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Determining topographic shielding from digital elevation models for cosmogenic nuclide analysis: a GIS model for discrete sample sites

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Abstract: Topographic shielding (TS) is an important factor in cosmogenic nuclide surface exposure dating. The development of geographic information systems (GIS) and the availability of digital elevation models (DEMs) make it possible to derive this factor directly from a DEM. Most available GIS models derive the TS factors for an area (all cells in a DEM) without the consideration of surface conditions of individual sites, such as the strike, dip, and height above ground, into the calculation. This paper presents a new GIS model to derive the TS factors for discrete sample sites. This model uses the Skyline and Skyline Graph functions in ArcGIS to extract the set of azimuth and elevation angles of topographic obstructions around each site from a DEM (considering the sample height above ground) and then incorporates the strike and dip information of the sample surface to derive the TS factor. All processing tools and steps are streamlined in ArcGIS modelbuilder and this model can be run like a standard ArcGIS geoprocessing tool. It provides an easy and user-friendly means to derive the TS factors for discrete samples based on a DEM and the measured strike, dip and sample height for each site.

Keywords: Cosmogenic nuclides; Topographic shielding; Digital elevation models (DEMs); ArcGIS modelbuilder

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Introduction

Cosmogenic nuclides (e.g. ^{10}Be, ^{26}Al, and ^{36}Cl) have been widely used in geomorphology, quaternary geology, and geochronology to determine surface exposure ages and denudation rates of various earth surface processes (Gosse and Phillips 2001; Li and Harbor 2009). These nuclides are produced within a few meters of rock and sediment's surfaces and their production rates are affected by many factors, including topography that may block a portion of the cosmic radiations at a sample site to reduce the nuclide production (Dunne et al. 1999). In addition, sample surface conditions, such as the strike, dip, and height above ground, may also affect the amount of incoming cosmic radiations at a site. Thus, it is important to determine the topographic shielding (TS) factor for a sample site based on its surrounding topography and surface conditions (Dunne et al. 1999; Balco et al. 2008).

The TS factor was traditionally determined by measuring the strike and dip information for a sample site and recording a set of azimuth and elevation angles of topographic obstructions around the site in the field. These measurements were then used to derive the TS factor based on the method described in Dunne et al. (1999) or using the procedures from the CRONUS-Earth online calculator (Balco et al. 2008) or the Excel-based

CosmoCalc calculator (Vermeesch 2007). However, it is time-consuming to measure this information for multiple sites and may cause uncertainties and/or inconsistency among different investigators (Li 2013).

With the development of geographic information systems (GIS) and the availability of digital elevation models (DEMs), methods have been developed to directly derive the TS factors from the DEM (Codilean 2006; Li 2013). For example, Li (2013) introduced a python tool in ArcGIS to determine the topographic shielding for an area and validated DEM-derived factors with field-measured values. This tool can save time in the field and produce consistent results for different investigators and regions. Although most available GIS models are area-based that were designed to derive the TS factors for an area (all cells in a DEM), some of these models have been increasingly used for individual samples (Li et al. 2014; Chen et al. 2015; Heyman et al. 2016; Li et al. 2016, Zhang et al. 2016; Tomkins et al. 2016; Baroni et al. 2017; Dong et al. 2017; Liu et al. 2017). However, several limitations exist in using the area-based models for discrete sample sites. First, the strike and dip of the sampled surface are not considered and the height above ground for each sample site is simply assumed as zero in the calculation. Second, it may take relatively long time to derive the TS raster for a large area or using a high-resolution DEM, whereas the requested values for discrete samples are only for a few sites. Thus, it is computationally inefficient to use the area-based models for discrete samples. It is therefore necessary to develop a specific tool to derive the TS factors for discrete samples using a DEM.

This paper presents a new GIS model to determine the TS factors for discrete sample sites. It integrates the shielding from surrounding topography and the measured strike, dip, and sample height above ground information to derive the TS factor for each site. All analyses are streamlined in ArcGIS modelbuilder and the model can be run like a standard geoprocessing tool. It provides an easy, efficient, and user-friendly means to determine the TS factors for multiple sample sites.

1 Method

The TS factor is defined as the ratio of the received cosmic flux by a site to the maximum flux of this site if assuming an unshielded exposure (Dunne et al. 1999; Gosse and Phillips 2001; Codilean 2006). It is commonly calculated using the following equation (Dunne et al. 1999):

$$C_T = 1 - \frac{1}{2\pi}\sum_{i=1}^{n}\Delta\phi_i \sin^{m+1}(\theta_i) \quad (1)$$

where C_T is the TS factor, n is the number of topographic obstructions that are measured around a sample site and each obstruction is represented by a pair of azimuth (ϕ_i) and elevation (θ_i) angles, and m is a constant with a value of 2.3 in most studies (Nishiizumi et al. 1989; Gosse and Phillips 2001; Balco et al. 2008).

Codilean (2006) introduced a method to simulate the topographic shadow of a DEM based on a series of azimuth and elevation angles using the hillshade function in GIS and then determine the TS factor for each cell of the DEM. Li (2013) developed a python code to automate the whole process. This method derives the topographic shielding for each cell of the DEM. Thus, it is computationally intensive and may require relatively long time to derive the TS raster for a large area or using a high-resolution DEM. As a widely used GIS software for DEM-related analysis, ArcGIS also provides the Skyline and Skyline Graph functions to determine the azimuth and elevation angles from a DEM for a site (http://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/skyline.htm). The Skyline function generates a 3D ridgeline (skyline) to represent the farthest visible points along the lines of sight of a set of azimuth angles around a site (Figure 1A&B). The Skyline Graph function exports the horizontal and vertical angles from this site to all vertices on the skyline (Figure 1C). Note that the horizontal and vertical angles exported from the Skyline Graph function are different from the azimuth and elevation angles defined in Equation 1 (a horizontal angle of 0° is east, and 90° is north; a vertical angle of 90° is horizontal, and 0° is straight up, Figure 1C). Specifically, the azimuth angle is equal to 90° minus the horizontal angle and the elevation angle is equal to 90° minus the vertical angle.

If a sample is not collected from a horizontal surface, cosmic radiation is also blocked by the dipping surface. Balco introduced a method to account for the shielding from a dipping surface

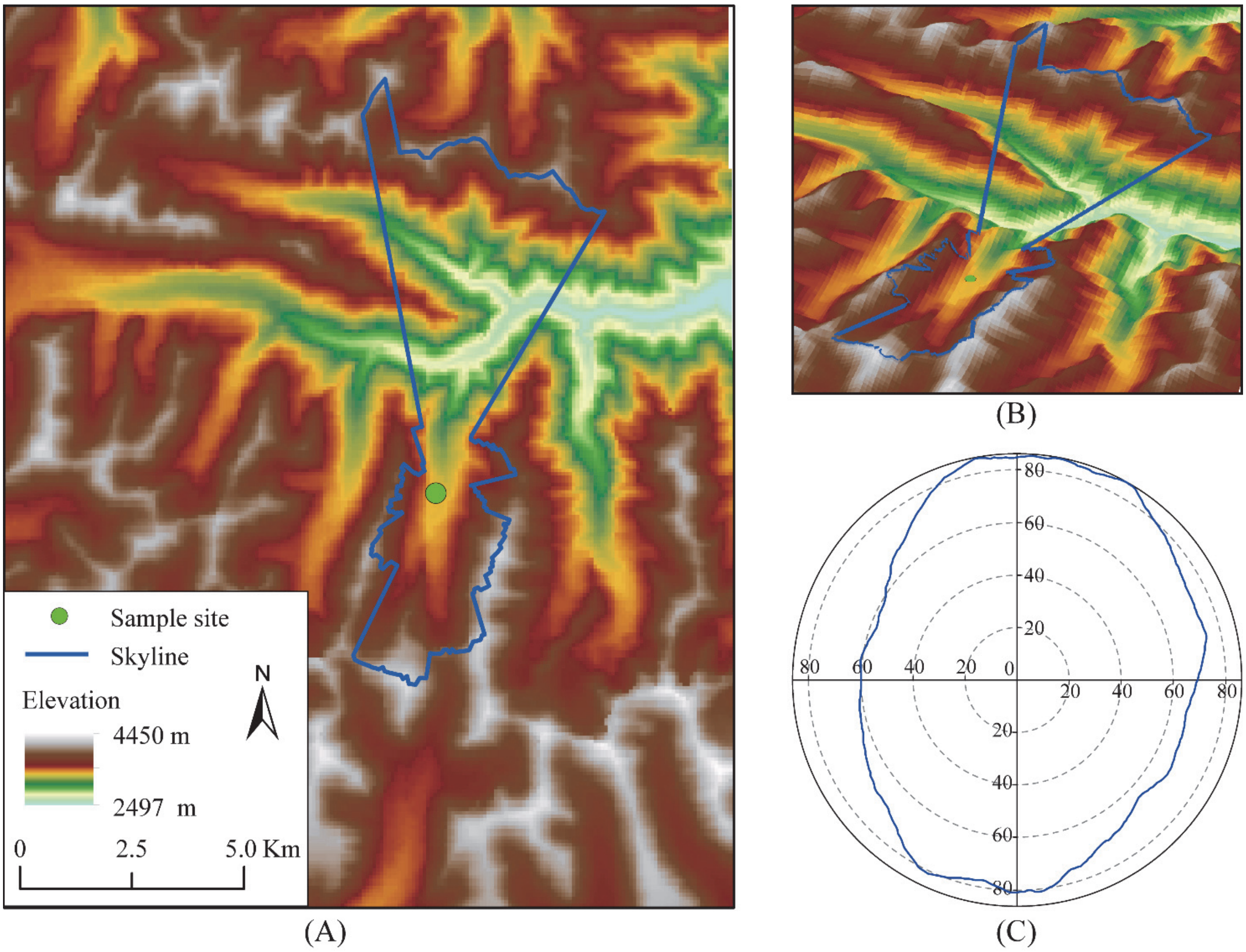


Figure 1 (A) The ridgeline (skyline) produced by the Skyline function for a sample site (in ArcMap); (B) The skyline viewed from a 3D perspective in ArcScene; and (C) The polar graph of the skyline generated by the Skyline Graph function. The horizontal angle is started from east (0°) with an anticlockwise direction (90° is north) and vertical angle is started from straight up (0°) to horizontal (90°), representing the sky openness to the sample site. These angles will be converted to the azimuth and elevation angles for the topographic shielding calculation.

(https://hess.ess.washington.edu/math/docs/al_be_v2/al_be_fctn_desc/node23.html). It divides the range of azimuth (0° to 360°) into 1° increments and calculates the elevation angle (θ) for each azimuth using

$$\theta = \arctan[\tan\theta_d \cos(\phi - \phi_s)] \qquad (2)$$

where θ_d is the dip and ϕ_s is the strike of the dipping surface. Then, the maximum elevation angle can be determined for each azimuth by comparing the elevation angle derived from the surrounding topography with the value derived from the dipping surface. The maximum elevation angle for each azimuth will be used in Eq. 1 to derive the TS factor for the sample site.

Based on the methods described above, the general workflow to determine the TS factors for multiple sample sites in ArcGIS is to: (1) extract the elevation from the DEM for each point and add the sample height (above ground) to this elevation. Then, convert this point to a 3D point feature using the modified elevation as the z-dimension; (2) run the 3D point feature through the Skyline and Skyline Graph functions to obtain the horizontal and vertical angles from surrounding topography (DEM) (horizontal angle from 0° to 360° by 1° increment) and convert the horizontal and vertical angles to azimuth and elevation angles; (3) compare the derived azimuth and elevation angles with the values calculated using the strike and dip information (Eq. 2) and determine the maximum elevation angle for each azimuth; (4) calculate the TS factor for the sample site based on Eq. 1; and (5) repeat the upper steps to derive the TS factors of other sample sites.

2 Model Design and Interface

All analysis tools and steps are streamlined using ArcGIS modelbuilder. The whole model includes a main model and two sub-models to run the analysis. The first sub-model is to determine the TS factor for a single sample site (Figure 2). This model first extracts the elevation for the sample site from the DEM using the Extract Values to Points tool and then adds the sample height above ground to this extracted elevation (the Calculate Field tool). Then, convert this point to a 3D feature using the Feature to 3D by Attribute tool and run the Skyline and Skyline Graph tools. The result is a skyline table to list all horizonal and vertical angles from the surrounding topography for this site. After adding some fields to save the converted azimuth and elevation angles, the elevation angle for the dipping surface is calculated for each azimuth using the strike and dip information of the sample site, and then the maximum elevation angle is determined for each azimuth. The TS factor is calculated using Eq. 1 based on the maximum elevation angle (steps from the Add Field to the Summary Statistics tools). Finally, the calculated TS factor is saved to a predefined field in the attribute table of the sample site (steps from the Get Field Value to the Calculate Field tools).

The second model is to iterate the above single point-based sub-model for all sample sites (Figure 3). This model uses the Iterate Feature Selection tool to run the single point-based sub-model for all points. Each point is processed separately to generate an output point file. The Collect Values Tool is then used to collect all separated files into a list of output point files for further analysis. Only the tools that need to be iterated are included in

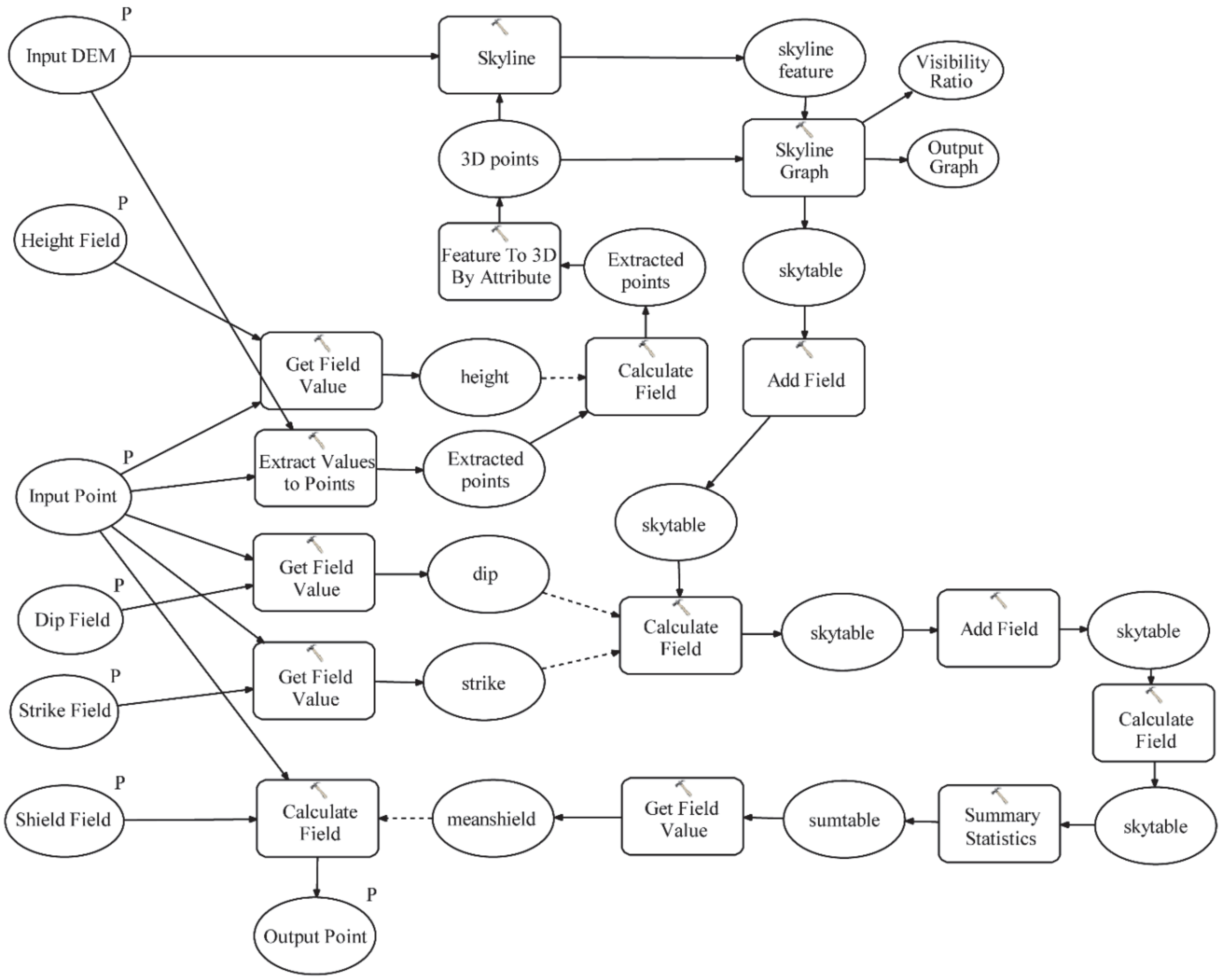


Figure 2 The single point-based sub-model for the topographic shielding factor calculation of a point.

this sub-model because all geospatial tools within a modelbuilder model will be iterated.

The main model is to define input and output datasets as well as the required fields to run the whole analysis (Figure 4). This model specifies the input DEM, input sample points, the strike, dip, and height above ground field from the sample points for the TS factor calculation. The model first makes a copy of the input points (using the Copy Features tool) to keep the original dataset unchanged and adds a new field to the copied point file (using the Add Field tool) to save the calculated

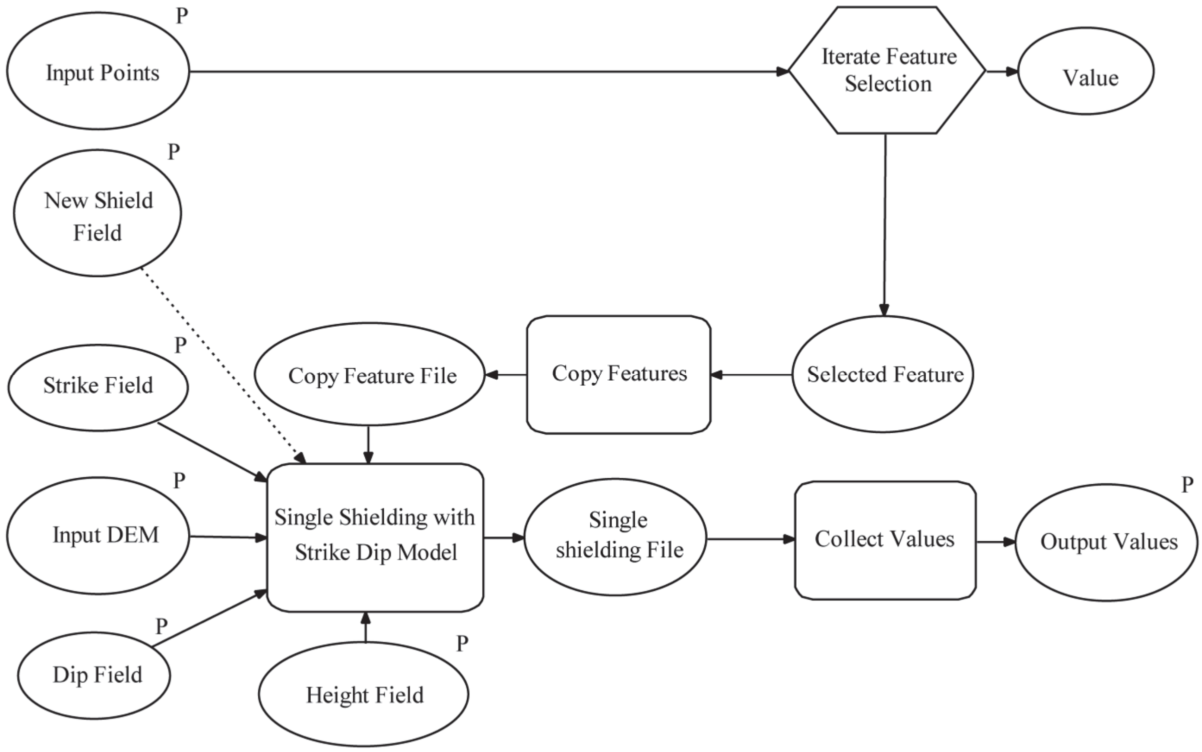


Figure 3 The sub-model for the topographic shielding factor calculation of multiple points.

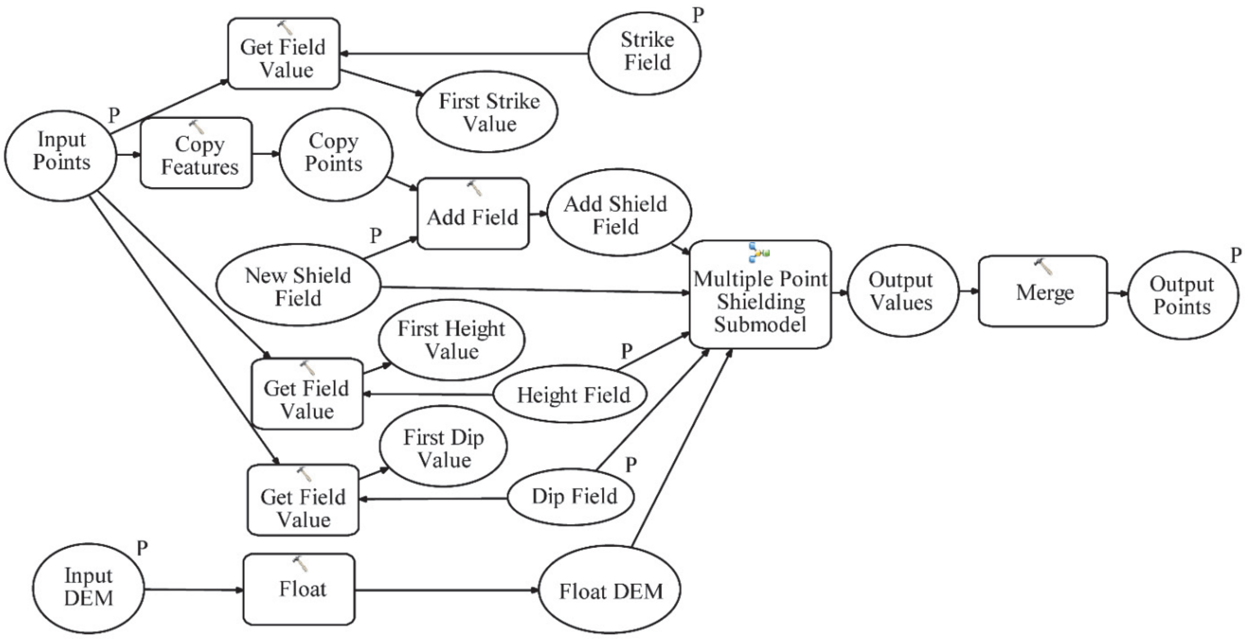


Figure 4 The main model to run the whole topographic shielding factor calculation.

TS factor. Then, the model uses these parameters to run the multiple point sub-model (Figure 3) to generate the collected point files with the derived TS factors and merge these files into one output point file (using the Merge tool).

ArcGIS provides two major ways to perform the GIS model created using modelbuilder. One is to run the model within the modelbuilder environment, so that the individual steps and results can be examined. The other is to run the model like a standard ArcGIS tool by double clicking the model in Catalog (the ArcGIS toolbox of this model is available as a supplementary file). Figure 5 illustrates the interface of the main model by running it like a standard tool. It requires seven parameters: 1) Input DEM; 2) Input Points; 3) Strike Field; 4) Dip Field; 5) Height Field; 6) New Shield Field; 7) Output Points. Note that the DEM and the sample points must have the same coordinate system (map projection) to avoid the unexpected errors in the calculation. The strike, dip, and sample height (above ground) for each site are stored as separated fields in the attribute table (use zero if they were not measured for a site). A python tool is also created to make the input of these fields optional and allow for the model run without having to specify these fields for each sample (the ArcGIS toolbox, including the python tool, is available at: http://web.utk.edu/~yli32/pointshielding.zip).

3 Example and Result Comparison

Li (2013) determined the TS raster using the area-based python tool and validated the results through the comparison of the field measurements of 10 sample sites in the source area of the Urumqi River, Tian Shan, China (Li et al. 2014, Figure 6A). The DEM used in the calculation was the 3 arc-second (90-m) resolution Shuttle Radar Topography Mission (SRTM) DEM (http://srtm.csi.cgiar.org) and includes 308 × 540 cells. The TS factors of these sample sites were recalculated using the same DEM and the new GIS model introduced in this paper. Then, the calculated TS factors were compared with the results derived using the python tool based on a 5° interval in

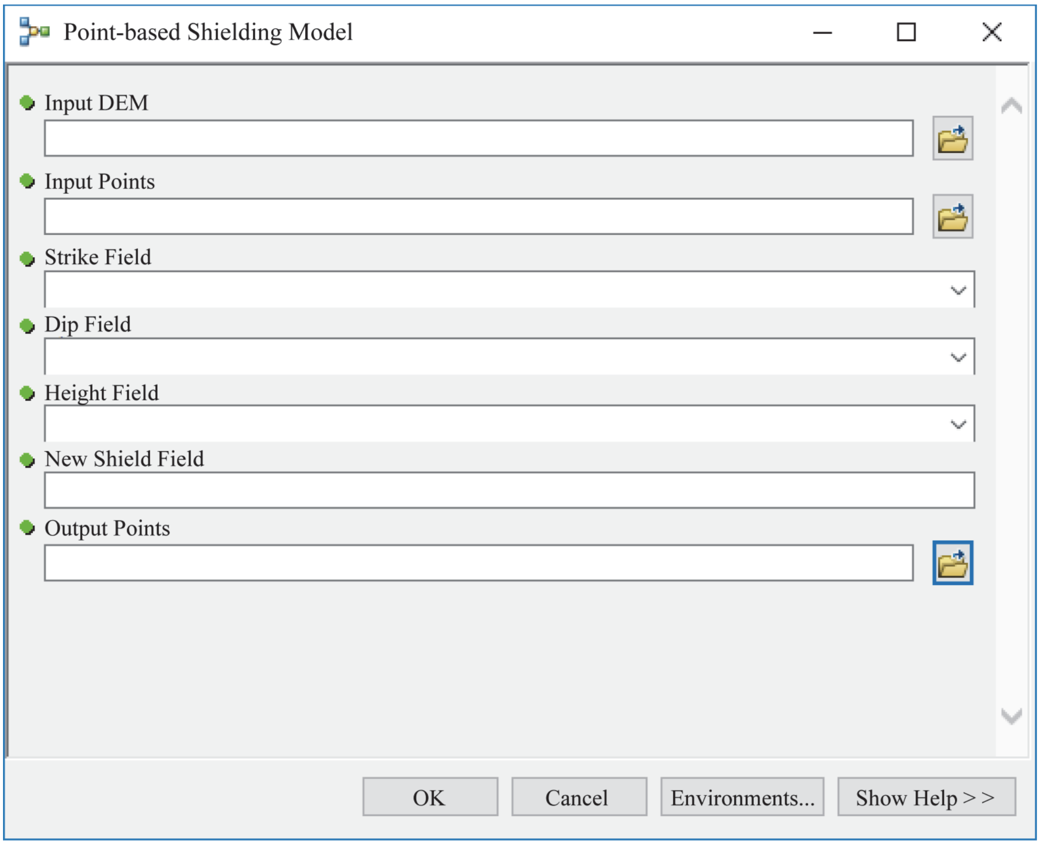
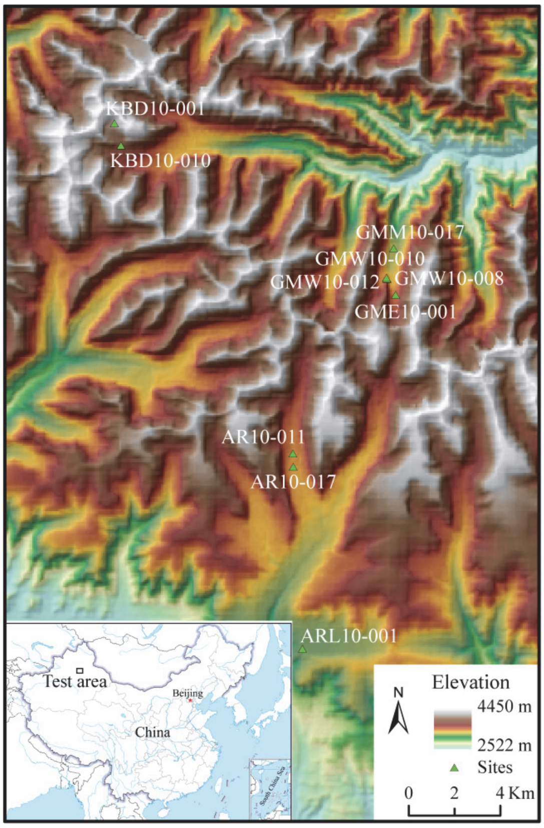


Figure 5 The interface of the main model in ArcGIS.

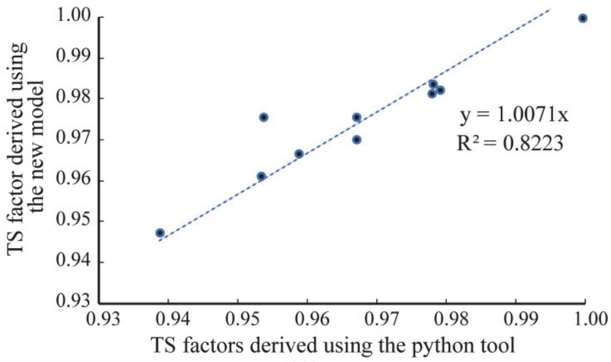


(A)

Sample ID	PDTS	NMTS	FMTS
KBD10-001	0.9388	0.9475	0.9291
KBD10-010	0.9792	0.9818	0.9874
GME10-001	0.9534	0.9613	0.9567
GMW10-008	0.9538	0.9755	0.9677
GMW10-010	0.9672	0.9762	0.9708
GMW10-012	0.9672	0.9757	0.9690
GMM10-017	0.9588	0.9666	0.9641
AR10-011	0.9780	0.9822	0.9869
AR10-017	0.9781	0.9820	0.9688
ARL10-001	0.9996	0.9998	0.9997

PDTS: python tool derived topographic shielding factor
NMTS: new model derived topographic shielding factor
FMTS: field-measured topographic shielding factor

(B)



(C)

Figure 6 Comparison of the topographic shielding (TS) factors derived using the two methods. (A) The SRTM 90-m DEM of the source area of Urumqi River, Tian Shan, China and the 10 sample sites. The inlet map of China is modified from http://bzdt.nasg.gov.cn/; (B) The comparison table between the TS factors derived using the new model (NMTS), the python tool (PDTS, Li 2013), and the field measurements (FMTS); and (C) the X-Y plot between the TS factors derived using the python tool (Li 2013) and the new model.

azimuth and a 2° in elevation angles, the values suggested by Li (2013) for the TS factor calculation. Zero values are used in the new model for the strike, dip, and height above ground of these sample sites because the python tool (Li 2013) does not incorporate the local sample conditions in the calculation. Therefore, the TS factor derived using the new model only accounts for the shielding from the surrounding topography of each sample site in this comparison.

The comparison results indicate that the difference between the TS factors calculated using these two methods are minor (<0.01 for most samples except GMW10-008, Figure 6B) and the values are highly correlated each other (the regression slope is close to 1.0 with R^2 = 0.8223, Figure 6C). The processing time for this new model is about 1 minute (58 seconds) using a Lenovo laptop with Inter (R) Core (TM) i7-4510U CPU @ 2.00 GHz and 8 GB memory. In contrast, the area-based python tool (Li 2013) needs to run about 88 minutes to derive the TS raster for this DEM. Therefore, it is much faster to use the new method to derive the TS factors for induvial sample sites.

Two other DEMs in this area were also used to test the sensitivity of the TS factors derived using this model to different DEM resolutions. One is the SRTM 1 arc-second (30-m) global elevation data (version 3, https://lta.cr.usgs.gov/SRTM1Arc) that is available for this area in 2015. Before 2015, only the 90-m resolution SRTM DEMs (versions 1 and 2) were available for areas outside of the US. Four tiles of DEMs were downloaded and merged into one DEM. The merged DEM was then re-projected to the UTM projection and masked using the boundary of the SRTM 90-m DEM illustrated in Figure 6A. The masked DEM includes 916 × 1607 cells. The other is the High Mountain Asia (HMA) 8-m DEMs (released in 2017) downloaded from the NASA National Snow and Ice Data Center

Distributed Active Archive Center. These DEMs are produced using the very-high-resolution DigitalGlobe satellite imagery collected from 2002 to 2016 (https://nsidc.org/data/highmountainasia, Shean et al. 2016). Three DEMs are available in the source area of the Urumqi River, but does not cover all sample sites (ARL10-001 is not covered). These three DEMs were merged and masked using the SRTM 90-m DEM boundary (Figure 6A). The resulted DEM includes 3053 ×5356 cells. The projection of this DEM is already the UTM, so no project transformation is required.

The processing times to calculate the TS factors of these sample sites are about 58, 66, and 111 seconds for the SRTM 90-m, SRTM-30 m and HMA-8 m DEMs, respectively. They are all less than 2 minutes and do not increase exponentially with the increasing DEM cell numbers, indicating the efficiency of this model. Table 1 lists the TS factors calculated for these sample sites using these DEMs. Basically, the calculated TS factors are similar for different DEMs. It is almost identical for the TS factors derived from the SRTM 30-m and the HMA 8-m DEMs (<0.003) and the difference between the SRTM 30-m and the SRTM 90-m DEMs are minor (<0.02). This suggests that the calculated TS factors are relatively stable for different DEMs.

Table 1 The Topographic shielding factors derived using three different DEMs

Sample ID	SRTM 90-m	SRTM 30-m	HMA 8-m
KBD10-001	0.9475	0.9295	0.9311
KBD10-010	0.9818	0.9797	0.9803
GME10-001	0.9613	0.9590	0.9564
GMW10-008	0.9755	0.9741	0.9730
GMW10-010	0.9762	0.9738	0.9709
GMW10-012	0.9757	0.9700	0.9693
GMM10-017	0.9666	0.9658	0.9633
AR10-011	0.9822	0.9834	0.9833
AR10-017	0.9820	0.9812	0.9812
ARL10-001	0.9998	0.9997	No Data*

*This sample is not covered by the available HMA 8-m DEM

4 Discussion and Conclusions

This paper introduced a newly developed ArcGIS model to derive the TS factors for multiple sample sites. Different from other available tools that derive the TS factors for all cells in a DEM, this new model only derives the TS factors for the sample sites based on the skyline delineation of each sample site using 1° increment in azimuth (0° to 360°). This new model also incorporates the local sample conditions, including the strike, dip, and height about ground, into the calculation and can be used for more general situations because it is not always the case to collect samples from perfectly flat surfaces. In addition, this new model is developed using ArcGIS modelbuilder, a visual environment and interface to streamline the geospatial analyses. All geospatial tools and parameters of the model are accessible and transparent to the users. It is easier for users to understand the model logic, adjust model parameters, and even revise model steps (if necessary) based on the specific requirements.

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References

Balco G, Stone JO, Lifton NA, Dunai TJ (2008) A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quaternary Geochronology 3: 174-195. https://doi.org/10.1016/j.quageo.2007.12.001

Baroni C, Casale S, Savatore MC, et al. (2017) Double response of glaciers in the Upper Peio Valley (Rhaetian Alps, Italy) to the Younger Dryas climatic deterioration. Boreas 46(4): 783-798. https://doi.org/10.1111/bor.12284

ChenYX, Li YK, Wang YY, et al. (2015) Late Quaternary glacial history of the Karlik Range, easternmost Tian Shan, derived from ^{10}Be surface exposure and optically stimulated luminescence dating. Quaternary Science Reviews 115: 17-27. https://doi.org/10.1016/j.quascirev.2015.02.010

Codilean AT (2006) Calculation of the cosmogenic nuclide production topographic shielding scaling factor for large areas using DEMs. Earth Surface Processes and Landforms 31: 785-794. https://doi.org/10.1002/esp.1336

Dong G, Zhou W, Yi C, et al. (2017) Cosmogenic ^{10}Be surface exposure dating of 'Little Ice Age' glacial events in the Mount Jaggang area, central Tibet. Holocene 27(10): 1516-1525. https://doi.org/10.1177/0959683617693895

Dunne J, Elmore D, Muzikar P (1999) Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces. Geomorphology 27: 3-11. https://doi.org/10.1016/S0169-555X(98)00086-5

Gosse JC, Phillips FM (2001) Terrestrial cosmogenic nuclides: theory and applications. Quaternary Sciences Review 20: 1475-1560. https://doi.org/10.1016/S0277-3791(00)00171-2

Heyman J, Applegate PJ, Blomdin R, et al. (2016) Boulder height – exposure age relationships from a global glacial ^{10}Be compilation. Quaternary Geochronology 34: 1-11. https://doi.org/10.1016/j.quageo.2016.03.002

Li YK (2013) Determining topographic shielding from digital elevation models for cosmogenic nuclide analysis: a GIS approach and field validation. Journal of Mountain Science 10: 355-362. https://doi.org/10.1007/s11629-013-2564-1

Li YK, Harbor J (2009) Cosmogenic Nuclides and Geomorphology: Theory, Limitations, and Applications. In: Ferrari DM and Guiseppi AR (eds.), Geomorphology and Plate Tectonics. Nova Science Publishers, Inc., Hauppauge, NY. pp 1-33.

Li YK, Liu GN, Chen YX, et al. (2014) Timing and extent of Quaternary glaciations in the Tianger Range, eastern Tian Shan, China, investigated using ^{10}Be surface exposure dating. Quaternary Science Reviews 98: 7-23. https://doi.org/10.1016/j.quascirev.2014.05.009

Li YN, Li YK, Harbor J, et al. (2016) Cosmogenic ^{10}Be constraints on Little Ice Age glacial advances in the eastern Tian Shan, China. Quaternary Science Reviews 138: 105-118. https://doi.org/10.1016/j.quascirev.2016.02.023

Liu JH, Yi CL, Li YK, et al. (2017) Glacial fluctuations around the Karola Pass, eastern Lhagoi Kangri Range, since the Last Glacial Maximum. Journal of Quaternary Science 32(4): 516-527. https://doi.org/10.1002/jqs.2946

Nishiizumi K, Winterer EL, Kohl CP, et al. (1989) Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. Journal of Geophysical Research 94(B12): 17907-17915. https://doi.org/10.1029/JB094iB12p17907

Shean DE, Alexandrov O, Moratto Z, et al. (2016). An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very high-resolution commercial stereo satellite imagery. ISPRS Journal of Photogrammetry and Remote Sensing 116: 101-117. https://doi.org/10.1016/j.isprsjprs.2016.03.012

Tomkins MD, Dortch JM, Hughes PD (2016) Schmidt Hammer exposure dating (SHED): Establishment and implications for the retreat of the last British Ice Sheet. Geochronology 33: 46-60. https://doi.org/10.1016/j.quageo.2016.02.002

Vermeesch P (2007) CosmoCalc: An Excel add-in for cosmogenic nuclide calculations. Geochemistry, Geophysics, Geosystems 8: Q08003. https://doi.org/10.1029/2006GC001530

Zhang M, Chen YX, Li YK, Liu GN (2016) Late Quaternary glacial history of the Nalati Range, central Tian Shan, China, investigated using ^{10}Be surface exposure dating. Journal of Quaternary Science 31(7): 659-670. https://doi.org/10.1002/jqs.2891