



A contour-gradient approach for improving glacier centerline extraction in High Mountain Asia

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Abstract: Glacier centerlines are fundamental to glacier inventory, ice-flow dynamic modeling, and thickness estimation. Although numerous approaches exist for extracting glacier centerlines, they often involve complex processes, require excessive parameters, and produce noticeable deviations, particularly in the accumulation zones of larger glaciers leading to significant discrepancies in subsequent glacier dynamic modeling and thickness estimation. To address this issue, we propose a novel method that extracts glacier centerlines using only a DEM and glacier outlines as input. Our approach integrates contour gradient derived ridge lines and steep terrain constraints to effectively regulate flow direction, while also incorporating a cost grid and hydrological flow routing for enhanced centerline delineation. This approach is characterized by its fully automatic nature, algorithmic simplicity, and high computational efficiency. A total of 134,790 glacier centerlines were derived across High Mountain Asia using our proposed algorithm. Our approach proves effective in extracting centerlines for individual valley glaciers without manual intervention with robust performance even in



34 rugged terrain. The average glacier length is 1.072 km. In total, 607 glaciers in HMA
35 exceed 10 km, and 6 extend beyond 50 km. The longest centerline extracted in our
36 dataset is 82.371 km, corresponding to Siachen Glacier in the Karakoram. We found
37 the centerlines have a good consistency with glacier velocity, indicating it can represent
38 real flow path for glaciers. Our centerlines extraction approach may be beneficial for
39 glacier conceptual models.

40 **Keywords:** Glacier centerline, Contour gradient, High Mountain Asia

41

42 1. Introduction

43 Glaciers across High Mountain Asia (HMA) are experiencing unprecedented changes,
44 characterized by accelerated ice thinning, widespread terminus retreat, and substantial
45 alterations in ice velocity patterns (Bhattacharya et al., 2021; Dehecq et al., 2019; Zemp
46 et al., 2025). These rapid changes have generated cascading impacts, leading to
47 potential future water resource shortages and increasing risks of glacier-related hazards,
48 such as glacier surges and glacial lake outburst floods (GLOFs) (Veh et al., 2025). As a
49 result, glacier dynamics have received considerably increasing scientific attention over
50 recent decades (Bai et al., 2025; Zhang et al., 2023). In this context, glacier centerlines
51 have become an essential geometric representation for understanding glacier evolution
52 and flow characteristics. Centerline-based approaches have been extensively developed
53 and applied in glacier thickness estimation, runoff projection, and investigations of
54 glacier dynamic processes (Leclercq et al., 2012; Wang et al., 2018; Wells et al., 2025).
55 The increasing availability and importance of accurate centerline datasets have
56 therefore become widely recognized in modern glacier research.

57 Various approaches have been developed for glacier centerline extraction,
58 including manual digitization, semi-automated methods, and fully automated
59 algorithms. The earliest manual centerline extraction can be traced back to Krimmel
60 (1992), who identified the highest and lowest elevations of glaciers and connected the
61 central nodes of 2 km contour intervals to derive glacier centerlines. Similar approaches
62 have subsequently been applied in other studies (Farinotti et al., 2009; Gantayat et al.,
63 2014; Linsbauer et al., 2009). Although manual digitization is extremely time-



64 consuming, it remains the most accurate method for centerline delineation (Linsbauer
65 et al., 2012). Compared with manual approaches, semi-automated methods have been
66 developed to improve efficiency. For example, the axis approach implemented in
67 ArcGIS was proposed to extract glacier centerlines (Le Bris and Paul, 2013; Qin et al.,
68 2017). However, this method generally extracts only one centerline for each glacier and
69 does not necessarily correspond to the longest glacier flowline (Machguth and Huss,
70 2014). Consequently, numerous automated approaches have been introduced. Surface
71 flow-path-based methods extract centerlines by simulating glacier surface flow;
72 however, the derived flow paths are often longer than the actual glacier main axes,
73 causing centerlines to deviate toward glacier margins in low-elevation regions (Schiefer
74 et al., 2008). Thiessen polygon-based approaches can also automatically derive glacier
75 flowlines (Le Moine and Gsell, 2015; Pieczonka et al., 2018), although their
76 performance is strongly influenced by glacier geometry. The least-cost route approach
77 has been demonstrated as an effective method for glacier centerline extraction
78 (Kienholz et al., 2014), and has been incorporated into the Open Global Glacier Model
79 (OGGM) framework (Maussion et al., 2019), producing reliable results (Maussion et
80 al., 2023). Nevertheless, most existing algorithms perform well for small glaciers with
81 simple geometries but exhibit considerable discrepancies in the accumulation areas of
82 large glaciers. This limitation is mainly attributed to their strong dependence on glacier
83 geometry and surface morphology, which may not adequately represent complex
84 glacier flow structures.

85 To address the discrepancies in glacier accumulation areas, several studies have
86 attempted to improve existing centerline extraction algorithms (Machguth and Huss,
87 2014; Pieczonka et al., 2018; Zhang et al., 2021). Generally, glaciers with extensive
88 accumulation areas exhibit simplified outlines, particularly in high-elevation regions
89 where rock outcrops and steep headwalls are often included within the glacier
90 boundaries. To overcome this issue, Pieczonka et al. (2018) applied a slope threshold
91 of 30° to redefine glacier extents by excluding areas with slopes exceeding this value.
92 The modified glacier extents were subsequently used for centerline extraction based on
93 Thiessen polygons. However, this approach remains limited for glaciers with gentle



94 slopes or hanging glaciers, where slope-based filtering may not effectively distinguish
95 glacierized areas from surrounding terrain. Consequently, Machguth and Huss (2014)
96 proposed an automated approach that incorporates glacier surface slope, distance to
97 glacier margins, and a series of trade-off functions to derive centerlines within
98 accumulation areas. By assigning slope-based weights, this method allows extracted
99 centerlines to deviate moderately from the geometric center of the glacier and better
100 represent glacier flow characteristics. Furthermore, Zhang et al. (2021) introduced an
101 Euclidean allocation-based method by incorporating auxiliary mountain ridge lines to
102 prevent centerlines from crossing exposed bedrock areas. Although theoretically
103 effective, the complex extraction of mountain ridge lines can introduce some
104 uncertainties, resulting in deviations in the accumulation zones of large glaciers (Zhang
105 et al., 2022). Therefore, despite recent methodological improvements, uncertainties
106 associated with centerline extraction in glacier accumulation areas remain unresolved.

107 In this study, we primarily aim to address discrepancies in glacier centerlines over
108 rugged high-altitude terrain, particularly the issue of centerlines crossing mountain
109 ridges or failing to follow the expected glacier flow pathways. To achieve this goal, we
110 propose a new approach that integrates a contour-gradient method with grid-based cost
111 functions and hydrological flow modeling. The proposed algorithm was applied to
112 extract centerlines for all valley glaciers across HMA. The resulting centerlines were
113 evaluated using the Randolph Glacier Inventory (RGI) 7.0 centerlines and ITS_LIVE
114 ice velocity datasets to assess their reliability and consistency with glacier geometry
115 and surface flow characteristics.

116 **2. Study area**

117 The developed algorithm was tested on individual glaciers across HMA, which
118 represents the largest concentration of mountain glaciers outside the polar regions in
119 terms of glacier number, area, and volume (Farinotti et al., 2019; Immerzeel et al., 2020).
120 HMA is widely recognized as the “water tower of Asia” because many major river
121 systems depend on glacier meltwater contributions (Pritchard, 2019). The region
122 comprises 18 mountain ranges containing 134,790 glaciers with a total area of



123 approximately $10 \times 10^4 \text{ km}^2$ (Fig. 1), accounting for nearly 50% of the global mountain
124 glacier number according to the Randolph Glacier Inventory (RGI) 7.0.

125 The glaciers tested in HMA encompass a wide range of morphometric types,
126 including small glaciers, large valley glaciers, cirque glaciers, and ice caps. Their areas
127 range from approximately 0.01 km^2 to more than 1087 km^2 . Valley glacier systems
128 dominate the region, while a small number of ice caps, such as the well-known Guliya
129 ice cap, are also present (Hou et al., 2025). Glaciers larger than 1 km^2 account for
130 approximately 75% of the total glacierized area, and those exceeding 10 km^2 contribute
131 about 37%. Glacier characteristics vary substantially among different regions of HMA.
132 The steep and rugged terrain surrounding many glaciers promotes considerable snow
133 accumulation through avalanching, which contributes to extensive debris-covered
134 glacier surfaces (Bolch et al., 2012). These topographic conditions also influence
135 glacier mass distribution and morphological characteristics. Meanwhile, regional
136 differences in median glacier elevation and surface slope are pronounced due to the
137 complex climatic conditions across HMA (Guo et al., 2015). Consequently, the diverse
138 glacier geometries, topographic settings, and climatic environments make HMA an
139 ideal region for evaluating the performance of the proposed algorithm.

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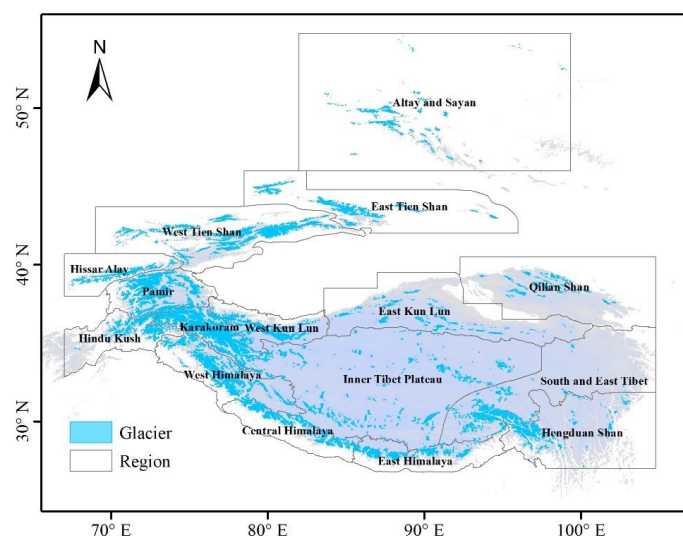


Figure 1. Distribution of glaciers and mountain regions across HMA

3. Data

3.1 Glacier outlines and centerlines

The glacier outlines used in this study were derived from the Randolph Glacier Inventory (RGI) 7.0 (RGI Consortium, 2023). RGI 7.0 is a globally complete inventory of glacier outlines that includes glacier-specific attributes and auxiliary information, excluding the ice sheets of Greenland and Antarctica (Maussion et al., 2023). One limitation of RGI is that the glacier outlines were primarily generated around the year 2000, which may not fully represent recent glacier changes. The inventory includes all glaciers larger than 0.01 km². In this study, all 134,790 glaciers in HMA, ranging in area from 0.01 km² to more than 1087 km², were selected for centerline extraction.

In addition, RGI 7.0 provides glacier centerline shapefiles and associated attributes for each glacier in HMA. These reference centerlines were generated using the algorithm developed by Kienholz et al. (2014) and implemented in the Open Global Glacier Model (OGGM) framework (Maussion et al., 2019). Therefore, the RGI-derived centerlines provide a valuable benchmark for evaluating the performance of the newly developed centerline extraction method.



159 **3.2 DEM data**

160 We selected the Copernicus DEM as the reference DEM for delineating glacier outlines.
161 The primary reason for this selection is that the glacier centerlines provided by RGI 7.0
162 were generated using the Copernicus DEM; therefore, using the same DEM source
163 improves the comparability between the existing RGI-derived centerlines and our
164 extracted results. The Copernicus DEM is an openly available global Digital Surface
165 Model (DSM) with a spatial resolution of 30 m and complete global coverage without
166 data voids (Copernicus, 2019). It was generated from synthetic aperture radar (SAR)
167 interferometry using data acquired by the TanDEM-X radar satellite between December
168 2010 and January 2015.

169 We extracted the DEM data covering HMA glaciers from the global Copernicus
170 DEM dataset. However, for small glaciers, the number of available grid cells within the
171 glacier boundary is extremely limited at the original 30 m resolution, which cannot
172 satisfy the requirements for reliable centerline extraction. Therefore, the DEM
173 resolution was adjusted according to glacier size. For glaciers with an area greater than
174 0.4 km², the original 30 m resolution was retained. For glaciers with areas between 0.2
175 and 0.4 km², the DEM was resampled to 15 m using bilinear interpolation. For glaciers
176 smaller than 0.2 km², the DEM was further interpolated to a 10 m resolution.

177 **3.3 ITS_LIVE data**

178 The mean and annual glacier velocity products from the NASA MEaSUREs ITS_LIVE
179 project were publicly released (Gardner et al., 2025), and were used in this study to
180 evaluate the derived glacier centerlines. ITS_LIVE velocity products (Version 2) are
181 generated using Landsat, Sentinel-1 and Sentinel-2 imagery acquired between 1985 and
182 2024, providing glacier surface velocity estimates at a spatial resolution of 120 m.
183 These datasets have been widely applied in glacier dynamics studies (Dehecq et al.,
184 2019; Miles et al., 2021; Wells et al., 2025). In this study, we used the multi-year
185 averaged ITS_LIVE velocity data from 2013 to 2022 because of its high data quality
186 and relatively complete spatial coverage, and then resampled the velocity fields to
187 match the DEM resolution.



188 **4 . Method**

189 In this study, we propose a novel approach that incorporates contour gradients to
190 constrain the flow direction of glacier centerlines. The contour gradients mainly
191 represent geomorphological features, including mountain ridgelines, exposed rugged
192 bedrock, and steep glacier surfaces, which provide critical constraints on the potential
193 flow paths of glaciers. The proposed workflow consists of three main steps, all of which
194 are implemented using the MATLAB programming language. The detailed procedure
195 for glacier centerline extraction is described below.

196 **4.1 Potential glacier head and terminus**

197 The extraction of glacier centerlines generally tracked from the glacier head toward the
198 terminus. Therefore, it is necessary to identify all potential glacier heads and termini,
199 particularly for large and complex glaciers containing multiple branches and
200 corresponding heads. To achieve this, the DEM is first masked using the glacier
201 polygons to generate a glacier-only raster in the UTM coordinate system, with grid cells
202 outside the glacier assigned NoData values. Based on the resulting glacier raster, all
203 glacier boundary lines are extracted, including internal boundaries such as those
204 surrounding nunataks. The grid points along each boundary line are then sequentially
205 coded, starting from the point with the minimum elevation. All potential glacier heads
206 are identified from these boundary lines.

207 A potential glacier head must satisfy two criteria. The first criterion is based on the
208 local elevation variation along the glacier boundary. Specifically, the elevation of a
209 potential head must be higher than that of its neighboring points on both sides of the
210 boundary line. In this study, a point is identified as a potential glacier head when its
211 elevation is higher than that of the 15 neighboring points on both its left and right sides.
212 This 15-point neighborhood was selected to balance the identification of individual
213 glacier branches and the suppression of spurious local maxima. If the threshold is too
214 large, glacier heads associated with some smaller branches may not be detected;
215 conversely, if the threshold is too small, an excessive number of potential glacier heads
216 may be identified.



217 The other criterion requires potential glacier heads to be located at relatively high
218 elevations. Kienholz et al. (2014) assumed that potential heads should be located where
219 the local elevation is higher than one-third of the elevation range between the lowest
220 point and the highest point of the corresponding glacier, thereby avoiding the
221 assignment of centerlines to low-lying minor tributaries. In contrast, Machguth and
222 Huss (2014) and Zhang et al. (2021) assumed that potential heads should be located
223 above the equilibrium line altitude (ELA). However, the ELA is not directly monitored
224 for the vast majority of glaciers, and its determination at the individual glacier scale is
225 therefore challenging. In many cases, the median glacier elevation has been used as a
226 proxy for the ELA. Following this approach, we use the median elevation of each
227 glacier as the threshold for identifying potential heads, retaining only candidate head
228 points located above the median elevation. Although the median elevation may not
229 accurately represent the ELA of glaciers in HMA (Miles et al., 2021), this criterion is
230 primarily intended to exclude low-lying minor tributaries rather than to precisely
231 delineate the accumulation area. Therefore, its influence on the resulting glacier
232 centerline geometry and length is expected to be limited.

233 The above step may generate multiple potential heads for each glacier branch
234 because of the complex glacier boundaries, particularly in high-altitude regions. To
235 remove unreasonable or redundant potential heads, we introduced a distance parameter
236 r , such that the distance between any two adjacent potential heads must be greater than
237 r m. The value of r is defined as a function of glacier area S (km²), allowing the
238 minimum separation distance between potential heads to vary according to glacier size:

$$239 \quad r = \begin{cases} q_1 * S + q_2, & r \leq r_{max} \\ r_{max}, & r > r_{max} \end{cases} \quad (1)$$

240 Where q_1 is $2 \times 10^{-6} \text{ m}^{-1}$ and q_2 is 500 m. The detailed procedure for applying this
241 criterion follows the approach described by Kienholz et al. (2014).

242 If the above procedure still fails to identify any potential heads, indicating that the
243 glacier is relatively small, we designate the highest-elevation point of the glacier as its
244 potential head. For glacier termini, previous studies have adopted different approaches.
245 Machguth and Huss (2014) identified the terminus using automatic grid tracking,



246 whereas other studies defined the terminus as the lowest-elevation point of the glacier
247 (Le Bris and Paul, 2013; Kienholz et al., 2014; Zhang et al., 2021). Following the latter
248 approach, we designate the lowest-elevation point of each glacier as its terminus.

249 **4.2 Glacier contour gradient and cost grid**

250 In the high-elevation regions of glaciers, steep rock walls and ridgelines are commonly
251 present and can exert a strong influence on the flow direction of glacier centerlines. To
252 minimize their influence and prevent centerlines from crossing these topographic
253 features, we calculated the contour gradient and used it to define a spatial constraint.
254 First, each glacier was divided into multiple elevation bands at 50 m intervals based on
255 the DEM. The elevation bands were then numbered sequentially from the lowest to the
256 highest elevation, with the lowest band assigned a value of 1 and the subsequent bands
257 assigned values of 2, 3, ..., n. Figure 2a shows the elevation-band numbers
258 automatically generated for Duofeng Glacier (RGI2000-v7.0-G-13-48984), located in
259 the West Kunlun Mountains. Subsequently, the contour gradient was calculated for each
260 glacier grid cell to characterize the local topographic gradient. The contour-gradient
261 function is defined as follows:

$$262 \quad |\nabla H| = \sqrt{\left(\frac{\partial H}{\partial x}\right)^2 + \left(\frac{\partial H}{\partial y}\right)^2} \quad (2)$$

263 where the gradient is a vector characterized by both magnitude and direction. Its scalar
264 value is obtained by calculating the modulus of the gradient vector, which represents
265 the local slope. The x- and y-components of the gradient represent the rates of elevation
266 change per unit horizontal distance in the x- and y-directions, respectively. The
267 calculated contour-gradient values are shown in Fig. 2b. Areas within individual
268 elevation bands exhibit no gradient values because adjacent grid cells have the same
269 elevation-band code, whereas areas near elevation-band boundaries and regions with
270 densely spaced contour lines, which generally correspond to steep terrain, exhibit
271 relatively large gradient values.

272 Subsequently, we repeated the above procedure to generate a second set of
273 elevation bands. However, in this step, the elevation assigned to each band was
274 represented by its median elevation rather than the original elevation values, and the



bands were sequentially coded as 1, 2, 3, ..., n (Fig. 2d). The contour gradient was then
recalculated for each glacier grid cell using these coded median elevations (Fig. 2e).
Both sets of contour-gradient grids exhibit large values in areas where the elevation
bands are closely spaced, corresponding to densely distributed contour lines, whereas
the gradient values also change near the boundaries of adjacent elevation bands
according to the local configuration of the contour lines. To identify steep areas, we
combined the two contour-gradient datasets using a binary intersection approach. Grid
cells with non-zero values in both datasets were assigned a value of 1, whereas cells
containing a zero value in either dataset were assigned a value of 0. This procedure
produced a preliminary mask of steep areas (Fig. 2c). The steep-area mask initially
consisted mainly of scattered pixels rather than continuous patches. To improve its
spatial continuity, the imdilate and imerode functions in MATLAB were subsequently
applied to the mask. These morphological operations connected nearby scattered pixels
and removed isolated pixels, resulting in continuous patches of steep terrain (Fig. 2f).
The resulting areas mainly include ridgelines, exposed rock walls, and steep glacier
surfaces. Although the proposed method is conceptually similar to identifying areas
with large slopes, it avoids the need to specify a fixed slope threshold. A universal slope
threshold is difficult to determine because of the substantial differences in glacier
morphology and terrain steepness among individual glaciers. Therefore, the proposed
contour-gradient approach provides a more robust and adaptive method for delineating
steep areas that may constrain glacier centerline extraction.

The grid points representing the extracted steep areas were combined with the
glacier boundary points to form a new set of boundary points. Together, these points
serve as boundary constraints for glacier centerline extraction. For each grid point i
located within the glacier, the cost value p_i is calculated using the following formula
(Kienholz et al., 2014):

$$p_i = \left(\frac{\max(d) - d_i}{\max(d)} \right) + \left(\frac{z_i - \min(z)}{\max(z) - \min(z)} \right) \quad (3)$$

where d_i represents the Euclidean distance from grid cell i to the nearest glacier
boundary, and $\max(d)$ denotes the maximum Euclidean distance among all grid cells



304 within the glacier. Z_i represents the elevation of grid cell i , while $\max(Z)$ and $\min(Z)$
305 denote the maximum and minimum glacier elevations, respectively.

306 The term $\frac{\max(d)-d_i}{\max(d)}$ normalizes the Euclidean distance, producing cost values
307 ranging from 0 to 1. The minimum value of 0 occurs at the grid cell with the maximum
308 distance from the glacier boundary, which is generally located near the glacier center,
309 whereas the maximum value of 1 occurs along the glacier boundary. The term
310 $\frac{z_i-\min(z)}{\max(z)-\min(z)}$ normalizes the elevation of each grid cell within the glacier and
311 generates an elevation-based cost value. The minimum value occurs at the lowest-
312 elevation point of the glacier, corresponding to the terminus, while the maximum value
313 occurs at the highest-elevation point. These two cost components constrain the flow
314 paths of glacier centerlines within the glacier: the first term favors paths toward the
315 glacier interior, whereas the second term favors paths toward lower elevations.

316 Based on Eq. (3), we generated the glacier cost grid for non-steep areas, as shown
317 in Fig. 2g. However, this cost grid covers only the non-steep portions of the glacier and
318 therefore does not extend across the entire glacier. Because potential glacier heads are
319 often distributed within steep areas, the missing cost grid must be supplemented to
320 ensure the continuous progression of centerline tracking. To address this issue, we
321 calculated the cost value for every grid cell across the entire glacier without considering
322 the steep-area constraints (Fig. 2h). The cost values from Fig. 2h were then used to fill
323 the missing steep-area portions of the cost grid in Fig. 2g. To ensure that centerline
324 tracking proceeds from the potential heads toward the terminus rather than being
325 diverted toward the glacier boundary, the minimum cost value of the replacement grids
326 must be greater than the maximum cost value of the original cost grid in Fig. 2g. In this
327 way, the cost structure of the non-steep areas remains dominant during the tracking
328 process. Without elevation-based cost constraints in steep areas, centerline tracking
329 tends to follow the natural hydrological flow direction, causing most centerlines
330 crossing steep terrain to deviate toward the glacier boundary (Schiefer et al., 2008).

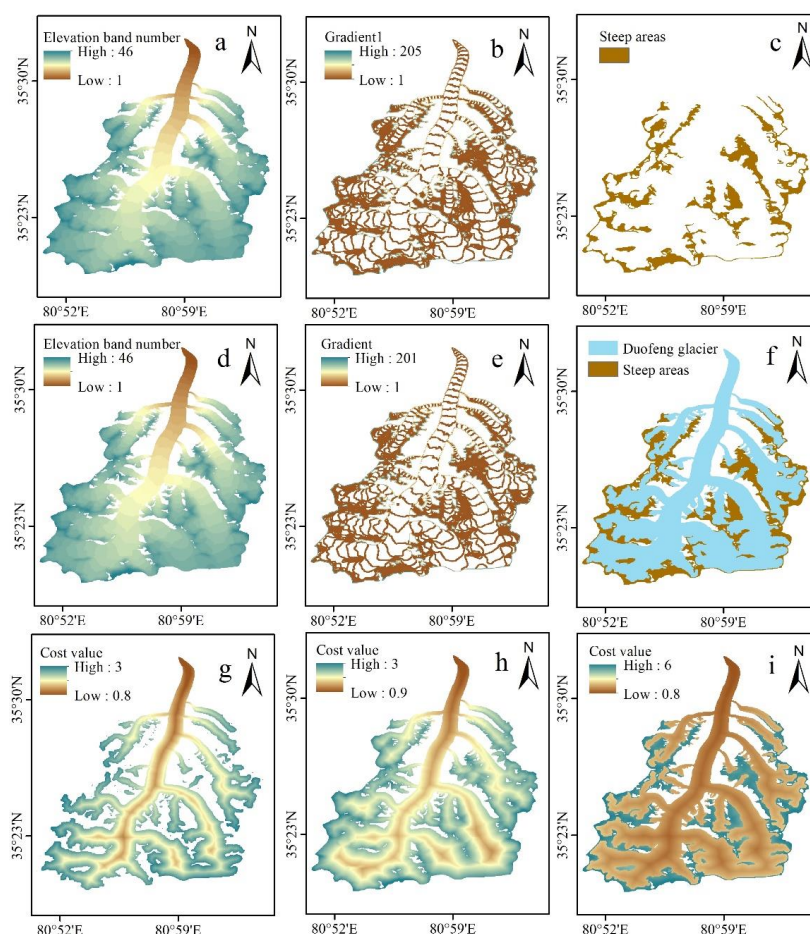


Figure 2. Contour-gradient and cost-grid calculation process. (a, d) Elevation-band numbers. (b, e) Contour-gradient distributions for the glacier. (c, f) Distributions of the identified steep areas. (g–i) Cost grids for the glacier.

4.3 Glacier centerline extraction

Starting from each potential glacier head, the centerline is tracked along the cost grid toward the glacier terminus. The natural hydrological flow method, which has been used to identify glacier centerlines in previous studies (Machguth and Huss, 2014; Schiefer et al., 2008), is adopted in this study. This approach is appropriate because the constructed glacier cost grid effectively constrains the tracking direction, guiding the centerlines away from the glacier boundary toward the glacier interior and from higher to lower elevations. Based on these constraints, we developed a grid-based tracking



method for extracting glacier centerlines. Starting from a potential head, the eight neighboring grid cells are examined, and the centerline is directed toward the neighboring cell with the lowest cost value. This procedure is repeated iteratively until the centerline reaches the glacier terminus. However, the presence of sinks in the cost grid may cause the tracking process to become trapped in a loop and prevent it from reaching the terminus. Therefore, a sink-filling algorithm is applied to eliminate these sinks and ensure continuous centerline tracking. The resulting glacier centerlines are shown in Fig. 3a.

Certain outlier points along the extracted centerlines can be removed through smoothing. We used the exponential kernel-based PAEK algorithm and its associated functions to smooth the centerlines (Kienholz et al., 2014; Machguth and Huss, 2014; Zhang et al., 2022). A moving-window smoothing approach was adopted to achieve an optimal smoothing effect, with the window size determined according to the length of each centerline. This procedure is particularly useful for large glaciers, which generally have wider tributary branches and longer main centerlines, whereas its effect is less pronounced for small glaciers. However, the smoothing process may also cause portions of the centerlines to extend beyond the glacier boundary, similar to the situation reported by Machguth and Huss (2014). Such deviations typically occur in areas where the glacier boundary is irregular or inaccurately delineated. Figure 3b shows the centerlines after smoothing.

We further calculated the centerline lengths and determined the Strahler numbers (hydrological orders) based on the smoothed centerlines. First, the length of each centerline branch was calculated. The longest centerline was designated as the main centerline, which also represents the glacier length (Maussion et al., 2023; Paul et al., 2009). The remaining branch centerlines were then trimmed at their connection points with the main centerline using a distance equivalent to one grid-cell length, thereby separating the branches from the main centerline. Among the remaining branches, the longest centerline was subsequently selected and processed in the same manner. This procedure was repeated iteratively until all branches were separated, yielding the centerline for each individual branch (Fig. 3c).



373 The Strahler number (hydrological order) of each branch was then determined
374 following the method of Kienholz et al. (2014). The highest-order branch corresponds
375 to the main centerline, whereas lower-order branches generally represent progressively
376 shorter tributary centerlines. However, some very short branches may result from noise
377 or irregularities in the glacier boundary and should therefore be removed. We adopted
378 a length threshold of 1/25 of the main centerline length and removed all branches
379 shorter than this threshold. This criterion is particularly effective for large glaciers,
380 where numerous small branches can otherwise be generated. In contrast, branches in
381 small glaciers are generally shorter, and therefore a larger proportion of their branches
382 are retained.

383 This filtering procedure is important for glacier thickness estimation based on
384 centerline interpolation, because retaining numerous very short and potentially spurious
385 branches may introduce unnecessary complexity into the interpolation. At the same
386 time, excessive removal of branches can reduce the representation of the glacier's flow
387 structure and affect the operational efficiency of glacier dynamic models. Our filtering
388 criterion differs from that of Kienholz et al. (2014), who adopted a relatively larger
389 length threshold and consequently removed more branches, including some branches
390 that may contain meaningful glacier-flow information.

391 The remaining branches constitute the final set of glacier centerlines. For Duofeng
392 Glacier (Fig. 3d), 61 centerline branches were initially identified, of which 14 were
393 removed because their lengths were shorter than the threshold. The final centerline
394 network therefore contains 47 branches.

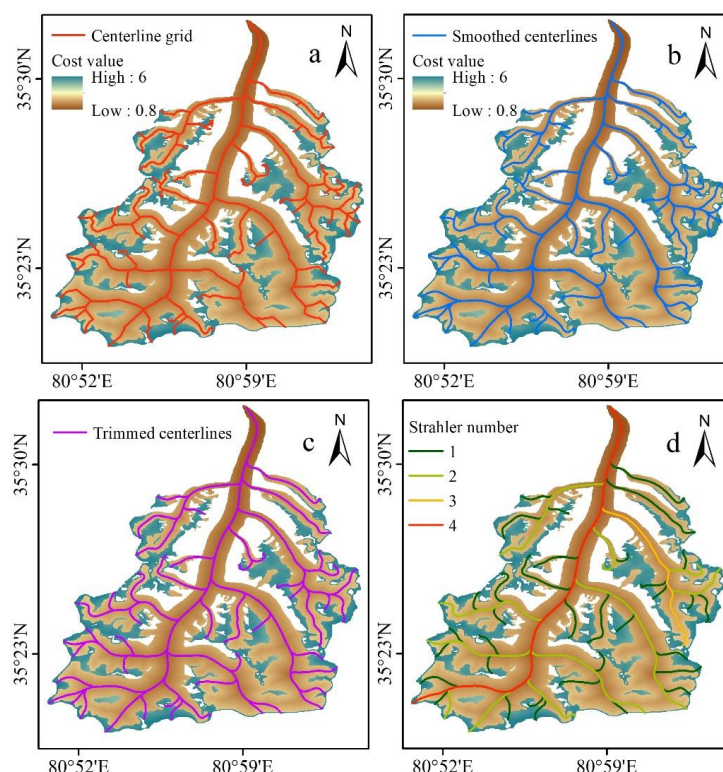


Figure 3. Main processing steps for glacier centerline extraction. (a) Initial centerline grid paths before processing. (b) Smoothed centerlines. (c) Trimmed centerlines. (d) Strahler number assignment of glacier centerlines.

4.4 Validation of algorithm

Some studies have used manually delineated centerlines to evaluate automatically extracted centerlines (Machguth and Huss, 2014; Zhang et al., 2021). However, manual delineation is often subject to subjective interpretation, as different researchers may have different perceptions of the appropriate centerline location. Therefore, independent validation of automatically extracted centerlines is essential to ensure their reliability and comparability (Kienholz et al., 2014). In this study, we compared our automatically extracted centerlines with those provided in RGI 7.0, as both datasets were derived using the same DEM and glacier outlines. Centerline length was used as a quantitative metric, and the comparison was conducted for all glaciers larger than 0.01 km² across HMA.



411 The comparison of glacier lengths is presented in Fig. 4. The coefficient of
412 determination R^2 of the fitted curve in the scatter plot is 0.98, indicating a strong overall
413 consistency between the centerline lengths derived by our method and those reported
414 in RGI 7.0. This high consistency is largely attributable to the predominance of small
415 glaciers in the study area (Fig. 4b). Among all investigated glaciers, those with an area
416 smaller than 5 km² account for 78% of the total number, and their centerline length
417 ratios are generally close to 1. This agreement can be attributed to the relatively simple
418 morphology of small glaciers, which generally results in similar centerlines being
419 extracted by the two methods, except for small glaciers with complex terrain.

420 In contrast, the remaining glaciers exhibit relatively larger discrepancies in
421 centerline length. Because these glaciers constitute a smaller proportion of the total
422 population, their discrepancies have a limited influence on the overall correlation and
423 are therefore less apparent in the statistical results. These glaciers include both small
424 glaciers with substantial deviations from a length ratio of 1 and larger glaciers (Fig. 4b).
425 The discrepancies are particularly evident for large glaciers, which show considerable
426 deviations from the fitted curve (Fig. 4a). This result indicates that our method and RGI
427 7.0 can produce substantially different centerline geometries and lengths for large and
428 morphologically complex glaciers.

429 To further investigate these differences, particularly for large glaciers, we used
430 ITS_LIVE glacier velocity data as an independent reference. Machguth and Huss (2014)
431 suggested that centerlines derived with the aid of glacier velocity fields can provide
432 more accurate representations of glacier flow, although obtaining and applying velocity
433 data for centerline extraction remains challenging. Kienholz et al. (2014) similarly
434 noted that actual glacier velocity fields would provide an ideal reference for validating
435 extracted centerlines. Therefore, we used ITS_LIVE velocity data to further evaluate
436 the performance of our method.

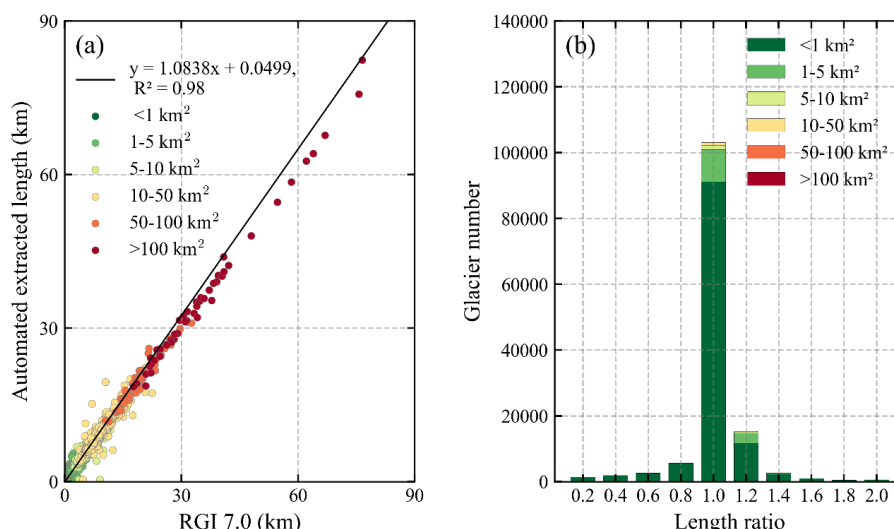


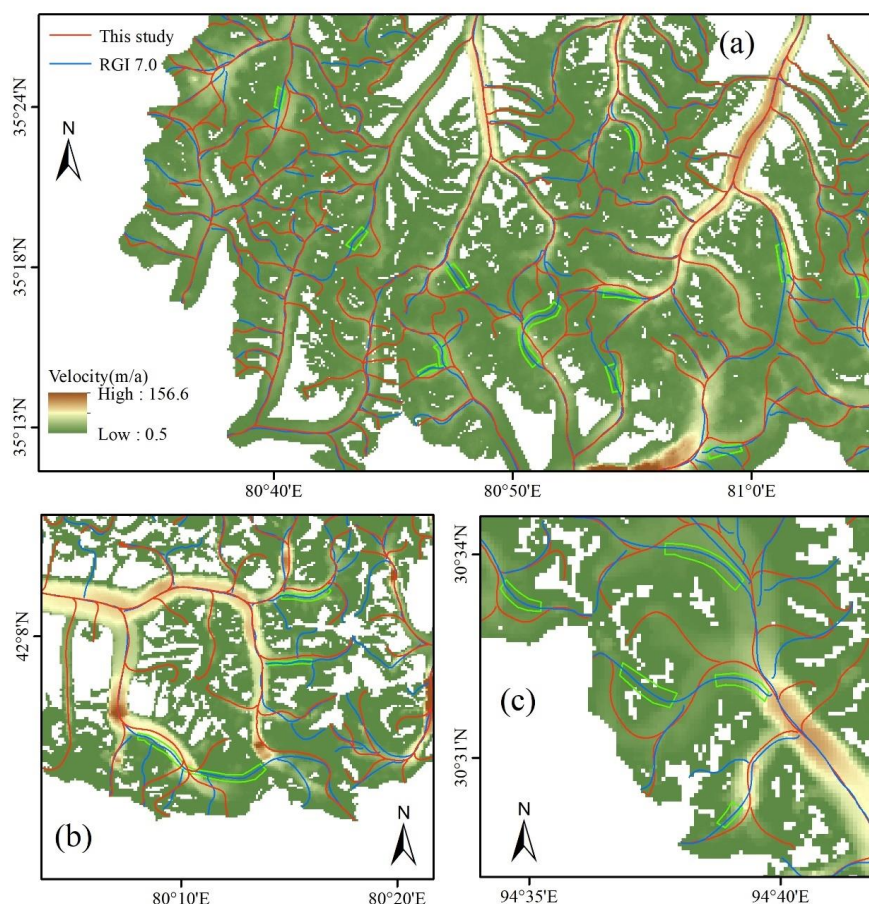
Figure 4. Comparison of glacier lengths derived in this study and from RGI 7.0. (a) Linear regression between the two datasets. (b) Ratio of glacier length derived in this study to that from RGI 7.0.

The selected glaciers are distributed across three representative regions of HMA: the West Kunlun, West Tianshan, and southern and eastern Tibetan Plateau. Figure 5 shows the spatial relationship between the extracted centerlines and the 2013–2022 multi-year mean glacier velocity from ITS_LIVE. Notably, both our centerlines show good agreement with the velocity field in the ablation zones at lower elevations, and both methods generally capture the zones of maximum glacier velocity. However, substantial differences occur in the accumulation zones at higher elevations. Compared with our results, the RGI 7.0 centerlines in the accumulation zones of large glaciers frequently deviate from the observed velocity field, as highlighted by the green polygons in Fig. 5. In these areas, the RGI 7.0 centerlines fail to follow the zones of relatively high glacier velocity.

This pattern is observed across most of the investigated glaciers (Fig. 5a–c). In some cases, the RGI 7.0 centerlines even cross ridgelines. A particularly prominent example is the longest purple polygon in Fig. 5b, where the RGI 7.0 centerline crosses from one glacier branch into an adjacent branch, which is inconsistent with the expected direction of glacier flow. These deviations may result from the reliance on geometric



458 morphology in centerline extraction without sufficiently accounting for topographic
459 constraints. Although such deviations may have a limited effect on the total glacier
460 length, they can substantially affect applications that depend on the spatial distribution
461 of centerlines, such as glacier thickness estimation based on centerline interpolation
462 and glacier dynamic modeling.



463 **Figure 5.** Relationship between glacier centerlines and ITS_LIVE multi-year mean velocity. (a)
464 Glacier RGI2000-v7.0-G-13-48984 and surrounding glaciers in the West Kunlun. (b) Glacier
465 RGI2000-v7.0-G-13-28434 and surrounding glaciers in the West Tianshan. (c) Glacier RGI2000-
466 v7.0-G-13-73770 and surrounding glaciers in southern and eastern Tibet. Green polygons indicate
467 areas where the RGI 7.0 centerlines fail to capture the maximum glacier flow velocity.
468

469 Overall, our results demonstrate that the proposed method performs well in
470 extracting centerlines for large glaciers and glaciers with complex terrain, particularly



471 in the high-elevation accumulation zones where geometric approaches are more prone
472 to deviations from the actual glacier flow direction.

473 **5. Calculated length for all glaciers across HMA**

474 Based on the proposed centerline extraction algorithm, complete centerline networks
475 were successfully extracted for 134,790 glaciers with areas greater than 0.01 km² across
476 HMA. The results show substantial differences in centerline length among individual
477 regions, as summarized in Table 1. Among the maximum centerline lengths recorded
478 for each region, the shortest is 10.3 km in the Qilian Mountains. The mean centerline
479 length varies considerably among regions, ranging from 0.87 km in the Hissar Alay to
480 1.55 km in the Central Himalaya, with an overall mean length of 1.072 km per glacier.

481 In total, 607 glaciers in HMA have centerlines longer than 10 km. Of these,
482 approximately 23% are located in the Karakoram, followed by the Pamir and Central
483 Himalaya, each accounting for approximately 11%. Six glaciers have centerlines longer
484 than 50 km. The longest centerline identified in HMA is 82.371 km, corresponding to
485 Siachen Glacier in the Karakoram. Siachen Glacier is also the largest glacier in HMA,
486 covering an area of 1087 km², and contains a complex network of multiple branches
487 (Fig. 6). Its centerline network reaches a maximum Strahler number of 6.

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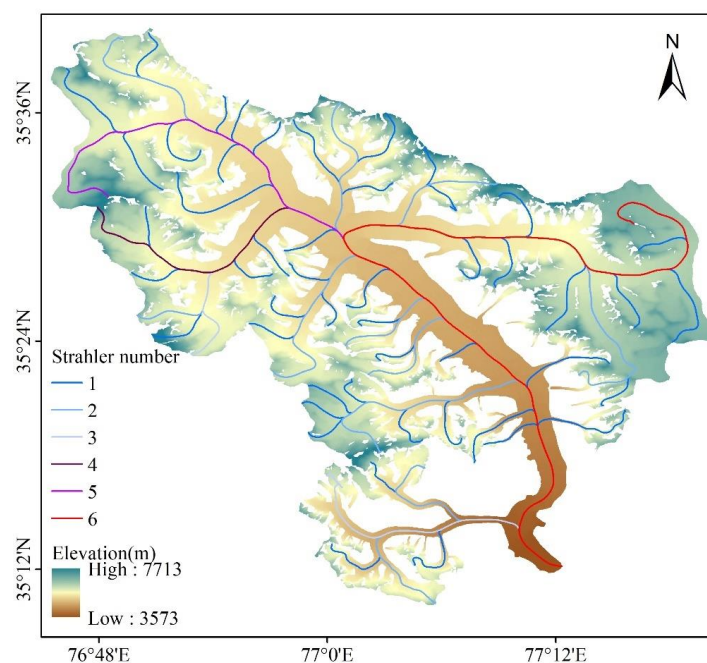
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Table 1. Statistics of glacier centerline lengths for each region in HMA

Number	Region name	Max length (m)	Average length (m)	Number (length >10km)	Number (length >50km)
1	Altay and Sayan	11896	876	3	0
2	Hissar Alay	26121	848	8	0
3	Pamir	75700	1074	68	1
4	West Tianshan	64107	1030	39	1
5	East Tianshan	13877	1003	7	0
6	West Kunlun	31541	1232	48	0
7	East Kunlun	20900	1162	13	0
8	Qilian Shan	10301	985	1	0
9	Inner Tibet Plateau	18779	1102	25	0
10	South and East Tibet	35952	974	30	0
11	Hindu Kush	31200	910	23	0
12	Karakoram	82371	1300	137	5
13	West Himalaya	31253	1102	59	0
14	Central Himalaya	32070	1555	65	0
15	East Himalaya	26711	1428	49	0
16	Hengduan Shan	33235	1042	20	0



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Figure 6. The longest centerline in HMA, with a length of 82.371 km, was extracted for Siachen Glacier (RGI2000-v7.0-G-14-20040).



6. Discussion

6.1 Comparisons to alternative methods

To date, numerous methods have been developed to automatically extract glacier centerlines in HMA using programming-based approaches (Le Bris and Paul, 2013; Kienholz et al., 2014; Le Moine and Gsell, 2015; Machguth and Huss, 2014; Maussion et al., 2019; Pieczonka et al., 2018; Schiefer et al., 2008; Zhang et al., 2021). However, these methods differ substantially in their underlying algorithms and performance. In general, existing approaches can be divided into two categories: (1) methods that rely primarily on glacier geometric morphology and (2) methods that incorporate topographic constraints, such as slope and ridgelines. The first category includes the hydrological approach (Schiefer et al., 2008), glacier-axis approach (Le Bris and Paul, 2013), Thiessen polygon approach (Le Moine and Gsell, 2015; Pieczonka et al., 2018), and cost-grid/least-cost-path approach (Kienholz et al., 2014). Among these, the cost-grid/least-cost-path approach has generally been regarded as one of the better-performing methods for glacier centerline extraction (Machguth and Huss, 2014; Maussion et al., 2019; Zhang et al., 2022).

The second category represents an enhancement of the first by incorporating additional topographic constraints. These constraints can reduce deviations in extracted centerlines, particularly for glaciers in complex terrain. Pieczonka et al. (2018) incorporated a slope threshold of 30° into the Thiessen polygon approach; however, this fixed threshold may still result in discrepancies for HMA glaciers with relatively gentle slopes. Using a trade-off function, Machguth and Huss (2014) extracted glacier centerlines and lengths at the global scale. However, their method excluded the centerlines of individual glacier branches, which may lead to underestimation of glacier length (Zhang et al., 2022). To address this limitation, Zhang et al. (2022) developed a new global dataset of mountain glacier centerlines and lengths based on the method of European allocation.

Here, we selected glacier length data from RGI 7.0 and RGI 6.0 for comparison, considering their public availability. The two datasets were generated using different approaches: the cost-grid least-cost route implemented in the OGGM model (the first



category) (Maussion et al., 2019) and the European allocation method of Zhang et al. (2021) (the second category). Three glaciers representing different size classes, a small glacier (RGI2000-v7.0-G-13-26920), a medium-sized glacier (RGI2000-v7.0-G-13-26161), and a large glacier (RGI2000-v7.0-G-13-48984), were selected, with consistent glacier areas between the two datasets (Table 2). This selection was intended to evaluate the performance of the proposed algorithm across glaciers of different scales. This comparison is particularly important because we found that, although the differences in glacier length between methods may be relatively small, their performance can vary substantially among individual glaciers.

Table 2. Glacier information used to comparison

RGI id	lon	lat	Area (km ²)	Length (m)		
				Zhang et al., 2022	RGI 7.0	This study
RGI2000-v7.0-G-13-26920	78.82	42.09	4.2	3101	4499	5112
RGI2000-v7.0-G-13-26161	78.23	41.81	33.5	8051	10162	10827
RGI2000-v7.0-G-13-48984	81.01	35.43	208.5	29512	29026	28963

Fig. 6 shows a comparison of the centerlines extracted for the three glaciers using the different methods. Several common characteristics can be identified. First, the centerlines extracted by the three methods are generally consistent in the ablation zones. This is likely because all three methods incorporate Euclidean distance, while the glacier boundaries in the ablation zones are relatively simple and are less affected by topographic features such as ridgelines. The positions of the glacier heads are also generally consistent among the three methods. Where minor differences occur, they are likely attributable to variations in the DEM data and differences in the clipping and raster-processing procedures implemented using different programming languages.

However, the most pronounced differences are observed in the accumulation zones of the glaciers. Even for small glaciers with relatively simple morphological features, substantial differences remain, as shown in Fig. 7a–c. The centerline trajectories derived from RGI 6.0 and RGI 7.0 cross the glacier’s ridgelines. Moreover, the RGI 6.0 centerline is located close to the glacier boundary, whereas the RGI 7.0 centerline follows the geometric morphology of the glacier more closely. Centerlines that cross ridgelines are physically unreasonable (Kienholz et al., 2014; Machguth and



561 Huss, 2014), and this is further supported by the glacier velocity field from ITS_LIVE
562 (Fig. 8a). In contrast, our method prevents the centerline from crossing ridgelines by
563 incorporating contour-gradient constraints, resulting in a trajectory that is more
564 consistent with the observed glacier flow field. These results indicate that, for mountain
565 glaciers in HMA, centerlines extracted solely from geometric or distance-based
566 information can exhibit substantial deviations in complex accumulation zones when
567 topographic constraints are not explicitly considered. Although RGI 6.0 also
568 incorporates ridgeline information, this constraint does not appear to effectively
569 influence the resulting centerline in this case. Alternatively, the anomalous trajectories
570 may be related to the position of the ELA, particularly where the ELA lies above the
571 ridgelines in small glaciers, potentially weakening the effectiveness of geometry-based
572 constraints.

573 This phenomenon is also observed in medium-sized glaciers (Fig. 7d–f) and large
574 glaciers (Fig. 7g–i). These multi-branched compound glaciers are characterized by
575 more complex terrain than the small glaciers, and centerline trajectories approaching
576 steep glacier margins occur more frequently. In some cases, even the centerlines
577 derived from RGI 6.0 cross ridgelines (Fig. 7g). We also found that the centerlines from
578 both RGI 6.0 and RGI 7.0 fail to capture some glacier branches (Fig. 7d–e and Fig. 7g–
579 h). This is mainly because only glacier heads located along the outermost glacier
580 boundaries were identified, whereas heads associated with internal boundaries were
581 overlooked. In contrast, our method identifies potential heads along both outer and
582 internal boundaries, allowing the centerlines of individual branches to be more
583 completely represented. Furthermore, from the perspective of the glacier velocity field,
584 our centerlines are more consistent with the observed flow patterns (Fig. 8c). This
585 further demonstrates the advantage of incorporating topographic constraints into
586 centerline extraction, particularly for valley glaciers with complex terrain in HMA. To
587 some extent, the centerlines generated by our method in areas of complex terrain should
588 not be interpreted as strict geometric centerlines; rather, they more closely approximate
589 the potential flow lines of the glacier.

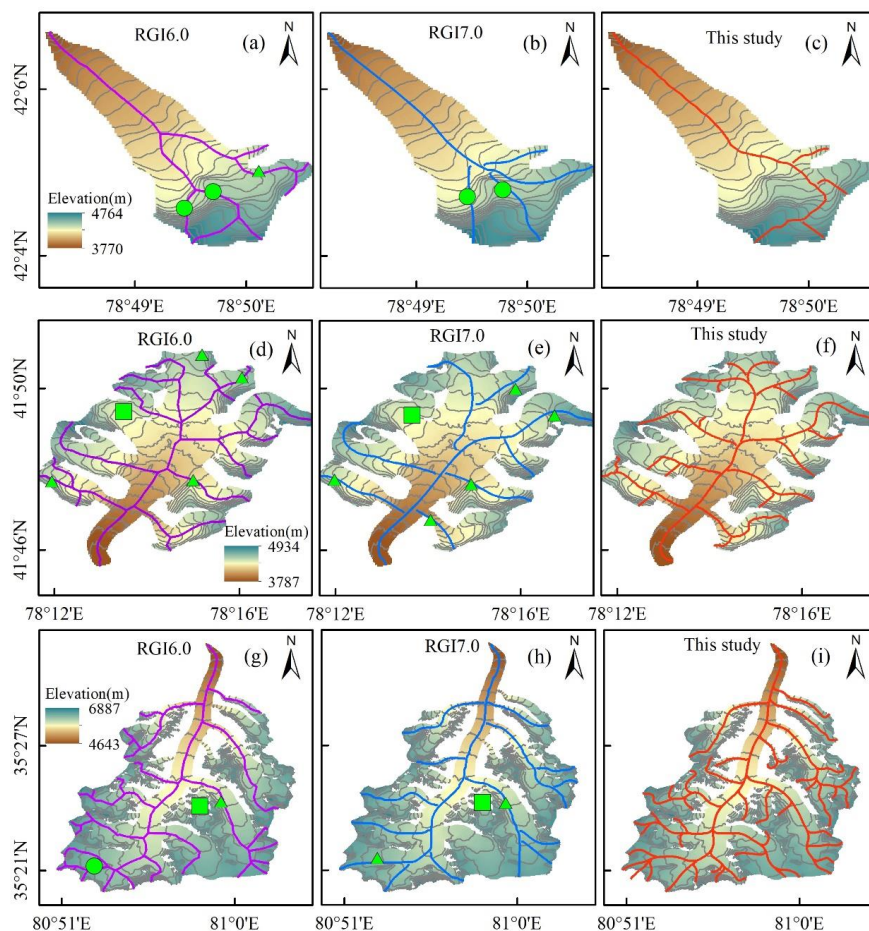


Figure 7. Comparison of centerlines for small (a–c, RGI2000-v7.0-G-13-26920), medium-sized (d–f, RGI2000-v7.0-G-13-26161), and large (g–i, RGI2000-v7.0-G-13-48984) glaciers derived from Zhang et al. (2022), RGI 7.0, and this study. Green circles indicate centerlines that cross ridgelines, green triangles indicate centerlines approaching steep terrain margins, and green squares indicate missing centerlines. Black lines represent contour lines.



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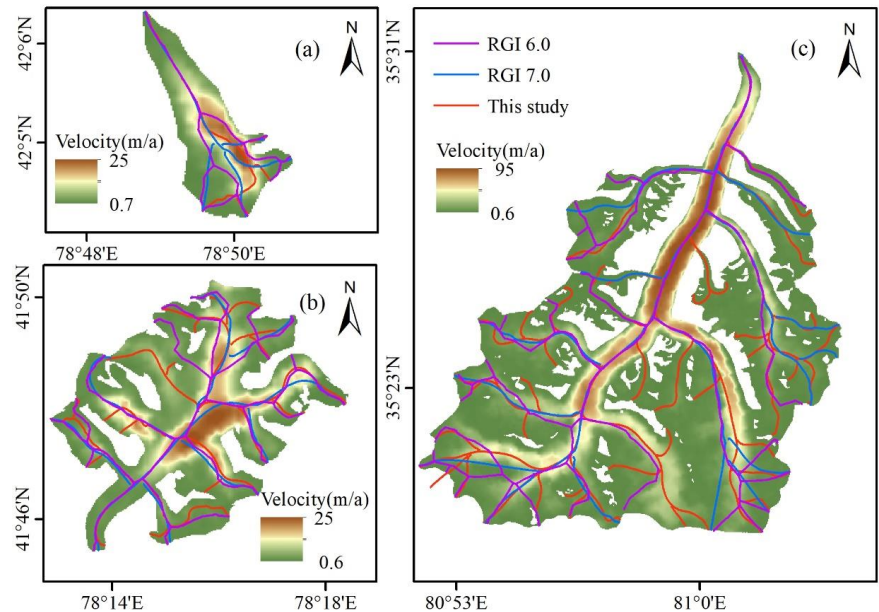


Figure 8. Comparison of the centerlines extracted using different methods with the 2013–2022 multi-year mean glacier velocity field from ITS_LIVE.

6.2 Influence factors of centerlines extraction

The factors affecting the accuracy of centerline extraction can be broadly attributed to three aspects: DEM quality, glacier outlines, and algorithm design. Previous studies have shown that systematic biases in DEMs have relatively limited effects on centerline extraction, whereas blunders caused by DEM artifacts can have a substantial impact (Kienholz et al., 2014). This issue is particularly important in glacier accumulation zones, where DEM artifacts are often not located along the actual glacier centerline but instead occur along steepest downward gradients, making the extracted centerlines highly susceptible to such artifacts (Le Bris and Paul, 2013; Schiefer et al., 2008). In our method, DEM artifacts can affect the calculation of contour gradients because local blunders, such as artificial bumps or depressions, may be incorrectly interpreted as steep terrain. When such artifacts occur near glacier heads or termini, they can consequently alter the centerline trajectory or lead to incorrect identification of the starting or ending points. Machguth and Huss (2014) reported that low-quality DEMs can cause extracted centerlines to shift toward adjacent glaciers, obstruct their



618 progression toward the glacier tongue, or terminate prematurely. Nevertheless, it is
619 worth noting that the centerlines extracted using the method of Le Bris and Paul (2013)
620 are relatively insensitive to DEM quality, suggesting that algorithm design can play an
621 important role in mitigating the influence of DEM artifacts.

622 Compared with the approach of Machguth and Huss (2014), which is relatively
623 insensitive to glacier outlines because it primarily relies on slope information, our
624 method has a stronger dependency on the accuracy of glacier outlines. This is expected
625 for centerline extraction methods that rely on glacier geometry. When the ice divide is
626 inconsistent with the watershed divide, the extracted centerline may cross the watershed
627 divide (Kienholz et al., 2014). In this study, the glacier outlines are approximately from
628 2000, whereas the DEM data represent the period 2010–2015. Therefore, using non-
629 contemporaneous glacier outlines and DEM data may result in some spurious branch
630 centerlines. However, this issue is mainly associated with small branches, where glacier
631 retreat has subsequently altered the surface elevation and drainage geometry. Our
632 method also has limitations when applied to cirque and apron glaciers because their
633 termini may not correspond to the expected positions of glacier flow termination. In
634 contrast, the presence of nunataks and exposed bedrock within glacier boundaries does
635 not have a significant influence on centerline extraction. The contour-gradient
636 constraint can intervene in the extraction process and force the centerlines to detour
637 around these obstacles, thereby maintaining trajectories within the surrounding
638 glacierized area.

639 The algorithm itself exerts a significant influence on centerline extraction. In our
640 method, the highest-elevation points along the glacier boundary are identified as
641 potential heads, with each point initially assumed to correspond to a single branch.
642 However, a single high-elevation point may in fact represent multiple branches,
643 particularly in larger and more complex glacier systems. This issue is also supported by
644 the parameter adjustment experiments of Kienholz et al. (2014). A similar problem
645 occurs in the identification of glacier termini. Many large compound glaciers drain into
646 multiple glacier tongues, whereas our algorithm identifies only one terminus for each
647 local elevation minimum, potentially failing to capture all drainage branches. During



648 the tracking process from glacier heads to termini, the extracted centerlines tend to
649 deviate toward the geometric center of the glacier in relatively flat terrain. Such
650 centerlines may not adequately represent the actual flow paths, particularly in regions
651 with relatively complex flow dynamics.

652 In addition, some branch centerlines are removed according to the predefined
653 length threshold because short centerlines may be generated by noise or minor
654 irregularities in glacier geometry. The selection of this threshold therefore involves a
655 trade-off. If the threshold is set too high, legitimate short branches may be incorrectly
656 removed, resulting in incomplete representation of the glacier network. Conversely, if
657 the threshold is set too low, spurious centerlines caused by noise may be retained,
658 increasing the number of erroneous centerlines.

659

660 **7. Conclusions**

661 We proposed a new approach for automatically extracting glacier centerlines by
662 identifying ridge lines and steep terrain from contour gradients to effectively constrain
663 the flow direction of glacier centerlines. By integrating these terrain constraints with a
664 cost grid and hydrological flow analysis, the proposed method can extract glacier
665 centerlines using only DEMs and glacier outlines as input data. The approach is fully
666 automated, computationally efficient, and requires no manual intervention. It
667 successfully extracts individual centerlines of valley glaciers across the HMA and
668 performs particularly well in rugged and topographically complex terrain. Validation
669 against ITS_LIVE glacier velocity data indicates that the extracted centerlines are
670 generally more consistent with observed glacier movement patterns, capturing flow
671 characteristics that have been difficult to represent using previous approaches. The
672 resulting glacier length dataset for HMA provides a valuable basis for glacier dynamic
673 modelling and glacier thickness estimation.

674 Based on the extracted centerlines, we calculated the Strahler number for each
675 glacier and derived the centerlines of individual branches accordingly. The results show
676 that the average glacier centerline length in HMA is 1.072 km, with 607 glaciers having
677 centerlines longer than 10 km and six exceeding 50 km. The longest centerline



678 identified in HMA is 82.371 km for Siachen Glacier in the Karakoram. We also
679 identified several factors that influence the accuracy of the extracted centerlines,
680 including the quality of DEMs, glacier outlines, and velocity data, as well as the
681 complexity of glacier morphology and terrain. As more accurate and higher-resolution
682 datasets become available, we will further refine the algorithm and develop updated,
683 high-quality glacier centerline datasets for HMA.

684

685 *Code availability.* The code developed in this study is available upon request.

686 *Data availability.* The database of glacier centerlines in HMA is available in the
687 supplementary material.

688

689 *Author contributions.* RJ W designed this algorithm of extracting centerlines, run the
690 program and edited the manuscript. WQ G participated in the algorithm design and
691 extracted the DEM of each glacier with IDL language. M S checked the quality of
692 glacier centerlines. DH SG, SS W, DZ, SJ W, QD Z and DH reviewed and edited the
693 manuscript.

694

695 *Competing interests.* The authors declare that they have no conflict of interest.

696

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