Performance comparison among typical open global DEM datasets in the Fenhe River Basin of China

Shangmin Zhao a, Danning Qi b, Rongping Li b, Weiming Cheng a and Chenghu Zhou c

aDepartment of Surveying and Mapping, College of Mining Engineering, Taiyuan University of Technology, Taiyuan, China; bLiaoning Ecological Meteorology and Satellite Remote Sensing Center, Shenyang, China; cState Key Laboratory of Resources and Environmental Information Systems, Institute of Geographic and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

ABSTRACT

This paper aims to compare the performance of typical open global DEM datasets by using the indexes of elevation error, relative error and hydrologic network. Taking Fenhe River Basin of China as the study area, this research made quantitative performance comparison among four typical open global DEM datasets including SRTM data with 1" (SRTM1) and 3" (SRTM3) resolutions, ASTER Global DEM data at the 2nd version (GDEM-v2) and ALOS World 3D-30 m (AW3D) data. Through process and selection, more than 80,000 ICESat/GLA14 points were used as the reference data, and the elevation error was computed and compared accordingly. Furthermore, relative error was analyzed using slope values, and false slope ratio index was computed and categorized compared. Finally, the hydrologic networks extracted from the four DEM datasets were compared to the reference hydrologic network acquired by visual interpretation from remote sensing images. The research results show that the AW3D has the best performance, which is approximate to but a little better than SRTM1. The performance of SRTM3 and GDEM-v2 is similar, which are much worse than that of AW3D and SRTM1, and the performance of GDEM-v2 is the worst of all.

ARTICLE HISTORY
Received 4 December 2019
Revised 24 March 2020
Accepted 14 February 2021

KEYWORDS
Performance comparison; typical open global DEM datasets; elevation error; relative error; hydrologic network; ICESat/GLA14

Introduction

Topography is important for research and engineering in many fields, such as geosciences, geology and geomorphology, natural disasters, hydrology and water resources management and so on (Barbarella et al., 2017; Courtal et al., 2019; Jarihani et al., 2015; Moore et al., 1991; Siart et al., 2009). It is preliminary measured by contour lines and ground control points in topographic maps. With the development of science and technology, digital elevation model (DEM) is used to represent topography by an ordered array of numerical elevation grid (Avtar et al., 2015).

Global open DEM dataset is an important data source for DEM data. The typical open global DEM datasets include: Shuttle Radar Terrain Mission (SRTM) DEM data with 3" (about 90 m at the equator) resolution (SRTM3) is released in 2003, which is the first global DEM data with 90 m spatial resolution (Farr et al., 2007). SRTM3 DEM data achieve big success, and then many other global DEM datasets are released successively. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global DEM data at the 1st version (GDEM-v1) in 2009 and the 2nd version (GDEM-v2) in 2011 are the first released global DEM data with 30 m spatial resolution. Resample from the DEM dataset with 5 m resolution, ALOS World 3D-30 m (AW3D) DEM data is regarded as the most precise global DEM dataset at 30 m resolution level (https://www.eorc.jaxa.jp/ALOS/en/index.html) (Tadono et al., 2014, 2015). AW3D data are preliminary released in 2015, and the newest version is released in 2019.

Multiple global DEM products not only provide multi choices for users, but also bring selection puzzles about how to choose proper DEM product in researches and applications. Meanwhile, uncertainties in different global DEM products due to technical limits, acquisition modes and other factors result to different accuracy for the DEM datasets. The feasibility of DEM’s applications depends on its accuracy (Barreiro-Fernández et al., 2016; Mukherjee et al., 2013). Moreover, the error in DEM data can propagate in its applications (Leigh et al., 2009; Yue et al., 2010). Hence, many researches were conducted to compare the accuracy among different DEM products. For example, Hirano et al. (2003) made validation and accuracy assessment of the DEM product acquired from ASTER stereo images. Nikolakopoulos et al. (2006) compared the SRTM3 data and DEM data created from ASTER stereo-pairs images using global positioning system (GPS) measurements. Berry et al. (2007) estimated the accuracy of SRTM3 DEM data using satellite radar altimetry at global scale. Zhao et al. (2011) compared the vertical

CONTACT Shangmin Zhao zhaochangmin@tyut.edu.cn Department of Surveying and Mapping, College of Mining Engineering, Taiyuan University of Technology, No. 79 Yingze West Street, Taiyuan 030024, China
© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (http://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.
accuracy of SRTM3 and GDEM-v1 data in China using ground control points in topographic maps. Suwandana et al. (2012) evaluated GDEM-v2 in comparison with GDEM-v1, SRTM3 and DEM product derived from topographic maps using differential GPS data Lee et al. (2015) assessed the accuracy of the DEM data generated by using ERS and Envisat cross-interferometry techniques based on the elevation data from the Ice, Cloud, and land Elevation Satellite (ICESat). X. Li et al. (2017) compared five global DEM products and their relevant derived attributes using the data acquired from Geoscience Laser Altimeter System (GLAS) boarded on ICESat. Grohmann (2018) compared the TanDEM-X DEM data and global open DEM data on selected Brazilian sites. González-Moradas and Viveen (2020) evaluated the vertical accuracy and derived geomorphological parameters of the global open DEM datasets using ground control points.

The above examples show that previous researches most focus on the vertical accuracy. The aim of evaluating and comparing the accuracy among different DEM products is proper use and rational selection in applications, especially in topographic analysis. Hence, some researches not only pay attention to assesses the vertical accuracy (elevation error), but also to compare the relative error and hydrologic network extraction results among different DEM products. Through evaluating the performance (including elevation error, relative error and hydrologic network extraction results) of the DEM datasets, it not only provides important support for the DEM’s selection in applications, but also provides feasibility and accuracy guarantees for the DEM’s applications (Patel et al., 2016; Satgé et al., 2016). Meanwhile, some researches show that slope values have close relationship to the DEM’s accuracy, and higher slope value generally corresponds to higher error (Satgé et al., 2015).

Based on the above and taking Fenhe River Basin of China as the study area, this research aims to conduct performance comparisons among typical open global DEM datasets including AW3D, SRTM1, SRTM3 and GDEM-v2 in the whole study area and different slope classes. Through analysis and comparison of the vertical error, relative accuracy and hydrologic network extraction results for the four open global DEM datasets, this research will provide reference for open global DEM datasets selection and applications in different fields.

**Study area and datasets**

**Study area**

Located in northern and middle part of China, Fenhe River Basin distributes between the latitudes of 35°N and 39°N and longitudes of 110°E and 114°E (Figure 1). Fenhe River Basin has an elevation range of 356 m to 2804 m. The elevation decreases from north-to-south and is high in two sides. With a drainage area of about 3.97 × 10⁴ km², Fenhe River Basin refers to the region controlled by Fenhe River and its tributaries. Across two important cities of Taiyuan and Linfen, the mainstream of Fenhe River flows from north-to-south in the middle section of Fenhe River Basin. Fenhe River has a length of about 695 km (Sun et al., 2013), which is the biggest river in Shanxi Province and the second largest tributary of Yellow River (the mother river of China).

With average annual precipitation of 504.8 mm, Fenhe River Basin belongs to semi-arid continental monsoon climate region. The distribution of the rivers or hydrologic networks is important for economy development and ecology sustainability of the region. Distributed in the eastern part of the Loess Plateau, Fenhe River Basin suffers serious ecological environment and water and soil loss problems. Hence, many researchers pay great attention to conduct geosciences research in the Fenhe River Basin using DEM datasets (Guo & Wu, 2016; Liu et al., 2011).

**Datasets**

The main datasets in this research include the open global DEM dataset, the 14th product of the ICESat/GLAS (ICESat/GLA14) data and remote sensing images which can be used to extract reference hydrologic network.

**DEM datasets**

The DEM datasets used in this research mainly refer to SRTM1, SRTM3, GDEM-v2, and AW3D data.

Collected over 11 days in February 2000, SRTM data were originally released by the United States Geological Survey (USGS) in 2003, which had two versions: SRTM1 in the USA and SRTM3 outside the USA. Acquired from synthetic aperture radar (C band system, 5.6 cm), SRTM data cover the land between 60°N and 56°S, about 80% of global land. As a homogeneous-quality elevation data with high spatial resolution around the world, SRTM3 achieves great success after its release. Then, SRTM1 data were released in 2015. Fortunately, there were no holes for SRTM1 in the study area (Figure 1). After its release, many comparisons have been conducted among SRTM1, SRTM3 and other DEM datasets (Hu et al., 2017; Zhao et al., 2011). Acquired by global ASTER stereo images, GDEM-v1 is released in June 2009, which has higher spatial resolution (1”, about 30 m) and wider coverage (83°N–83°S) than SRTM3. So GDEM-v1 has gained much attention after its release. GDEM-v2 was released in October 2011, which can be downloaded from USGS Global Data Explorer. GDEM-v2 is an upgraded version of GDEM-v1, which is developed using an advanced algorithm and more data sources.
(Zhao et al., 2015). GDEM-v2 may replace GDEM-v1 in researches and applications in the future.

Launched in January 2006, the PRISM (Panchromatic Remote-Sensing Instrument for Stereo Mapping) sensor onboard the ALOS (Advanced Land Observing Satellite) satellite has spatial resolution of 2.5 m. Based on the PRISM scenes, an automated process was used to generate a global DEM with 5 m resolution. The grid value in AW3D is calculated by average or median when resampling from the 5 m resolution DEM data, so AW3D data are regarded as the most precise global DEM dataset at 30 m resolution level. The “World 3D Topographic Data” with 5 m spatial resolution may be freely released in the future, so it is much significant to estimate the performance of AW3D data in advance (Grohmann, 2018).

**ICESat/GLA14 Data**

ICESat/GLA14 data can be downloaded from the U.S. National Snow and Ice Data Centre (NSIDC), which is collected from January 2003 to February 2010 (Zwally et al., 2002). The ICESat/GLA14 data is point data with footprint size of about 70 m and the distance of about 172 m between two points. The inter-track spacing distance is 30 km near the equator.

About the accuracy of the ICESat/GLA14 data, Fricker et al. (2005) verified that the absolute vertical accuracy was within 2 cm over the Uyuni Salar in Bolivia compared to kinematic GPS measurements. Baghdadi et al. (2011) deemed that a vertical accuracy of 5 cm of the ICESat/GLA14 data in monitoring a French lake. Zwally et al. (2002) showed that the vertical accuracy is approximately 15 cm at the global scale. So the accuracy of the ICESat/GLA14 data is much higher than that of the four open global DEM datasets. It is reasonable to take ICESat/GLA14 points as the reference to assess the performance of these DEM datasets.

**Remote sensing images**

To evaluate the performance of the four DEM datasets, the hydrologic networks extracted from the DEM datasets were compared to the reference hydrologic networks extracted from the ICESat/GLA14 data.
network (RHN). The RHN can be obtained from different sources, such as hydrologic database, higher-accuracy DEMs and high-resolution remote sensing images (El Haget al., 2012; Lindsay et al., 2019; Metz et al., 2011). In this research, the RHN was interpreted from the remote sensing images, which were downloaded from Geospatial Data Cloud (http://www.gscloud.cn/). The downloaded images include Landsat 8 products in 2015 and Landsat global composite products (1999–2003). Landsat global composite products adopt 7, 4 and 2 bands with false natural colour. To keep band spectrum consistency, Landsat 8 products adopt 7, 5 and 3 bands. After a series of process, such as band composition, mosaic, rectification, projection and clip, remote sensing images in the study area were acquired in both 2015 and about 2000.

Methods
The workflow for this research is shown in Figure 2:

Figure 2 shows that the performance comparison is conducted for the four DEM datasets, which includes error comparison and hydrologic network comparison. Through processing, the ICESat/GLA14 data can be used as a reference, and then the elevation error and relative error are computed using various indexes and at different slope classes. Meanwhile, the hydrologic networks are extracted and compared based on the DEM datasets and the remote sensing images.

ICESat/GLA14 and DEM Datasets processing
The ICESat/GLA14 data has ellipsoid and geoid systems of Topex/Poseidon, but the global DEM datasets are using WGS84/EGM96. To keep ellipsoid and geoid systems consistency, the Topex geoid for the ICESat/GLA14 data was converted to WGS84 ellipsoid using the NSIDC provided IDL tool called "IDL Ellipsoid Conversion" (http://nsidc.org/data/icesat/tools.html) (Zhang et al., 2011). Meanwhile, the EGM96 geoid value was computed for the ICESat/GLA14 data using the interpolation program available on the NGA website (http://earth-info.nga.mil/GandG/wgs84/egm96/egm96.html).

Then, the elevation values for the four DEM datasets were computed for all the ICESat/GLA14 data using ArcGIS software. Through computing the difference by subtracting the ICESat/GLA14 elevation from the four DEM datasets, the GCPs (Ground Control Points) were selected by removing the ICESat/GLA14 data whose absolute difference values were higher than 50 m (Bhang et al., 2007; Satgé et al., 2015). A total of 82,378 GCPs were left for this study.

Finally, slope data were computed using ArcGIS Spatial Analyst Tools based on the SRTM1 data. The use of the SRTM1 data in slope computation can check the performance of the AW3D data more persuasively. The slopes derived from SRTM3 and GDEM-v2 data were not used due to the low performance in this research. The computed slope data were divided into five classes (0°-3°, 3°-8°, 8°-15°, 15°-25° and >25°) (Lindsay et al., 2019; Zhou et al., 2009). Hence, the elevation error and relative error can be analyzed at the global scale and in different slope classes.

Elevation error acquisition
The elevation error is computed by subtracting the elevation value of the ICESat/GLA14 data from the elevation value of different DEM datasets at all the GCPs. The equations of the indexes to represent the elevation error are the following (Godone & Garnero, 2013):

\[
\text{ME} = \frac{\sum_{i=1}^{n} (x_i - y_i)}{n}
\]  
(1)

\[
\text{MAE} = \frac{\sum_{i=1}^{n} |x_i - y_i|}{n}
\]  
(2)

Figure 2. Workflow for this research.
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n-1}} \quad (3)

STD = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{y})^2}{n-1}} \quad (4)

where n is the number of the values, x is the ICESat/GLA14 elevation value (m), y is the DEM elevation value (m). In the equations (1–4), ME, MAE, RMSE and STD are short for mean error, mean absolute error, root mean square error and standard deviation, respectively.

**Relative Error Acquisition**

Relative error is to measure the matching degree of the point-to-point elevations that are extracted from the DEM datasets and the GCPs (Figure 3). The locations of the points are selected as the same as the GCPs. The evaluated two GCPs form a point pair (Satge et al., 2016). Considering the vertical accuracy of the GCPs and the horizontal resolution of the SRTM3 data, the point pair is selected using the conditions of elevation difference between DEMs and GCPs higher than 1 m and horizontal distance between 100 m and 500 m. Then, a total of 669,268 point pairs are chosen accordingly. Slope values between are computed to quantify the relative error, which is computed by dividing the elevation difference using horizontal difference between the point pairs. Through computing, the slope values for the point pairs, the error indexes (ME, MAE, RMSE and STD) are computed analyzed both at the global scale and for all the slope classes.

Slope values as the relative errors can be two options: positive value or negative value. It may results in two conditions for the DEMs and GCPs: (a) DEMs and GCPs have the same slope trend; (b) DEMs and GCPs have the opposite slope trend (Figure 2). Based on the two conditions, False Slope Ratio (FSR) can be computed using the following equation (5):

\[ FSR = \frac{B}{A + B} \times 100\% \quad (5) \]

where A and B are the total number of cases “A” and “B” in Figure 2, respectively.

**Hydrologic network extraction and estimation**

Hydrologic network can be extracted from DEM dataset through successive computational steps. It can provide indirect information about a DEM’s relative accuracy through comparing hydrologic network derived from the DEMs and the RHN. Referencing the hydrologic database at 1:250,000 and the DEM-derived hydrological networks (DHNs), the RHN is acquired through visually interpretation from the Landsat remote sensing images. The matching degree between the RHN and the DHNs can represent the relative accuracy of the DEM data (Satge et al., 2016). The mismatch between RHN and the DHNs can generate small polygons called for “register regions” in this research (Figure 4).

The total area of the register regions represents the mismatching degree between RHN and DHN. To quantify the mismatching degree, register difference (RD) is put forward, whose equation is the following (Liu et al., 2012):

![Vertical view of DEMs and GCPs](image1)

![Horizontal view of DEMs and GCPs](image2)

**Figure 3.** SRTM1 data, ICESat/GLA14 point and RHN distribution in the study area (Satge et al., 2016).
Meanwhile, four AW3D datasets neglected STD values metric for the four DEM datasets in the study area and different slope distribution regions.

\[
RD = \frac{\sum_{i=1}^{n} A_i}{A_S} \times 100\% \tag{6}
\]

where RD is the register difference; \( A_S \) is the total area of the basin; \( n \) is the number of the small polygon between RHN and DHN; \( A_i \) is the area of the small polygon between RHN and DHN.

**Results**

In this section, the elevation error, relative error and hydrologic network are compared for the four DEM datasets in the study area and different slope distribution regions.

**Elevation error comparison**

The elevation error distribution histograms for the four DEM datasets are shown in Figure 5. Meanwhile, Figure 5 also presents the elevation error indexes including ME, MAE, RMSE and STD for the four DEM datasets.

Figure 5 shows that all the four histograms are symmetric to the vertical axis approximately to 0 m. The ME values are approximately to 0 m for the four DEM datasets, which results to that the RMSE values and the STD values are similar. Hence, the STD values are neglected in this research. The SRTM1 data and the AW3D data have similar MAE and RMSE values, 3.9 m and 5.8 m, respectively. The SRTM3 data have higher MAE and RMSE values, 6.7 m and 10.0 m, respectively. The GDEM-v2 data have the highest MAE and RMSE values, 7.8 m and 10.6 m, respectively. Overall, therefore, the SRTM1 data and the AW3D data have the best and approximate performance; then the SRTM3 data has much worse performance than the former two datasets; the GDEM-v2 data have the worst performance of all.

Through computing the ME, MAE and RMSE values of the elevation error for the four DEM datasets, the results are presented in Table 1.

Table 1 shows that the MAE and RMSE values increase with the slope increasing for the four DEM datasets. Nevertheless, the increasing velocity is different for different DEM datasets. The SRTM3 data have much higher increasing velocity than other three DEM datasets. As to the ME value, it increases with the slope increasing for three DEM datasets except for SRTM3 data.

**Relative error comparison**

Through computing the relative errors, the values of the ME, MAE and RMSE indexes are obtained in Table 2 for the four DEM datasets.

Table 2 shows the ME value is approximate to 0% for all the four DEM datasets. As to the MAE and RMSE values, the AW3D data have the lowest value,
then the SRTM1 data, and the GDEM-v2 data has much higher value than the former two datasets, and the SRTM3 data have the highest value of all.

Then, the indexes of the relative errors are computed for all the slope classes which are shown in Table 3.

Table 3 shows that the ME values of the relative error are approximate to 0% for the four DEM datasets. Overall, the slope class of 15°-25° has the highest
values for the ME index for the four DEM datasets except for the SRTM3 data. Both the MAE and RMSE values increase with the slope classes increasing for all the four DEM datasets. The SRTM3 DEM data have the highest increasing velocity for all the three indexes, then the GDEM-v2 data. The SRTM1 and AW3D data both have the approximately lowest increasing velocity, except for that the increasing velocity values for the GDEM-v2 and AW3D data are negative for the ME index.

As to the FSR index, the value distribution histogram for the four DEM datasets at the whole study area and different slope classes is computed and shown in Figure 6.

Figure 6 shows that at the global scale, the AW3D data have the lowest FSR value, then the SRTM1 data, and the SRTM3 data have much higher value than the former two datasets, and the GDEM-v2 data have the highest value of all. For different slope classes, the FSR value is the highest at the slope class of 0°-3°, then at the slope class of 3°-8°, especially for the GDEM-v2 data. The FSR values are similar at other three slope classes for the four DEM datasets. The FSR value for the SRTM3 data is a little higher than that for the GDEM-v2 data at the latter three slope classes, but much lower than that for the GDEM-v2 data at the former two slope classes.

### Table 3. Computed ME, MAE and RMSE values for the four DEM datasets based on a relative error assessment for different slope classes (%).

| DEM datasets | Number of Point Pairs | Slope(°) | 0–3 | 3–8 | 8–15 | 15–25 | >25 | Increasing velocity |
|--------------|-----------------------|----------|-----|-----|------|-------|-----|-------------------|
| SRTM1        | 143,831               | 123,377  | 183,781 | 155,851 | 123,377 | 183,781 | 155,851 | 123,377 |
| SRTM3        | 143,831               | 123,377  | 183,781 | 155,851 | 123,377 | 183,781 | 155,851 | 123,377 |
| GDEM-v2      | 143,831               | 123,377  | 183,781 | 155,851 | 123,377 | 183,781 | 155,851 | 123,377 |
| AW3D         | 143,831               | 123,377  | 183,781 | 155,851 | 123,377 | 183,781 | 155,851 | 123,377 |

**Hydrologic network comparison**

The comparisons between DHNs and RHN are shown in Figure 7 for the four DEM datasets. From Figure 7 we can see that although in some areas (such as the middle and upper regions), the DHNs and RHN have evident discrepancy (especially for the GDEM-v2 data), the DHNs and RHN are consistent in most areas.

To illustrate the overlapping conditions between DHNs and RHN in different sloping regions, the comparison between DHNs and RHN are made in different sloping regions for the four global DEM datasets as shown in Figure 8.

Two local areas of mountain region and plain region show that the RHN and the DHNs extracted from the four DEM datasets are consistent generally in mountain regions. As to the plain region, the DHN extracted from the AW3D data has the best matching degree to the RHN; the DHNs extracted from the SRTM1 and the SRTM3 data have similar matching degree, which is much worse than that extracted from the AW3D data. The DHN extracted from the GDEM-v2 data has the worst matching degree of all.

To quantify the matching degree between DHNs and RHN, the RD value is computed for the four DEM datasets as shown in Table 4.

Table 4 shows that the AW3D data have the lowest RD value, then the SRTM1 data. The SRTM3 data have much higher RD value, and the GDEM-v2 data has the highest RD value of all. Hence, according to the RD value, AW3D has the best performance, then the SRTM1 data; the SRTM3 data have much worse performance than the former two datasets, and the GDEM-v2 data have the worst performance of all.

### Discussion

This research compared the performance of the four typical open global DEM datasets through elevation error, relative error and hydrological network extraction results. Elevation error represents vertical
Figure 7. Comparison between DHN and RHN in the study area (a. SRTM1; b. SRTM3; c. GDEM-v2; d. AW3D).
accuracy, which is often evaluated in previous researches (González-Moradas & Viveen, 2020; Zhao et al., 2011). In this research, the ME values for the elevation error are approximate to 0 m for the four global DEM datasets, which results in the RMSE and STD values are similar. Furthermore, the ME values remain stable for all considered slope classes, which may be due to the symmetrical distribution of the elevation error (Figure 5).

Relative error is to measure the elevation difference between the GCPs point pairs at a fixed horizontal distance. Compared to previous relative error assessment researches which mainly focus on the FSR values (Satgé et al., 2015; Satge et al., 2016), this research also assessed the relative error values through elevation difference divided by horizontal distance. So the relative error evaluation in this research is more accurate and rational than previous researches. In addition, the ME values are approximate to 0% for the four DEM data, which is probably due to the symmetric distribution of the relative error values. Furthermore, the FSR mainly focuses on the miss-classified cases; so the performance of FSR values decreased with larger slope. This is consistent with previous researches over the South American Andean Plateau (Satge et al., 2016).

As to the hydrologic network, the data of the Landsat images can affect the fit between the RHN and DHNs because the DEMs are collected in different periods. Furthermore, the matching degree between DHNs and RHN has better performance in mountain region, but worse performance in plain region. It because that the plain region suffers heavier human modification. Meanwhile, the valley is narrow in the mountain region. Even so, the resister region and RD values provide important evidence for hydrological network comparison. It may provide important reference for DEM’s selection and applications (Courty et al., 2019; Liu et al., 2012).

The four typical open global DEM datasets are collected from different sources or methods, such as radar stereo images (Farr et al., 2007), ASTER stereo images and resamples from 5 m global DEM datasets (Tadono et al., 2014, 2015). Different sources and acquisition methods may affect the errors and performance, which should be taken into account in DEM’s selection and applications. This point deserves further researches in the future.

### Conclusions

Based on the ICESat/GLA14 data and remote sensing image interpretation result, the performance of four typical open global DEM datasets is compared using the indexes of elevation error, relative error and hydrologic network. Through this research, the following conclusions can be obtained.

About the elevation error, the ME values are approximate to 0 m for the four global DEM datasets. The AW3D data and the SRTM1 data have the lowest MAE and RMSE values, then the SRTM3 data, and the GDEM-v2 data have the highest MAE and RMSE values. As to the relative error, the ME values are approximate to 0% for the four DEM data. About RMSE and MAE values, the AW3D data and the SRTM1 data are similar, which are much lower than

### Table 4. RD values for four global DEM datasets.

| DEM datasets | SRTM1 | SRTM3 | GDEM-v2 | AW3D |
|--------------|-------|-------|---------|------|
| Area(km²)    | 597.270 | 804.363 | 1084.017 | 505.004 |
| RD (%)       | 1.50  | 2.03  | 2.73    | 1.27  |
the GDEM-v2 data and the SRTM3 data. The latter two data also have similar RMSE and MAE values. Through hydrological comparison, the four DEM datasets have better performance in mountain region, but worse performance in plain region. The register difference values show that the AW3D data is the lowest, and then the SRTM1 data. The SRTM3 data are much higher than the former two datasets, and the GDEM-v2 data is the highest of all.

Overall, the performance of the SRTM3 data and the GDEM-v2 data is similar, which are much worse than that of the AW3D data and the SRTM1 data, and the performance of the GDEM-v2 data is the worst of all. The performance of the SRTM1 data is approximate to but a little worse than the AW3D data. The AW3D data has the best performance of all generally, especially on the basis of that the slope data are computed based on the SRTM1 data. Hence, this research provides strong foundation for the applications using AW3D data.

This research is conducted in the Fenhe River Basin of China. To verify the research results, similar comparison researches can be conducted in other regions, especially in the regions with different conditions (Giribabu et al., 2013; Zhao & Cheng, 2014). In addition, more indexes and application fields can be made to compare the performance of the DEM datasets (Pulighe & Fava, 2013; Argyriou et al., 2016; MeleMelelli et al., 2017). Furthermore, the performance of more DEM datasets can be evaluated and compared, and some new DEM datasets can be developed accordingly, such as Tan-DEM, Merit DEM and EarthEnv-DEM90 (Baade & Schmullius, 2016; Robinson et al., 2014; Yamazaki et al., 2017). Meanwhile, new and future missions can provide more global datasets (such as ICESat-2, SWOT, Cryosat-2 and Sentinel-3) (Gao et al., 2017; Iđžanović et al., 2019; Ma & Han, 2019). Finally, through accuracy evaluation and performance comparison, the accuracy of the DEM datasets can be improved using different methods (Q. Gao et al., 2019; F. Li et al., 2018; O’Loughlin et al., 2016).

Acknowledgments

Wenjiao Wu provides important data and materials. We would like to express our sincere gratitude to the editor and anonymous reviewers.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key Research and Development Program [2017YFB0503603]; the Natural Science Foundation of Shanxi Province [2019J1D11098]; the National Natural Science Foundation of China [41631179, 41771443].

ORCID

Shangmin Zhao http://orcid.org/0000-0002-5197-0192
Weiming Cheng http://orcid.org/0000-0003-1580-4979

References

Argyriou, A., Sarrisb, A., & Teeuw, R. (2016). Using geoinformatics and geomorphometrics to quantify the geodiversity of Crete, Greece. *International Journal of Applied Earth Observation and Geoinformation*, 51, 47–59. https://doi.org/10.1016/j.jag.2016.04.006
Avtar, R., Yunus, A. P., Kraines, S., & Yamamuro, M. (2015). Evaluation of DEM generation based on Interferometric SAR using TanDEM-X data in Tokyo. *Physics and Chemistry of the Earth*, 83, 166–177. https://doi.org/10.1016/j.pce.2015.07.007
Baade, J., & Schmullius, C. (2016). TanDEM-X IDEM precision and accuracy assessment based on a large assembly of differential GNSS measurements in Kruger National Park, South Africa. *ISPRS Journal of Photogrammetry and Remote Sensing*, 119, 496–508. https://doi.org/10.1016/j.isprsjprs.2016.05.005
Baghdadi, N., Lemarquand, N., Abdallah, H., & Bailly, J. S. (2011). The Relevance of GLAS/ICESat elevation data for the monitoring of river networks. *Remote Sensing*, 3(12), 708–720. https://doi.org/10.3390/rs3040708
Barbarella, M., Fiani, M., & Zollo, C. (2017). Assessment of DEM derived from very high-resolution stereo satellite imagery for geomorphometric analysis. *European Journal of Remote Sensing*, 50(1), 534–549. https://doi.org/10.1080/22797254.2017.1372084
Barreiro-Fernández, L., Buján, S., Miranda, D., Diéguez-Aranda, U., & González-Ferreiro, E. (2016). Accuracy assessment of LiDAR-derived digital elevation models in a rural landscape with complex terrain. *Journal of Applied Remote Sensing*, 10(1), 016014. https://doi.org/10.1117/1.jrs.10.016014
Berry, P. A. M., Garlick, J. D., & Smith, R. G. (2007). Near-global validation of the SRTM DEM using satellite radar altimetry. *Remote Sensing of Environment*, 106(1), 17–27. https://doi.org/10.1016/j.rse.2006.07.011
Bhang, K., Schwartz, F., & Braun, A. (2007). Verification of the vertical error in C-band SRTM DEM using ICESat and Landsat-7, Otter Tail County, MN. *IEEE Transactions on Geoscience and Remote Sensing*, 45(1), 36–44. https://doi.org/10.1109/TGRS.2006.885401
Courty, L. G., Soriano-Monzalvo, J. C., & Pedrozo-Acuña, A. (2019). Evaluation of open-access global digital elevation models (AW3D30, SRTM, and ASTER) for flood modelling purposes. *Journal of Flood Risk Management*, 12(S1), e12550. https://doi.org/10.1111/jfr3.12550
El Hage, M., Simonetto, E., Faour, G., & Polidori, L. (2012). Evaluation of elevation, slope and stream network quality of spot DEMs. In *International archives of photogrammetry, remote sensing and spatial information sciences; XXII ISPRS congress* (Shortis, M., Shi, J., & Guilbert, E., eds). Copernicus Publications, 1–2, 63–67.
Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E.,
assessments of digital elevation models and related derived attributes. *Journal of Applied Remote Sensing*, 11 (4), 046027.

Liu, Y., Zhou, M., Chen, Z., & Li, S. (2012). Comparison of drainage network extraction from different DEM data sources: A case study of Hanjiang river basin. *Scientia Geographica Sinica*, 32(9), 1112–1118. https://doi.org/10.1007/s10704-012-1112-07

Ma, H., & Han, G. (2019). Reconstruction of the surface inshore labrador current from SWOT sea surface height measurements. *Remote Sensing*, 11(11), 1264. https://doi.org/10.3390/s11111264

Medelli, L., Vergari, F., Liucci, L., & Monte, M. (2017). Geomorphodiversity index: Quantifying the diversity of landforms and physical landscape. *Science of the Total Environment*, 584, 701–714. https://doi.org/10.1016/j.scitotenv.2017.01.101

Metz, M., Mitsaoua, H., & Harmon, R. S. (2011). Efficient extraction of drainage networks from massive, radar-based elevation models with least cost path search. *Hydrology and Earth System Sciences*, 15(2), 667–678. https://doi.org/10.5194/hess-15-667-2011

Moore, I. D., Grayson, R. B., & Ladson, A. R. (1991). Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. *Hydrological Processes*, 5(1), 3–30. https://doi.org/10.1002/hyp.336005103

Mukherjee, S., Joshi, P., Mukherjee, S., Ghosh, A., Garg, R., & Mukhopadhyay, A. (2013). Evaluation of vertical accuracy of open source digital elevation model (DEM). *International Journal of Applied Earth Observation & Geoinformation*, 21, 205–217. https://doi.org/10.1016/j.jag.2012.09.004

Nikolakopoulos, K. G., Kamaratakis, E. K., & Chrysoulakis, N. (2006). SRTM vs ASTER elevation products. Comparison for two regions in Crete, Greece. *International Journal of Remote Sensing*, 27(21), 4819–4838. https://doi.org/10.1080/01431160600835853

O’Loughlin, F. E., Paiva, R. C. D., Durand, M., Alsdorf, D. E., & Bates, P. D. (2016). A multi-sensor approach towards a global vegetation corrected SRTM DEM product. *Remote Sensing of Environment*, 182, 49–59. https://doi.org/10.1016/j.rse.2016.04.018

Patel, A., Katiyar, S. K., & Prasad, V. (2016). Performances evaluation of different open source DEM using

Differential Global Positioning System (DGPS). The Egyptian Journal of Remote Sensing and Space Sciences, 19(1), 7–16. https://doi.org/10.1016/j.ejrs.2015.12.004

Pulighe, G., & Fava, F. (2013). DEM extraction from archive aerial photos: Accuracy assessment in areas of complex topography. European Journal of Remote Sensing, 46(1), 363–378. https://doi.org/10.5721/EuJRS20134621

Robinson, N., Regetz, J., & Guralnick, R. P. (2014). EarthEnv-DEM90: A nearly-global, void-free, multi-scale smoothed, 90m digital elevation model from fused ASTER and SRTM data. ISPRS Journal of Photogrammetry and Remote Sensing, 87, 57–67. https://doi.org/10.1016/j.isprsjprs.2013.11.002

Satge, F., Bonnet, M. P., Timouk, F., Calmant, S., Pillico, R., Molina, J., Lavado-Casimiro, W., Arsen, A., Crétaux, J. F., & Garnier, J. (2015). Accuracy assessment of SRTM v4 and ASTER GDEM v2 over the Altiplano watershed using ICESat/GLAS data. International Journal of Remote Sensing, 36(2), 465–488. https://doi.org/10.1080/01431161.2014.999166

Satge, F., Denezine, M., Pillico, R., Timouk, F., Pinel, S., Molina, J., Garnier, J., Seyler, F., & Bonnet, M. (2016). Absolute and relative height-pixel accuracy of SRTM-GL1 over the South American Andean Plateau. ISPRS Journal of Photogrammetry and Remote Sensing, 121, 157–166. https://doi.org/10.1016/j.isprsjprs.2016.09.003

Siart, C., Bubenzier, O., & Eitel, B. (2009). Combining digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphological mapping: A multi-component case study on Mediterranean karst in Central Crete. Geomorphology, 112(1–2), 106–121. https://doi.org/10.1016/j.geomorph.2009.05.010

Sun, J., Liu, Y., Wang, Y., Bao, G., & Sun, B. (2013). Tree-ring based runoff reconstruction of the upper Fenhe River basin, North China, since 1799 AD. Quaternary International, 283, 117–124. https://doi.org/10.1016/j.quaint.2012.03.044

Suwandana, E., Kawamura, K., Sakuno, Y., Kustiayanto, E., & Raharjo, B. (2012). Evaluation of ASTER GDEM2 in Comparison with GDEM1, SRTM DEM and Topographic-Map-Derived DEM using inundation area analysis and RTK-dGPS Data. Remote Sensing, 4(8), 2419–2431. https://doi.org/10.3390/rs4082419

Tadono, T., Ishida, H., Oda, F., Naito, S., Minakawa, K., & Iwamoto, H. (2014). Precise global DEM generation by ALOS PRISM. ISPRS Ann. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-4, 71–76. https://doi.org/10.5194/insis-2014-71–2014

Tadono, T., Takaku, J., Tsutsui, K., Oda, F., & Nagai, H. (2015). Status of ALOS World 3D (AW3D) Global DSM Generation. 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Milan, 3822–3825. https://doi.org/10.1109/IGARSS.2015.7326657

Yamazaki, D., Ikeshima, D., Taiwari, R., Yamaguchi, T., O’Loughlin, F., Neal, J., Sampson, C., Kanae, S., & Bates, P. (2017). A high-accuracy map of global terrain elevations. Geophysical Research Letters, 44(11), 5844–5853. https://doi.org/10.1002/2017GL072874

Yue, T., Chen, C., & Li, B. (2010). An adaptive method of high accuracy surface modeling and its application to simulating elevation surfaces. Transactions in GIS, 14(5), 615–630. https://doi.org/10.1111/j.1467-9671.2010.01213.x

Zhang, G., Xie, H., Kang, S., Yi, D., & Ackley, S. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009). Remote Sensing of Environment, 115(7), 1733–1742. https://doi.org/10.1016/j.rse.2011.03.005

Zhao, S., & Cheng, W. (2014). Transitional relation exploration for typical loess geomorphologic types based on slope spectrum characteristics. Earth Surface Dynamics, 2(2), 433–441. https://doi.org/10.5194/esurf-2-433-2014

Zhao, S., Cheng, W., Zhou, C., Chen, X., Zhang, S., Zhou, Z., Liu, H., & Chai, H. (2011). Accuracy assessment of the ASTER GDEM and SRTM3 DEM: An example in the Loess Plateau and North China Plain of China. International Journal of Remote Sensing, 32(23), 8081–8093. https://doi.org/10.1080/01431161.2010.532176

Zhao, S., Wang, L., Cheng, W., Liu, H., & He, W. (2015). Rectification Methods Comparison for the ASTER GDEM V2 data using the ICESat/GLA14 data in the Lvliang Mountains, China. Environmental Earth Sciences, 74(8), 6571–6590. https://doi.org/10.1007/s12665-015-4614-1

Zhou, C. H., Cheng, W. M., & Qian, J. K. (2009). Remote sensing interpretation and cartography to digital geomorphology. Science Press.

Zwally, H. J., Schutz, B., Abdalati, W., Abshine, J., Bentley, C., Brenner, A., Babbit, J., DeZio, J., Hancock, D., Harding, D., Herring, T., Minster, B., Quinn, K., Palm, S., Spin Hirne, J., & Thomas, R. (2002). ICESat’s laser measurements of polar ice, atmosphere, ocean, and land. Journal of Geodynamics, 34(3–4), 405–445. https://doi.org/10.1016/S0266-3707(02)00042-X