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ORIGINAL ARTICLE

Identification of the 'Best' DEM via Analysis of Morphological Parameters Derived From Different DEMS, and Applying Linear Regression for Accuracy Enhancement

Janavathsasarma, B. *, Illeperuma, I. A. K. S.

Department of Remote Sensing and GIS, Faculty of Geomatics, Sabaragamuwa University of Sri Lanka, Sri Lanka

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ABSTRACT

In recent years, numerous Digital Elevation Models (DEMs) derived from satellite data have become available, offering varying resolutions and accuracies. These datasets are crucial for analyzing the topographic characteristics of river basins through the assessment of morphometric parameters. Researchers have extensively utilized these DEMs to explore basin characteristics and their drainage networks. However, the impact of DEM resolution, accuracy, and sources on these analyses remains a significant question. This study aims to evaluate the influence of DEM accuracy and sources on morphometric analysis. Additionally, it investigates a method to enhance DEM accuracy through the application of linear regression. The study initially employs DEMs from ASTER GDEM and SRTM 1-arc second to analyze the relief, surface, size, shape, and texture properties of a mountainous drainage basin. Elevations extracted from both DEMs for the same locations of available reference data were compared. The linear regression model was applied to both DEMs to enhance accuracy. The model demonstrated greater efficacy with the ASTER DEM, yielding a more accurate representation of terrain elevations compared to the SRTM DEM. However, the presence of outliers influenced the results, highlighting the importance for careful consideration of these anomalies. The study concludes by recommending further exploration of alternative models such as decision tree regression, random forest regression, support vector regression, and neural network regression, to potentially identify a more universally applicable approach for improving DEM accuracy.

1 Introduction

Geomorphometry is the quantitative analysis of land surface used to determine parameters and objects such as slope, aspect, drainage networks, and topographic characteristics (Pike, 1995; Pike, 2000; Pike et al., 2009; Rasemann et al., 2004), providing crucial information for river basin studies and understanding the physical features of study areas (Ozdemir and Bird, 2009). It is applied across a wide range of disciplines, including geography, geology, hydrology, environmental science, forestry, agriculture, and urban planning. This can be classified into two types: general and specific. General geomorphometry which analyses the overall land surface form, particularly in drainage basin analysis, is widely applied and involves calculating morphometric properties such as size, relief, surface, shape, and texture attributes while specific geomorphometry examines the characteristics of individual landforms (Evans, 2012). Numerous studies have employed geomorphometric analysis to examine the morphometric characteristics of landforms, providing insights into the physical attributes of study areas, particularly in river basin research (Karabulut and Özdemir, 2019).

In river basin studies, where the physical aspects of the basin are influenced by topographical features (Summerfield and Hulton, 1994), it is essential to analyse the region's topography quantitatively to determine the relative efficiency of its components (Lague et al., 2003; Pike, 2000). The morphometric parameters such as drainage texture, basin geometry, and relief characteristics of a catchment are the quantitative features which are extracted from the topography, surface elevations, and drainage networks (Goudie, 2004; Niyazi et al., 2019).

There are several methods and techniques to extract the boundaries and drainage networks of river basins. Traditionally, topographical maps are used to extract features along with field surveys to improve the required accuracy. The 1:50,000 scaled topographic maps were

* Corresponding author: B. Janavathsasarma, Department of Remote Sensing and GIS, Faculty of Geomatics, Sabaragamuwa University of Sri Lanka, Sri Lanka.

E-mail address: janavathsanravi@gmail.com (B. Janavathsasarma).

digitized using ArcGIS desktop and used to describe the drainage networks in studies by Vijith and Satheesh (2006) and Vincy et al. (2012) while Eze and Efiong (2010) and Ket-ord et al. (2013) used field surveying and topographic maps of the same scale. In an advanced way, Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) are produced by Geographic Information System (GIS) and remote-sensing techniques to derive parameters (Ahmed et al., 2010; Farhan et al., 2015; Máčka, 2001; Magesh and Chandrasekar, 2014; O'Callaghan and Mark, 1984; Ozdemir and Bird, 2009; Rinaldo et al., 1998).

Topographic maps serve as crucial resources for unveiling surface topography features. However, the lack of detailed topographic maps for various study areas worldwide, the intricate process involved in generating DEMs from such maps, the limited availability of DEMs meeting desired accuracy standards and free from data voids, as well as the seamless nature and global coverage of remote DEMs, coupled with the ease of integrating them with GIS software, motivate researchers to seek freely accessible high-resolution satellite DEMs for their studies. Over the past decade, there has been an emergence of more sophisticated resolutions and convenient accessibility options for DEMs, such as the 90 m and 30 m SRTM, 30 m ASTER, and 30 m ALOS (Karabulut and Özdemir, 2019; Niyazi et al., 2019).

The accuracy, resolution, and sources of DEMs are important in morphometric comparison. In watershed area studies for a large (100 km^2) area, the efficiency of low resolution and high resolution DEM gave similar results (Ghumman et al., 2017) while for a smaller area of less than 1 km^2, efficiency is affected by the resolution (Sampson et al., 2015; Woodrow et al., 2016). The morphometric parameter analysis is affected by different sources and accuracy, even when DEMs share the same resolution (Niyazi et al., 2019; Weydahl et al., 2007).

This research investigates the source and vertical accuracy of various Digital Elevation Models (DEMs) with the primary objective of identifying the most accurate satellite DEM and assessing their vertical accuracy through morphological analysis. The study utilizes two freely available DEMs, SRTM 30 m and ASTER 30 m, whose vertical accuracy varies based on location and terrain. For SRTM, the vertical accuracy is generally within ±5-10 m in flat terrain and up to ±16 m in rugged terrains. Similarly, ASTER exhibits accuracies of approximately ±10 m in flat areas and up to ±20 m in more challenging terrains. To enhance the accuracy of these DEMs, linear regression, a machine learning algorithm, is employed for predictive analysis.

2 Materials and Methodology

2.1 Study Area

Part of Kalu Ganga was selected as the study area to analyze the morphometric parameters due to its well-defined boundaries and hydrological significance. The significance of the Kalu Ganga river basin are higher rainfall and frequent flooding (Herath et al., 2024), continuous sediment transportation (Samarasinghea et al., 2010) and a diverse ecosystem (Panditharathne et al., 2019). The study area covers an area of about 1150 km^2 and lies between 6° 27' N and 6° 52' N latitude and 80° 11' E and 80° 40' E longitude as per the WGS84 coordinate system. Fig. 1 shows a map of the study area.

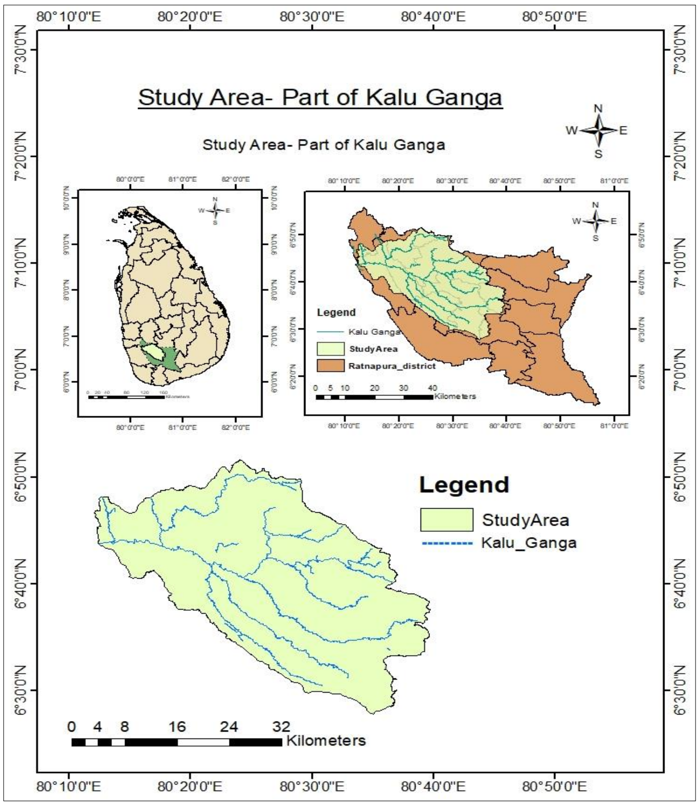

Fig. 1: Study area.

2.2 Data and Resources

In this study, free ASTER and SRTM DEMs were downloaded from the NASA Earthdata and the USGS Earth Explorer websites respectively. The spot height dataset and digital contours on a 1:50,000 scale were obtained (±12.5 m accuracy) from the Survey Department of Sri Lanka. The general information about the data sources used is given in Table 1.

Table 1: Metadata about the data sources.

No	Production Authority	Details
1	NASA, USA	SRTM: N06_E080, 30 m
2	NASA, USA	ASTER GDEMV003:N06E080, 30 m
3	Survey Department of Sri Lanka	Spot heights, Digital contour, 1:50,000 (20 m contour interval)

2.3 Methods

Initially, DEMs were projected and extracted within the confines of ArcMap 10.8 to generate both basic and derived morphometric parameters. They were first pre-processed through the operations of filling the data gaps. Subsequently, a flow direction tool was applied to assign flow from each pixel to one of its steepest downslopes among eight neighbours, which is known as the D8 method (O'Callaghan and Mark, 1984). Consequently, flow direction was coded with values ranging from 1 to 128, corresponding to various directions.

Table 2: Selected Morphometric parameters for this study (Das et al., 2016; Karabulut and Özdemir, 2019).

No.	Attribute Description	Morphometric Parameter	Method
01	Drainage Network	Stream order (u)	Stream with highest Strahler-order in the basin, from the hydrology analysis.
02		Stream numbers in the highest order	Number of streams belonging to the highest order, based on the attribute table.
03		Stream numbers (Nu)	Total number of stream segments across all the Strahler orders in the basin, based on the attribute table.
04		Stream length in km (LU)	Total length of all stream segments within the basin.
05		Bifurcation ratio (Rb)	Represents the average ratio at which streams of an order merge with those of the next higher-order.
06		Main channel length in km (MC)	Length of the stream segment with highest Strahler-order within the basin, using the measurement tool.
07	Basin Geometry	Basin area in km^2(A)	Area of river basin calculated using the 'calculate geometry' tool.
08		Basin length in km (Lb)	Longest direct distance from the mouth of basin to its boundary in its uppermost reach.
09		The basin perimeter in km (Pr)	Perimeter of the basin, calculated using the 'calculate geometry' tool
10		Basin width (W) in km	Difference between the area and the length of the basin.
11		Circularity ratio (Rc)	Comparison of the basin's area to that of a circle with the same circumference.
12		Elongation ratio (Re)	Comparison of the basin's longest dimension from the mouth to the diameter of a circle with an equivalent area.
13	Drainage Texture	Stream frequency in km^2 (F)	Density of streams per unit area
14		Drainage density in km^{-1} (D)	The total length of streams within each grid clipped accordingly
15		Drainage pattern (Dp)	Stream network using GIS software analysis
16	Relief Characteristics	Maximum elevation of basin in m (H_{max})	GIS software analysis utilizing DEM data.
17		Minimum elevation of basin in m (H_{min})	GIS software analysis utilizing DEM data.
18		Mean elevation of basin in m (H_{mean})	GIS software analysis utilizing DEM data.
19		Basin relief (Rf) in m	Difference between the highest and lowest elevation
20		Relief ratio (Rr)	Relative relief of the basin normalized by the basin length.
21		Mean slope (S_{mean})	Direct extraction from DEMs using relevant algorithm available in the software interface.
22		Hypsometric integral in m (HI)	Difference between $(H_{mean} - H_{min})$ and $(H_{max} - H_{min})$

Table 3: Basic and Derived Morphometric Parameters from DEMs.

No	Morphometric Parameter	SRTM	ASTER
01	Stream order (u)	4	4
02	Stream numbers in the highest order	950	891
03	Stream numbers (Nu)	9372	9394
04	Stream length in km (LU)	334.791	335.65
05	Bifurcation ratio (Rb)	1.831	1.920
06	Main channel length in km (MC)	33.61	32.12
07	Basin area in km^2(A)	1119.532	1116.744
08	Basin length in km (Lb)	52.809	52.505
09	The basin perimeter in km (Pr)	196.723	195.188
10	Basin width (W) in km	21.200	21.269
11	Circularity ratio (Rc)	0.364	0.368
12	Elongation ratio (Re)	0.715	0.718
13	Stream frequency in km^2 (F)	8.371	8.412
14	Drainage density in km^{-1} (D)	0.299	0.301
15	Drainage pattern (Dp)	dendritic	dendritic
16	Maximum elevation of basin in m (H_{max})	1927	1898
17	Minimum elevation of basin in m (H_{min})	22	13
18	Mean elevation of basin in m (H_{mean})	954.95	946.67
19	Basin relief (Rf) or relative relief in m	1905	1885
20	Relief ratio (Rr)	0.036	0.036
21	Mean slope (S_{mean})	13.522	13.611
22	Hypsometric integral in m (HI)	0.490	0.495

Finally, the drainage network was extracted by calculating flow accumulation and applying a threshold value of 8,000, followed by ordering the network using the Strahler (1954) scheme (Das et al., 2016). All of the 22 morphometric parameters were extracted and categorized into drainage network, basin geometry, drainage texture, and relief characteristics as shown in Table 2 for the comparison.

Contours were generated from the satellite DEMs and were labelled. These contours were then compared with each other to understand how the elevations were distributed within the DEMs. Spot heights were used as reference data, and the elevations corresponding to the same locations of spot heights (696 points) were extracted from both ASTER and SRTM DEMs for model creation. To enhance accuracy, extracted elevations were trained in the linear regression models to achieve the values equal to the heights of reference spot heights and linear equations were obtained. The created models were statistically validated and evaluated. The detailed overview of the methodology used in this study is illustrated in Fig. 2.

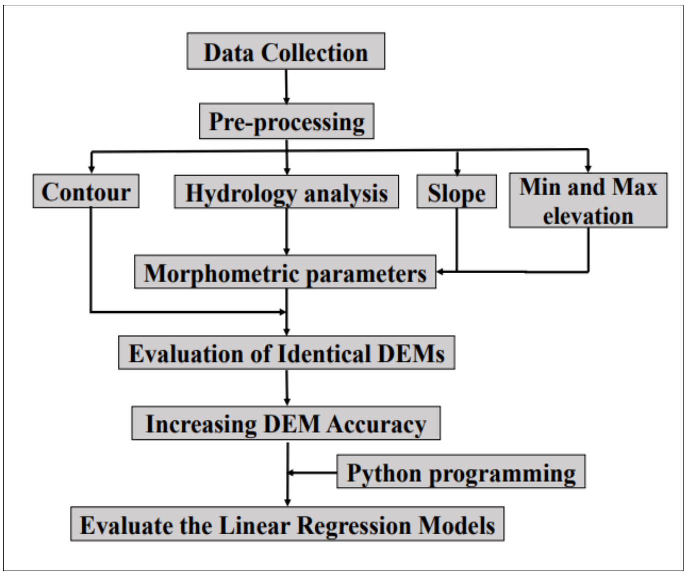

Fig. 2: Flow chart of the methodology.

3 Results and Discussion

The evaluation and comparison of the fundamental and derived morphometric measures of the study area are shown in Table 3. The results indicate that both DEMs exhibit similar characteristics as observed by Ahmed et al. (2010) and the reason for the small differences between the results can be due to a combination of vertical accuracy, sensor characteristics, noise and artifacts, and the intrinsic complexity of the terrain.

Fig. 3 (a) - (e) were derived from the hydrology analysis to obtain basic measures. The slope was reclassified to derive basin parameters, and contours were analysed to confirm the elevation distribution across the DEM surface.

Elevations were extracted from both DEMs for the same locations of reference spot heights and trained in the linear regression models to obtain the linear equations for each DEM.

The gradients given in Table 4 were obtained from the linear regression model. They were approximately equal to one, which indicate that the equations satisfied the criteria for linear equation.

Table 4: Gradient and intercept of linear models.

DEM Model	Gradient(m)	Intercept(c)
SRTM	1.0081	-0.3776
ASTER	1.0057	13.8809

The intercept value derived for the ASTER model suggested that an additional 13 m should be incorporated into the elevations of ASTER to align them more closely with the actual elevations in the terrain.

The equations used to calculate average 1 and average 2 in the Table 5 are given as follow;

Average 1 = |extracted elevation(i) – actual height in the terrain(i)|, for i in range of R_i (1)

Average 2 = |predicted elevation(i) – actual height in the terrain(i)|, for i range of R_i (2)

Table 5: Average values obtained from model.

DEM Models	Average 1	Average 2
SRTM	7.279	7.066
ASTER	17.636	11.563

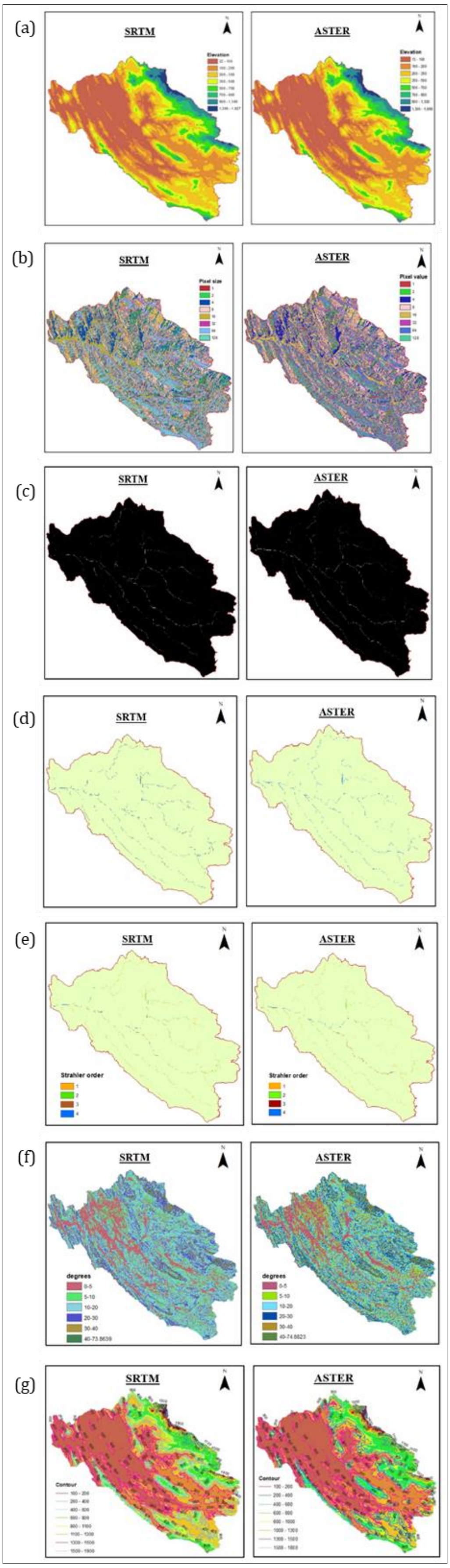

Fig. 3: (a) Fill Sinks, (b) Flow Direction, (c) Flow Accumulation, (d) Threshold, (e) Stream Order, (f) Reclassified Slope, and (g) Contour Generation.

Statistically, average 1 has demonstrated that the values extracted from SRTM exhibit a notable proximity to the reference elevation points in comparison to ASTER. This average 1 value suggests that, within the specified study region, SRTM outperforms ASTER. The average 2 has indicated that the efficacy of the model was higher compared to SRTM.

The reference elevation against percentage differences in Fig. 4 visualize how much the heights extracted from the satellite DEMs differ from the corresponding actual heights percentage-wise. In the above graphs, the elevations above and below 100 m show two different patterns. Instead of deriving a common equation, effective models can be obtained by separately considering the elevations above and below the 100 m as two different data sets to train the samples. Finally, over-fitted models were obtained with the R^2 score values of 99.79% and 99.42% for SRTM and ASTER respectively. However, from the results, the linear regression models can be applied to upscale the elevations for both SRTM and ASTER.

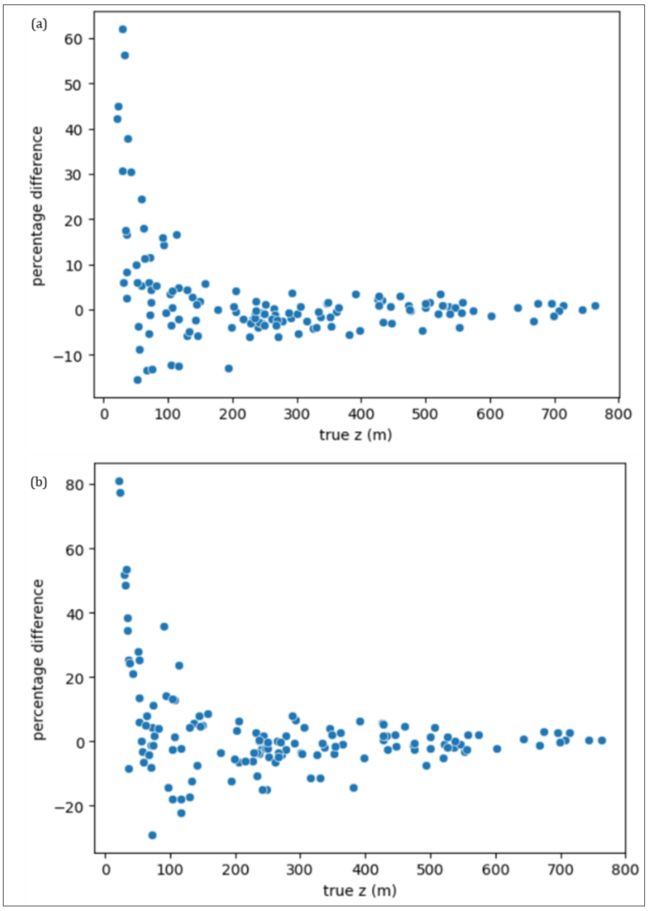

Fig. 4: Reference elevation z against percentage differences, (a) SRTM, and (b) ASTER.

4 Conclusion

(DEMs) have garnered growing interest and usage due to their convenient application in river basin studies. The basin morphometry investigations play a pivotal role in furnishing valuable insights into the drainage network. In this study, the selected morphometric parameters were derived from two freely available satellite DEMs, namely SRTM30 and ASTER30. Upon morphological analysis, it is evident that both SRTM and ASTER-derived DEMs exhibit similar differences. However, statistical analysis, as presented in Table 5, indicate that the values extracted from SRTM30 for the same location of reference spot heights show a notable proximity to the reference elevation points in comparison to ASTER30.

Interestingly, the effectiveness of Linear Regression models shows a massive increment in the accuracy of ASTER compared to SRTM. This study underscores the importance of validation data to achieve more precise results. The 1:50,000 digital contour dataset and the spot heights used in this study were insufficient to create a DEM and derive parameters that could adequately validate the morphological parameters obtained from satellite DEMs.

Generally, a higher R^2- value suggests a better fit of the model to the dataset. However, it is important to recognize that a high R^2value does not necessarily imply a good model, as it may indicate over-fitting due to complex models or noise within the data. In this study, the R^2values were not useful, as the linear regression models exhibited over-fitting. Nevertheless, the elevations derived from the DEMs reveal two distinct patterns in the horizontal and vertical directions. Notably, elevation values below 100 m played a significant role in model fitting. Considering this factor, future studies may lead to the development of more accurate models.

This study recommends using reference data of higher accuracy. In regression modelling, this study recommends focusing on other models such as decision tree regression, random forest regression, support vector regression, neural network regression, etc. In the future, studies on several models may result in finding a common method to enhance DEM accuracy. This study again proved that the source of the DEMs plays a crucial role in morphological comparisons even if the resolutions are the same.

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Author Contributions

Conceptualization J.B., methodology and analysis J.B. and I.A.K.S.I, writing - original draft preparation, J.B., review I.A.K.S.I., and editing, J.B. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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