic	Main student activities	Materials Used	Research skills developed
Changes in the Size and Spatial Distribution of the Population of the Almaty Region	Formulating a research question; collecting and comparing demographic data; identifying territorial differences and trends; explaining the identified changes	Thematic maps, statistical data, tables, diagrams	Problem definition; information search and selection; data analysis and interpretation; drawing conclusions
Water Resources of the Almaty Region: Use and Challenges of Rational Water Management	Problem definition; studying the territorial distribution of water bodies; analyzing water resource use patterns; identifying problems and justifying possible solutions	Physical and thematic maps, statistical data, diagrams, information sources	Research question formulation; data collection and systematization; source comparison; analysis and argumentation
Anthropogenic Pressure on the Natural Complexes of the Talgar District	Identifying sources of anthropogenic impact; analyzing their spatial distribution; assessing possible consequences; developing proposals to reduce anthropogenic load	Territorial maps, statistical and graphic materials, open information sources	Research planning; data collection and analysis; interpretation of geographic data; drawing and defending conclusions

Source: compiled by the authors based on the content of the formative stage.

The projects followed a consistent sequence of research activities. Initially, students were presented with a problematic situation related to the geographic topic under consideration. After analyzing it, the object of study and the main problem were determined, and a research question and expected outcome were formulated. Next, the students developed a work plan, identified the necessary sources and methods for obtaining information, and, when completing group projects, distributed tasks among participants. During the research phase, students independently searched for and selected information, collected the necessary geographic data, and worked with cartographic, statistical, and graphic materials. The obtained information was systematized and compared, identifying spatial differences and relationships between the phenomena and processes under consideration. Based on the analysis, the students interpreted the obtained results in accordance with the research question. During the project work, the teacher played a primarily organizational and advisory role. The teacher presented the initial problematic situation, monitored the sequence of stages, and, when necessary, consulted with students on the selection and use of information sources and provided feedback. The students themselves were responsible for data collection, selection of analysis methods, and formulation of final conclusions, ensuring their direct involvement in the research process. At the final stage, students summarized their research results, formulated conclusions, and designed the final project product. The results were presented to the class, followed by discussion. During the defense, students explained the problem posed, explained the sources and methods used for analyzing geographic information, presented their data, and substantiated their conclusions. The discussion focused on assessing the relevance of their conclusions to the research question and the validity of the evidence provided.

The control group studied the same sections of the 9th-grade geography curriculum, but the instruction was conducted without systematically engaging students in the full cycle of research-oriented PjBL. Thus, the content of the material covered in the two groups remained comparable, while the main difference lay in the way the learning activities were organized.

2.3 Research skills assessment criteria

To evaluate the effectiveness of pedagogical interventions, research skills were presented as a system of interconnected components reflecting the main stages of independent research. When defining the criteria, the specific nature of geography education was taken into account, which involves not only information retrieval but also working with cartographic, statistical, and spatial data.

The assessment was conducted according to the following criteria:

- ability to define a research problem;
- ability to formulate a research question and put forward a hypothesis;
- planning the sequence of research activities;

- searching for and selecting relevant information sources;
- collecting the necessary geographic data;
- systematization, comparison, and analysis of the obtained information;
- interpretation of cartographic, statistical, and graphic materials;
- formulating conclusions based on the obtained data;
- reasoned presentation and defense of research results.

A four-level scale was used for each criterion: 1 point—low level, 2 points—average, 3 points—sufficient, and 4 points—high level of skill development. The final score was calculated as the sum of the scores for all criteria (possible range: 9–36 points). The pre-test and post-test assessments were conducted using the same set of criteria.

2.4 Data collection and processing

Diagnostic instrument. At both stages, students completed a written diagnostic assignment consisting of nine tasks (one task per criterion) based on a short geographic case that included a thematic map, a statistical table, and a diagram describing a regional problem of Kazakhstan. The tasks required students to identify the problem presented in the materials, formulate a research question and hypothesis, outline a plan of investigation, select relevant sources, extract and organize data, interpret the cartographic and statistical materials, formulate conclusions, and justify them in writing. Parallel versions of the assignment, equivalent in structure and difficulty but based on different territorial cases, were used at the pre-test and post-test stages. The completion time was __ minutes. An example of the diagnostic tasks is provided in Appendix A. — AUTHORS: please adjust this paragraph so that it describes the tasks actually used.

Data were collected during the pre-test and post-test stages of the pedagogical experiment. The primary source of quantitative data was the results of diagnostic tasks, assessed according to the developed criteria. The results of research assignments and project work by students in the experimental group were also analyzed. The mean (M) and standard deviation (SD) were calculated for each group. In the first stage of the analysis, the baseline scores of the experimental and control groups were compared, which allowed us to determine the degree of their comparability before the start of the formative intervention. Next, the dynamics of scores within each group between the pre-test and post-test were analyzed separately, after which the post-test results of the experimental and control groups were compared.

Statistical analysis was performed using software and version, e.g., IBM SPSS Statistics 26 / JASP 0.18 / R 4.3. Before applying parametric tests, the normality of the distributions was checked using the Shapiro–Wilk test — please confirm, and the homogeneity of variances using Levene's test — please confirm. Between-group comparisons (experimental vs. control) at the pre-test and post-test stages were performed using the independent-samples Student's t-test ($df = 45$), and within-group changes from pre-test to post-test were assessed using the paired-samples t-test ($df = 22$ for the experimental group and $df = 23$ for the control group). Because nine components were compared, the Holm–Bonferroni correction (Holm, 1979) was applied to the component-level p-values to control the family-wise error rate. Differences were considered statistically significant at $p < 0.05$. Effect sizes were calculated using Cohen's d (Cohen, 1988) to assess the practical magnitude of the observed differences. For between-group comparisons, d was calculated as the difference between the group means divided by the pooled standard deviation. For within-group (pre-test/post-test) comparisons, the effect size $d(av)$ was calculated as the mean change divided by the average standard deviation of the two measurements, $\sqrt{((SD^2_{pre} + SD^2_{post})/2)}$ (Lakens, 2013). Values of 0.2, 0.5, and 0.8 were interpreted as small, medium, and large effects, respectively.

2.5 Reliability of the assessment procedure

To ensure reliability and comparability of results, the same criteria, scale, and assessment procedure were used in the pre-test and post-test stages in both the experimental and control groups. The assessment tasks were aligned with nine identified components of research skills and involved relevant research

activities rather than the retrieval of factual geographic knowledge. The assessment covered skills in defining a research problem, formulating a research question, planning the work, searching for information and collecting data, analyzing and interpreting geographic data, formulating well-founded conclusions, and presenting research results.

The assessment criteria corresponded to the sequence of research activities outlined in the study and took into account the specifics of geography, including working with cartographic, statistical, graphical, and spatial data. The same criteria and a four-point scale (from 1 to 4) were used at both stages of the assessment. The pre-test and post-test assessments were conducted under comparable conditions for both groups. The unification of the assessment procedure ensured consistency of measurements and the possibility of correct comparison of changes in students' research skills between groups and at different stages of the study.

Assessors and inter-rater reliability. The written work of all students at both stages was assessed independently by two assessors: the geography teacher and an external expert (a geography teacher-methodologist who was not involved in teaching the participating classes). Before assessment, the works were coded, so the assessors were blind to group membership and to the stage of the experiment. — AUTHORS: if only one teacher assessed the work, replace this with an accurate description and add this to the limitations. Inter-rater agreement was estimated using the intraclass correlation coefficient (two-way random effects, absolute agreement (Koo & Li, 2016) for the total score, ICC = 0.xx (95% CI 0.xx–0.xx), and weighted Cohen's kappa for individual criteria, $\kappa_w = 0.xx-0.xx$. Discrepancies of more than one point on a criterion were resolved through discussion, and the mean of the two assessors' scores was used in the analysis. The internal consistency of the nine-criterion scale was assessed using Cronbach's alpha: $\alpha = 0.xx$ at the pre-test and $\alpha = 0.xx$ at the post-test stage. The use of analytic rubrics with explicit level descriptors and assessor calibration is considered an effective way to increase the reliability of performance assessment (Jonsson & Svingby, 2007).

3 Results and discussion

The pre-test allowed us to establish the students' baseline research skills before the start of the formative intervention. Comparisons were made both for the overall score and for individual components of research activities. This approach allowed us to assess not only the overall level of research skills but also to identify which activities presented the greatest challenge for the students.

The pre-test results are presented in Table 2.

Table 2. Pre-test results of students' research skills in the experimental and control groups.

Assessed Skill	Experimental group (n = 23), M±SD	Control group (n = 24), M±SD	t(45)	p
Defining the research problem	2.09±0.60	1.92±0.72	0.88	0.383
Formulating the research question and hypothesis	2.26±0.45	2.08±0.65	1.10	0.274
Research planning	1.96±0.64	2.04±0.46	-0.49	0.627
Searching for and selecting information	2.22±0.60	2.12±0.61	0.57	0.574
Collecting geographic data	2.26±0.45	2.04±0.75	1.21	0.228
Organizing and analyzing information	2.22±0.60	2.12±0.54	0.60	0.552
Interpreting cartographic, statistical, and graphical materials	1.91±0.67	2.00±0.51	-0.52	0.608
Formulating conclusions	1.83±0.65	2.08±0.65	-1.32	0.194
Presenting and justifying results	2.09±0.42	2.25±0.61	-1.04	0.299
Overall score	18.83±1.15	18.67±1.79	0.36	0.716

Note: M – mean; SD – standard deviation; t – independent-samples Student's t-test. Source: compiled by the authors based on experimental data.

At the initial stage, the distribution of indicators in the two groups was examined primarily from the standpoint of their comparability. The difference in the overall score between the experimental and control groups was only 0.16 points and did not reach statistical significance ($t(45) = 0.36$; $p = 0.716$). There were also no statistically significant between-group differences for any of the nine components assessed ($|t(45)|$

≤ 1.32 ; all $p > 0.05$). Thus, before the start of the formative stage, the experimental and control groups were comparable in terms of the development of research skills. This is important for the subsequent interpretation of the dynamics, as it supports the assumption that the more pronounced changes in the experimental group were associated with the specific organization of educational activities rather than with an initial advantage of one group. Analysis of individual components allowed us to obtain a more meaningful characterization of the initial state of research skills. In the experimental group, the lowest scores were found in formulating conclusions based on the data obtained (1.83 ± 0.65), interpreting cartographic, statistical and graphic materials (1.91 ± 0.67), and planning the study (1.96 ± 0.64). Slightly higher results were found in searching for and selecting information (2.22 ± 0.60), systematizing and analyzing information (2.22 ± 0.60), formulating a research question and hypothesis (2.26 ± 0.45), and collecting geographic data (2.26 ± 0.45).

The resulting distribution shows that students experienced greater difficulty not so much in finding the necessary information, but in transitioning to its investigative use: determining the sequence of work, interpreting the obtained data, and formulating an evidence-based conclusion. These operations distinguish investigative activity from the simple reproduction of discovered information. This distinction is essential for geographic education. A validation study by Sadykova et al. (2023), conducted among 826 Kazakhstani schoolchildren aged 13-18, demonstrated the need to assess geographic inquiry as a set of interrelated procedural skills, rather than reducing it to subject knowledge or spatial thinking. The authors also note a shortage of practically applicable tools for assessing geographic inquiry skills in the school environment. Therefore, the analysis of individual components in this study allows us to determine not only the final level but also the structure of changes that occurred during pedagogical intervention.

After completion of the formative stage, repeated diagnostics revealed different dynamics of the studied indicators. To assess changes, post-test results were compared with baseline values separately in each group (Figure 1).

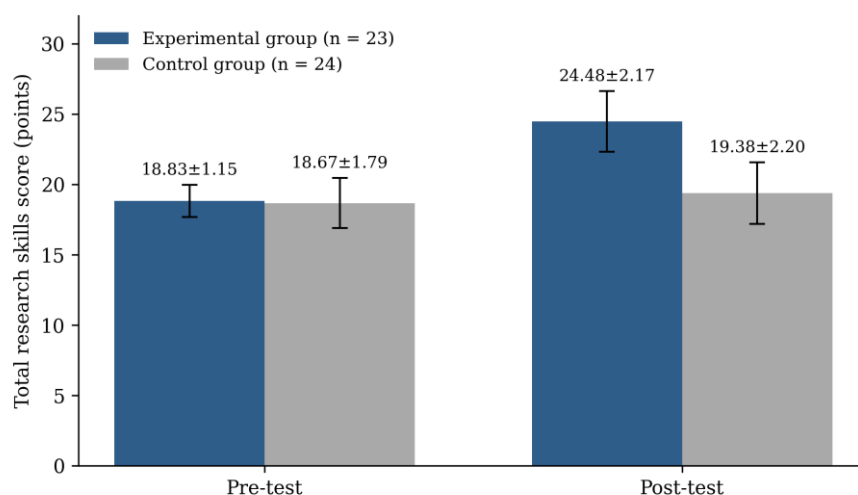


Figure 1. Overall research skills score of the experimental (n = 23) and control (n = 24) groups at the pre-test and post-test stages (M±SD; error bars show standard deviations; maximum possible score = 36).

Source: compiled by the authors based on experimental data.

In the experimental group, the overall research skills score increased from 18.83 ± 1.15 to 24.48 ± 2.17 points. This difference was 5.65 points, or 30.0% relative to the baseline score. The paired-samples t-test confirmed significant differences between the pre-test and post-test results ($t(22) = x.xx$; $p < 0.001$). The

within-group effect size ($d(av)$, see Section 2.4) was 3.25, indicating a very large practical effect of the pedagogical intervention.

In the control group, the score changed from 18.67 ± 1.79 to 19.38 ± 2.20 points, an increase of 0.71 points, or 3.8%. This change also reached statistical significance ($t(23) = 2.20$ — value back-calculated from $p = 0.038$; please verify with your output; $p = 0.038$), but its practical significance was considerably lower: the effect size was $d(av) = 0.36$ (small effect).

In this case, comparing the rates of change between the two groups is more significant than the actual increase in final scores. Some positive dynamics in the control group may be due to the natural mastery of the geography course content, the accumulation of learning experience, and repeated completion of research assignments. Moreover, the relative increase in the overall score in the experimental group was 30.0% versus 3.8% in the control group, almost eight times higher. Therefore, the primary evidence of the effectiveness of the experimental intervention is the more pronounced dynamics in the experimental group under comparable initial conditions.

To determine the nature of these changes, the results were examined separately for each of the nine research skills (Figure 2; Table 3).

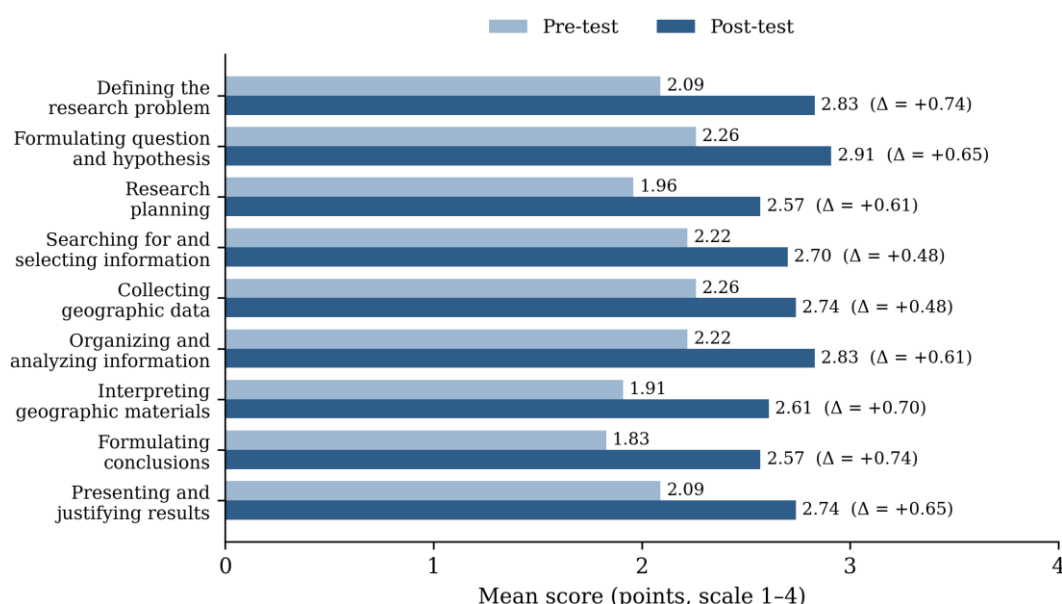


Figure 2. Mean scores of the nine research skill components in the experimental group ($n = 23$) at the pre-test and post-test stages (scale 1–4; Δ – absolute change; standard deviations are given in Table 3).

Source: compiled by the authors based on experimental data.

The data obtained show that the pedagogical intervention did not affect only individual skills, but rather shaped overall positive dynamics across all components of research activity. Statistically significant changes were found for all nine criteria ($p < 0.01$), and all of them remained significant after the Holm–Bonferroni correction — please confirm with exact p -values (Table 3). The largest absolute increase was observed in the ability to define a research problem (+0.74 points) and formulate conclusions based on the obtained data (+0.74 points). A significant change was also recorded in the interpretation of cartographic, statistical, and graphic materials (+0.70 points). Formulating a research question, hypothesizing, and presenting results increased by 0.65 points, while planning and analyzing information increased by 0.61 points.

The most pronounced increase in the ability to formulate conclusions is of particular interest, since this component had the lowest initial score - 1.83 ± 0.65 points. After the formative stage, its value increased to 2.57 ± 0.84 points. This indicates that the activities of analyzing data and formulating conclusions in the

context of project work are no longer isolated learning exercises for students. To complete the project, they were required to consistently use the information collected to solve the problem at hand and justify the conclusion reached. At the same time, an increase in the indicator of defining a research problem from 2.09 ± 0.60 to 2.83 ± 0.58 points and formulating a research question from 2.26 ± 0.45 to 2.91 ± 0.73 points indicates the positive dynamics of the early stages of the research cycle associated with the independent organization of cognitive activity.

Table 3. Pre-test and Post-test results for the nine research skill components in the experimental and control groups.

Assessed skill	Group	Pre-test, M $\pm$ SD	Post-test, M $\pm$ SD	Δ	t	p	d(av)
Defining the research problem	EG	2.09 ± 0.60	2.83 ± 0.58	+0.74	t	<0.01	1.25
	CG	1.92 ± 0.72	M $\pm$ SD	Δ	t	p	d
Formulating the research question and hypothesis	EG	2.26 ± 0.45	2.91 ± 0.73	+0.65	t	<0.01	1.07
	CG	2.08 ± 0.65	M $\pm$ SD	Δ	t	p	d
Research planning	EG	1.96 ± 0.64	2.57 ± 0.57	+0.61	t	<0.01	d
	CG	2.04 ± 0.46	M $\pm$ SD	Δ	t	p	d
Searching for and selecting information	EG	2.22 ± 0.60	2.70 ± 0.57	+0.48	t	0.006	d
	CG	2.12 ± 0.61	M $\pm$ SD	Δ	t	p	d
Collecting geographic data	EG	2.26 ± 0.45	2.74 ± 0.57	+0.48	t	0.008	d
	CG	2.04 ± 0.75	M $\pm$ SD	Δ	t	p	d
Organizing and analyzing information	EG	2.22 ± 0.60	2.83 ± 0.57	+0.61	t	<0.01	d
	CG	2.12 ± 0.54	M $\pm$ SD	Δ	t	p	d
Interpreting cartographic, statistical, and graphical materials	EG	1.91 ± 0.67	2.61 ± 0.84	+0.70	t	<0.001	0.92
	CG	2.00 ± 0.51	M $\pm$ SD	Δ	t	p	d
Formulating conclusions	EG	1.83 ± 0.65	2.57 ± 0.84	+0.74	t	<0.01	0.99
	CG	2.08 ± 0.65	M $\pm$ SD	Δ	t	p	d
Presenting and justifying results	EG	2.09 ± 0.42	2.74 ± 0.57	+0.65	t	<0.01	d
	CG	2.25 ± 0.61	M $\pm$ SD	Δ	t	p	d
Overall score	EG	18.83 ± 1.15	24.48 ± 2.17	+5.65	t	<0.001	3.25
	CG	18.67 ± 1.79	19.38 ± 2.20	+0.71	2.20	0.038	0.36

Note: EG – experimental group (n = 23); CG – control group (n = 24); Δ – post-test minus pre-test mean; t – paired-samples t-test (df = 22 for EG, df = 23 for CG); p – two-tailed p-value (Holm–Bonferroni-adjusted for the nine components); d(av) – within-group effect size (see Section 2.4). Source: compiled by the authors based on experimental data.

The smallest, although also statistically significant, increase was found in searching and selecting information (+0.48 points; $p=0.006$) and collecting geographic data (+0.48; $p=0.008$). This may be due to the fact that the corresponding indicators at the initial stage were relatively higher than a number of other research skills. The main change, therefore, occurred not so much in the ability of students to find information, but in their subsequent analytical use. Changes in skills for working with specific geographic sources also appear important. The average score for interpreting cartographic, statistical, and graphic materials increased from 1.91 ± 0.67 to 2.61 ± 0.84 points ($\Delta=+0.70$; $p<0.001$). Analyzing a map, table, or diagram in a typical academic assignment often has a predetermined goal, whereas in research, the choice of source and its use are determined by the question posed. As a result, cartographic and statistical information is no longer an object of reproduction, but a source of evidence. It is this shift that allows us to speak of the development of geographic research itself.

Modern research confirms the importance of such a work organization. In a study by Adipranata et al. (2026), conducted with 425 10th-grade students, the integration of geospatial technologies with PjBL within a quasi-experimental pre-test/post-test design ensured the development of students' spatial thinking. Although spatial thinking is not identical to research skills, this result is important for the interpretation of the present study: working with spatial data in a project creates conditions in which

geographic information becomes a tool for analysis and problem solving, and not just content to be remembered.

The most significant comparison for assessing the effectiveness of the approach used is the comparison of the results of the experimental and control groups after the completion of the formative stage (Figure 3).

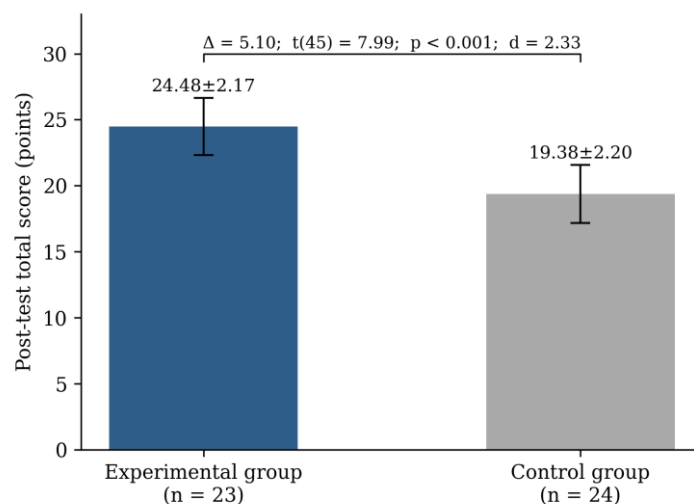


Figure 3. Post-test overall research skills scores of the experimental (n = 23) and control (n = 24) groups (M $\pm$ SD; error bars show standard deviations; independent-samples t-test).

Source: compiled by the authors based on experimental data.

Based on the post-test results, the average score of the experimental group was 24.48 $\pm$ 2.17 points, while in the control group it was 19.38 $\pm$ 2.20 points. The between-group difference was 5.10 points, or 26.3% relative to the post-test mean score of the control group. This difference was statistically significant ($t(45) = 7.99$; $p < 0.001$). The resulting effect size, Cohen's $d = 2.33$, indicates a high practical significance of the identified difference. A comparison of the pre-test and post-test scores further confirms the nature of the changes. Before the formative stage, the difference between the groups was only 0.16 points and was not statistically significant ($t(45) = 0.36$; $p = 0.716$). After the pedagogical intervention, it increased to 5.10 points, with $p < 0.001$. Thus, the advantage of the experimental group was not due to its higher initial level.

The statistically significant advantage of the experimental group confirms hypothesis H1 on a positive impact of PjBL on the development of research skills in geography studies. However, interpreting the effect solely as a consequence of increased student engagement would be insufficient. A more significant change appears to be the change in the structure of the learning activity itself: students sequentially progress from posing a question to obtaining and defending their own results, and the intermediate research activities acquire a functional interrelationship. A similar result was obtained by Nontol and Aguilar (2024) in a quasi-experimental study involving 71 schoolchildren. After implementing PjBL, 77.1% of students in the experimental group achieved a higher level of research competence; between-group differences in the final assessment were statistically significant ($Z = -7.259$; $p < 0.001$). Significantly, the authors examined research competence through cognitive, procedural, and communicative components. This is consistent with the logic of the present study, in which outcome is assessed not through a single indicator of academic performance, but through the totality of actions that comprise the research process.

However, direct comparison of absolute values between studies is inappropriate due to differences in the age of the participants, the content of the learning tasks, and the assessment instruments. The significance of this study lies primarily in confirming that the effect of project-based learning can manifest itself specifically at the level of research competence, and not only in final subject grades. These results should be considered within the context of their subject-specific nature. Research activities in geography

lessons include both general research operations and activities specific to the discipline itself. The former includes problem formulation, evidence search, analysis, argumentation, and conclusion; the latter includes reading and interpreting maps, comparing territories, using spatial and statistical data, and establishing spatial relationships.

It is the combination of these two levels that explains the structure of the observed dynamics. Positive changes were recorded across all nine components, but the most significant increases were observed in defining the research problem (+0.74), formulating conclusions (+0.74), and interpreting geographic data (+0.70). These three components reflect different parts of the unified research cycle: defining the problem, working with evidence, and obtaining a substantiated result. The observed increases in data analysis (+0.61) and research planning (+0.61) further confirm that the changes affected not only the final presentation of results but also the intermediate stages of the research cycle. Together, this pattern, in which the largest gains occurred in problem formulation, interpretation of geographic materials, and evidence-based conclusions rather than in information retrieval and data collection, supports hypothesis H2.

The results of a systematic review by Yusri et al. (2024), which covered PjBL studies published in Scopus-indexed journals, show that the most frequently reported outcomes of project-based learning are related to the development of critical thinking, problem solving, collaboration, communication, and creative and innovative thinking. This is important for the current study in two respects. First, research skills are not developed in isolation: data analysis requires critical evaluation, planning is associated with problem solving, and defending results requires argumentation and communication. Second, the broad range of skills developed in PjBL demonstrates the need for multi-component assessment, as a single achievement test may not reflect the nature of the changes occurring.

However, not every educational project can be automatically considered research-based. The content of the student's activity is key. If a project is limited to searching for existing information and presenting it, the opportunities for developing research skills remain limited. A more pronounced effect should be expected in a situation where the student is faced with a question that requires him to independently identify sources, obtain or select data, compare them, and justify his own conclusion. This position is supported by the results of a study by Musyawarah et al. (2026) on research-oriented PjBL in geography education. The authors consider the integration of research activities directly into the project structure as a prerequisite for the transition from the assimilation of theoretical material to working with empirical data and developing critical thinking. Consequently, the significant factor is not the existence of a project product itself, but the organization of the process for its production.

Additional support is provided by the results of Laiskhanov and Barat (2024), who studied the use of PjBL directly in school geography instruction. In an experiment with 10th-grade students, project-based learning was used over a nine-week period during the study of nature management and geoecology. Students in the experimental group demonstrated higher learning activity, and their final test score, on average, exceeded the control group's score by 3.07 points. The authors associate the use of PjBL not only with the deepening of students' geographical knowledge but also with the expansion of opportunities for students' research activities. For the Kazakhstani school context, this result is of particular interest, as it demonstrates the applicability of the project-based approach directly to the content of school geography. In the present study, the experimental group's final advantage was more pronounced: the difference between the groups was 5.10 points, compared to a baseline difference of only 0.16 points. However, a direct quantitative comparison of these values with the results of Laiskhanov and Barat (2024) is not possible, as the scales used, student ages, and duration of pedagogical intervention differ. The significant difference is the similarity in the overall direction of change.

When interpreting the obtained results, it is important to consider that the effectiveness of PjBL is determined not only by the chosen pedagogical model but also by the quality of its implementation. Recent reviews show significant variability in PjBL design: project duration, student autonomy, group work methods, the nature of the final product, and the role of the teacher vary. Yusri et al. (2024) found

significant diversity in research designs and PjBL implementation models, making direct comparison of results across studies difficult. Therefore, the changes identified in this work should be associated primarily with the specific organization of the research cycle, and not automatically extended to any form of project activity. The practical implication of the findings is that when teaching PjBL geography, it is useful to design around the research question and working with data. Creating a presentation, map or other product in this case is the final stage of the research, but not its main goal.

The question of the transferability of the proposed PjBL modules to other grade levels and regions also deserves attention. The modules are built on a generic research cycle (problem – question – plan – data – analysis – conclusion – defense) and on openly available cartographic and statistical sources, so their structure is not tied to a specific territory: the topics of population change, water resources, and anthropogenic pressure can be replaced by equivalent local problems in any region of Kazakhstan (e.g., urbanization, land degradation, or the use of transboundary rivers). For grades 7–8, the modules can be simplified by providing students with a prepared data set and a partially formulated research question, whereas in grades 10–11 they can be extended by including students' own field observations, GIS tools, and elements of spatial statistics. In rural schools with limited digital resources, printed maps and statistical yearbooks can replace online sources without changing the logic of the research cycle. However, the transferability of the effect itself requires empirical verification in other age groups and regions.

However, the study's results have several limitations. The sample included 47 students from two classes at a single secondary school, so the findings cannot be generalized to the entire ninth-grade population without further verification. The quasi-experimental nature of the design also requires the use of existing classes, making it impossible to completely exclude the influence of initial group characteristics, even in the absence of statistically significant differences on the pre-test. In addition, a testing effect associated with repeated completion of similar diagnostic tasks cannot be completely excluded, although it would have affected both groups equally.

Another limitation is the dependence of the results on the diagnostic instrument used. The nine identified criteria allow us to cover the main stages of research activity, but assessing a complex skill using a scoring rubric inevitably involves a certain degree of expert judgment, although this risk was reduced by independent blinded double assessment and satisfactory inter-rater agreement — adjust to the actual procedure. The reliability of the findings can be further enhanced by combining rubric assessment with analysis of research products, observation, and standardized instruments. In this regard, the scale of geographical research procedural skills developed and validated by Sadykova et al. (2023) represents a promising tool for subsequent research in the Kazakhstani educational context. Furthermore, measuring immediately after the completion of the pedagogical intervention allows us to establish short-term dynamics, but does not answer the question of the sustainability of the skills developed. A promising direction is to conduct a delayed assessment and expand the sample to include multiple schools and different age groups. This will help determine whether the PjBL effect persists after the project's completion and whether the developed research approach transfers to new geographic tasks.

4 Conclusion

The study demonstrated that the use of Project-Based Learning in geography teaching creates conditions for the consistent development of students' research skills. The most significant result is associated not with individual learning activities, but with the change in the nature of students' work with geographic information: from searching for and reproducing existing information to independently posing problems, meaningfully analyzing data, and justifying their conclusions.

Experimental data confirmed the effectiveness of the proposed approach. With a comparable baseline level, after completing the formative stage, the experimental group demonstrated a statistically significant advantage in the integrated research skills indicator ($p < 0.001$; $d = 2.33$), which confirms hypothesis H1. Positive changes encompassed all assessed components, with the most pronounced dynamics characteristic of defining the research problem, interpreting geographic data, and formulating

conclusions, which supports hypothesis H2. This demonstrates that project-based learning fosters the development of not only individual techniques for working with information but also the ability to construct a holistic research framework.

The practical significance of the obtained results lies in the possibility of integrating PjBL into the school geography curriculum without making project-based learning a separate element. A research project can be organized directly around the geographic problem being studied, using cartographic, statistical, and spatial data. The effectiveness of this approach is determined not by the creation of the project product itself, but by engaging students in the full research cycle and providing them with sufficient independence at its key stages.

Based on these results, the following practical recommendations can be offered. For geography curriculum developers: (1) to include in the 9th-grade geography curriculum at least one research project per term built around a local or regional geographic problem, with expected learning outcomes defined for each stage of the research cycle; (2) to include a criterion-based rubric of research skills, similar to the nine-criterion scale used in this study, in the assessment guidelines so that procedural research skills, not only subject knowledge, are assessed. For school teachers: (1) to formulate project assignments as research questions that require the selection and analysis of cartographic and statistical data rather than the compilation of ready-made information; (2) to provide targeted guidance and formative feedback at the stages of problem definition, data interpretation, and formulation of conclusions, which proved to be the most difficult for students at the pre-test stage.

These findings are relevant for improving geography teaching methods and can be used in developing research assignments and organizing project-based learning for secondary school students. Further research should be directed toward testing the sustainability of the acquired skills, expanding the sample, and assessing the transferability of the acquired research experience to new geographic problems.

Appendix A. Example of a diagnostic task

AUTHORS: replace this example with the task actually used. Case: "Population of the Almaty region". Materials: (a) a map of population density by districts of the Almaty region; (b) a table of district population in 2015 and 2024; (c) a diagram of the migration balance. Tasks: 1) What geographic problem do the materials reveal? (criterion 1); 2) Formulate a research question and a hypothesis (criterion 2); 3) Draw up a 4–5-step plan for investigating the problem (criterion 3); 4) Name two additional sources of information you would use and explain your choice (criterion 4); 5) Using the table, calculate the change in population for three districts (criterion 5); 6) Group the districts by the type of change and present the result in a table (criterion 6); 7) Using the map and the diagram, explain the spatial pattern of the changes (criterion 7); 8) Formulate a conclusion supported by at least two pieces of evidence (criterion 8); 9) Write a short argument (5–6 sentences) defending your conclusion (criterion 9).

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Gulzira Aksanbayeva	✓	✓			✓	✓	✓	✓	✓	✓	✓			
Duman Aliaskarov	✓	✓		✓	✓	✓				✓		✓		
Evren Atış	✓			✓						✓		✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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Biographies of Authors



Gulzira Aksanbayeva

Master's student, Department of Geography and Ecology, Faculty of Natural Sciences and Geography, Abay Kazakh National Pedagogical University, Almaty, Kazakhstan
 Geography Education
gulziraaksanbaeva454@gmail.com
<https://orcid.org/0009-0007-0973-0439>



Duman Aliaskarov

PhD, Associate Professor, Department of Geography and Ecology, Faculty of Natural Sciences and Geography, Abay Kazakh National Pedagogical University, Almaty, Kazakhstan
 Earth and Environmental Sciences; Geography
d.aliaskarov@abaiuniversity.edu.kz
<https://orcid.org/0000-0002-7628-1246>
<https://www.scopus.com/authid/detail.uri?authorId=57197876414>
<https://www.webofscience.com/wos/author/record/JZD-9986-2024>



Evren Atış

Dr., Department of Geography, Faculty of Humanities and Social Sciences, Kastamonu University, Kastamonu, Türkiye
 Geography; Engineering; Communication
evrencografya@gmail.com
<https://orcid.org/0000-0002-5686-3169>
<https://www.scopus.com/authid/detail.uri?authorId=57216887028>

Article

Managing urban floods with GIS, SWMM and green infrastructure: a critical review with implications for Central Asian cities

Aruzhan Oserbay ¹, Yerkin Kakimzhanov ^{1*}, Naci Yastikli ², Fusun Balik Sanli ²

¹ Farabi University, Faculty of Geography and Environmental Sciences, Department Geography, Land management and Cadastre, Almaty, Kazakhstan; (A.O.) userbai1503@gmail.com, <https://orcid.org/0009-0005-5640-0454>; (Y.K.) erkinkakimzhanov@gmail.com, <https://orcid.org/0000-0002-1919-6459>

² Yildiz Technical University, Faculty of Civil Engineering, Department of Geomatic Engineering, Istanbul, Turkey; (N.Y.) ynaci@yildiz.edu.tr, <https://orcid.org/0000-0001-9045-9672>; (F.B.S.) fbalik@yildiz.edu.tr, <https://orcid.org/0000-0003-1243-8299>

* Corresponding author: Yerkin Kakimzhanov, Kazakhstan, Almaty 050060, 146/1 Serkebayev Street, erkinkakimzhanov@gmail.com, +77078314331

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SECTION

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Urban flood; GIS; SWMM; HEC-RAS; green infrastructure; LID/SUDS; aryk drainage; Central Asia.

Abstract: Urban flooding is intensifying with urbanization, climate change and ageing drainage infrastructure, particularly in data-scarce foothill cities. This critical narrative review, based on a transparently reported selection procedure informed by PRISMA 2020, examines how geographic information systems (GIS), hydrological-hydraulic models (EPA SWMM, StormCAD, HEC-RAS and related 1D/2D tools), green infrastructure (GI/LID/SUDS) and machine learning are combined in urban flood management, and what this implies for Central Asian cities drained by open aryk networks. Searches of Scopus, Web of Science and Google Scholar, supplemented by Russian and Kazakh-language sources and citation searching, were used to select 33 sources published in 2002–2026 (28 from database searching and 5 from other methods), of which 26 are primary case or modelling studies. A structured data-extraction table summarizes the study area, tools, input data, calibration/validation and quantitative outcomes of each primary study. GIS-hydrological-hydraulic model integration was the largest thematic cluster (14 of 33 sources), whereas calibration or validation against observed flood data was reported in only some primary studies and several reported none. Reported GI/LID effects are not directly comparable because they refer to different metrics and design storms: LID covering 9.81% of a catchment in Palembang reduced runoff volume by 21.0–35.4% and peak discharge by 11.3–37.7%, whereas a combined GI scenario in Istanbul reduced the flooded area by 36.94%. Peer-reviewed evidence on urban drainage in Central Asian cities remains scarce. We recommend combining digitized aryk networks, high-resolution DEM/LiDAR data and locally derived design rainfall with calibrated 1D/2D models and GI scenarios, and we outline research priorities for the region.

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1 Introduction

Urban flooding is one of the most widespread environmental and engineering hazards associated with urbanization, climate change and the deterioration of infrastructure. As impervious surfaces expand, less rainfall infiltrates into the soil, which leads to greater surface runoff, higher peak flows and increased hydraulic pressure on urban drainage systems. The problem becomes especially pronounced during short, intense rainfall events, when sewer networks, open channels and stormwater infrastructure no longer have sufficient capacity to convey the generated runoff (Price & Vojinovic, 2008; Guo et al., 2021).

In urban drainage management, GIS platforms provide the spatial basis for delineating catchments, characterizing land cover, mapping flood-prone areas and visualizing model outputs (Abedin & Stephen, 2019; Jahangiri, 2019). Hydrological–hydraulic models, including EPA SWMM, StormCAD and HEC-RAS, are widely used to simulate rainfall–runoff processes, the conveyance capacity of pipe networks and flood propagation in open channels (Rossman, 2015; Abd-Elhamid et al., 2020; Ertan & Celik, 2021; Palaka et al., 2021).

In recent years, green infrastructure (GI), Low Impact Development (LID) and Sustainable Urban Drainage Systems (SUDS) have increasingly been viewed as nature-based solutions for mitigating urban flood risk. These terms overlap but are not synonymous: LID originated in North American site-design practice, SUDS in the United Kingdom and water-sensitive urban design (WSUD) in Australia, whereas GI is a broader planning concept that also covers ecological and social functions (Fletcher et al., 2015). Rain gardens, bioswales, permeable pavements, green roofs and detention ponds slow surface runoff, enhance infiltration and improve water quality (Porse, 2018; Skrygan et al., 2018; Al Amin et al., 2024).

Several reviews have already synthesized parts of this field. Teng et al. (2017) reviewed flood inundation modelling methods, recent advances and uncertainty analysis; Guo et al. (2021) compared urban surface water flood models and discussed their future challenges; and Tom et al. (2022) reviewed flood modelling in developing cities and informal settlements using Nairobi as an example. The hydrological performance of LID practices has been reviewed by Ahiablame et al. (2012) and Eckart et al. (2017), and machine learning approaches to flood prediction by Mosavi et al. (2018).

However, these reviews usually address a single family of tools – inundation models, LID practices or data-driven methods – and mostly draw on cities with dense monitoring networks and fully digitized pipe systems. Much less attention has been paid to how GIS, network models of the SWMM type, open-channel hydraulic models and GI scenarios can be combined in data-scarce foothill cities whose stormwater is conveyed largely through open channels. This situation is typical of Central Asia, where cities such as Almaty, Bishkek and Tashkent rely on *aryk* networks – open channels originally built for irrigation that also convey stormwater – and where peer-reviewed studies of urban flooding are still few (Ceresa et al., 2025; Mirlas et al., 2025; Mukhanbet et al., 2026; Linh et al., 2026).

The aim of this review is to critically synthesize the methodological advantages, limitations and future directions of GIS, SWMM, StormCAD, HEC-RAS, GI/LID/SUDS and machine learning approaches used in urban flood management, and to derive implications for Central Asian cities. Three research questions guided the review: RQ1 – how are GIS, hydrological–hydraulic models, GI/LID/SUDS and machine learning combined in the reviewed studies, and which data do they require? RQ2 – how large and how comparable are the reported effects of GI/LID/SUDS measures, and why do they differ between cities? RQ3 – which model combinations are applicable under data scarcity, and what are the research gaps and practical priorities for Central Asian *aryk*-drainage systems? Compared with earlier reviews, this review (i) considers GIS, network, open-channel and GI modelling within one framework; (ii) provides a structured extraction of the included studies, including their calibration status and quantitative results; and (iii) explicitly addresses data-scarce foothill cities of Central Asia.

2 Materials and methods

2.1 Review type

This study is a critical narrative review (Grant & Booth, 2009) with a selection procedure informed by the PRISMA 2020 statement (Page et al., 2021). It is not a full systematic review: no protocol was registered in advance and no meta-analysis was performed, because the included studies use heterogeneous models, metrics and design storms. PRISMA 2020 was used as a reporting guideline for the search and selection stages, and the selection stages are shown in Figure 1. The PRISMA statement is cited as a methodological reference and is not part of the analysed corpus.

2.2 Information sources and search strategy

The searches covered Scopus, Web of Science Core Collection and Google Scholar, as well as Russian- and Kazakh-language scientific journals, theses and official project reports, which capture regional evidence that is rarely indexed in international databases. The searches were limited to publications from 2002 to 2026; the search strings and terms are given in Table 1. Because the review was designed as a narrative review, the numbers of records retrieved at the identification and screening stages were not recorded systematically; Figure 1 therefore shows the selection stages and reports numbers only for the documented stages (re-appraisal and final inclusion). During the revision in 2026, backward and forward citation searching of the included studies and a targeted search for peer-reviewed studies on Central Asian cities were also carried out; these yielded five additional studies.

Table 1. Search strategy

Source	Search string / terms
Scopus	TITLE-ABS-KEY (("urban flood*" OR "pluvial flood*" OR stormwater OR "urban drainage") AND (GIS OR SWMM OR "HEC-RAS" OR StormCAD OR LiDAR OR DEM) AND ("green infrastructure" OR "low impact development" OR LID OR SUDS OR "flood risk" OR "machine learning")) AND PUBYEAR > 2001
Web of Science Core Collection	TS = (same Boolean structure as for Scopus); publication years 2002–2026
Google Scholar	Combinations of: urban flood; stormwater management; GIS; SWMM; HEC-RAS; StormCAD; green infrastructure; LID; SUDS; DEM; LiDAR; flood risk assessment; urban drainage; machine learning flood prediction
Russian-/Kazakh-language sources	«городское наводнение», «ливневая канализация», «арычная сеть», «ГИС-моделирование», «отвод поверхностного стока»; «қалалық су тасқыны», «нөсер кәрізі», «арық желісі»
Other methods	Backward/forward citation searching; targeted search for peer-reviewed studies on Almaty, Bishkek, Tashkent and Central Asia (five studies included)

Source: compiled by the authors.

2.3 Eligibility criteria

The eligibility criteria are summarized in Table 2. Peer-reviewed journal articles, conference papers and reviews were the main type of included source. Theses and official project reports were admitted only when they were publicly accessible and provided unique evidence for an under-represented region (Central Asia) or a methodological contribution not available in the peer-reviewed literature; such sources are flagged as grey literature in Appendix A and are used for context rather than for quantitative comparison. The time frame was harmonized to 2002–2026: Burian and Edwards (2002) is the earliest included source and was retained as a historical–methodological reference on urban drainage.

Table 2. Inclusion and exclusion criteria

Criterion	Inclusion criteria	Exclusion criteria
Document type	Peer-reviewed article, conference paper or review; publicly accessible thesis or official project report providing unique regional or methodological evidence	Journalistic material; inaccessible full text; duplicate record; methodological guideline without urban flood content; journal outside the subject area or without a clear peer-review process
Thematic relevance	Urban drainage, GIS, SWMM/HEC-RAS/StormCAD and related models, GI/LID/SUDS, urban flood risk, flood susceptibility	Rural hydrology, coastal flooding or only indirectly related work
Spatial context	Urban or urbanized catchments, metropolitan areas, foothill cities; regional studies that report results for cities	Natural river basins without urban infrastructure
Methodological content	A model, map, scenario, numerical result or methodological conclusion is provided	Method not sufficiently described or results only stated in general terms
Time frame	Published 2002–2026	Publication year or publication status unclear

Source: compiled by the authors.

2.4 Screening and selection

After removal of duplicates, the records were screened by the authors in two steps: first by title and abstract and then by full text against the criteria in Table 2; disagreements were resolved by discussion. During the revision of the manuscript, the corpus was re-appraised: the PRISMA 2020 statement (a methodological guideline) and one article published in a journal outside the subject area were removed, leaving 28 sources from database searching. Together with the five studies identified by other methods, 33 sources were included in the synthesis (Figure 1).

Stage	Records	Records removed / excluded
Identification	Records identified from Scopus, Web of Science, Google Scholar and Russian-/Kazakh-language sources (2002–2026)	Duplicates removed
Screening	↓ Records screened by title and abstract	Records excluded as not relevant to urban flooding, drainage modelling or GI
Eligibility	↓ Full texts assessed against the criteria in Table 2	Full texts excluded: not urban; no model, map or quantitative result; full text not available; duplicate publication
Re-appraisal during revision	↓ Sources retained from databases (n = 30)	Removed (n = 2): methodological guideline (PRISMA 2020 statement, n = 1); journal outside the subject area (n = 1)
Other methods	Citation searching and targeted search for peer-reviewed studies on Central Asian cities	Studies added (n = 5)
Included	↓ Studies included in the synthesis (n = 33): 28 from databases + 5 from other methods; 26 primary studies and 7 reviews/conceptual works	

Figure 1. Flow of records through the selection procedure (PRISMA 2020-informed)

Source: compiled by the authors.

2.5 Quality appraisal and data extraction

Each primary study was appraised with a simple four-item checklist: (Q1) the study area and input data are clearly described; (Q2) the model or method is described in sufficient detail to be reproduced; (Q3) calibration or validation against observed data is reported; and (Q4) quantitative results are reported. The appraisal was not used to exclude studies but to weight their interpretation; its key element, the calibration/validation status, is reported for every primary study in Appendix A. Data were extracted with a standard form containing the following fields: author and year; country and city; study type; tools and models; input data (DEM, rainfall, drainage network, land use); calibration/validation and performance metrics; scenarios; main quantitative result; and limitations. Extraction was carried out by the authors and cross-checked against the original publications. The completed extraction table is given in Appendix A (Table A1) and serves as the list of included studies.

2.6 Synthesis

The corpus was first described by publication period, study region and thematic cluster (Table 3, Figure 2). The primary studies were then compared narratively and critically along the three research questions, with particular attention to the metrics used to report effects, the design storms, the calibration status and the availability of input data. Figure 2 was produced in Python using the Matplotlib Basemap toolkit.

Bibliometric diagrams were not used in the revised version because several included sources are not indexed in bibliographic databases.

3 Results

3.1 Characteristics of the included literature

Of the 33 included sources, 26 are primary case or modelling studies and seven are reviews or conceptual works (Burian & Edwards, 2002; Price & Vojinovic, 2008; Merz et al., 2014; Tsakiris, 2014; Skrygan et al., 2018; Guo et al., 2021; Tom et al., 2022). The number of sources increased over time: three were published in 2002–2010, seven in 2011–2018, twelve in 2019–2022 and eleven in 2023–2026, so that 23 sources (69.7%) appeared after 2018 (Table 3). Early sources mainly address probabilistic flood risk and the historical development of urban drainage (Apel et al., 2004; Merz et al., 2014), whereas later ones are dominated by GIS–hydrology integration, 2D hydraulics, LID scenarios and machine learning (Guo et al., 2021; Al Amin et al., 2024; Linh et al., 2026).

Table 3. Distribution of the included sources (n = 33) by period, region and thematic cluster

Category	Number	Share, %	Sources / main content
Publication period			
2002–2010	3	9.1	Historical foundations of urban drainage; probabilistic flood risk
2011–2018	7	21.2	Flood risk concepts; GIS-based modelling; GI and open data
2019–2022	12	36.4	GIS–SWMM/HEC-RAS integration; GI scenarios; developing cities; machine learning
2023–2026	11	33.3	Modelling under data scarcity; LID scenarios; Central Asian studies; explainable machine learning
Study region			
South Asia	6	18.2	India (4), Pakistan (1), Bangladesh (1)
Central Asia	6	18.2	Kazakhstan (3), Uzbekistan (1), Kyrgyzstan (1), regional study of five countries (1); two of six are grey literature
North America	4	12.1	USA: Las Vegas, Philadelphia, Los Angeles, Sacramento
East and Southeast Asia	3	9.1	China, Thailand, Indonesia
Middle East	3	9.1	Saudi Arabia, Iraq, Iran
Africa	3	9.1	Senegal, Burkina Faso, Kenya (review of Nairobi)
Europe	2	6.1	Germany, Turkey
Reviews / conceptual (no single study area)	6	18.2	General reviews and conceptual works
Thematic cluster			
GIS and hydrological–hydraulic modelling	14	42.4	SWMM, StormCAD, HEC-RAS, PCSWMM, MODFLOW; drainage-area delineation; network capacity
GI/LID/SUDS	6	18.2	Rain gardens, bioretention, permeable pavements, green roofs, multifunctional channels
Flood risk, probabilistic and climate approaches	6	18.2	Monte Carlo, return periods, design rainfall, regional risk models
General reviews and drainage practice	5	15.2	Model reviews, developing cities, history of drainage, aryk-network project
Machine learning and flood susceptibility	2	6.1	GARP/QUEST, explainable machine learning

Note: shares are calculated from n = 33 and may not sum to 100 because of rounding. Source: compiled by the authors from Table A1.

Geographically, the primary studies are spread across South Asia and Central Asia (six sources each), North America (four), East and Southeast Asia, the Middle East and Africa (three each) and Europe (two) (Table 3, Figure 2). The Central Asian group was strengthened during revision by four peer-reviewed studies on design rainfall and groundwater flooding in Almaty, regional flood risk in Central Asia and flood susceptibility in Kyrgyz cities; two further Central Asian sources are grey literature. GIS and

hydrological–hydraulic modelling is the largest thematic cluster (14 sources, 42.4%), followed by GI/LID/SUDS and flood-risk approaches (six each).

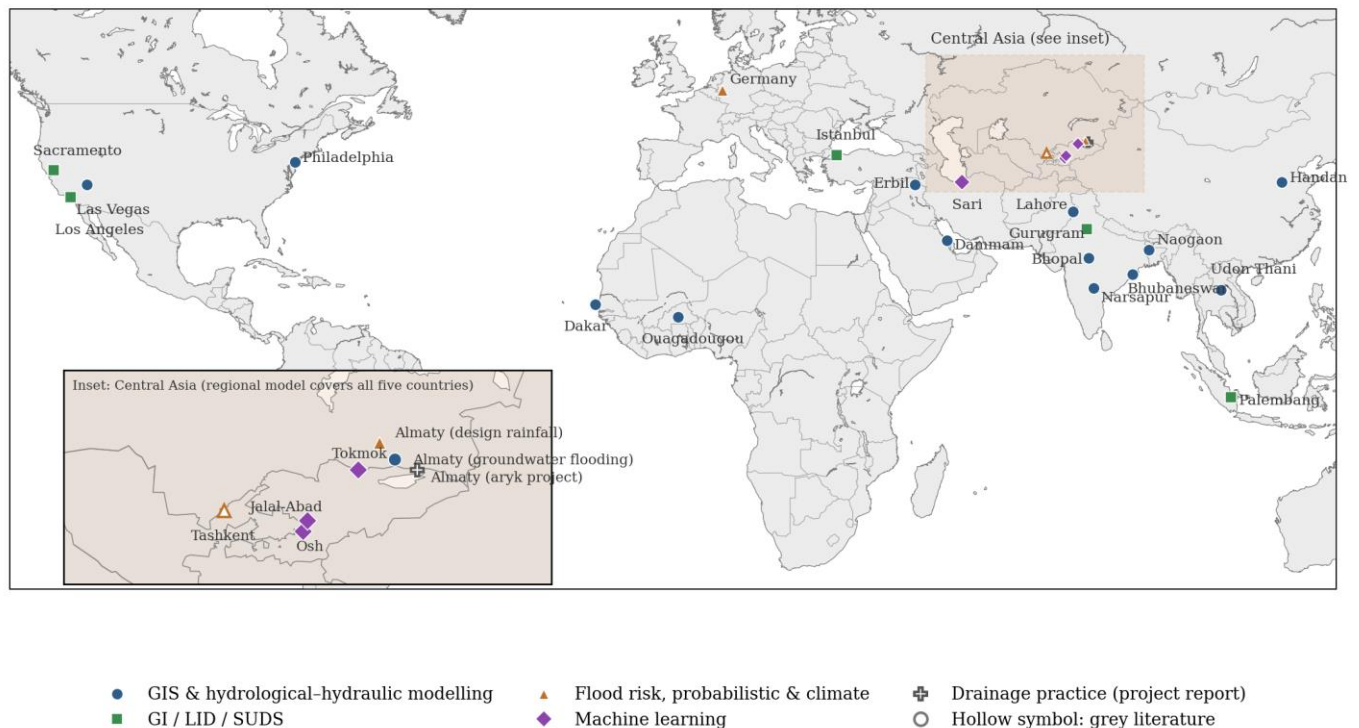


Figure 2. Study areas of the 26 primary studies by thematic cluster; the inset shows Central Asia, and the regional study of Ceresa et al. (2025) covers all five Central Asian countries

Source: compiled by the authors from Table A1; base map: Matplotlib Basemap toolkit.

3.2 Role of GIS platforms and DEM/LiDAR data

GIS platforms provide the initial spatial framework for studying urban drainage systems. ArcGIS, ArcHydro and QGIS are used to delineate catchments, determine flow directions, analyze land cover and map areas with high flood susceptibility. Abedin and Stephen (2019) developed a GIS workflow for spatiotemporal flood mapping on a university campus in Las Vegas; calibrating the DEM resolution, the temporal resolution of rainfall and a clogging factor of the inlets, they obtained the best agreement with a 5 m DEM and a clogging factor of 0.83, with an error of 24% between estimated and observed flood depth. Jahangiri (2019) combined ArcHydro and LiDAR data to delineate the drainage areas of green stormwater infrastructure (GSI) automatically and highlighted the influence of DEM quality on the results.

DEM resolution therefore plays a decisive role in identifying catchment boundaries, flow directions and water-accumulation zones. Low-resolution DEMs may fail to represent urban microrelief, curbs, buildings and artificial barriers, whereas high-resolution LiDAR data can refine drainage areas and correctly incorporate GSI/LID elements into a model (Jahangiri, 2019; Guo et al., 2021). As shown in Figure 3, the drainage area delineated for the same GSI site increased several-fold – by up to about an order of magnitude – when the 1–2 ft (0.3–0.6 m) LiDAR DEM was replaced by DEMs with 3.2 ft (about 1 m) and 5–10 ft (1.5–3 m) resolution.

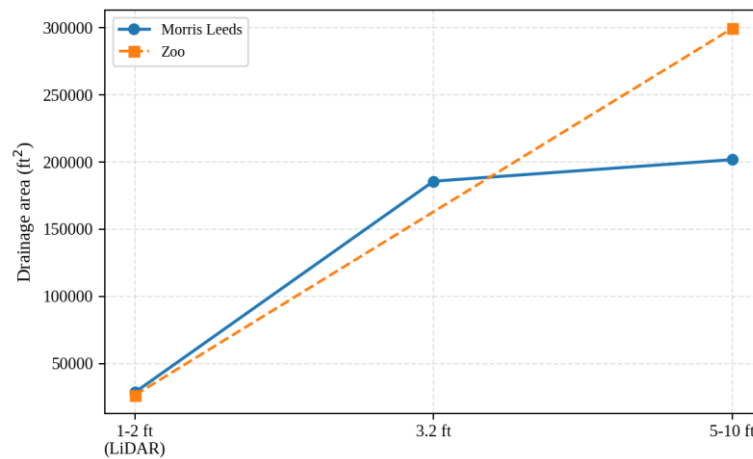


Figure 3. Effect of DEM resolution on the drainage area delineated for two green stormwater infrastructure sites ("Morris Leeds" and "Zoo") analysed by Jahangiri (2019); DEM resolution 1–2 ft = 0.3–0.6 m (LiDAR), 3.2 ft ≈ 1 m, 5–10 ft = 1.5–3 m; drainage area in ft² (1 ft² = 0.0929 m²)
Source: adapted from Jahangiri (2019).

3.3 Application of SWMM, StormCAD and HEC-RAS

EPA SWMM is the most frequently used tool in the corpus. It is a dynamic rainfall–runoff and routing model that simulates the transformation of rainfall into surface runoff, the hydraulic regime of sewer and channel networks and the effect of LID controls over time (Rossman, 2015). Palaka et al. (2021) used SWMM and GIS to analyze and redesign the stormwater drains of the central zone of Narsapur town (India), checking channel capacity with Manning's equation. Under data scarcity, Ahmad et al. (2024) generated design hyetographs for Lahore (Pakistan) with the log-Pearson type III distribution and the alternating block method; in a 2.71 km² community, a 2-year storm inundated about 60% of the area, showing that the existing system designed for a 2-year return period was inadequate. In Handan (China), Liu et al. (2022) showed that the increase in impervious surfaces from 32.44% to 76.57% between 1987 and 2017 raised the simulated flood volume from 7.89×10^4 to 3.85×10^5 m³, whereas expansion of the drainage network alone reduced it by 27.56%; the model was checked against 11 flooding locations reported on social media. Ahmed et al. (2026) calibrated a 1D–2D SWMM model for Udon Thani (Thailand) and found the curve number and imperviousness to be the most influential parameters, followed by sub-catchment width and slope. Other applications in the corpus combine SWMM and GIS for campus-scale drainage assessment (Patel et al., 2024), apply large-scale GIS-based urban flood modelling in Ouagadougou (Bouvier et al., 2018) or use remote sensing and GIS to assess flood damage by land-use type (Al Faisal et al., 2018).

StormCAD relies on the Rational Method ($Q = CiA$) and IDF curves for the engineering design of pipe networks. For three developing zones near Dammam (Saudi Arabia), Abd-Elhamid et al. (2020) reported that increasing the runoff coefficient C from 0.2 to 0.6 increased peak discharge 3–7 times and increasing it to 0.8 increased it 4–9 times, depending on the return period, while construction costs rose up to 3.5 times. The 12-fold increase reported in that study refers to the combined worst case in which C increases from 0.2 to 1.0 and the design return period from 5 to 100 years. Because peak discharge is linear in C under the Rational Method, ratios exceeding the ratio of the C values reflect the simultaneous increase in design rainfall intensity with the return period. HEC-RAS, in turn, is suited to 1D/2D modelling of open channels and floodplains: Ertan and Celik (2021) combined a 1D HEC-RAS model, GIS and the Rational Method for a 1,653 ha urban section of the Kağıthane Stream in Istanbul to compare urbanization and GI scenarios.

Table 4 summarizes the main tools. In addition to the tools used in the included studies, it lists widely used 1D/2D packages (MIKE URBAN/MIKE+, InfoWorks ICM, TUFLOW and LISFLOOD-FP) that are discussed in model reviews (Teng et al., 2017; Guo et al., 2021).

Table 4. Main tools used for urban flood modelling

Tool	Model type	Application area	Advantages	Limitations
EPA SWMM	1D hydrological-hydraulic	Urban sewer systems, stormwater runoff, LID scenarios	Dynamic simulation; LID module; free and open source	Requires reliable rainfall and network data for calibration; no 2D surface flow
StormCAD	1D engineering design	Pipe-network design	Rapid peak-discharge estimation with the Rational Method and IDF curves	Steady-state design; does not represent 2D surface inundation
HEC-RAS	1D/2D hydraulic	Open channels, rivers, floodplains	Free; detailed channel and floodplain hydraulics	Requires high-quality geometric data; limited pipe-network representation
PCSWMM 2D	Coupled 1D/2D	Urban flooding and LID scenarios	Couples pipe networks with 2D surface runoff	Commercial; computational demand and calibration effort
MIKE URBAN / MIKE+	Coupled 1D/2D	Urban drainage and surface flooding	Integrated network and surface modelling; widely used by utilities	Commercial licence; high data requirements
InfoWorks ICM	Coupled 1D/2D	Integrated catchment modelling	Combined sewer, river and surface flow in one model	Commercial licence; high data requirements
TUFLOW	1D/2D hydrodynamic	Overland and urban flooding	Detailed 2D solution on high-resolution grids	Commercial licence; computational cost at fine resolution
LISFLOOD-FP	2D raster-based	Large-area inundation	Computationally efficient; suitable for large domains (Bates & De Roo, 2000)	Simplified physics; usually no explicit pipe network
GIS + machine learning	Spatial-statistical	Flood susceptibility mapping	Uses many conditioning factors; does not need a drainage network	Depends on flood inventory quality; no hydraulic process representation

Source: compiled by the authors based on Rossman (2015), Teng et al. (2017), Guo et al. (2021) and the included studies.

3.4 Effectiveness of green infrastructure and LID/SUDS

GI/LID/SUDS elements are designed to retain stormwater at the source, increase infiltration, slow surface runoff and reduce the peak load on drainage networks. They include rain gardens, bioretention cells, permeable pavements, infiltration trenches, green roofs and detention ponds (Greco & Larsen, 2014; Porse, 2018; Skrygan et al., 2018). The quantitative results of the included GI studies are summarized in Table 5. They differ not only in magnitude but also in what is measured: runoff volume, peak discharge, flooded area or channel conveyance.

Table 5. Reported effects of GI/LID/SUDS measures in the included studies

Study, city	Approach	Metric	Reported effect	Calibration / validation
Al Amin et al. (2024), Palembang, Indonesia	PCSWMM 2D; five LID types on 9.81% of an 18.37 km ² catchment; 2- to 25-year storms	Runoff volume; peak discharge	Volume -21.0 to -35.4%; peak -11.3 to -37.7%	Calibrated against the December 2021 flood (NSE = 0.948; r = 0.987)
Sehrawat & Shekhar (2025), Gurugram, India	SWMM + GIS; green roofs, permeable pavements, rain barrels in eight high-runoff sub-catchments; 2- to 10-year storms	Runoff volume; peak discharge	Green roofs about -41% volume; combined LID up to -72.31% volume and -54.05% peak	Compared with Rational Method estimates (NSE, RMSE), not with observed floods
Ertan & Celik (2021), Istanbul, Turkey	1D HEC-RAS + GIS + Rational Method; six urbanization/GI scenarios	Flooded area (flood mitigation rate)	Combined GI scenario -36.94%; green roofs + permeable pavements -18.93%; full urbanization without GI +86.89%	No calibration described
Greco & Larsen (2014), Sacramento River, USA	Channel-width and roughness scenarios for flood-control channels	Conveyance (Manning's n allowed)	Wider channel allowed nearly four times higher roughness (riparian vegetation) while keeping 100-200-year protection	Scenario analysis
Porse (2018), Los Angeles, USA	GIS and open data; statistical analysis of sewer locations and sociodemographic indicators	Spatial priority	Watersheds suitable for multi-benefit, equity-oriented GI projects identified	Not applicable
Jahangiri (2019), USA	ArchHydro + LiDAR; automated GSI drainage-area delineation	Drainage area	Delineated area strongly dependent on DEM resolution (Figure 3)	Agreement with design drainage areas reported

Source: compiled by the authors.

3.5 Flood risk, uncertainty and machine learning

Urban flood risk assessment combines the components of hazard, vulnerability and exposure. Apel et al. (2004), Tsakiris (2014) and Merz et al. (2014) emphasize the need to assess flood risk probabilistically, to account for uncertainty and to model scenarios under climate change. Monte Carlo methods, return periods and IDF curves are important for testing the reliability of drainage infrastructure. For Almaty, Mukhanbet et al. (2026) analyzed annual maximum precipitation at five stations for 2000–2023, found the generalized extreme value distribution to fit best at most stations and derived design rainfall for 10-, 50- and 100-year return periods. At the regional scale, Ceresa et al. (2025) built a probabilistic riverine flood risk model for the five Central Asian countries using the TOPKAPI-X hydrological model (1 km grid) and the CA2D inundation model (about 90 m), validated against discharge observations, satellite flood extents and historical losses.

Machine learning methods are increasingly combined with GIS layers to map flood susceptibility. Algorithms such as random forest, gradient boosting, GARP and QUEST can analyze topography, impervious surfaces, rainfall, drainage density and land use together (Mosavi et al., 2018; Darabi et al., 2019). Linh et al. (2026) applied random forest, XGBoost and AdaBoost with SHAP-based explanation to map flood susceptibility in Jalal-Abad, Osh and Tokmok (Kyrgyzstan), using a Sentinel-1 flood inventory; success and prediction rates exceeded 84%. Darabi et al. (2019) mapped urban flood risk in Sari (Iran) from 113 flooded locations, with AUC-ROC values of 93.5% for GARP and 89.2% for QUEST. These models do not require a digitized drainage network, which makes them attractive under data scarcity, but they depend on the quality of historical flood inventories, require independent validation and do not represent hydraulic processes.

3.6 Calibration and data availability in the primary studies

The extraction (Appendix A) shows large differences in the evidence base of the primary studies. Calibration or validation against observed flood data was reported explicitly by Abedin and Stephen (2019; flood depth from photographs), Liu et al. (2022; social-media reports), Al Amin et al. (2024; NSE = 0.948) and Ceresa et al. (2025; discharge, satellite extents and losses), and machine learning studies validated their susceptibility maps against flood inventories. In contrast, Vahida and Sahoo (2022) and Ertan and Celik (2021) did not report calibration, and Dieme et al. (2025) state explicitly that the necessary data for validating their Dakar model could not be obtained. Several studies replaced missing observations with proxies: design hyetographs derived from daily rainfall (Ahmad et al., 2024; Ali & Mawlood, 2023), satellite rainfall and DEM products (Sehrawat & Shekhar, 2025) or crowdsourced flood reports (Liu et al., 2022).

4 Discussion

4.1 Why reported effects of green infrastructure differ between cities

The reported GI/LID effects range from about 11% to more than 70% (Table 5), but these numbers cannot be combined into a single range. First, they refer to different metrics: runoff volume and peak discharge (Al Amin et al., 2024; Sehrawat & Shekhar, 2025) respond differently from the flooded area (Ertan & Celik, 2021), and a reduction in runoff volume does not translate proportionally into a reduction in flood extent. Second, the effect depends on the design storm: in Palembang the reductions span 21.0–35.4% for volume and 11.3–37.7% for peak discharge across 2- to 25-year storms, consistent with reviews showing that LID performance generally declines as storm size increases (Ahiablame et al., 2012; Eckart et al., 2017). Third, the implementation area and placement differ: 9.81% of the catchment in Palembang versus eight selected high-runoff sub-catchments in Gurugram. Fourth, soil infiltration capacity, baseline imperviousness and maintenance condition all modify performance (Eckart et al., 2017). Finally, the evidence differs in strength: only the Palembang model was calibrated against an observed flood, whereas the Gurugram model was compared with Rational Method estimates and the Istanbul model was not calibrated. GI effectiveness should therefore be reported together with the metric, design storm,

implementation area and calibration status, and verified through local modelling rather than transferred as a universal percentage.

4.2 Common data limitations and model combinations under data scarcity

The most common limitations are incomplete or undigitized drainage-network data, rainfall records available only at daily resolution, coarse DEMs that do not resolve urban microrelief, and the absence of observed flood depths or extents for calibration. The studies suggest several practical combinations for such conditions. Where network data exist but rainfall data are short, SWMM can be driven by design hyetographs derived from frequency analysis and the alternating block method (Ahmad et al., 2024). Where calibration data are scarce, sensitivity analysis helps to concentrate the calibration effort on the most influential parameters, such as the curve number and imperviousness (Ahmed et al., 2026). Crowdsourced reports and photographs can provide qualitative validation (Abedin & Stephen, 2019; Liu et al., 2022). Where no network data exist, GIS-based simplified routing (Dieme et al., 2025) or machine-learning susceptibility maps (Darabi et al., 2019; Linh et al., 2026) can be used for screening, followed by detailed 1D/2D modelling in priority areas. Reliance on a single model is therefore insufficient: GIS integrates spatial data, SWMM simulates rainfall–runoff and network dynamics, StormCAD supports pipe design, HEC-RAS represents open-channel flow and machine learning assesses multi-factor susceptibility.

4.3 Implications for Central Asian cities and aryk-drainage systems

Peer-reviewed evidence on urban drainage in Central Asian cities remains limited, but the available studies outline the main conditions. In Almaty, extreme rainfall shows strong spatial variability across stations and is best described by the generalized extreme value distribution (Mukhanbet et al., 2026), and urbanization-related groundwater flooding has been documented in the Akbulak micro-district in the north of the city, where reduced infiltration and the clogging of a Karasu-type stream concentrated runoff that then recharged a shallow aquifer (Mirlas et al., 2025). Regional risk modelling covers riverine floods at a resolution of about 90 m (Ceresa et al., 2025), which is too coarse for street-scale pluvial flooding, and machine learning has been applied to flood susceptibility in three Kyrgyz cities (Linh et al., 2026). Grey literature documents the reconstruction of aryk networks and storm sewers in eastern Almaty (Zhumabekov, 2021) and the influence of the urban landscape on rainfall flood hazard (Myagkov et al., 2021).

Aryk networks differ from the pipe systems for which most tools were developed. They are open, often irregular channels that combine irrigation and stormwater functions, are prone to clogging by sediment and debris, and run down steep foothill gradients. In SWMM they can be represented as open conduits with irregular cross-sections, and in HEC-RAS as channels coupled with 2D overland flow; however, both require surveyed cross-sections, inverts and connections that are usually not digitized. A clogging factor, as used by Abedin and Stephen (2019) for inlets, may also be relevant for aryk inlets and culverts. At the same time, aryks offer an opportunity for GI: vegetated aryk corridors and adjacent tree strips could function as bioswales and infiltration trenches if their capacity and maintenance are ensured.

4.4 Limitations of this review

This review has several limitations. It is a narrative review with a PRISMA-informed selection procedure rather than a registered systematic review, and no meta-analysis was performed because of the heterogeneity of metrics and models. The corpus is small (33 sources) and includes five grey-literature sources (two theses or conference papers and three Russian-language reports), which were retained to represent under-studied regions but were not used for quantitative comparison. The numbers of records at the identification and screening stages were not recorded, which limits the reproducibility of the search. Some information in Appendix A could not be extracted because it was not reported in the original studies.

Finally, the search was limited to English, Russian and Kazakh sources, so studies in other languages (e.g., Chinese) may be under-represented.

5 Conclusion

This critical review synthesized GIS, SWMM, StormCAD, HEC-RAS, GI/LID/SUDS and machine learning approaches to urban flood management on the basis of 33 sources, 26 of which are primary case or modelling studies. GIS platforms play a central role in the spatial analysis of urban drainage, whereas SWMM, StormCAD and HEC-RAS have complementary functions in evaluating rainfall–runoff dynamics, pipe design and open-channel flood propagation. High-resolution DEM/LiDAR data substantially change the delineated drainage areas and therefore the model results.

Reported GI/LID effects are context-specific: depending on the metric, design storm, implementation area and calibration status, they range from about 11% to more than 70% and should not be generalized as a single percentage. Calibration against observed flood data was reported in only some of the primary studies, which limits the comparability of the results.

For Central Asian cities, and for the aryk-drainage system of Almaty in particular, the following practical steps are recommended: (1) digitize the aryk and storm-sewer network, including cross-sections, inverts, culverts and connections, using GNSS and UAV/LiDAR surveys; (2) derive design hyetographs from local extreme-rainfall statistics (Mukhanbet et al., 2026); (3) represent aryks as open channels in a coupled 1D/2D model and calibrate it with observed flooding locations, including crowdsourced reports; and (4) test GI options such as vegetated aryk corridors, bioswales and permeable pavements in priority sub-catchments, together with maintenance scenarios.

Future research should prioritize (i) observed flood-depth and extent datasets for calibrating models in Central Asian cities; (ii) comparative studies of the hydraulic, ecological and economic effectiveness of GI under local soil and climate conditions; (iii) the joint modelling of pluvial and groundwater flooding, as indicated for northern Almaty; and (iv) near-real-time monitoring systems that integrate GIS, SWMM/HEC-RAS, IoT sensors and machine learning.

Appendix A. Data extraction for the primary studies (n = 26)

Table A1. Data extraction for the primary studies included in the review

Study	Location	Tools / model	Main input data	Calibration / validation	Main quantitative result
Apel et al. (2004)	Rhine reaches downstream of Cologne, Germany	Stochastic flood-risk model of simplified process components in a two-layer Monte Carlo framework	Parameters derived from deterministic DFNK process models (rainfall to damage)	Not applicable (uncertainty analysis)	Epistemic uncertainty significantly altered risk estimates obtained from aleatory uncertainty alone
Greco & Larsen (2014)	Sacramento River flood-control system, USA	Channel-width and Manning's n scenarios	Channel geometry, design floods	Scenario analysis	Wider main channel allowed nearly four times higher roughness while keeping 100–200-year protection
Bouvier et al. (2018)	Ouagadougou, Burkina Faso (whole agglomeration)	GIS-based model: SCS runoff, lag-and-route, kinematic wave in streets and channels	10 m DTM, urban blocks, drainage axes, soils; 1,057 catchments	No validation reported	Flood mapping for the whole city with fast computation, suitable for decision support
Al Faisal et al. (2018)	Naogaon District, Bangladesh	Remote sensing + GIS (ERDAS Imagine)	Landsat TM/OLI images, 2004–2017	Not applicable	Flood-related land-use losses by year (built-up and agricultural land)

Table A1. (Continued)

Study	Location	Tools / model	Main input data	Calibration / validation	Main quantitative result
Porse (2018)	Los Angeles County, USA	GIS, open data, statistical analysis	Sewer locations, design parameters, sociodemographic data	Not applicable	Watersheds suitable for multi-benefit GI identified
Abedin & Stephen (2019)	UNLV campus, Las Vegas, USA	GIS workflow: delineation, runoff hydrographs, inundation mapping	DEM (best 5 m), rainfall, inlet clogging factor	News reports and photographs	24% error in flood depth (66 vs 86 cm) with clogging factor 0.83
Jahangiri (2019) [thesis]	Two GSI sites, USA	ArcHydro + LiDAR	LiDAR DEM (1–2 ft) and coarser DEMs	Agreement with design drainage areas reported	Drainage area increased several-fold with coarser DEMs (Figure 3)
Darabi et al. (2019)	Sari, Iran	GARP and QUEST machine learning + GIS; fuzzy ANP for vulnerability	113 flooded locations; 8 hazard and 5 vulnerability factors	AUC-ROC and kappa	GARP: AUC 93.5%, $\kappa = 0.86$; QUEST: AUC 89.2%, $\kappa = 0.79$
Abd-Elhamid et al. (2020)	Three zones near Dammam, Saudi Arabia (0.4–0.7 km ²)	StormCAD, Hyfran, GIS	Rainfall series, C = 0.2–1.0, return periods 5–100 years	Design scenarios; no calibration reported	Peak discharge $\times 3$ –7 (C 0.6) and $\times 4$ –9 (C 0.8); $\times 12$ in combined worst case; cost up to $\times 3.5$
Ertan & Celik (2021)	Kağıthane Stream, Istanbul, Turkey (1,653 ha)	1D HEC-RAS + ArcGIS + Rational Method	DEM, 1:1000 base maps, cross-sections, stormwater network	No calibration described	Flooded area $\sim 36.94\%$ (combined GI); $+86.89\%$ under full urbanization
Palaka et al. (2021)	Narsapur town, Telangana, India	SWMM + GIS	Road and drain network survey, elevations	Capacity check with Manning's equation	Redesigned drains to convey peak discharge without inundation
Zhumabekov (2021) [project report]	Eastern Almaty, Kazakhstan	Engineering design and environmental impact assessment of aryk and storm-sewer reconstruction	Project design documentation	Not applicable	Qualitative assessment of planned reconstruction and its environmental impacts
Myagkov et al. (2021) [report]	Uzbekistan	Analysis of urban landscape factors of rainfall flood hazard	Report not available online	Not applicable	Qualitative assessment of the influence of urban landscape on rainfall flood hazard
Vahida & Sahoo (2022) [conference paper]	Saheed Nagar, Bhubaneswar, India (1.47 km ²)	SWMM	Rainfall, sub-catchments, drainage network	None reported	Peak runoff and flow volume at outfalls estimated
Liu et al. (2022)	Handan, China	SWMM + ArcGIS; control-variable scenarios	1 m imagery, drainage database, DEM, 1987–2017	11 flooding points from social media (July 2016)	Flood volume $7.89 \times 10^4 \rightarrow 3.85 \times 10^5$ m ³ with imperviousness 32.44 $\rightarrow$ 76.57%; network expansion -27.56%
Ali & Mawlood (2023)	Erbil, Iraq (23 sub-catchments)	SWMM (dynamic wave, Horton infiltration)	Daily maximum rainfall 1992–2022 converted to hourly (IMD method)	None reported	10–14 flooded nodes per event; network capacity insufficient
Ahmad et al. (2024)	Lahore, Pakistan (2.71 km ²)	GIS-SWMM with LPT-III and alternating block design hyetographs	Rainfall frequency analysis, drainage network	Design-storm scenarios	2-year storm: about 60% of the area inundated
Al Amin et al. (2024)	Bendung watershed, Palembang, Indonesia (18.37 km ²)	PCSWMM 2D + five LID types (9.81% of area)	Observed December 2021 flood, design storms 2–25 years	NSE = 0.948; r = 0.987	Runoff volume ~ 21.0 to -35.4% ; peak ~ 11.3 to -37.7%

Table A1. (Continued)

Study	Location	Tools / model	Main input data	Calibration / validation	Main quantitative result
Patel et al. (2024)	MANIT campus, Bhopal, India	SWMM + ArcGIS	Campus drainage network, rainfall	Not specified	Runoff at outfall nodes analyzed; planning interventions proposed
Sehrawat & Shekhar (2025)	Gurugram, India (eight sub-catchments)	SWMM + GIS; green roofs, permeable pavements, rain barrels	Sentinel-2, ALOS PALSAR DEM, soil data, GPM IMERG 2000–2023	NSE/RMSE vs Rational Method	Combined LID up to –72.31% volume and –54.05% peak
Dieme et al. (2025)	Dakar periphery, Senegal (about 400 km ²)	GIS-based hydrological model + 1D network routing (25 m ² cells)	5 m DTM, building footprints, 297 channel sections, 106 basins, IDF curves	Not validated (no data available)	10-year storm: overflows of 1–18 m ³ /s at several sections
Mirlas et al. (2025)	Akbulak micro-district, northern Almaty, Kazakhstan	Visual MODFLOW groundwater flow model	Field survey of the water table (0.25–1.2 m below ground over 0.07 km ²)	Scenario simulation consistent with field observations	Runoff accumulation up to eight times the annual average precipitation; clogged Karasu-type stream concentrated runoff
Ceresa et al. (2025)	Five Central Asian countries	TOPKAPI-X (1 km) + CA2D (about 90 m) + CAPRA	ERA5-Land 1981–2020, exposure and vulnerability data	Discharge observations, satellite flood extent, historical losses	Highest relative average annual loss in Kazakhstan and Tajikistan (> 6%)
Ahmed et al. (2026)	Udon Thani, Thailand	1D–2D SWMM; one-factor-at-a-time sensitivity analysis	Design storm (5-year, 1-h), catchment data	Iterative calibration to design-storm performance	Curve number and imperviousness most influential
Mukhanbet et al. (2026)	Almaty, Kazakhstan (five stations)	Extreme value analysis (GEV, lognormal, gamma)	Annual maximum precipitation 2000–2023	Goodness-of-fit testing	GEV best fit; design rainfall for 10-, 50- and 100-year return periods
Linh et al. (2026)	Jalal-Abad, Osh and Tokmok, Kyrgyzstan	Random forest, XGBoost, AdaBoost + SHAP	Sentinel-1 flood inventory; flood-contributing factors	AUC-ROC, kappa and other metrics	Success and prediction rates > 84%; very high susceptibility class 8.44%, 12.01% and 37.8% of area

Note: [thesis], [conference paper], [report] – grey literature. NSE – Nash–Sutcliffe efficiency. Source: compiled by the authors.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aruzhan Oserbay	✓	✓		✓	✓	✓	✓	✓	✓	✓				
Yerkin Kakimzhanov	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Naci Yastikli	✓		✓		✓		✓		✓		✓			
Fusun Balik Sanli		✓		✓		✓		✓	✓			✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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Biographies of Authors



Aruzhan Oserbay

Master's student, Department of Cartography and Geoinformatics, Faculty of Geography and Environmental Management, Al-Farabi Kazakh National University, Almaty, Kazakhstan
Geoinformatics
userbai1503@gmail.com
<https://orcid.org/0009-0005-5640-0454>



Yerkin Kakimzhanov

PhD, Associate Professor; Head of the Center for Geospatial Technologies and GeoAI, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan
Geography; Geographic Information Systems (GIS); Remote Sensing; Cartography; Geospatial Technologies; GeoAI
erkinkakimzhanov@gmail.com
<https://orcid.org/0000-0002-1919-6459>
<https://www.scopus.com/authid/detail.uri?authorId=56946816100>



Naci Yastikli

Professor, Department of Geomatic Engineering, Faculty of Civil Engineering, Yildiz Technical University, Istanbul, Türkiye
Geomatic Engineering; Geographic Information Systems; Photogrammetry; Remote Sensing; Image Processing; Laser Scanning; LiDAR; 3D Modeling
ynaci@yildiz.edu.tr
<https://orcid.org/0000-0001-9045-9672>
<https://www.scopus.com/authid/detail.uri?authorId=9247717200>



Fusun Balik Şanlı

Professor, Department of Geomatic Engineering, Faculty of Civil Engineering, Yildiz Technical University, Istanbul, Türkiye
Geographic Information Systems; Environmental Information Systems; Remote Sensing; Image Processing; 3D Modeling
fbalik@yildiz.edu.tr
<https://orcid.org/0000-0003-1243-8299>
<https://www.scopus.com/authid/detail.uri?authorId=23098475900>

Article

Current development trends in pedagogical education: competency-based education in natural sciences

Sholpan Karbayeva ¹, Yenglik Khorgasbay ^{1*}

¹ Abai Kazakh National Pedagogical University, Faculty of Natural Sciences and Geography, Department of Geography and Ecology, Almaty, Kazakhstan; (S.K.) karbaevash@mail.ru, <https://orcid.org/0000-0003-4135-5740>; (Y.K.) enlikt0106@gmail.com, <https://orcid.org/0009-0007-3522-7001>

* Corresponding author: Yenglik Khorgasbay, Kazakhstan, Almaty 050010, 13 Dostyk Avenue, enlikt0106@gmail.com, +77026309301

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SECTION

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Abstract: The reform of national education systems is driven by rapid technological and economic change, unequal access to quality education, the digital economy, the growing mobility of students and teachers, the alignment of qualifications with international standards, the changing role of the teacher (tutor, facilitator, mentor) and the development of lifelong learning. Under these conditions, teacher education has to adopt international standards and good practice and remain flexible, and its leading paradigm is the competency-based approach. The aim of this study is to analyse current trends in the development of pedagogical education and to substantiate competency-based education in the natural sciences, using the innovative educational programmes introduced at Abai Kazakh National Pedagogical University as an example. The study is conceptual and analytical: publications identified in Scopus, Web of Science and Google Scholar, policy documents and programme documentation were examined by content and comparative analysis. The results systematize the main research areas, specify the structural components of competency-based education (target, content, process, assessment, resource and reflective components) and compare international and domestic research on scientific and functional literacy, research competence, digital competence and problem solving in the natural sciences. The implementation of the approach is illustrated by the educational programme 6B01515-Geography, in which new courses link subject knowledge with research-based, practice-oriented, STEM and CLIL teaching and with the Sustainable Development Goals. The study concludes that the successful implementation of competency-based programmes depends on their methodological support and on the continuous professional development of university teachers, and it formulates practical recommendations for programme developers and teaching staff.

* * * * *

1 Introduction

The sustainable development of pedagogical education in Kazakhstan is aimed at the continuous modernization of the education system and its adaptation to the changing requirements of society and the labour market, so that competitive teachers can be trained. It creates conditions for the professional development of teachers through lifelong learning and bases the content of teacher education on competence, innovation and the effective use of digital technologies.

Modern higher education institutions are active organizational systems that take part in the life of society at global and local levels and are continuously transformed by globalization. Carnoy (2016) shows that, under globalization, states give priority to education and change the mission, organizational

structures and educational programmes of universities in order to increase competitiveness. Current trends in teacher education also lead to a reorientation of teaching skills: transversal or meta-disciplinary skills, 21st-century skills and soft skills are in growing demand in the labour market (Deming & Silliman, 2024). These changes reflect a volatile, uncertain, complex and ambiguous (VUCA) world and determine the competencies needed by future professionals.

Digital technologies and the Internet are taking education and training to a new level. Innovation, access to education, sustainability, quality, differentiation and integration, partnership and research-based education have become key concepts in planning the future university (Sagintayeva et al., 2021). Practice-oriented models of teacher training are being developed and implemented, such as the Professional Development School (Hunzicker, 2019) and project-based and work-based learning models used, for example, in Finland and Australia. These models are characterized by an equal partnership between university and school teachers, a close connection with practice and a learning environment that supports the solution of educational problems; they emphasize meta-skills, soft skills and universal competencies (Sharples et al., 2014; Sulima, 2017; Darling-Hammond, 2017).

In the Republic of Kazakhstan, the methodological base of competency-based educational programmes rests on socio-economic, regulatory, scientific, pedagogical and methodological prerequisites that reflect the strategic directions of the national education system. The transformation of higher and postgraduate education gives priority to a competency-based approach, the quality of educational content, learning outcomes expressed as competencies and the formation of the competencies required by the labour market and the economy (Kunanbayeva, 2016). Within the Modernization of Education project of the Ministry of Science and Higher Education and the World Bank, academic staff and experts from Kazakhstani and Finnish higher education institutions carry out two related projects, Strengthening the Capacity of Pedagogical Education (KZEMP/QCBS-03) and Implementation of the Pedagogical Education Model and Strengthening Its Content (KZEMP/DS-02), which aim to develop and harmonize Kazakhstani teacher education and to improve its methodological and regulatory tools (ENIC-Kazakhstan, 2026). The Development Program of Abai University for 2023–2029 sets the goal of implementing an innovative model of pedagogical education as a centre of academic excellence.

The main problem of modern pedagogical education is the gap between the training of future teachers at universities and the innovations introduced in general secondary schools. The traditional information- and subject-centred paradigm is still preserved in the educational process, and teaching methods are insufficiently focused on students' research skills. Growing competition between teacher-training programmes and new requirements for pedagogical universities (a competency-based approach, dual education, multilingualism and practice orientation) call for a redesign of programmes. In the natural sciences this problem is especially acute, because the scientific literacy of school students depends directly on how their teachers were prepared.

The aim of this study is to analyse current trends in the development of pedagogical education and to substantiate competency-based education in the natural sciences. The objectives are: (1) to systematize the main areas of research on trends in pedagogical education; (2) to specify the structural components of competency-based education; (3) to compare international and domestic research on the competencies developed in natural science education; and (4) to show how the approach is implemented in the innovative educational programmes of a pedagogical university, using the Geography programme as an example.

2 Materials and methods

The study is conceptual and analytical. It did not include a pedagogical experiment; its conclusions are based on the analysis of publications, policy documents and programme documentation.

Three groups of sources were examined. The first group comprised scientific publications. International publications were searched in Scopus and Web of Science, and Kazakhstani and Russian-language publications in Google Scholar, using the keywords “competency-based education”, “competence

approach", "teacher education", "pedagogical education", "natural science education", "scientific literacy", "functional literacy" and "professional competence of teachers" in English, Kazakh and Russian. Publications were included if they addressed teacher education or natural science education, described a concept, model or empirical result related to competencies, and were available in full text; foundational works were included irrespective of their year of publication. The second group comprised reports and frameworks of international organizations (UNESCO, the OECD and the European Commission). The third group comprised national and institutional documents: the Concept for the Development of Pedagogical Education, the Development Program of Abai University for 2023–2029, the documentation of the World Bank projects and the innovative educational programmes in the natural sciences.

The sources were analysed in three steps. Content analysis was used to assign publications to research areas (the theory and development of education, the competency approach, and digitalization and innovation) and to identify the structural components of competency-based education. Comparative analysis was used to relate international and domestic findings on the competencies developed in natural science education. Finally, the documentation of the educational programme 6B01515 - Geography was analysed to show how the components are implemented in practice. A systems approach was applied throughout, in which the phenomenon under study is considered as a system of interconnected elements.

3 Results and discussion

3.1 Research areas and trends in pedagogical education

The content analysis showed that research on trends in pedagogical education forms four areas (Table 1). Studies of the theory and development of education consider teacher training, educational policy and teaching quality as a continuous process aimed at forming the teacher's professional competence. In this view, the modern teacher is not only an educator but also a facilitator, researcher, reflective practitioner and organizer of an innovative learning environment, so teacher education programmes should focus on competency-based and practice-oriented training, a culture of inquiry and lifelong professional development (Darling-Hammond, 2017; Loughran, 2006; Grossman, 2018). Shulman (1986) showed that teaching requires pedagogical content knowledge, that is, the integration of subject knowledge with knowledge of how to teach it.

Table 1. Areas of research on trends in the development of modern education

Research area	International scholars and organizations	Scholars of Kazakhstan and the CIS	Main focus
Theory and development of education	L. Darling-Hammond, L. Shulman, A. Hargreaves, J. Loughran, P. Grossman	V.V. Kraevsky, I.Ya. Lerner, M.N. Skatkin, E.V. Bondarevskaya, V.V. Serikov, N.D. Khmel, A.A. Beisenbayeva	Teacher training, content of education, teaching quality, holistic pedagogical process
Competency approach	P. Perrenoud, G. Le Boterf, J. Delors	V.A. Slstenin, V.A. Bolotov, A.V. Khutorskoy, K.K. Zhampeisova, N.N. Khan, M.Zh. Zhadrina, S.S. Kunanbayeva	Competence as the mobilization of knowledge and experience in a specific situation; key competencies
Digitalization and innovation in education	P. Mishra, M. Koehler	E.D. Patarakin, A.Yu. Uvarov, M.V. Moiseeva, E.S. Polat, Zh.A. Karaev, Zh. Sardarova, G. Salgaraeva	Technological pedagogical content knowledge; digital learning environment
Frameworks of international organizations	UNESCO, OECD, European Commission, Education International	–	Key competences for lifelong learning; scientific literacy; education for sustainable development

Source: compiled by the authors.

Kraevsky and Berezhnova (2006) treat education as a socio-cultural process that ensures the all-round development of the personality; its content should combine scientific knowledge, practical experience,

creative experience and value orientations. The development of pedagogical education therefore requires that the content of education be updated on a scientific basis and that teachers be able to design the educational process. In Kazakhstan, the theory of the holistic pedagogical process (Khmel, 1998) shows that professional experience is formed when theory is combined with practice.

The competency approach treats the outcome of education not as a set of knowledge, skills and abilities but as the ability to mobilize knowledge and experience in a specific professional situation. Le Boterf (2018) defines competence as the ability of an individual to mobilize knowledge, experience, skills and other resources effectively in a professional or life situation; competence is therefore determined not by the possession of knowledge but by its effective application. Khutorskoy (2013) considers the main result of competency-based education to be a competent person who can apply theoretical knowledge in practice. The European framework of key competences for lifelong learning describes competences as a combination of knowledge, skills and attitudes that are formed in formal, non-formal and informal learning and are assessed by their application in specific situations (European Commission, 2019). These works form the methodological foundation of the modern competency-based model and of the unity of theory and practice in teacher education.

3.2 Structural components of competency-based education

On the basis of the analysed works, competency-based education can be described as a system of six interrelated components (Table 2). The target component defines competencies as intended learning outcomes; the content component organizes the curriculum in modules around these outcomes; the process component relies on active, research-based and practice-oriented methods; the assessment component uses criterion-based assessment of performance; the resource component provides a digital learning environment and partnership with schools; and the reflective component supports self-assessment and continuous professional development (Loughran, 2002). The components are implemented together: a change in learning outcomes requires corresponding changes in content, methods and assessment.

Table 2. Structural components of competency-based education and their implementation in natural science teacher education

Component	Content	Example of implementation in the educational programme 6B01515 Geography
Target	Competencies formulated as learning outcomes of the programme, modules and courses	The programme aims to train geography teachers with subject, communicative, digital and professional competencies and inclusive education skills
Content	Modular curriculum; integration of subject, pedagogical and research content; Sustainable Development Goals	Courses "Theories and concepts of modern geography", "Environment and sustainable development", "Climate change and its consequences"
Process	Active, student-centred, research-based and practice-oriented methods; STEM/STEAM, CLIL, inquiry-based learning	Course "Geographical research, development and innovation"; independent monitoring of weather and climate change
Assessment	Criterion-based assessment of learning outcomes in authentic tasks	Learning outcomes of each course are formulated as observable actions (analyses, assesses, applies)
Resource	Digital and artificial intelligence tools; partnership between university and school; teaching materials	Educational and methodological support of the programme; pedagogical practice at schools
Reflective	Self-assessment, reflective practice, continuous professional development	Course "Planning geography teaching and individualization of teaching"; professional development of university teachers

Source: compiled by the authors.

3.3 Research on competencies in natural science education

The second objective of the analysis was to compare research on the competencies that natural science education is expected to develop (Table 3). Scientific literacy is the central concept. Roberts (2007) distinguishes two visions: one oriented towards the concepts and methods of science itself and the other towards situations in which citizens meet science in everyday life. The OECD framework follows the second vision and defines scientific literacy through three competencies: explaining phenomena scientifically, evaluating and designing scientific enquiry, and interpreting data and evidence scientifically (OECD, 2019). In Kazakhstan, the corresponding concept is functional literacy, understood as the ability to apply knowledge in real situations; it has become an explicit goal of school and teacher education.

Research competence is developed mainly through inquiry-based learning, whose phases are orientation, conceptualization, investigation, conclusion and discussion (Pedaste et al., 2015). A meta-analysis of experimental and quasi-experimental studies showed a positive mean effect of inquiry-based science teaching on learning of about half a standard deviation, with larger effects for teacher-guided than for student-led inquiry (Furtak et al., 2012). For geography, Sadykova et al. (2023) validated a scale of geographic inquiry process skills on a sample of Kazakhstani school students and showed that inquiry should be assessed as a set of interrelated procedural skills. Digital competence is described by the technological pedagogical content knowledge framework (Mishra & Koehler, 2006) and by the European framework for the digital competence of educators (Redecker, 2017). Problem solving and transversal skills are emphasized in the key-competence frameworks (European Commission, 2019) and in education for sustainable development (UNESCO, 2017).

Table 3. Comparison of international and domestic research on competencies in natural science education

Competence	International research and frameworks	Research and practice in Kazakhstan	Main finding
Scientific and functional literacy	Roberts (2007); OECD (2019)	Functional literacy as a goal of updated school content; PISA results (OECD, 2023)	Literacy means applying knowledge in real contexts; in PISA 2022 the mean science score of Kazakhstan was 423 points against an OECD average of 485
Research (inquiry) competence	Pedaste et al. (2015); Furtak et al. (2012)	Sadykova et al. (2023); research-based courses in innovative programmes	Guided inquiry improves learning; inquiry skills should be taught and assessed as interrelated procedures
Pedagogical content knowledge	Shulman (1986); Grossman (2018); Loughran (2006)	Theory of the holistic pedagogical process (Khmel, 1998)	Subject and pedagogical knowledge should be integrated and practised in core teaching practices
Digital competence	Mishra & Koehler (2006); Redecker (2017)	Digital and artificial intelligence tools in programme outcomes	Technology should be integrated with content and pedagogy rather than taught separately
Problem solving and transversal skills	European Commission (2019); UNESCO (2017); Deming & Silliman (2024)	Competence-based approach in higher education (Kunanbayeva, 2016)	Transversal skills are in growing demand and are formed in authentic, interdisciplinary tasks

Source: compiled by the authors.

The comparison shows that international and domestic research agree on the goal – the ability to apply knowledge – but differ in emphasis. International studies provide operational frameworks and empirical evidence on the effectiveness of particular methods, whereas domestic studies have concentrated on the theoretical justification of the competency approach and on programme design; empirical studies of the competencies of natural science students and teachers are still few. The gap between Kazakhstan and the OECD average in the PISA science results (OECD, 2023) indicates that the application of knowledge remains a weak point and confirms the need to prepare teachers who can organize inquiry and work with data and evidence.

3.4 Implementation in the innovative educational programmes of pedagogical universities

Academic staff of the pedagogical universities of Kazakhstan have developed and introduced educational programmes in the field of Pedagogical Sciences within the World Bank project on strengthening the capacity of pedagogical education. The main goal of these programmes is to enable students to act in changing situations, to develop their knowledge independently and to make responsible decisions. Since the 2023–2024 academic year, innovative educational programmes (IP) have been introduced at pedagogical universities, including Abai Kazakh National Pedagogical University, in order to implement competency-based education in the natural sciences, and 100–150 university teachers have upgraded their qualifications.

As a result, the professional competence of teachers of the natural sciences has been developed in the following areas: the use of competency-based teaching methodologies and innovative pedagogical technologies; the formation of students' functional literacy; criterion-based assessment of learning outcomes; the use of digital and artificial intelligence tools; interdisciplinary links; STEM/STEAM, CLIL and inquiry-based teaching methods; the integration of the Sustainable Development Goals into teaching; and the formation of students' 21st-century skills.

The educational programme 6B01515 Geography illustrates this approach. Its goal is to train geography teachers who have modern subject, communicative, digital and professional competencies and inclusive education skills and are able to create high-quality educational content and organize the educational process. The competence of a geography teacher combines pedagogical and subject-specific competencies: knowledge of the theory and methodology of geography, practical methods of teaching geography, research competencies and value orientations. The programme integrates practice-oriented models of teaching, in particular STEM and content and language integrated learning (CLIL), which bring theoretical knowledge closer to real situations. Several new courses were introduced into the cycles of basic and major disciplines (Table 4).

Table 4. Examples of new courses in the educational programme 6B01515 - Geography (IP)

No.	Module	Course	Purpose	Learning outcomes
1	Supporting learners as individuals	Planning geography teaching and individualization of teaching	To develop skills in individualizing teaching, taking into account learner diversity and using geography teaching technologies on the basis of pedagogical and independent research	Applies the principles of teaching and guidance to learners as individuals; takes individual needs into account; supports personal development and self-esteem
2	Teacher – regulatory practitioner	Geographical research, development and innovation	To form research-oriented thinking and the ability to develop, update and apply innovative methods and technologies of teaching geography in a changing society and educational environment	Develops teaching skills through research-based approaches; takes part in research and in cooperation between the university and stakeholders
3	Geographical picture of the world	Theories and concepts of modern geography	To acquire knowledge of the geographical sciences and of modern theories and concepts of geography	Knows the conceptual ideas underlying methodological and theoretical content; selects research methods suitable for teaching; applies developments in geographical science in the educational process
4	Interaction of society and nature	Environment and sustainable development	To study the current state of the environment and the sustainable development of regions	Studies the interaction between humans and the environment; analyses the sustainable development of Kazakhstan; assesses the state of the environment
5	Interaction of society and nature	Climate change and its consequences	To study current issues of global climate change	Monitors weather and climate change independently; analyses approaches to studying climate change

Note: the title, purpose and learning outcomes of several newly introduced courses are given as examples. Source: compiled by the authors from the programme documentation.

The examples show how the structural components in Table 2 are implemented. The learning outcomes are formulated as actions that can be observed and assessed; the content links geographical science with sustainable development and climate change; and the courses on research and on the individualization of teaching develop research and reflective competencies. Competency-based programmes also take into account what motivates students to participate fully in learning: the active methods used in basic and major courses support students' independence and take their social, cultural, cognitive and motivational characteristics into account.

The analysis also revealed a need for educational and methodological support. The innovative programmes in the natural sciences require systematic teaching materials of a scientific and applied nature, presented in a form convenient for learning and teaching and organized by structure, function and competence. Developing this methodological base is a condition for a stable and effective learning environment.

The study has limitations. It is based on the analysis of literature and documents and does not report experimental or pilot data on the effectiveness of the programmes; the outcomes of the innovative programmes, including the competencies of their first graduates, should be evaluated empirically in further research.

4 Conclusion

Despite changes in the economy and society, the demand for well-prepared teachers remains high, and the requirements for them are changing with technology and educational standards. The analysis of the theoretical foundations of competency-based education and of international experience (the OECD, UNESCO, the European Commission and practice-oriented models of teacher education) showed that modern pedagogical education is moving from the transmission of knowledge to the development of professional competence, research skills, reflective practice and the ability to apply knowledge in real educational situations.

Competency-based education was described as a system of target, content, process, assessment, resource and reflective components. The comparison of research on the natural sciences showed agreement on the goal of applying knowledge and a shortage of domestic empirical studies. The innovative educational programmes introduced at pedagogical universities of Kazakhstan since 2023–2024, illustrated by the Geography programme, implement these components through new courses, research-based and practice-oriented teaching and the professional development of university teachers.

On this basis, the following practical recommendations are proposed. (1) Programme developers should formulate learning outcomes as assessable competencies and align the content, teaching methods and criterion-based assessment of every course with them. (2) Universities should provide innovative programmes in the natural sciences with systematic educational and methodological materials and update them regularly using feedback from students, graduates and employers. (3) The continuous professional development of university teachers should focus on competency-based teaching and assessment, digital and artificial intelligence tools, and STEM, CLIL and inquiry-based methods. (4) Research-based learning and partnership with schools should be extended so that students apply their knowledge in real pedagogical situations. (5) The effectiveness of competency-based programmes should be monitored empirically, including the scientific and functional literacy and research competence of students.

The implementation of competency-based educational programmes in the natural sciences within the new model of pedagogical education is a key stage of the reform of higher education in Kazakhstan. Its success depends on the methodological support of the programmes and on strengthening the capacity of the teaching staff.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sholpan Karbayeva	✓	✓				✓	✓	✓	✓	✓				

Yenglik Khorgasbay	✓		✓	✓	✓		✓		✓	✓	✓	✓		
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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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Biographies of Authors



Sholpan Karbayeva

Candidate of Pedagogical Sciences, Associate Professor, Department of Geography and Ecology, Faculty of Natural Sciences and Geography, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan

Geography education; teaching technology; methodology

karbaevash@mail.ru

<https://orcid.org/0000-0003-4135-5740>

<https://www.scopus.com/authid/detail.uri?authorId=57223021799>



Yenglik Khorgasbay

PhD, Department of Geography and Ecology, Faculty of Natural Sciences and Geography, Abay Kazakh National Pedagogical University, Almaty, Kazakhstan

Geography education

ekhorgasbay@abayuniversity.edu.kz

<https://orcid.org/0009-0007-3522-7001>

<https://www.scopus.com/authid/detail.uri?authorId=57913097600>