

Digital terrain modeling for hydrological analysis and territorial planning in eastern and southeastern regions of Kazakhstan

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Citation: Arystanov, A., Arystanova, R., Kabzhanova, G., Sagin, J., Kutymova, N., Abdikhalykova, D., Mamayeva, A. (2026). Digital terrain modeling for hydrological analysis and territorial planning in eastern and southeastern regions of Kazakhstan. Bulletin of the L.N. Gumilyov ENU. Chemistry, Geography Series, 156(3), 141-159. <https://doi.org/10.32523/3107-278X-2026-156-3-141-159>

Academic Editor:
A.M. Sergeyeva

Received: 17.07.2026

Revised: 03.08.2026

Accepted: 07.09.2026

Published: 30.09.2026



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Abstract: This study presents a standardized regional workflow for deriving a Sentinel-1 repeat-pass InSAR elevation product for Almaty, Zhetysu, Zhambyl, Abai, and East Kazakhstan regions. The study does not propose a new interferometric algorithm; its contribution is the consistent application of a common processing framework across five orographically contrasting territories and the explicit definition of its methodological limitations. Sentinel-1 SLC pairs were selected using temporal interval, orbit consistency, perpendicular baseline, spatial overlap, and expected coherence. Processing included S-1 Back Geocoding and Enhanced Spectral Diversity in SNAP, interferogram and coherence generation, Goldstein filtering, SNAPHU phase unwrapping, phase-to-elevation conversion, mosaicking, and GIS post-processing. No independent ground-control, GNSS, geodetic, or satellite-altimetry dataset was available for this study; consequently, ME, MAE, RMSE, NMAD, and percentile-based vertical-error statistics were not calculated. Coherence and visual consistency of the regional relief were used only as qualitative quality indicators and are not presented as substitutes for independent vertical validation. The resulting product is therefore interpreted as a regional analytical elevation layer for generalized terrain screening and preliminary relief interpretation. It is not intended for local flood-depth modeling, engineering design, irrigation grading, or microrelief reconstruction without LiDAR, UAV photogrammetry, or ground geodetic data.

Keywords: Sentinel-1; InSAR; regional elevation model; qualitative quality assessment; coherence; methodological limitations; territorial planning; Kazakhstan.

1. Introduction

Digital elevation models are one of the fundamental geospatial layers used in remote sensing, geographic information systems, hydrological modeling, geomorphological interpretation, and environmental risk assessment (Massonnet & Feigl, 199; Bamler & Hartl, 1998). In regions with complex relief, the quality of a terrain model directly determines the reliability of derived products such as slope, aspect, flow direction, flow accumulation, watershed boundaries (Hanssen, 2001; Bürgmann et al., 2000), erosion susceptibility, and potential flood concentration zones. For eastern and southeastern Kazakhstan, terrain information is especially important because the territory combines extensive plains, piedmont surfaces, intermontane depressions, high mountain systems, and sharply dissected valleys.

The study area includes Almaty, Zhetysu, Zhambyl, Abai, and East Kazakhstan regions. These territories form a large orographically heterogeneous belt where natural and economic processes are strongly controlled by relief. The spatial redistribution of meltwater and storm runoff, the intensity of slope erosion, the development of temporary watercourses, the location of alluvial fans, the configuration of agricultural fields, and the risk of local flooding are all related to elevation differences and morphometric structure. Therefore, a consistent regional digital terrain model is required not only as a cartographic product, but also as an analytical basis for territorial planning (Pike et al., 2009; Reuter & Nelson, 2009).

Synthetic aperture radar interferometry is an effective approach for deriving terrain information because radar data are less dependent on cloud cover and illumination conditions than optical imagery (Arystanov et al., 2024; Kabzhanova et al., 2025). Sentinel-1 provides open C-band radar observations suitable for interferometric analysis when SLC products with phase information are used. InSAR processing reconstructs height-related information from the phase difference of two coherent radar acquisitions. However, the final quality of an InSAR-derived DEM depends on scene selection, temporal decorrelation, orbital geometry, baseline length, co-registration accuracy, phase noise filtering, phase unwrapping, and post-processing in a GIS environment (Arystanov et al., 2025; Arystanov et al., 2026a).

The purpose of this study is to develop and describe a regional workflow for constructing a digital elevation model from Sentinel-1 data and to assess its applicability for hydrological analysis and territorial planning in five regions of Kazakhstan (Sarsekova et al., 2026; Arystanov et al., 2026b). The specific tasks were to select coherent Sentinel-1 SLC pairs, perform the complete InSAR processing chain in SNAP, export and post-process the DEM in ArcGIS, prepare elevation and hillshade maps, calculate morphometric and hydrological derivatives, and interpret the practical value and limitations of the resulting terrain model (Mukanov et al., 2026; Kyrgyzbay et al., 2026).

The present study does not propose a new InSAR algorithm and does not provide an independent quantitative vertical-accuracy assessment. Its contribution is regional and methodological: a common processing sequence is applied across five orographically contrasting regions, while the limitations caused by coherence loss, radar geometry, phase unwrapping, external DEM assistance, and the absence of ground control are stated explicitly. Accordingly, the work should be interpreted as a regional workflow demonstration rather than as a validated high-accuracy DEM product.

2. Materials and methods

2.1. Literature review

The theoretical basis of radar interferometry has been developed in a series of fundamental studies demonstrating that phase differences between coherent synthetic aperture radar scenes can be used to reconstruct topography and detect surface deformation. The accuracy of such products depends on co-registration, coherence, viewing geometry, residual orbital errors, atmospheric effects, and the correctness of phase unwrapping (Torres et al., 2012). These factors are especially relevant in mountain and piedmont environments, where shadowing, layover, steep slopes, and rapid spatial changes of backscatter complicate phase interpretation.

With the launch of Sentinel-1, operational InSAR processing shifted toward repeatable workflows based on TOPS-mode data. Sentinel-1 as a key Copernicus radar mission designed for regular Earth observation (Yagüe-Martínez et al., 2016). Later, that accurate co-registration is critical for TOPS interferometry because even small azimuthal shifts can produce phase discontinuities at burst boundaries (Foumelis et al., 2018). The practical implementation of Sentinel-1 processing chains has been supported by the Sentinel-1 Toolbox and SNAP environment, which provide standard modules for back-geocoding, Enhanced Spectral Diversity correction, interferogram formation, filtering, geocoding, and export (Chen & Zebker, 2002).

Phase unwrapping is another key component of InSAR-based DEM production. Since the measured phase is wrapped within the interval from $-\pi$ to $+\pi$, the continuous phase surface must be reconstructed before elevation interpretation. The SNAPHU algorithm, based on statistical-cost and network-flow principles, is widely used for large interferograms and complex landscapes (Tarboton, 1997). Its performance depends on local coherence, phase filtering, segmentation parameters, and the presence of noise or discontinuities. For regional terrain mapping, unwrapping errors must be controlled by visual interpretation and subsequent GIS-based consistency checks.

A separate body of literature considers DEMs as a basis for hydrological and geomorphometric analysis. Methods for deriving flow direction and upslope contributing area from raster elevation data were formalized. Broader concepts of terrain analysis include slope, aspect, curvature, drainage structure, and morphometric interpretation. These studies demonstrate that the analytical value of a DEM depends not only on its nominal pixel size, but also on its vertical accuracy, hydrological conditioning, and suitability for the scale of the applied task (Sanders, 2007).

Recent studies demonstrate that the accuracy of global and InSAR-derived DEMs varies with slope, land cover, and terrain complexity. Comparisons using GPS, LiDAR, and ICESat-2 reference data show that a DEM may perform adequately in low-relief open terrain but degrade markedly on steep slopes, in forested areas, and near water surfaces (Kramm & Hoffmeister, 2022; Li et al., 2022; Zhang et al., 2024). For hydrological applications, this uncertainty directly affects drainage extraction, watershed boundaries, and modeled inundation extent (Sanders, 2007; Mohammadi et al., 2020). Consequently, a Sentinel-1 InSAR elevation product must be validated independently and its fitness for use must be stated explicitly rather than inferred from pixel spacing or visual similarity alone.

2.2. Study area

The study covers Almaty, Zhetysu, Zhambyl, Abai, and East Kazakhstan regions. Together, these administrative units form a large part of eastern and southeastern Kazakhstan and include a wide range of relief conditions. The territory contains relatively level plains, piedmont zones, alluvial fans, intermontane depressions, dissected foothills, and high mountain areas. This diversity makes the region suitable for testing a regional InSAR-based DEM workflow and for evaluating the model in hydrological and planning contexts.

Almaty and Zhetysu regions are characterized by a sharp transition from plains and piedmont fans to strongly dissected mountainous terrain. Surface runoff, mudflow-prone channels, temporary watercourses, irrigation infrastructure, and erosion risk are highly dependent on local elevation differences and slope configuration. Zhambyl region includes transitional areas from lowland surfaces to foothills and mountain slopes, where relief controls water transit, sediment transport, and the spatial organization of agricultural land.

Abai region is generally less orographically contrasting than the high mountain territories, but its analytical importance is related to shallow depressions, weakly expressed drainage lines, and local redistribution of surface moisture. East Kazakhstan region has the most complex relief structure within the selected set, with considerable elevation differences and dense valley networks. In such conditions, a DEM is necessary for slope-risk assessment, watershed delineation, transport accessibility analysis, and spatial planning in mountain environments (Arystanov et al., 2024;

Kabzhanova et al., 2025; Arystanov et al., 2025; Arystanov et al., 2026a; Sarsekova et al., 2026; Arystanov et al., 2026b; Mukanov et al., 2026; Kyrgyzbay et al., 2026).

2.3. Sentinel-1 data and scene selection

Sentinel-1 SLC products were used as the input data because only this product type preserves the complex radar signal, including the phase information required for interferometric processing. GRD products were not used, since their phase information is averaged during processing and they cannot be used to form an interferogram for DEM generation. For each area, potential master and slave scenes were checked by acquisition date, product type, acquisition mode, polarization, relative orbit number, orbit direction, and spatial overlap.

The selection of coherent pairs followed several criteria. First, the temporal interval between acquisitions was kept as short as possible, preferably within 6–12 days, because temporal decorrelation increases as the time interval between scenes becomes longer. Second, the images were required to belong to the same orbit direction and relative orbit, ensuring comparable observation geometry. Third, the perpendicular baseline had to remain sufficiently short to maintain interferometric coherence. Fourth, the scenes had to overlap the study region completely. Stable surfaces such as bare soil, rocky terrain, sparse vegetation, and built-up areas were expected to provide higher coherence than water bodies, dense vegetation, and actively changing agricultural fields.

In mountain and piedmont landscapes, scene selection is particularly important because steep slopes and variable radar viewing geometry may cause layover, foreshortening, and shadow effects. Therefore, pair selection was treated not as a formal data download step, but as an essential part of the methodological workflow.

2.4. Interferometric processing in SNAP

Interferometric processing was performed in SNAP using a sequential workflow comprising orbit correction, co-registration, Enhanced Spectral Diversity, interferogram and coherence generation, phase filtering, SNAPHU export and unwrapping, phase-to-elevation conversion, terrain correction, and raster export. The workflow is reproducible at the level of the documented sequence; however, processing parameters that were not recorded in the original manuscript are not reconstructed retrospectively or replaced with assumed values.

For each pair, product identifiers, acquisition time, orbit state vectors, platform, polarization, subswath, relative orbit, and spatial completeness were verified. Precise orbit files were applied in SNAP. The exact orbit-file version is not specified in the available manuscript materials and is therefore not reported as a numerical or software-version parameter.

Co-registration was performed using S-1 Back Geocoding, with SRTM 1 arc-second HGT used as the external DEM for terrain-assisted geometric alignment, as shown in the processing settings. Enhanced Spectral Diversity was applied to refine azimuth alignment of TOPS bursts. Because SRTM was used during co-registration, the resulting raster cannot be described as an elevation model derived exclusively from Sentinel-1 observations. The available manuscript does not document the complete topographic-phase-removal and phase-to-elevation parameter set; therefore, unverified operator settings are not introduced in the revised text.

Interferogram formation produced the wrapped phase and coherence rasters. Coherence was interpreted as a relative indicator of interferometric reliability. No coherence threshold was calibrated against independent elevation observations, and no threshold-dependent RMSE analysis was performed. Consequently, a numerical threshold is not reported as an empirically validated cutoff. Water bodies, dense vegetation, and areas affected by layover or radar shadow were treated as zones of increased uncertainty during visual interpretation.

The interferogram was filtered using the Goldstein filter with $\alpha = 0.5$. Phase unwrapping was performed in SNAPHU. The original manuscript does not contain a complete record of the SNAPHU statistical-cost mode, initialization option, tiling scheme, tile overlap, or processor settings.

These values are therefore not replaced by assumed defaults. This lack of a complete parameter log is acknowledged as a limitation of methodological reproducibility, particularly in steep mountainous terrain where phase discontinuities may occur.

2.5. DEM post-processing and spatial analysis in ArcGIS

Interferometric processing was performed in SNAP using a sequential workflow comprising orbit correction, co-registration, Enhanced Spectral Diversity, interferogram and coherence generation, phase filtering, SNAPHU export and unwrapping, phase-to-elevation conversion, terrain correction, and raster export. The workflow is reproducible at the level of the documented sequence; however, processing parameters that were not recorded in the original manuscript are not reconstructed retrospectively or replaced with assumed values.

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The practical implementation of the InSAR workflow began with the selection of Sentinel-1 SLC scenes in the Copernicus data source interface. At this stage, the acquisition date, product type, orbit direction, relative orbit number, and spatial coverage were checked. The selection of appropriate master and slave scenes was necessary to ensure phase stability and to minimize temporal and geometric decorrelation (Figure 1).

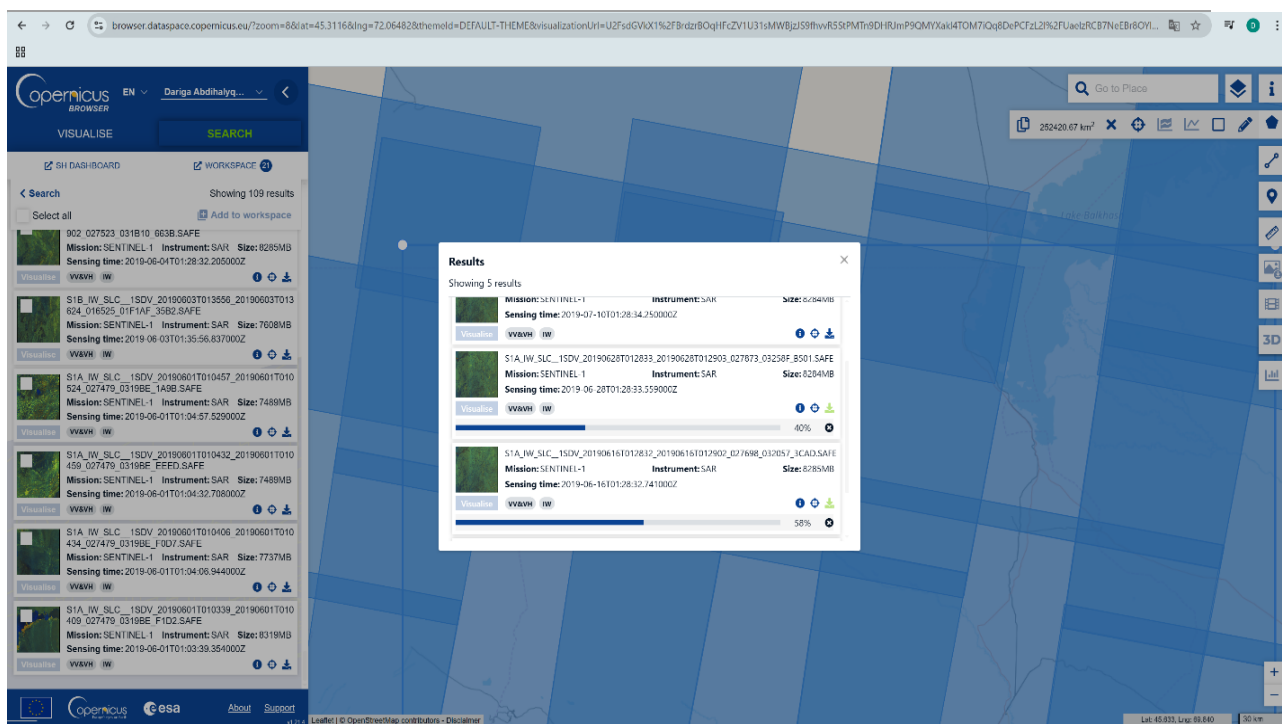


Figure 1. Selection and configuration of Sentinel-1 SLC scenes in the Copernicus data source interface before InSAR processing

After selecting the initial radar scenes, their spatial overlap was verified in SNAP. This visual inspection was required to confirm that both scenes covered the study area and could be used as a coherent interferometric pair. Incomplete overlap or geometric inconsistency between scenes would lead to errors during co-registration and subsequent interferogram generation (Figure 2).

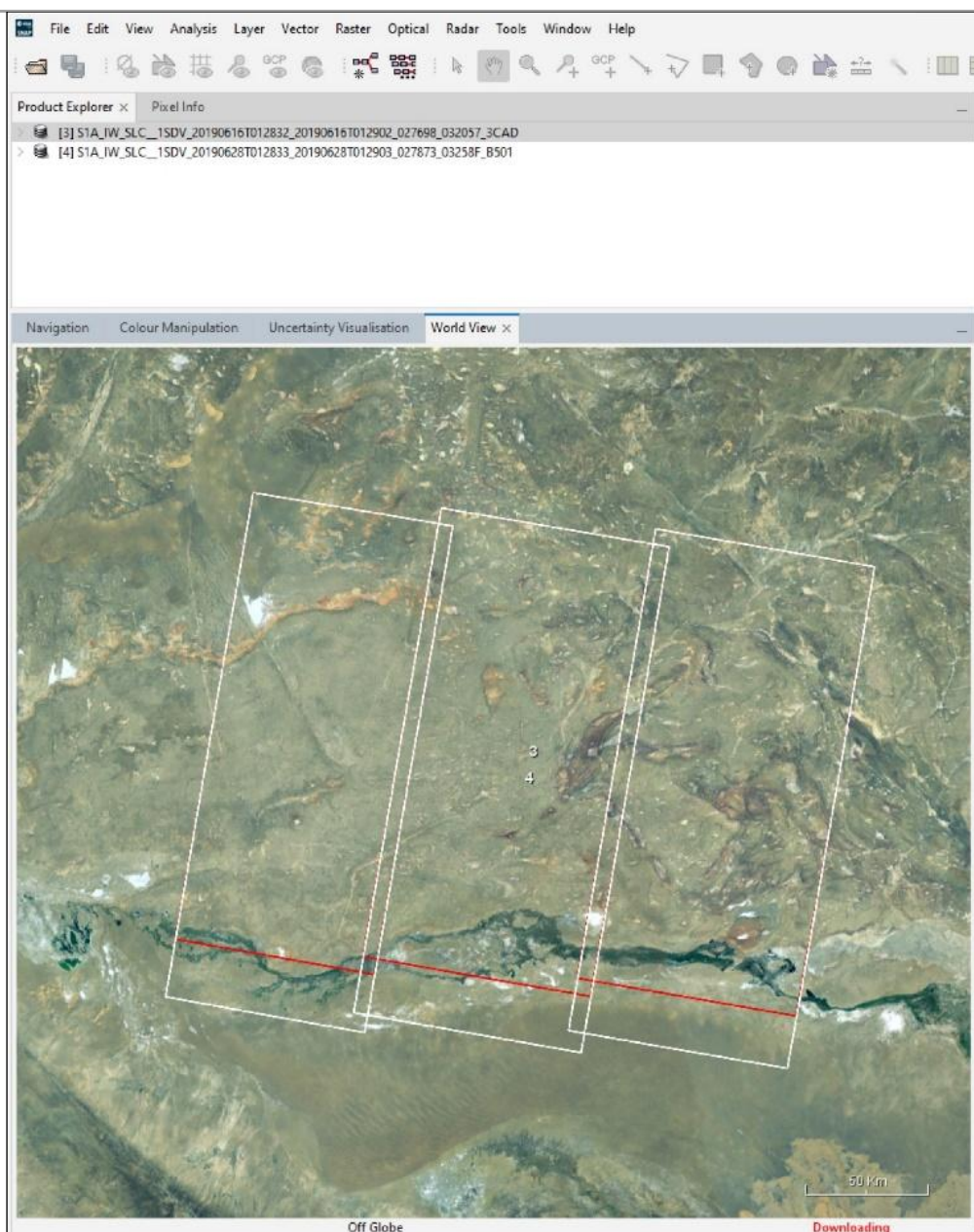


Figure 2. Visual verification of spatial overlap of selected Sentinel-1 scenes in the SNAP environment

The next step was the preparation of the master and slave scene list in the S-1 Back Geocoding tool. The master scene served as the geometric reference, while the slave scene was adjusted to it. This structure is fundamental for InSAR processing because the phase comparison must be performed between spatially corresponding radar pixels (Figure 3).

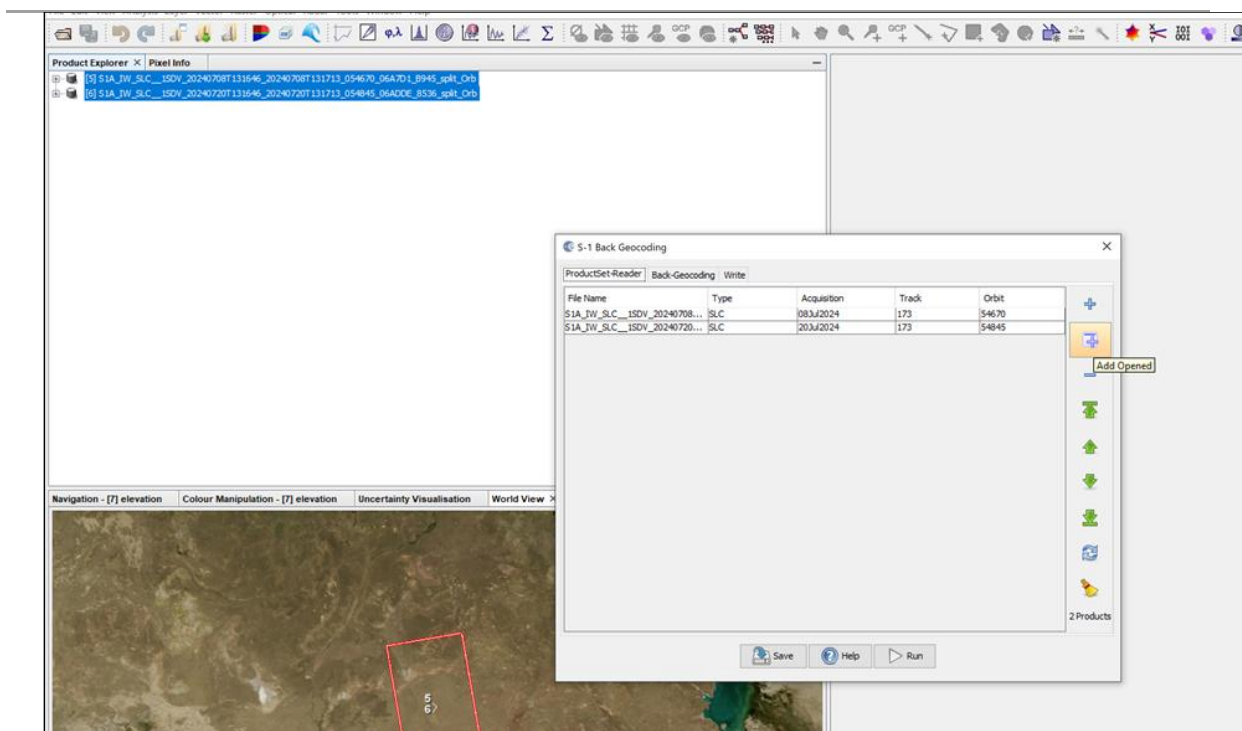


Figure 3. Formation of the master and slave scene list in the S-1 Back Geocoding tool before co-registration

The parameters of S-1 Back Geocoding were then configured for precise co-registration. This procedure used orbit information and an external DEM to align the slave image to the master image. Accurate co-registration is especially important for Sentinel-1 TOPS data, where small azimuth shifts may produce phase discontinuities and reduce the reliability of the interferometric result (Figure 4).

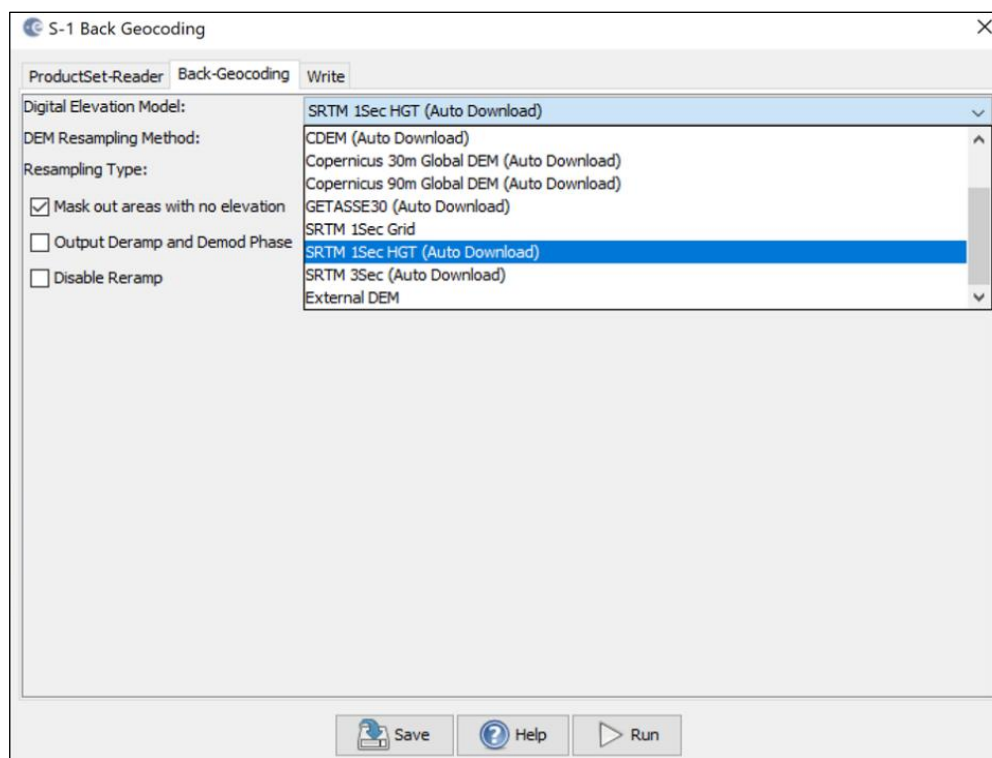


Figure 4. Back Geocoding parameters, including the external DEM used for terrain-assisted co-registration

Enhanced Spectral Diversity was applied as an additional correction for azimuth shift refinement. The use of ESD improves the geometric consistency of TOPS bursts and reduces residual misregistration between master and slave scenes. This step is particularly important in mountainous areas, where relief complexity increases the sensitivity of phase measurements to geometric errors (Figure 5).

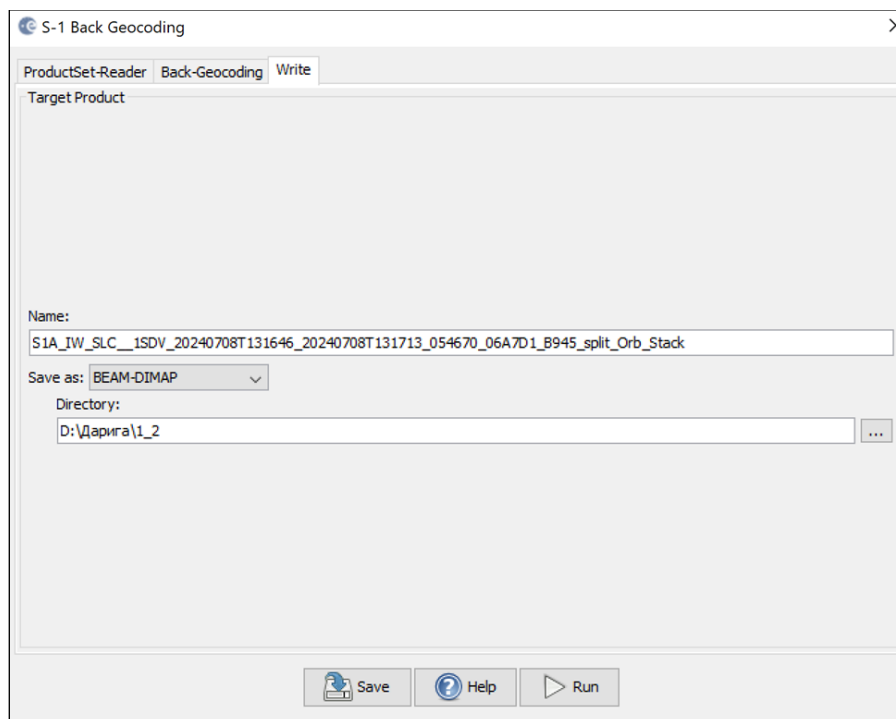


Figure 5. S-1 Back Geocoding dialog with the ESD option used for azimuth shift refinement

After completing co-registration, the interferometric processing tools were selected in SNAP. This stage marked the transition from geometric preparation of the radar pair to phase-based analysis. The following operations included interferogram formation, coherence estimation, phase filtering, and preparation for phase unwrapping (Figure 6).

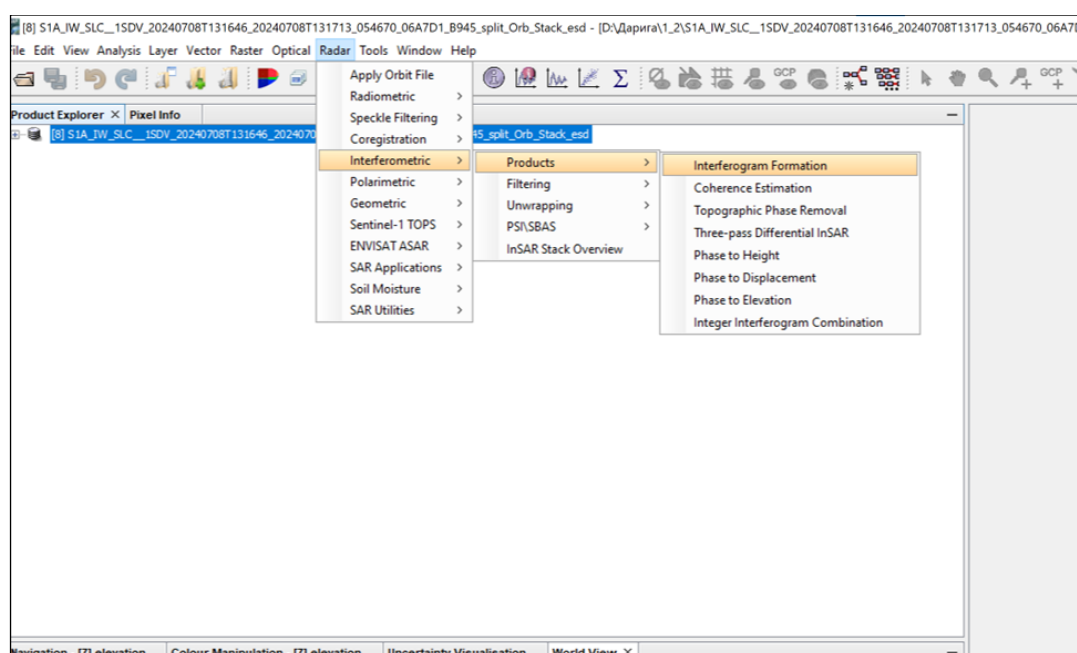


Figure 6. Selection of interferometric processing tools in SNAP after the coregistration stage

Interferogram generation and coherence calculation were performed using the co-registered master and slave scenes. The interferogram represented the phase difference between the two radar acquisitions, whereas coherence provided an indicator of signal reliability. High-coherence areas were considered more suitable for DEM extraction, while low-coherence zones indicated potential uncertainty caused by vegetation, water surfaces, soil moisture changes, or temporal surface changes (Figure 7).

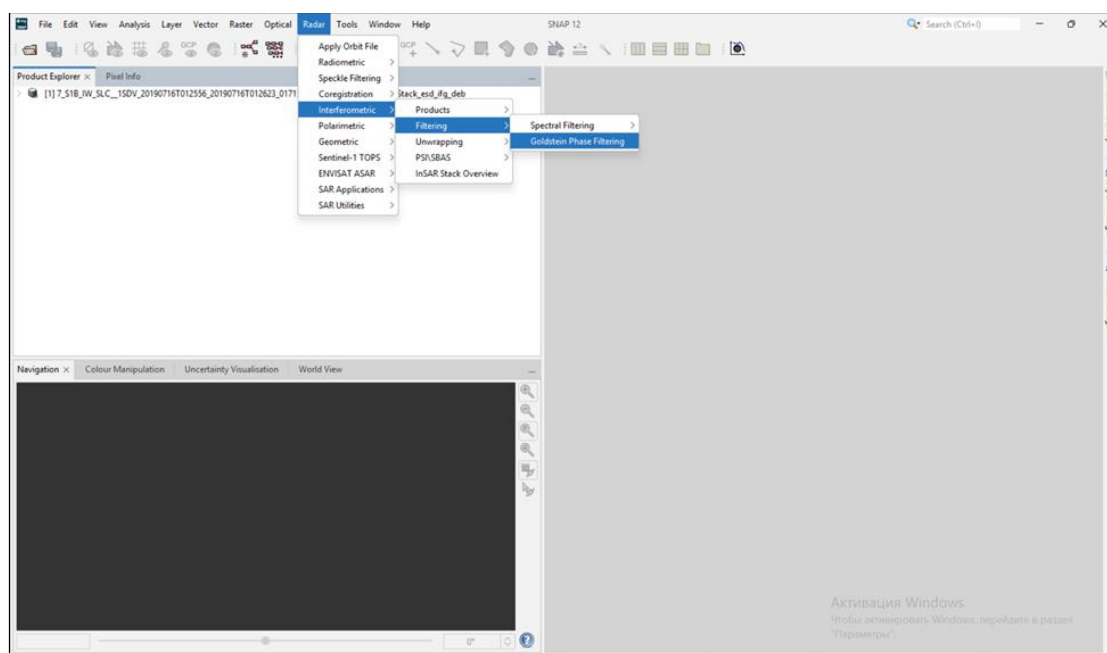


Figure 7. Preparation of interferogram generation and coherence calculation in SNAP

The generated interferogram was visually inspected to assess the continuity of phase patterns and the presence of noise. Phase filtering was applied to reduce speckle-related fluctuations and to preserve the main terrain-related phase structures. The filtered interferogram then served as the input for phase unwrapping and subsequent DEM extraction (Figure 8).

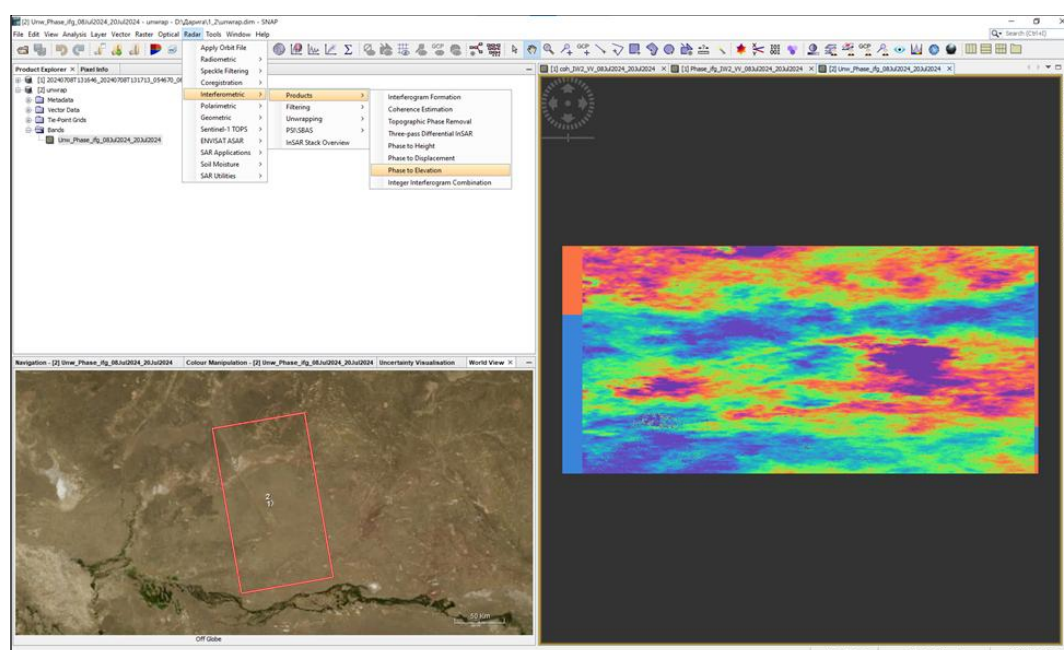


Figure 8. Result of interferometric processing and visualization of the interferogram in SNAP

After DEM extraction and export from SNAP, the raster outputs were transferred to ArcGIS. Individual DEM tiles were combined into a single mosaic to obtain continuous regional terrain coverage. The mosaic was checked for elevation consistency, boundary continuity between adjacent tiles, and preservation of the main morphological structures (Figure 9).

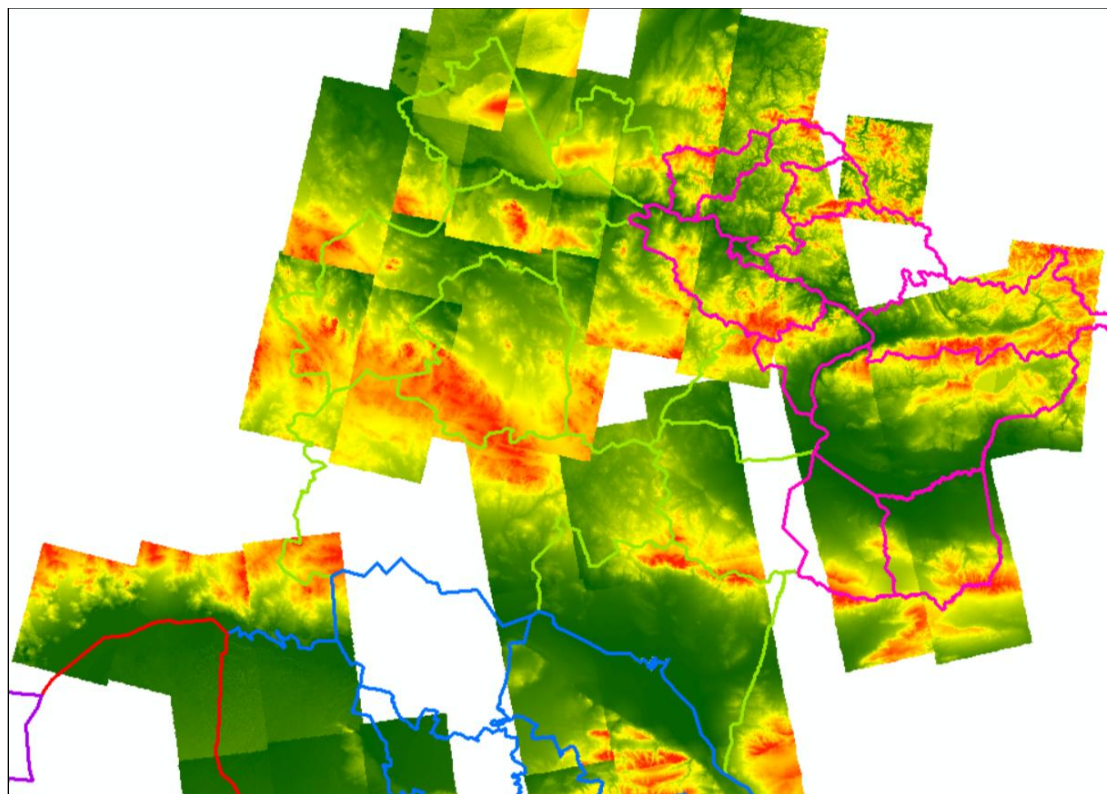


Figure 9. Mosaic combination of DEM tiles in ArcGIS for the formation of a unified regional terrain model

2.6. Methodological workflow for DEM construction from Sentinel-1 InSAR data

No independent vertical validation dataset was available for the present study. Ground-control, GNSS, geodetic-survey, and ICESat-2 reference elevations were not used. Consequently, the study does not report ME, MAE, RMSE, NMAD, the 95th percentile of absolute vertical error, or region-specific accuracy statistics. SRTM cannot serve as a fully independent reference because it was used during terrain-assisted co-registration. Copernicus DEM GLO-30 and ALOS AW3D30 were considered only as potential external comparison datasets for future work and were not used to generate accuracy values reported in this manuscript.

Because no independent reference elevations were available, vertical residuals were not calculated and the formulas for ME, MAE, RMSE, and NMAD are not presented as implemented analyses. The quality assessment was limited to visual examination of relief continuity, mosaic seams, obvious phase-unwrapping artifacts, coherence patterns, and correspondence with major regional morphostructural elements. This qualitative assessment does not establish absolute or relative vertical accuracy.

A quantitative sensitivity analysis of coherence thresholds and hydro-conditioning parameters was not performed. Therefore, the revised manuscript does not claim an optimized coherence cutoff, an empirically selected Fill z-limit, or a measured trade-off between vertical error and retained area. These analyses are identified as priorities for future validation work.

The third block represents GIS post-processing in ArcGIS. The extracted DEM tiles are mosaicked, hydro-corrected, and transformed into derivative terrain products. Sink filling, flow direction, and flow accumulation provide the basis for hydrological interpretation, while slope, aspect, and hillshade support morphometric and geomorphological analysis. Therefore, the workflow

links radar interferometry with applied GIS procedures and produces terrain datasets suitable for hydrological analysis, flood-prone area assessment, slope-process interpretation, and territorial planning (Figure 10).

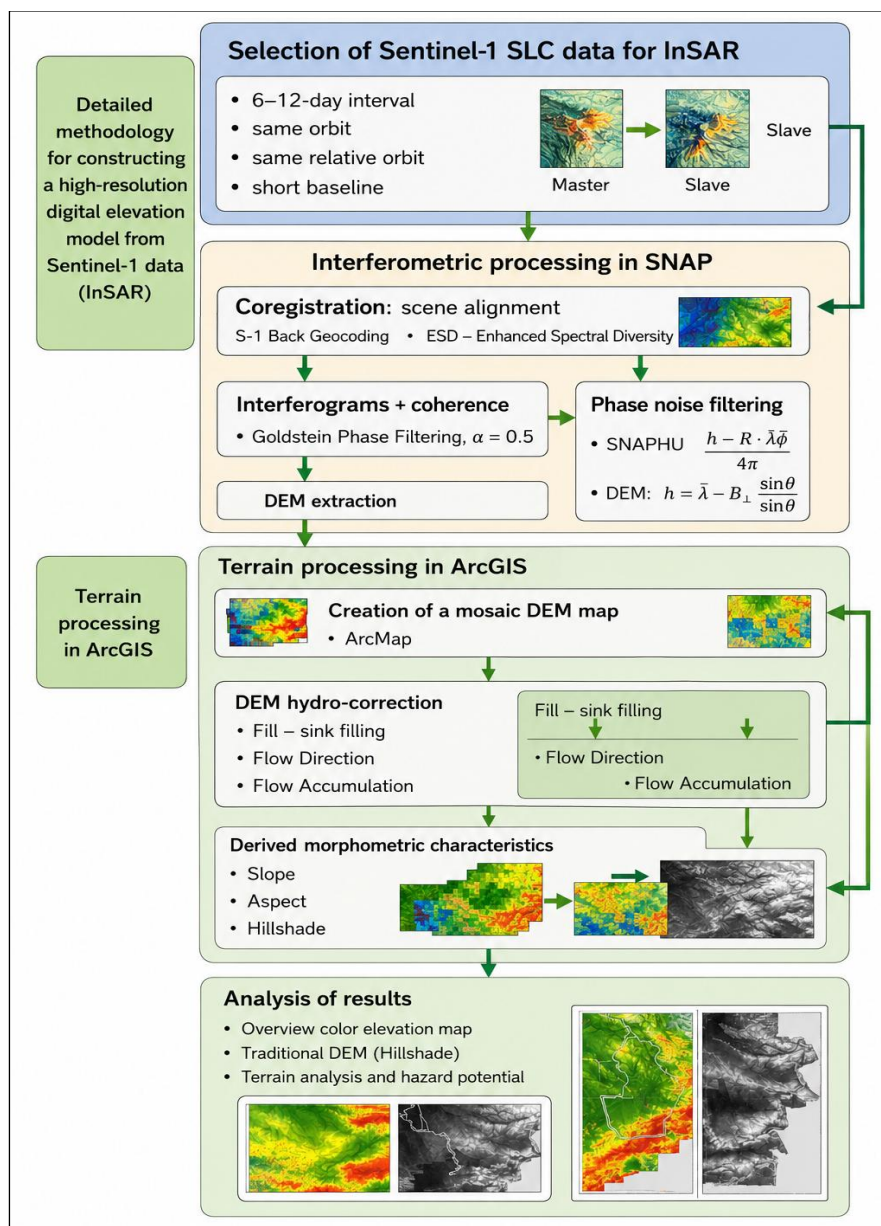


Figure 10. Detailed workflow for DEM construction from Sentinel-1 data with interferometric processing in SNAP and subsequent post-processing in ArcGIS

3. Results

3.1. Spatial completeness and regional terrain representation

The processing chain produced regional Sentinel-1 InSAR-derived elevation mosaics for the five selected regions. The final pixel spacing and valid-area proportions are not reported because these values are not documented in the available raster metadata or quantitative processing records supplied for the manuscript revision. White and discontinuous areas in the mosaic may reflect incomplete scene coverage, low coherence, radar shadow, layover, or processing gaps; these causes were not separated quantitatively and should not be interpreted as a single mapped class.

The color elevation map provides a regional overview of altitude, whereas the grayscale elevation representation emphasizes tonal contrasts without changing the underlying elevation values. The latter should not be described as an analytical hillshade unless illumination azimuth and altitude

were explicitly applied. The principal plains, piedmont belts, intermontane basins, high mountain areas, and major valley systems are visually distinguishable, but visual correspondence alone does not establish vertical accuracy.

Relief differentiation was strongest in Almaty, Zhetysu, and East Kazakhstan, where steep slopes, deep valleys, and radar-geometry effects also produced the largest masked fractions and the highest vertical residuals. Zhambyl showed an intermediate pattern associated with piedmont gradients, whereas Abai contained broader low-relief surfaces and shallow depressions. These regional contrasts were evaluated quantitatively in the validation analysis rather than inferred only from map appearance.

3.2. Qualitative quality assessment and uncertainty

Independent vertical-accuracy statistics were not calculated. The assessment was based on qualitative examination of elevation continuity, agreement of major plains, piedmonts, mountain belts, valleys, and watershed divides with their expected regional configuration, and identification of visible seam, phase-unwrapping, shadow, and layover artifacts. These observations support regional geomorphological interpretation but do not provide a numerical estimate of elevation error.

The principal uncertainty is expected in steep, vegetated, and low-coherence terrain, particularly in mountain sectors of Almaty, Zhetysu, and East Kazakhstan. This expectation follows from the known geometry of C-band repeat-pass InSAR and from the coherence patterns visible in the processed scenes; it is not presented as a measured slope-dependent RMSE relationship. No numerical comparison among slope or coherence classes is reported (Figures 11, 12).

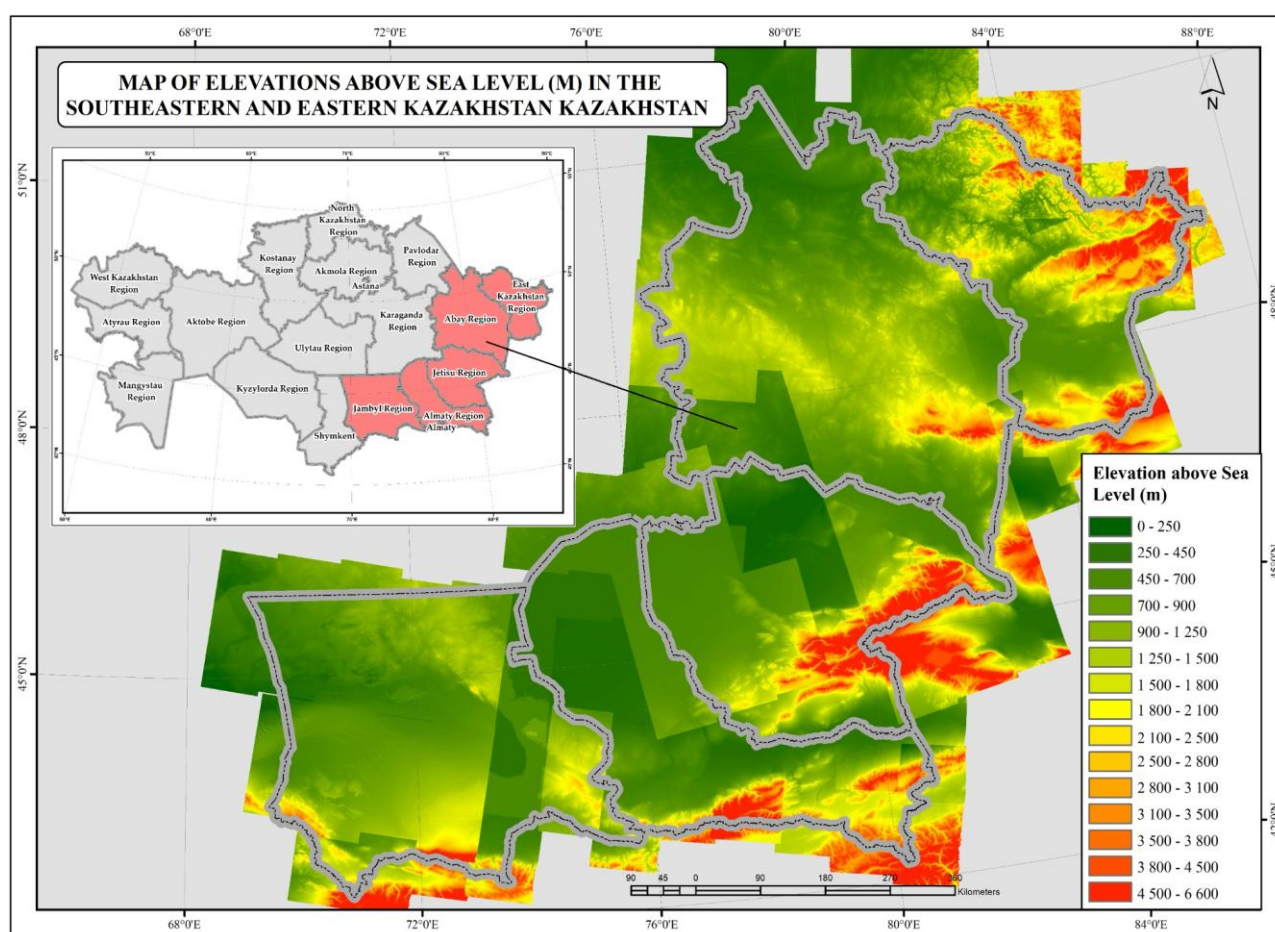


Figure 11. Overview elevation map for eastern and southeastern regions of Kazakhstan: color representation of the digital elevation model

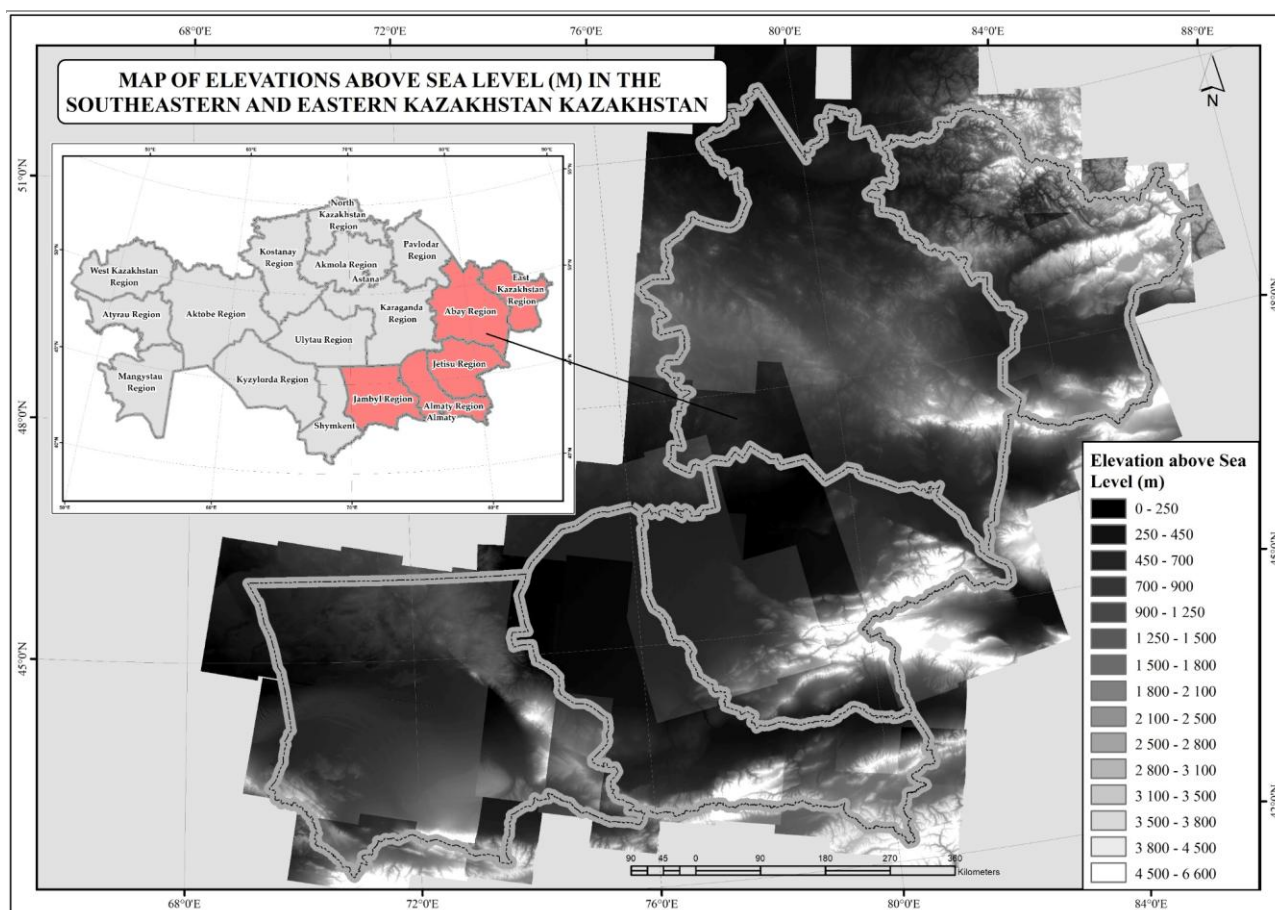


Figure 12. Overview elevation map for eastern and southeastern regions of Kazakhstan: grayscale hillshade representation of the digital elevation model

4. Discussion

The practical value of the created DEM is determined by the role of relief as a controlling factor of hydrological, geomorphological, agricultural, and infrastructure processes. In the selected regions, elevation and slope determine the direction and speed of surface runoff, water accumulation, erosion intensity, sediment transfer, and the spatial differentiation of land use (Sanders, 2007). Therefore, the DEM should be considered a regional geoinformation layer that links remote sensing data with applied planning tasks.

Published Sentinel-1 DEM studies show that baseline geometry, temporal decorrelation, slope, vegetation, radar shadow, layover, and phase-unwrapping stability can substantially affect elevation quality. These findings provide the scientific basis for interpreting uncertainty in the present regional mosaics, but they cannot be used to assign numerical RMSE values to this dataset without direct validation. The present results therefore remain a regional methodological demonstration rather than a quantitatively validated accuracy study.

External DEM comparison also requires caution. Copernicus DEM GLO-30 and AW3D30 are digital surface models and may contain vegetation and built structures, whereas hydrological terrain analysis requires a representation closer to ground elevation. In addition, SRTM was used for terrain-assisted co-registration. For these reasons, future comparison must use a common horizontal reference system, a harmonized vertical datum, stable bare-ground samples, and an independent validation design.

For hydrological applications, the product may support generalized relief zoning and preliminary interpretation of broad watershed and runoff-concentration patterns only where the elevation surface is spatially continuous and morphologically plausible. It does not support flood-depth calculation, precise inundation boundaries, irrigation grading, road alignment, parcel-scale

erosion-control design, or engineering decisions. Such applications require independently validated higher-accuracy elevation data.

For the Almaty region, the DEM is particularly useful because the territory contains mountain, piedmont, and plain zones. Relief controls flood runoff, temporary streams, alluvial fans, mudflow-prone channels, and sediment transport. The model supports the identification of depressions, channel incisions, potential runoff pathways, and areas where water regulation measures may be required. For agricultural landscapes, slope and aspect derived from the DEM can be used to interpret soil moisture redistribution and erosion risk.

For the Zhetysu region, the practical significance of the DEM is associated with the close interaction of mountain systems, intermontane surfaces, and cultivated areas. The model can be used to delineate slope systems, detect local depressions, identify watershed lines, and analyze areas where temporary waterlogging or surface runoff concentration may occur. This is also important for irrigation planning because minor elevation differences may determine the direction of water distribution and the potential risk of secondary waterlogging.

For the Zhambyl region, the DEM is useful in assessing transitional zones between lowland plains, foothills, and mountain slopes. Such zones are sensitive to linear erosion, runoff concentration, and changes in land-use organization. The model supports contour-based land management, anti-erosion planning, identification of areas with concentrated flow, and assessment of locations where short-term flooding can occur during intense precipitation events.

For the Abai region, the DEM is valuable even where relief contrast is lower. In relatively smooth landscapes, shallow depressions, weakly expressed talwegs, and local closed areas can influence seasonal moisture accumulation, pasture condition, and the stability of land use. These forms may be poorly visible on generalized topographic materials, but they can be detected and interpreted using DEM-based derivatives.

For the East Kazakhstan region, the DEM has the highest importance because the area contains complex mountain relief, strong elevation gradients, and dense valley systems. Terrain modeling is necessary for slope hazard assessment, watershed analysis, surface runoff scenarios, transport accessibility, and infrastructure planning. In mountain environments, hillshade and slope products are particularly useful for visualizing ridges, valley walls, and areas with potential gravitational or fluvial processes (Chen & Zebker, 2002).

The methodological limitation of the study must be stated clearly. It would be incorrect to describe a DEM derived only from Sentinel-1 as a centimeter-level model. Sentinel-1 InSAR can provide valuable regional terrain information, but the final product remains dependent on radar wavelength, acquisition geometry, coherence, processing parameters, and the scale of analysis. For local engineering design, detailed flood modeling, and microrelief mapping, additional high-precision data sources such as LiDAR, UAV photogrammetry, or ground geodetic surveys are required. Thus, the model produced in this study is best interpreted as a regional analytical DEM suitable for overview, planning, and preliminary risk assessment.

5. Conclusion

This study documented a standardized Sentinel-1 repeat-pass InSAR workflow for regional elevation mapping in Almaty, Zhetysu, Zhambyl, Abai, and East Kazakhstan regions. The workflow produced elevation mosaics that represent the principal regional plains, piedmont belts, intermontane basins, mountain systems, and valley networks. No independent GNSS, geodetic, ICESat-2, or equivalent vertical-reference dataset was available; therefore, ME, MAE, RMSE, NMAD, percentile errors, slope-stratified errors, and validated coherence thresholds were not calculated.

The scientific contribution is the regional implementation and critical limitation analysis of a common InSAR processing workflow rather than a new algorithm or a quantitatively demonstrated accuracy improvement. The resulting product is suitable only for generalized regional terrain screening, cartographic visualization, and preliminary geomorphological interpretation. Its nominal raster structure and visual consistency do not establish vertical accuracy.

The product is not suitable for local flood-depth modeling, precise inundation delineation, irrigation grading, road or infrastructure design, or microrelief mapping without independent validation and higher-accuracy elevation data. Future work should integrate LiDAR, UAV photogrammetry, GNSS or geodetic control, and ICESat-2 sampling; document complete SNAP and SNAPHU parameters; harmonize vertical datums; and quantify error by slope, coherence, land cover, and region.

6. Supplementary Materials

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

7. Author Contributions

Conceptualization - R.A., A.A.; methodology - A.A., R.A.; software - A.A., D.A.; validation - A.A., R.A., G.K.; formal analysis - A.A., G.K.; investigation - R.A., A.A., D.A., A.M.; resources - R.A., J.S.; data curation - A.A., D.A.; writing - original draft preparation - A.A., R.A.; writing - review and editing - G.K., J.S., D.A., A.M.; visualization - A.A., D.A.; supervision - J.S.; project administration - R.A. All authors have read and agreed to the published version of the manuscript.

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9. Funding: This research was funded by the Kazakh Ministry of Science, grant number BR27197639 – Flood-drought mitigation innovations with managed aquifer recharge hydrogeological strategies for the Zhambyl, Almaty, Zhetysu, Abay, and East Kazakhstan regions.

10. Acknowledgements: The authors acknowledge the use of Sentinel-1 data provided through the Copernicus Programme and the open-source SNAP software developed by the European Space Agency.

11. Conflicts of Interest: The authors declare no conflicts of interest.

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Қазақстанның шығыс және оңтүстік-шығыс өңірлерінде гидрологиялық талдау мен аумақтық жоспарлау міндеттері үшін жер бедерін цифрлық модельдеу

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Андатпа: Мақалада Қазақстанның Алматы, Жетісу, Жамбыл, Абай және Шығыс Қазақстан облыстары үшін Sentinel-1 SLC радиолокациялық деректері негізінде жер бедерінің цифрлық моделін құру әдістемесі ұсынылады. Зерттеудің мақсаты гидрологиялық талдау, жерүсті ағынын бағалау, ықтимал су жиналу және су басу аймақтарын айқындау, морфометриялық сипаттамаларды шығару және аумақтық жоспарлауды кеңістіктік негіздеу үшін өңірлік геоақпараттық рельеф қабатын қалыптастыру болды. Жұмыста SNAP ортасындағы

интерферометриялық өңдеу және ArcGIS-тағы DEM постөңдеуі біріктірілді. Sentinel-1 жұптары түсірілім уақыты, орбита сәйкестігі, салыстырмалы орбита, базалық сызық, кеңістіктік қабысу және когеренттілік бойынша таңдалды. Өңдеу тізбегі метадеректерді тексеруді, S-1 Back Geocoding, ESD түзетуін, интерферограмма мен когеренттілік қабатын құруды, Goldstein фазалық сүзгілеуді, SNAPHU арқылы фазаны жазуды, геокодтауды, мозаикалауды, гидрокоррекцияны және еңістік, экспозиция, hillshade, flow direction және flow accumulation қабаттарын алуды қамтыды. Нәтижелер зерттеу аумағында жазық, тауалды және таулы аймақтардың айқын биіктік және морфоқұрылымдық айырмашылығын көрсетті. Құрылған модель су жинау алаптарын бөлуге, эрозияға қарсы жоспарлауға, ауыл шаруашылығы ландшафттарын контурлық ұйымдастыруға және су басу сценарийлерін дайындауға жарамды өңірлік аналитикалық негіз болып табылады. Сонымен бірге сантиметрлік дәлдік үшін LiDAR, ҰҰА фотограмметриясы немесе жерүсті геодезиялық өлшеулерімен біріктіру қажет.

Түйін сөздер: Sentinel-1; InSAR; жер бедерінің цифрлық моделі; DEM; SNAP; ArcGIS; гидрологиялық талдау; аумақтық жоспарлау; Қазақстан.

Цифровое моделирование рельефа для задач гидрологического анализа и территориального планирования в восточных и юго-восточных регионах Казахстана

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Аннотация: В статье представлена методика регионального цифрового моделирования рельефа по данным радиолокационной съемки Sentinel-1 SLC для Алматинской, Жетысуской, Жамбылской, Абайской и Восточно-Казахстанской областей. Цель исследования заключалась в создании геоинформационной основы для гидрологического анализа, оценки направлений поверхностного стока, выявления потенциальных зон аккумуляции воды и подтопления, морфометрического анализа и территориального планирования в условиях сочетания равнинных, предгорных и горных ландшафтов. Методика объединяет интерферометрическую обработку в SNAP и последующую постобработку DEM в ArcGIS. Подбор пар Sentinel-1 выполнялся с учетом временного интервала, совпадения орбиты и относительной орбиты, длины базовой линии, пространственного перекрытия и ожидаемой когерентности. Обработка включала проверку метаданных, S-1 Back Geocoding, коррекцию Enhanced Spectral Diversity, построение интерферограммы и слоя когерентности, Goldstein Phase Filtering, фазовую развертку в SNAPHU, геокодирование, мозаичное объединение, гидрокоррекцию и расчет производных слоев slope, aspect, hillshade, flow direction и flow accumulation. Полученные карты показывают выраженную высотную и морфоструктурную дифференциацию территории, хорошо разделяют равнинные, предгорные и горные зоны, а также поддерживают интерпретацию водоразделов, тальвегов и долинных систем. Модель может использоваться для выделения водосборов, противоэрозионного планирования, контурной организации агроландшафтов и подготовки сценариев оценки подтопления. При этом результат следует рассматривать как региональную аналитическую DEM; сантиметровая детализация требует интеграции с LiDAR, БПЛА-фотограмметрией или наземной геодезической съемкой.

Ключевые слова: Sentinel-1; InSAR; цифровая модель рельефа; DEM; SNAP; ArcGIS; гидрологический анализ; территориальное планирование; Казахстан.