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Review paper

Review and critical analysis on digital elevation models

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Nowadays, digital elevation model (DEM) acts as an inevitable component in the field of remote sensing and GIS. DEM reflects the physical surface of the earth helps to understand the nature of terrain by means of interpreting the landscape using modern techniques and high-resolution satellite images. To understand and analyze the nature of the terrain, DEM is required in many fields in the improvement of developing the product and decision making, mapping purpose, preparing 3D simulations, estimating river channel and creating contour maps to extract the elevation and so on. DEM in various applications will be useful to replicate the overall importance of the availability of worldwide, consistent, high-quality digital elevation models. The present article represents the overall review of DEMs, its generation, development using various techniques derived from topographic maps and high-resolution satellite images over a decade to present. It is useful to understand the nature of topography, address the practical problems and fix them by applying innovative ideas, upcoming high-resolution satellite images and techniques.

Keywords: DEM, high resolution, satellite images, topography, accuracy, terminology, techniques and development

1. Introduction

Nowadays, it is important to know the physical nature of the earth surface, being disturbed by humans leads to change the shape, texture and pattern of natural resources. Digital elevation models (DEMs) are considered as important geospatial datasets because of versatile possibilities for using them by Gesch (2005). “Digital Elevation Model is regular gridded matrix representation of the continuous variation of relief over space” mention by Burrough (1986). To predict and analyze the topography of the terrain, DEM is essential. DEM provides the basis for modelling and analysis of spatial-topographic information. DEM analysis includes four important steps namely (i) Acquisition of data (ii) Data modelling (iii) Data management (IV) Application development. Acquisition of data is capturing terrain images or scanning the earth surface, Sharma (2010) using various techniques to develop digital elevation models. The DEM quality depends upon various interrelated factors such as methods of data acquisition; the nature of input data and techniques employed to develop DEM by Richardson and van Oosterom (2002). Data modelling is created using interdisciplinary approaches such as image processing, photogrammetry etc. Data management is developed using various techniques such as data coding, data structuring, spatial database technique, computer graphics etc. Application of DEM plays a vital role in several disciplines such as photogrammetry, remote sensing, mining engineering, urban planning, surveying, geomorphology, facility management, civil engineering, resource management, geological engineering, landscape design, environmental management, geography, tank route planning, cartography, computer games, battle simulation, missile and airplane navigation, flight simulation etc. Various interrelated factors such as methods of data acquisition; nature of input data, vertical resolution and techniques employed to develop DEM are basic requirements where the DEM quality depends on and the good accuracy of DEM can be achieved by increasing the number of GCP by San and Suzen (2005). Hence, with technological advancement, the digital elevation models have improved in accuracy, resulting in a much more useful model of the Earth and help to address the real issues by incorporate other spatial information. The present review article explains various aspects of generation of DEM based on remote sensing and GIS themes, DEM terminology and development stages for generation of DEM, types, structure of DEM, DEM files format and data records, accuracy assessment of DEMs, recent satellite-based DEM's and high resolution DEM's, and applications of digital elevation model. Apart from this, the present work also explains the comparison of traditional methods with recent techniques, a brief summary of achievements and drawback areas of DEM together with an outlook into the future.

2. Digital elevation model (DEM)

Digital elevation model is simply the continuous representation of terrain surface contains XYZ coordinates. Shingare and Kale (2013) are derived from the concept of DTM (Digital Terrain Model). DTM refers to a representation of earth surface without any objects. The word elevation in DEM implies altitudes of elevation of the points contained in a data. DEM act a synonym of the digital surface model (DSM), digital terrain model (DTM) and digital height model (DHM). All of them provide elevation information of the earth surface together with other topographic information, such as data about land cover, slopes, and aspects of the terrain. DEMs are the indispensable quantitative environmental variable in most of the research studies in remote sensing described by San and Suzen (2005). DEMs are represented in two formats: 1) Contour maps: where the terrain surface is represented by lines of constant elevation at equal intervals; and, 2) Point heights: Here the elevation surface is sampled on the regular or irregular basis by Tian-Xiang (2011).

2.1. Development stages of DEM

People construct the buildings on the terrain for their survival or shelter and some geologists, geomorphologists started to investigate the formation of landscape. The topographic specialists analyzed by measuring and describing the surface properties in different ways such as maps, orthoimages, etc in different perspectives. In ancient times people used painting to represent the terrain as it provides general information about the terrain such as shape and colour mentioned by Zhilin et al. (2004). Due to its low accuracy, it cannot be used for engineering purpose. Then maps were used to represent the terrain still today. Due to its low metric quality, people start preferring contoured topographical maps in which all the features present in the terrain are projected orthogonally on to a two-dimensional horizontal datum. The terrain height and morphological information are represented by contour lines and symbols, due to loss of detail observed in scale. In 1849, photographs, and aerial photographs were used to record all features present in the earth mentioned by Zhilin et al. (2004). As an aerial photograph doesn't provide height information, so it cannot be used to derive true heights of ground point information. Satheesh et al. (2008) said rectifying the aerial images, three dimensional (3D) surfaces can be constructed using a pair of overlapping aerial photographs (within 60% of overlap) and this technique is called photogrammetry. Digital photogrammetry has the ability to digitally capture and process data over large areas but the major drawbacks are photogrammetric instruments and the expensive and time-consuming digital system. In 1970's, to complement aerial photography satellite images such as SPOT, IKONOS take overlapping images of the terrain have been used. The resolution of satellite images is still not well matched with aerial images. El-Sheimy (2005) told new resources such as radar, synthetic aperture radar, and laser altimetry, interferometry is developed to derive topographic information. Smith (2010) said surveying became the familiar method to draw topographical information from the area, done by incorporating a significant number of points on the terrain but it consumes much time and it is feasible only for small areas. Burrough et al. (2001) told ground survey is very helpful in mapping ground elevation in wooded regions that are inaccessible to remote sensing. Later total station and GPS receivers are used to collect elevation data described by Ravibabu and Kamal (2008). Total station, GPS and ground survey are slow, time-consuming, and too expensive to cover wide areas mentioned by Satheesh et al. (2008). Soon after the DEM was generated using airborne laser scannings such as LIDAR and RADAR techniques. To develop DEM using LIDAR and RADAR methods, some equipment is needed and arriving at some places and DEM generating can be troublesome by Kayadibi (2009). Sasaki et al. (2008) measure the elevation under vegetation, it provides more detailed topographic information than maps drawn from aerial survey mapping After, the DEM is generated using radar airborne (INSAR/IFSAR) technique. Data collection for IFSAR and LIDAR are based upon sampling as close to a regular raster grid as possible by Burrough et al. (2001). Yu et al. (2010) said the INSAR method is cost-effective, efficient and provides a wide coverage of DEM generation. Optical satellite system such as IKONOS, ASTER, and Geoeye-1, satellites are also used to generate DEM. Unfortunately, optical satellite systems do not work if the Earth's surface is covered by Amy Williams (2003). Nowadays DEMs are generated using high-resolution satellite data like SRTM, CARTOSAT etc. High-resolution satellite data provide a lot of advantages with respect to accuracy, time, money and effort consuming. The accuracy of DEM developed using satellite-based imagery depends upon accuracy and density of the ground control points by Kayadibi (2009). Newly emerging space technology results in the development of high resolution satellites such as IRS-1C/1D, ASTER, IKONOS, SPOT, Quick bird etc producing stereoscopic images facilitating the extraction of DEMs over large areas of the Earth's surface point out by Nikolakopoulos et al. (2006).

2.2. Digital elevation model terminology

Initially, the term DTM was coined by Miller and Laflamme (MIT) in 1958. Dana et al. (2008) clarified different kind of DEMs are available and their meaning varies slightly such as digital elevation model (DEM), digital ground model (DGM), digital height model (DHM), digital terrain elevation model (DTM). The term DEM was widely used in America by Tank (2009), DHM was derived in Germany, DGM in the United Kingdom, while DTEM was introduced and used by USGS. Traditionally DEM of the terrain is made of clay, wood, cardboard, foam, wax, rubber, thermoplastics, sand etc mentioned by Cadwell and Alexandria (2001). Roberts was the first to propose DEM, later Millar and Laflamme of MIT (Massachusetts Institute of Technology) described the development of DEM in detail. They used stereoscopic photography to extract road profiles and displayed it digitally in a computer to assist road designed by Ackermann (1992). DEM is an invention, used for gathering and storing of elevation information from the principles of traditional cartographic DEMs. Initially, elevation data is stored as printing plates and paper maps in the form of contour lines before start using DEMs. Still, contours act as a valid method for visualizing topography, from the perspective of data storage, but showing some deficiencies because of its non-continuous representation of the terrain, in which the selected contour intervals are unknown between the surface forms. Due to the reason, topographic details in the terrain are removed, while other forms are intentionally over-emphasized. Later, airborne laser scanning has become a common method in DEM production, storage and visualization of elevation data are separated for the first time in the history of cartography. Vashisth and Prasad (2013) act as a generic term for DTM, DSM and define DEM as a subset of DTM.

2.3. Types and structure of DEM

Typically, DEM is a gridded array of elevations. DEM in raw form, it is in the format of ASCII or Text or File form. Shingare and Kale (2013) acquire to store the elevation information from various sources DEM use different types of structures such as a) Regular grids of square b) Triangulated irregular networks (TIN) c) Contours based structure. In gridded models, elevation is estimated for each point in a grid. Gridded DEM (GDEM) stores the data in the form of the simple matrix, so the elevation values are easily accessed. The accuracy of the GDEM depends on the size of the data and the grid size. In case of TIN, Aziz (2008) represented in a network of non-overlapping irregular networks To capture the abrupt changes, TIN uses a dense network of triangles in a rough terrain, and a sparse network in a smooth terrain. TIN, DEM has been considered to be better than the GDEM because TIN has its capability to capture the topographic irregularity, without the significant increase in the data size in the case of hydrologic modeling. TIN DEM does not appear natural due to an edge of triangle grid TIN. A Disaster caused in mountainous areas mainly influenced by the pull of gravity is generally controlled by topography, i.e. slope gradient, aspect, etc. To analyze, understand, and predict such phenomena, contour based DEM mainly for deriving topographic attributes is essential to extract contributing attributes by Mizukoshiand Aniya (2002). Mahdi (2015) said the contour lines are traced from the topographic maps and are stored with their location and elevation information. Such type of process is lengthy and consumes time point out by Ozah and Kufoniyi (2006). It is due to differences in map units and contour intervals between the existing base maps and the new maps. Therefore, the method of topographic mapping turns out to be error-prone and highly-demanding in manpower resources by Ozah and Kufoniyi (2006).

2.4. DEM files format and data records

The DEM file format includes USGS DEM, SDTS DEM, DTED, and DIMAP. It has been replaced by the USGS own SDTS format but the USGS format remains popular due to large numbers of legacy files, self-containment, relatively simple field structure and broad and mature software support by Kangtsung (2012). Starting from 1992 to 2006, USGS produced five different digital elevation products. These are i) 7.5-Minute DEM 30 × 30 meter data spacing ii) 2-Arc-Second DEM 2 × 2 arc-second data spacing iii) 15-Minute Alaska DEM 2 × 3 arc-second data spacing iv) 7.5-Minute Alaska DEM 1 × 2 arc-second data spacing v) 1-degree DEM 3 × 3 arc-second data spacing (U.S. Geological Survey, 1993). Though the elevation products are seen as identical, each varies in the sampling interval, geographic reference system, areas of coverage, and accuracy but it varies in sampling interval of the data. USGS DEM format is a single file comprising 1024-byte ASCII-encoded blocks. A DEM file is organized into three record categories namely A (header record), B (profile records), and C (accuracy record). Record D-G consists of code definitions to interpret various data elements in the three records. All DEM data including numbers are represented in readable text form, as there is no cross-platform ambiguity. A record defines the characteristics of DEM, including header information relating to DEMs name, units of measurement, minimum and maximum data values, boundaries, projection parameters and the number of type B records by Elassal and Caruso (1983). For each DEM file, there is only one type A record and it appears before any other record. The type B record contains an elevation profile and its associated header information. The type C record contains statistics on the accuracy of data in the file. Each file contains a separate B record for each elevation profile, as profiles are the building blocks for DEMs and it contains a single A record and may contain a single C record. DEM is an open standard and middle-state format used throughout the world.

2.5. Comparison of traditional methods with recent techniques

Nowadays, use of satellite images for DEM generation has a tremendous advantage over traditional methods. The advantage of utilizing modern techniques to generate DEM is large and inaccessible areas can be identified easily within a short time and less cost. In traditional technique collection of data is difficult, laborious, maintaining the data is very tedious and consumes more time. Using modern technologies various forms of representations are easily produced, such as vertical and cross sections, topographic maps, 3-D animation in digital form and have good data precision owing to the use of the digital medium. In traditional techniques such as paper maps where the topographic details are recorded as slope map or shaded relief are sometimes inadequate as they failed to provide elevation information above sea level and its accuracy may be affected by its scale or may get deformed earlier. Data integration and updating are more comfortable in digital form than in analogue form. In the traditional method, DEM is generated by using aerial or satellite images manually to represent the topographic relief. However, it does not seem accurate to interpret the landscape features. Nowadays, using advanced technologies DEM is generated at different resolutions, provide a clear-cut representation of terrain surface. One disadvantage of modern technology is, optical spectral range requires a cloud-free view and appropriate light conditions in order to generate a good quality and high-resolution DEM. Table 1 clearly explains various sources, techniques, advantages and disadvantages to generating DEM.

Table 1. Sources, techniques, methods and limitations for generating DEM.

Methods	Data formats	Interpolations	Availability	Limitations
Ground surveys	Ground elevation point	Use TIN to Interpolation	Expensive and time consuming to collect data for large areas. Suitable for small areas only.	Not suitable for large areas. GPS does not provide reliable height under canopy. Problem with TIN interpolations.
Airborne photogrammetric surveys – manual interpretation.	Contours and measured points	Kriging	Require aerial photography and skilled operators	Problem with vegetation and measurement frequency.
Airborne photogrammetric surveys – using automatic interpretation method.	Using Correlated points	Kriging	Require aerial photography.	Problem with vegetation and non-ground points with medium frequency resolution.
Existing topographic map data.	Primarily contours	Kriging	Readily available and can be done relatively cheap.	Problem with vegetation and measurement frequency. Added errors with digitizing
Airborne laser scanning	Point data	Inverse distance weights (IDW)	Low cost. Aerial imagery did simultaneously for the small cost difference. High-resolution DEM, DSM and DTM are requested as products.	Problems may occur with steep slopes and heavy vegetated areas.
Automated Stereoscopic based satellite imagery	Point data	Use correlation for surface points and filtering is required.	Can do at a fraction of costs in Photogrammetry. Resolution is much lower. 30 m Aster DSM freely available.	Problem with clouds, non-ground points and vegetation with medium frequency resolution.
Radar based satellite imagery	Raster DEM	None	Cost is lower than Photogrammetry. High resolution is possible but lower than LIDAR. 30 m SRTM DSM freely available.	Problems with vegetation and steep slopes.
High resolution satellite data		Contour interpolation	Available at the cheaper cost. Higher resolution DEM is possible. Based on the resolution, data available for the free cost.	Requires a cloud-free view to generate a good quality and high resolution DEM.
LIDAR based satellite imagery	Point values either LAS format or ASCII point	Kriging	Provide high resolution DEM with good accuracy. Available at low cost than photogrammetric methods. Cover large area.	Suffers from an inability to penetrate in dense canopy. Difficult to interpret and process large datasets.

Sources: A Caribbean handbook on risk information and management (http://www.charim.net/use/92)

2.6. Different techniques to develop DEM: An outlook

There are infinite numbers of techniques available to generate DEM. The accuracy of DEM based on the resolution of the satellite sensor, nature of the terrain, and techniques used to process DEM. The techniques vary depending upon the satellite sensors used to process the image. DEMs are generated from different techniques such as contour lines, topographic maps, field surveys, photogrammetry techniques, interpolation techniques, radar interferometry, laser altimetry and DEM from high-resolution satellite images. DEM derived from contour data are provide good accuracy but not suitable for hilly areas and consumes time and resolution independent and good for visualization. Toz and Erdogan (2008) generated DEM from aerial photographs by image matching and contour line capturing and found that DEM developed using contour line provide two times better accuracy than image matching. Traditional methods such as field survey involve capturing of terrain directly from surface data using theodolite, total station and GPS mentioned by Aziz (2009). Total stations are a combination of electronic distance meter (EDM) and electronic theodolite used to the measure distance and angles and determine the position of the unknown point using trigonometric relationship. Yakar (2009) failed to measure characteristic points of the field surface with the scanning interval. Farah (2009) used GPS to generate DEM and compared with DEM derived using a total station and found GPS provide good accuracy and hence it is used for civil engineering applications and regional planning but Young (2012) recommended to use DGPS wherever small morphological changes were important. E and Yarrakula (2017) using the data sources to represent the topography is often too expensive and often requires technical and computer expertise for processing and data handling, but provide good accuracy. Barry and Coakley, (2013), Suwandana et al. (2012) take over GPS and total station using UAV Photogrammetry to collect geographic data and compared the accuracy of UAV Photogrammetry with RTK-GPS and found similar accuracy results in both techniques. Sunantyo et al. (2014), Gindraux (2017), Ajayi (2017), and Mancini (2013) found UAV provides GPS through rough estimates only. Arun (2013) found DGPS DEM was better than SOI DEM. Chowdhury (2017) obtained DEM using interpolation techniques such as IDW, ordinary kriging, ANUDEM, NN and spline. Interpolation works by using sample points to predict unknown values of geographic data such as elevation, chemical concentrations, noise levels, rainfall etc. IDW is a most suitable method to construct a DEM in urban environment and Kriging suitable for water catchment analysis and land use change by Susetyo (2016). In each interpolation method has its own advantages and drawbacks. To improve the accuracy of DEM needs further research to explore the possibilities by combining Interpolation methods and satellite-based approaches. Chen (2011) used a Coons patch method that provides high accuracy to generate grid-based DEM than classical interpolation methods such as a spline, natural neighbour, kriging and IDW regardless of sampling density. In traditional spatial interpolation methods, the sampled points were lost while processing. Baptista (2008) and Jiang et al. (2010) overcome such problems using elastic Gene Expression Programming to generate DEM that shows better performances. It is further improved using photogrammetric techniques, which are nothing, but measurement of 3D objects using stereo pair images taken from a spacecraft to obtain 3-D height information. Ahmed (2007) and Fabris and Pesci (2005) used photogrammetric techniques and Digital Photogrammetric Workstation (DPW) 770 to evaluate the accuracy of the models for an improvement of resolution and a fast result production. Rugged terrain with sharp slopes, tree canopy, and dense vegetation cannot be mapped with Photogrammetry techniques. In case of the photogrammetric method, there are normal format photo, small format photo and Unmanned Aerial Vehicle (UAV) format photo. The UAV is an aircraft without a human pilot aboard. It is deployed to fly below cloud cover. Gindraux et al. (2017) used UAV Photogrammetry or Drone to generate high resolution datasets but it has some drawbacks such as geometric distortion is large, small coverage for one image, payload limitation. To overcome this Geymen (2014) used InSAR techniques to generate DEM and compared with DEM from topographical map and founds that InSAR DEM has not yet reached the accuracy level but it cover wide-areas at low cost when compared to GPS surveying, or ground-based conventional topography and photogrammetric applications. InSAR is similar to GPS and total station. The major disadvantages of InSAR are atmospheric effects and data availability, while the advantage is that it covers large area continuously with no need of fieldwork. InSAR has some common similarities with optical stereo- imaging, where the common area in the two images viewed from different angles is joined to extract the topographic information, they vary only from the way used to obtain topographical information. Eldhuset (2017) used SAR and InSAR stereo data to generate DEM using other techniques but not accurate in hilly and rugged terrain SAR DEMs accuracy is lower to a few meters when compared with LIDAR-derived DEMs by Kamaruddin (2003). To overcome this problem, radar altimetry was developed especially for oceanographic applications. Later Laser altimeter was developed to overcome the limitations of radar altimeters to measure ice-sheet elevations. Radar-based satellite imagery provides high-resolution DEMs, but lower than LIDAR. Compared with traditional methods, like land surveying and Photogrammetry, LIDAR provide high density and high accuracy 3D terrain points data for the large area. Data collected using ground-based LIDAR are not only higher in resolution but also easier and faster to data capture as compared to the total station. LIDAR data derived DSM contain non-surface objects such as vegetation cover by Sharma (2010) and it can be removed using a slope threshold and a focal mean filter method. In coastal salt marshes, LIDAR-derived DEMs are unreliable because the laser pulse failed to penetrate into the dense grasses and underlying soil and hence it is adjusted using spatially variable correction technique but for micro tidal systems. LIDAR accuracy may not be adequate for some coastal modeling applications point out by Medeiros (2015). A high-resolution DEM could be obtained using LIDAR data but the high cost makes it difficult to be available for many studies. The DEM products have the low level quality of DEM in radar grammetry due to spatial resolution of SAR images and the terrain slope. Compared with interferometry, as it was sensitive to the direction of sensor movement, radar grammetry is less affected by atmospheric influence. To overcome these limitations radar grammetry technique acts as an alternative for DEM generation mentioned by Chen and Dowman (2001). It uses position matching InSAR calculates phase difference of the same ground targets in two images. Hoja et al. (2006) obtained good quality DEM cloud-free images are required and they provide good accuracy. For terrain with high relief and complexity DEM of different resolutions is limited. Good accuracy can be achieved through DEM fusion. Combining multi INSAR data produce DEMs that are more accurate. The use of LIDAR for terrain data collection and DEM generation is the most effective way and is becoming a standard practice in spatial science community. The use of LIDAR for terrain data collection and DEM generation is the most effective way and is becoming a standard practice in spatial science community. Traditional methods such as field surveying and Photogrammetry provide accurate results, but they are labor intensive, time consuming for large areas. LIDAR act as an example for high quality DEM generation by Liu (2008). InSAR method provides produce comparable results with DEM derived from different sources such as SRTM and GPS. Further research is needed to reduce phase noise and examine polarimetric InSAR. With future research involving polarimetric InSAR techniques, coherence might be improved and therefore, generation of high quality InSAR DEMS could be achieved. Technologies develop rapidly. However, which one is better for use depends on our requirements.

2.7. The consequence of error in DEM

The geographic information of the land surface elevation was available in the form of hard copy and later it is distributed in the form of digital elevation model. DEMs are available in different forms and each model of elevation surface consist of files containing a large number of records represents the height of earth surface and therefore a proportion of those measurements may subject to some level of error and uncertainty. Uncertainty is nothing but lack of knowledge about errors. Wechsler (2006) point out DEM error is mainly based on production methods that include field surveying using tachometers or global positioning system, photogrammetry, LIDAR, interferometry SAR and digitizing from existing maps. To understand the errors, arise and uncertainty is propagated knowledge about the spatial structure of error is important. The errors are to be identified from three main sources include the DEM derived from source data, density and distribution and by using interpolation method terrain surface carried out by Fisher and Tate (2006). Data providers distribute digital elevation model mostly in GRID format in which the vast majority of errors and uncertainties has been arising. The error in DEM can be properly determined by comparing with another data source, which has measurements that are more accurate and error free. The DEM from contour undergoes source map error arising from the processes of collection, recording, symbolization, generalization and production inherent in the cartographic process. Constructing DEM using manual and photogrammetry methods cause random errors due to lack of precision in the target points on the photograph while doing aerial triangulation, and systematic errors due to changes in the operator fatigue, instrument errors and from Film media. Digital photogrammetric systems based on hierarchical stereo image correlation produce gridded DEMs in an automatic manner, manual editing is optional, and the drawback is in the absence of any editing data of low accuracy. Airborne sensors such as LIDAR and INSAR uses the emission and reflection of light pulses contributing errors in data acquisition subsystems such as aircraft speed/flying height, global positioning system and inertial measurement unit and terrain surface because while working on LULC types such as forest it is difficult to determine whether the light pulse penetrated to ground. LIDAR systematic error was found to be 5cm for flat areas and maximum of 200cm for grass and scrubland, while random errors of 10 cm in flat areas to 200cm in hilly areas were noted. Liu and Jezek (1999) used directional variograms in the spatial domain and Fourier analysis in the frequency domain to investigate the anisotropic and scale-dependent nature of DEM errors. Still, there is a question what kind of DEM error models account for scale-dependent and nested anisotropic autocorrelation pattern that will improve the modeling of DEM errors. Erdogan (2010) investigated the size and spatial patterning of errors in a large-scale area, using global ordinary least square (OLS) and geographically weighted regression (GWR) regression techniques and find that GWR gave better results. The major problem OLS technique processes being examined are assumed to be constant over space when applied to spatial data and so the relationships between the absolute error and terrain parameters are examined using the GWR technique. Stephen (2010) used interpolation methods to identify the elevation error in 40 m DEM, he showed that poor predictor of RMSE in slope derivatives, and aspect RMSE of elevation is good predictor of RMSE. Gallay et al. (2010) investigated RMSE is the most widely used standard measure of DEM vertical accuracy, as it follows a Gaussian distribution that provide the rough approximation of actual situation. Even though RMSE is most widely used measures of DEM error, it is not the most appropriate since DEM error tends to be spatially correlated. Quantification of the errors and uncertainties need better solutions other than RMSE such as analytical models, unconditioned error or conditioned error, fuzzy logic approach, simulation models, and error propagation theorem and empirical error estimation by Podobnikar (2016).

2.8. Accuracy assessment

To develop good quality DEM, accuracy plays an important role because if the accuracy of DEM does not meet the requirements, redesign of the whole project is needed and thus, costs and efficiency are affected. The commercial and open source software available in the market to generate DEM includes ERDAS IMAGINE, QGIS, VISUAL SFM, MICRODEM, SAGA GIS, Agisoft PhotoScan, ArcGIS etc. The limited spatial resolution of DEMs, and different algorithms employed by different GIS packages suggested as possible sources for DEM inaccuracy and non-repeatability. The commercial software available for DEM generation has lack of quality assessment. The accuracy of DEM depends on the source and resolution of the data samples point out by Hanuphab et al. (2012). To validate the accuracy of the results, the data extracted using satellite stereo images and from conventional techniques such as field measurements, global positioning system (GPS) and aerial photogrammetry by Shaker et al. (2010). The accuracy of the DEM generated from high-resolution satellite images or from other sources mainly depends on control points and on the method of collecting the control points. DGPS or GPS are used for collecting GCPs, and these DGPS/GPS values are fed as input then the accuracy of DEM is high and accurate, but it is very cost effective. Satellite images and toposheet are also used to collect the ground control points (GCPs) if collections of samples are less reliable quality of DEM. The quality of DEM also depends mainly upon terrain roughness, grid resolution or pixel size, sampling density by Guoan et al. (2001), i.e., the method of collecting the data, interpolation algorithm, terrain analysis algorithm, and vertical resolution. Accuracy of DEM is assessed by comparing the contour elevation values obtained from the DEM generated with elevation values of other satellite-based DEM, SOI toposheet, Yarrakula et al. (2013) carried out the high resolution data provide good accuracy of DEM. The accuracy of DEM may also be affected by systematic errors associated with camera, topographic relief displacement, and earth curvature. Gooch and Chandler (2000) used Failure Warning Model (FWM) incorporated within ERDAS Imagine environment for the ERDAS OrthoMAX DEM generation to detect low accuracy areas and to make full use of the actual DEM output from the DPS.Hu et al. (2009) used approximation theory to assess the accuracy of DEM. They examined three interpolation methods namely linear interpolation in 1D, TIN interpolation, and bilinear interpolation in a rectangle. The authors concluded the accuracy of interpolation-generated DEMs could be improved by developing linear interpolation in 1D. Chen and Yue (2010) used error propagation theorem to compute terrain representation error and DEM error using surface modeling. The authors conclude that DEM error is due to not only sampling and interpolation error, but also evaluation of DEM accuracy depends on terrain representation error and used surface modeling based on the theorem of surfaces (SMTS). Another way of DEM generation and analysis of its accuracy is based on numerical test and real-world test to analyze SMTS and classical interpolation methods using ArcGIS software. Authors concluded that SMTS is more accurate than interpolation methods, but in real-world test, there is a large accuracy loss in terrain representation error. Mercuri et al. (2006) used RMSE to assess the IFSAR DEM accuracy and evaluated the DEM using benchmarks and DGPS. RMSE of GCPs and CPs are used to check the accuracy of DEMs. Castrignano et al. (2006) revealed that use of RMSE has no spatial distribution and use a single value for the whole DEM and it fails to indicate where the DEM errors are more likely. The authors used stochastic simulation to estimate local error, probabilistic assessment of DEM accuracy. Better DEM estimates were produced for the unknown error at each DEM node. This research needs additional sampling to improve the accuracy. Hohle (2009) used robust statistical such as median, normalized median absolute deviation, sample qualities to assess the accuracy assessment of DEM and concluded that robust method is better than quality assessment using visual inspection and stereo measurements because the outliers are be easily detected and removed. But this method is suitable only for DEMS derived by digital photogrammetry or laser scanning. Aguilar et al. (2007) revealed that non-parametric approach using Monte Carlo simulation is better than mean square error. It avoids the assumption of normal distribution tested unlike MSE and fails to characterize the spatial variations over interpolated surface. However, Darnell et al. (2008) found that Monte Carlo simulation method also has some disadvantages, that is, the numerical load, where the process gets repeated for 50–2000 simulation runs. Xiao and Liu (2012) used Horizontal Area Deviation (HAD) for DEM quality assessment using Reconstructed Contours Method (RCM) based on ANUDEM. They compared the proposed method with standard RMSE to assess the DEM accuracy and concluded HAD is better than RMSE statistics. Wang et al. (2015) assessed the accuracy of DEM using robust methods of three average error statistics such as mean, median, M-estimator. They concluded that median and M-estimator performs well compared with mean but still, further research is needed because the spatial autocorrelation has varying analytical effects upon error propagation in the proposed robust method. Chenetal (2015) used multiquadric method (MQ) based on an Improved Huber loss function (MQ-IH) to reduce the impact of outliers on DEM. The authors revealed that the proposed method is better compared to classical interpolation methods, such as natural neighbour, OK and ANUDEM. Still, the proposed method had some side effects from its simulation results, such as, contours in hilly areas do not seem accurate with the real world surface and computation cost is much higher than for classical methods. This can be further improved using the least sum of trimmed squares (LTS). Recently Gindraux et al. (2017) generated DSM using UAV Photogrammetry and gained enormous popularity among the users generating high resolution data sets. UAV survey is done using Sense Fly eBee system. Datasets are processed using Agisoft Photo Scan Pro 1.1.6. The accuracy of DSM increases with increasing number of GCPs and decreases when increasing the distance to the closest GCP. They used Unmanned Aerial Vehicles (UAV) to assess the accuracy of UAV-derived DSMs.

DSM accuracy is assessed by comparing DSM with points acquired with DGPS. Various techniques exist for assessing the accuracy of different DEM and every technique has its own advantages and disadvantages. Many authors have done comparative studies to evaluate DEM accuracy. Some studies revealed that the proposed methods are assured to be satisfying the DEM accuracy needs and some authors mentioned that among many existing techniques and methods one provides better accuracy than other methods, but still, there are some limitations present in every method that point to the need of further improvement. The ongoing research, however, provides some interesting possibilities for automated improvements of DEMs. There has been a large methodological progress in recent years and researchers have clarified the pending fundamental questions through emerging technologies and investigations. A Geiger-mode LIDAR (GmLIDAR) and single-photon LIDAR models are currently used as linear-mode LIDAR systems for airborne surveying. GmLIDAR offers the most accurate elevation data available. It is 10 times faster than existing linear LIDAR sensors. It collects a higher quantity of more accurate data than typical linear LIDAR by flying at a higher altitude, firing multiple pulses from multiple angles, and collecting data from a larger array. It provides a more accurate representation of the elevation of the ground, foliage, bodies of water, and buildings. However, older forms of LIDAR collection have the potential to yield incomplete data in the form of voids, areas where the pulses are unable to penetrate, resulting in a kind of "hole" on the elevation data map. Single photon LIDAR (SPL) provides the most efficient approach to rapid, high-resolution 3D mapping. Today it is 30 times faster than any other conventional airborne LIDAR operating system. The limitation in defining the reliability and accuracy of a DEM surface is, especially when the environment includes areas of high slope angle and deep shadowing. Table 2 shows accuracy corresponding to different methods.

Table 2 shows that every method provides different accuracy depending on the DEM and the methods employed, such as contour-based method, interpolation, photogrammetric survey, digital and stereo aerial photographs, Laser and DGPS, GPS techniques, InSAR radar grammetry method, LIDAR, etc. Among those methods, we can conclude that LIDAR based methods provide better accuracy than other methods.

Table 2. The accuracy of different methods used to analyze DEM.

SL.NO	Methods	Accuracy	Authors
1	Failure warning model (FWM)	RMSE – 22.5 m	Gooch (2000)
2	Benchmark from (NGS) laser levelling elevation points and DGPS	IFSAR GT3 10m – RMS error of 1.47 m and 2.88 m GT1 5 m – RMS error of 0.28 m and 0.55 m	Mercuri et al. (2006)
3	Stochastic simulation	RMSE – Less than 1 m	Castrignano (2006)

Table 2. Continued.

SL.NO	Methods	Accuracy	Authors
4	Reconstructed Contours Method based on Horizontal Area Deviation (HAD)	HAD – 0.8924 m RMSE – 0.8883 m	Xiao and Liu (2012)
5	Bi-linear interpolation method (mean, median and M-estimator) Classical t-distribution-based method.	Mean – 9 253.7613 m^2 Median – 3 024.5547 m^2 M-estimator – 4 727.0269 m^2	Wang et al. (2015)
6	Multiquadric method Based on an Improved Huber Loss Function and classical Huber Loss Function- classical MQ and MQ	MQ-IH – 0.3698 m MQ-CH – 0.3916 m Classical MQ – 1.4591 m	Chen et al. (2015)
7	UAV Photogrammetry	Vertical – 0.10 and 0.25 m Horizontal – 0.03 and 0.09 m	Gindraux et al. (2017)
8	Adaptive triangulation irregular network (ATIN) algorithm technique Kriging method Elevation of LIDAR DTM Field data	(GCPs)Slope RMSE – (0.993 and 0.870) (point cloud) Canopy RMSE – (0.989 and 0.924)	Salleh et al. (2015)
9	Photogrammetric techniques	DEM from archive aerial photos (RMSE = 4.90 m) TINITALY/01 (RMSE = 2.53 m) ASTER GDEM (RMSE = 12.95 m)	Pulighe and Fava (2013)
10	GPS (Stop & Go) and kinematic techniques	GPS (Stop & Go) - RMS error of 9.70 cm Kinematic GPS - RMS error 12.00 cm	Farah et al. (2008)
11	Spatial interpolation methods- Inverse distance weighting (IDW) Ordinary kriging (OK)	R^2 – 0.99 Relative error – 0.002 RMSE – 0.104 m	Chowdhury (2017)
12	LIDAR data for reference	Pleiades – R^2 of 0.92 with RMSE of 5.2 m. SRTM – R^2 of 0.74 (RMSE 7.5 m) ASTER – R^2 0.84 (RMSE 6.6 m)	Nasir et al. (2015)
Estimated vertical accuracies of DEM sources			
13	Geodesic and Laser beacons DGPS Digital Aerial photography Topographic map Stereo aerial photography LIDAR SAR data such as RADARSAT, ERS 1/2 Satellite data across track stereoscopy such as SPOT, IRS, IKONOS Satellite data along track stereoscopy such as JERS, ASTER IFSAR single pass such as TOPOSAR, SRTM	Vertical Accuracy – 2 cm and 10–15 cm Vertical Accuracy – 0.3–2.5 m Vertical Accuracy- Minimum: 7 to 15 cm; Maximum: 50 cm Vertical Accuracy varies and doesn't remain constant Vertical Accuracy – 0.15–1 m Vertical Accuracy – 10–50 m Vertical Accuracy- Approximately 25 m Vertical Accuracy- Approximately 25 m Vertical Accuracy – 10 m and 16 m	Mercuri et al. (2006)

Table 2. Continued.

SL.NO	Methods	Accuracy	Authors
14	Contour lines image matching	Contour lines RMSE ± 3m image matching RMSE ± 7m	Toz and Erdogan (2008)
15	digital Photogrammetry DGPS techniques	Cartosat-1 RMSE – 6.13m Standardized RMSE – 6.23 m	Panhalkar and Jarag (2016)
16	Area based image matching	KOMPSAT RMSE – 1.5 pixels	Ye and Lee (2001)
17	Interpolation methods	TIN RMSE – 0.844 m IDW RMSE – 0.7504 m Circular kriging RMSE – 0.8567 m Gaussian Kriging RMSE – 1.12 m Spherical Kriging RMSE – 0.8091 m	Susetyo (2016)
18	Image interpolation methods	RMSE – 1.3 m	Baltsavias et al. (2007)
19	Geostatistical approach GNSS and GPS	SRTM RMSE – 3.6 m ASTERGDEM2 RMSE – 5.3 m GMTED2010 DEMs RMSE – 4.5 m	Athmania and Achour (2014)
20	Photogrammetric techniques	Cartosat-1 undulation area RMSE – 4.38 m Cartosat-1 hilly area RMSE – 3.69 m	Ahmed et al. (2007)
21	Photogrammetric surveys interferometry SAR images Radar interferometry method	INSAR absolute mean different elevation mountain – 1.5 m Forest areas – 2 m Plain areas – 0.9 m Reference DEM and INSAR elevation difference 1.3 m	Geymen (2014)
22	LIDAR vegetation removal method	Vertical error of ±7.5 mm	Sharma et al. (2010)
23	UAV-based approach TLS method	TLS RMSE – 22 cm UAV-sfm RMSE – 10 cm	Mancini et al. (2013)
24	LIDAR- Median and quartile approach Median approach Quartile Approach	RMS of LIDAR DEM – 0.61±0.24 m RMS of adjusted DEM – 0.32±0.24 m quartile-adjusted DEM RMS- 0.65 m to 0.40 m	Medeiros et al. (2015)
25	Aerial Photogrammetry Airborne LIDAR Unmanned vehicle	RMSE of ALS – 0.15 m–0.18 m RMSE of aerial photogrammetry- 0.22 m to 0.40 m GSD values total error – 0.98–2.1	Hsieh et al. (2016)
26	RTK-GPS – Fuzzy logic (FL) Weighted averaging (WA)	FL and WA (RMSE) – 0.08 m RMSE of averaging each grid – 0.16 m	Aziz et al. (2009)

3. Sources of DEM

3.1. High resolution satellite sensors and their advantages and disadvantages

To obtain the DEM, varieties of the satellite images are available at different spectral, radiometric, spatial and temporal resolutions. An advantage of the DEM development using satellite images is that it reduces collecting the DEM for larger areas with respect to time, costs, and effort, and updated information. The internet is one of the great sources of data and information on digital elevation models. Cartosat-I, Cartosat-II, Eros A, Quick Bird, IKONOS, Orb View, Kompsat-2, Kompsat-3, Formosat, Aster and WorldView-1 are some of the satellite platforms launched in the past 1years which have very good stereoscopic capabilities and spatial resolution point out by Dana et al. (2008). In the beginning, the spatial resolution of the satellite images obtained were 90m or more. Today, the DEMs are available from the satellite images distributing with 0.50 m, 2 m, 15 m, 30 m ground sampling distance (GSD), such as Worldview-1, Cartosat-1, SRTM DEM, SOI DEM with 1:50 000 scale as given in toposheet. DEM is generated from different sources, such as, topographic maps are cost-effective for large areas and they give unimportant exactness in light of the fact that the spatial determination of DEM relies on form interim of a topographic guide fluctuate contingent on the measure of detail and nature of the landscape that could bring about loss of precision. Satellite imaging systems are classified into optical and radar systems mentioned by Rhyma et al. (2016). The optical satellite sensors used to generate DEM include IKONOS 2, EROS-A1, Quick Bird, CARTOSAT-1, ALOS (PRISM), EROS-B1, KOMPOSAT2, Worldview-1, Worldview-2, WorldView-3, ASTER, GeoEye-1, CARTOSAT 2, Pleiades 1B, and Pleiades 1A. The radar satellite sensors used to produce DEM include SPOT5, SPOT6, SRTM, COSMO-SkyMed, TerraSAR-X and TandemSAR-X, RadarSDat-2 etc. Based on the resolution, the satellite sensors are classified as high and medium resolution DEMs. High spatial stereo satellite imagery Pleiades-1A, Pleiades-1B, WorldView-1, WorldView-2, WorldView-3, GeoEye-1, and IKONOS provide more accurate terrain data in detail of site-specific locations on a global basis. ALOS, ASTER and SPOT-6 are medium resolution satellite imagery cover of large areas and they are cost-effective. If the satellite solution does not meet the desired requirement or manned aircraft is unavailable or expensive, DEM is also generated using a drone. It is a new alternative method for manned aircraft system. SPOT is the first satellite provides a stereoscopic image for DEM extraction but it is withdrawn from active service on 31st December 1990 and it is reactivated in 1997. SPOT 5 and 6 with 2.5–5 m and 1.5 m resolution launched on 3rd May 2002 and September 9, 2012, respectively. It provides cloud-free images. The major advantage of SPOT satellite sensor is geometry accuracy. One of the major disadvantages is that sizes of scenes are operated commercially, and imagery carries a high cost. Worldview-1, Worldview-2, Worldview-3 launched on September 2007, October 2009, August 2014 with 0.5, 0.46, and 0.31 m resolution, respecti-vely. Advantages of worldview sensors are risk reduction, cost saving and quick delivery to users. However, the major disadvantage is that it does not provide cloud-free images. Global Land One-km Base Elevation (GLOBE) with the 30 arc-second was released in 1996. In the same year, a Global 30 Arc-Second Elevation Data Set (GTOPO30) was also released by USGS with a horizontal resolution of 30 arc-seconds. In 1998, Earth Topography with a 5-minute resolution of ETOPO5 was released by NGDC. During the generation of elevation data, DEMs had coarser resolution due to multisensory and different techniques like GLOBE, GTOPO30, and ETOPO5.IKONOS was the first commercial satellite launched in September 1999, with 1 m panchromatic and 4 m multispectral in the VNIR region. It had the ability to extract vector features and geographic features in 3D such as roads, buildings, manmade structures and other terrain features. The concept of a rational polynomial coefficient started with IKONOS. Now, it is used in other satellites including Cartosat-1. In 2002, the Quick Bird was launched with improved resolution of 0.62m GSD for nadir view. It had a very high resolution, less than 1m. Its major limitation is that it covers a small area, while an advantage is it that it has the high spatial resolution. It is affected by cloud cover and thus, acquires images only during the daytime. ASTER satellite sensor was launched in December 1999. It acquired more than two million data scenes with along track stereovision of visible-near infrared (VNIR) telescopes. ASTER has six bands in the shortwave infrared (SWIR), three spectral bands in the visible near-infrared (VNIR), and five bands in the thermal infrared (TIR) regions, with 15-m, 30-m, and 90-m ground resolution, respectively. Later GDEM was developed and released to the public domain in June 2009 with one arc-second resolution respectively. GDEM data contains strongly visible noise ASTER GDEM version 2, a new global elevation dataset was released in October 2011 but its quality was very low. ASTER DEMs produce artifacts due to cloud cover was their major drawback. The Shuttle Radar Topography Mission (SRTM) Endeavour, back in February 2000 covered almost 80% of the Earth's land surface to acquire a DEM of all land between latitudes 60°N and 56°S. In 2014, a high-resolution SRTM was released with 30m spatial resolution. Still, SRTM struggled in sloping regions with the layover, shadow and foreshortening. CARTOSAT-1 was launched in May 2005, with 2.5 m spatial resolution. Cartosat-1 is not suitable for the generation of global DSMs without GCPs because the absolute geolocation accuracy is very poor and it varies from dataset to dataset. The major advantages of CARTOSAT-1 DEM data were production of high resolution images used in a variety of applications, while the cloud cover was the major disadvantage investigated by Baltsavias (2007). TanDEM-X is the name of TerraSAR-X's twin satellites launched in June 2010 for acquiring the most precise 3D map of the Earth's surface. It has 12.5 m spatial resolution and produces less than 2 m vertical accuracy. It offers remarkable accuracy when compared with other global datasets and is based on a uniform database. The major benefits are that it overcomes the limitations of temporal de-correlation and atmospheric disturbance in multi-pass data identified by Wecklich (2015). Zink (2015) mentioned a major drawback of power and thermal restrictions, onboard storage, and downlink capacity. TanDEM-X has a relative height error, above 1.8 m. COSMO-SkyMedis made up of four satellites called COSMO 1–4. It was launched by Italian Space Agency (ASI). The first two satellites were launched in 2007, and other two in 2008 and 2010, respectively. It can acquire data during both day and night because it does not require light to record the image. It contains an active sensor and can see through clouds with almost no interaction. It achieves a very high resolution of 1m. One of the main limits of COSMO-

SkyMed imagery is the significant cost required for acquiring a complete dataset. Pleiades-1A was launched on 16 December 2011. It has two very high-resolution optical Earth-imaging satellites. The main advantage that it provides stereoscopic coverage of high resolution. Pleiades-1A has the ability to provide high accuracy both forward and backwards looking stereo pair and provides information about the terrain (DTM), as well as, the height of the surface above ground (DSM). It has the ability to provide tri stereo-pair imagery at 0.5 m spatial resolution, unlike other satellite systems, such as Quick bird and IKONOS. Its major limitation is an area with high topographic variations. A nadir, forward and backward looking tri-stereo pair can be used to overcome the inaccuracies due to topography. Sentinel-1 was launched on 3rd April 2014. Amitrano (2014) designed to guarantee global coverage with a revisit time of 6 days. ALOS (PRISM), EROS-B1and KOMPOSAT are some of the optical satellite sensors that provide most precise global-scale elevation data but each has major limitations with respect to cloud cover and less accurate mapping. Overall, a drawback of optical satellite sensors is a cloud cover because they have a passive sensor on board, need light to record the image and can acquire the image during daytime only to generate a good quality and high-resolution DEM. However, radar satellites can operate during day and night are not affected by cloud cover. Optical satellites acquire images one pass/day at 10:00 local time and uplink the acquisition plan to the satellite in general up to 6 hours prior to passing. SAR satellites acquire images two passes/day at 07:00 and 19:00 local time and uplink the acquisition plan to the satellite in general up to 18 hours prior to the pass revalued by Grandoni (2013). Nowadays, most of the commercial high-resolution imagery comes from satellites operated by digital globe, GeoEyeInc and ImageSat International (for EROS series) with less than 1m panchromatic (black and white) resolution and multispectral (colour) with less than 2 m resolution point out by Gruen (2008). Each image produced by these satellite systems is made of millions of pixels, representing a 50 cm by 50 cm square surface of the ground identified by Raymond et al. (2014). The level of resolution is good for analyzing conflict areas, wherever small houses and alternative structures are destroyed by violence. The current satellites do not have the capability to capture individual people when viewed from above, it looks smaller than most imaging resolutions because of their dimensions. Rarely, images are seen where people, or more likely their shadows, are visible as single pixels. Very high-resolution satellites will be launched in near future, such as Cartosat- III with 0.3 m GSD and GeoEye-2 with 0.25 m GSD. Other upcoming satellite missions, such as Surface Water and Ocean Topography (SWOT), will provide repeated high-resolution elevation measurements designed especially to survey global surface water in hydrology. SWOT is scheduled to be launched in 2020, as an international collaboration between the US National Aeronautics and Space Agency (NASA) and Centre National Etudes Spatiales (CNES) of France, supported by the Canadian Space Agency (CSA) and the UK Space Agency (UKSA**)** declared by Musa (2015). Table 3 shows various high resolution DEMs available for DEM generation.

Table 3. Very high-resolution (VHR) optical satellites capable of producing stereo images for DEM extraction by Deilami and Hashim (2011).

Satellite sensor	Country/Company	Date of launch	Resolution	Swath width (m)	Stereo
IKONOS 2	USA/GeoEye	24th Sep 1999	Pan(N) 0.8 Multi(N) 3.2 Pan sharpened 0.8–1.0	11×11	Along track
EROS-A1	Israel/Image set	5th Dec 2000	Pan(N) 1.9	14×14	Along track
Quick Bird	USA/Digital Globe	18th Oct 2001	Pan 0.61 Multi 2.4	16.5×16.5	Along track Across track
Spot 5	France	3rd May 2002	Pan 2.5–5 Multi 10	60×60	Along track
Spot 6	France	9th Sep 2012	Pan 1.5 m Multi 6.0m	60×60	Along track
CARTOSAT-1	India	5th May 2005	Pan 2.5	26×26	Along track Across track
ALOS(PRISM)	Japan	24th Jan 2006	Pan 2.5	35×35	Along track
EROS-B1	Israel/Image set	25th Apr 2006	Pan 0.7	7 up to 21	Along track triplet of images
KOMPOSAT2	Korea/KARI	28th July 2006	Pan 1 Multi 4	15	Along track Across track
Worldview-1	USA/Digital Globe	18th Sep 2007	Pan(N) 0.5	17.6×17.6	Across track
Worldview-2	USA/Digital Globe	8th Oct 2009	Pan 0.46	48×110	Across track
Worldview-3	USA/Digital Globe	13th Aug 2014	Pan(N) 0.31 m Multi(N) 1.24 m	13.1 km	Across track
GeoEye-1	USA/Geo Eye	6th Sep 2008	Pan(N) 0.5 Multi(N) 2	224×28	Across track
Pleiades 1B	Space Agency of France	2nd Dec 2012	Pan 0.5 Multi 2	20	Along track Across track
Pleiades 1A	Space Agency of France	16th Dec 2011	Pan 0.5 Multi 2	20	Along track Across track
SRTM	USA/NASA	11th Feb 2000	1 Arc-second	1	Along track
ASTER	USA	18th Dec 1999	15 to 90 m	60 km	Along track
ASTER GDEM	USA	29th June 2009	1 Arc-second	60 km	Along track
Radarsat-2	Canadian Space Agency	14th Dec 2007	1 m – 100 m	18–500 km	Along track
TanDEM-X	German Aerospace Center	June 2010	HRTI-3 – 12 m (0.4 Arc-second) DTED-2 – 30 m (1 Arc-second)	30–50 km	Along track
TerraSAR-X	German Aerospace Center	15th June 2007	1–18.5 m	HS Spotlight: 5 to 10 km×5 km Spotlight: 10 km×10 km Strip Map: 30 km×50 km ScanSAR: 100 km×150 km	Along track

3.2. Role DEM resolution to improve the accuracy

Takagi (1998) increased the DEM accuracy for the desired level, it is necessary to understand the importance of DEM resolution It is also important to provide details about DEM sources, such as sampled elevations point to interpret the DEM resolution. Hanuphab et al. (2012) investigated the effects of DEM resolution for many processes such as hydrological models, solar radiation, landslide, soil erosion and watershed etc., Crosby (2006) found that if the DEM grid cell size increases, some of the topography index also increase. On the contrary, for low resolutions DEM the topography values get smaller constantly or under-represent slope class. Walker (1999) and Xia (2010) described the effect of DEM resolutions on geomorphology and hydrology with varying DEM grid spacing. They found that grid spacing less than 25 m is not suitable to identify stream network and catchment. In hydrology, differences in accuracy are mainly caused due to DEM resolution and DEM errors by Saksena (2014) and Shafique et al. (2011). Higher resolution DEMs resampling to coarser resolutions decrease the accuracy but smooth the floodplain, which can be corrected using field surveyed elevations. The parameters, such as soil, vegetation, precipitation, and underlying surface conditions are greatly influenced by DEM resolution. Zhang (2016) revealed DEM resolution plays an important role in the simulation process where higher DEM resolution results in the more accurate representation of terrain features. This is due to topography, which causes significant variations in solar irradiation over short distances. Pescador (2007) tended to that DEM determination assumes an imperative part to examine the distinction between the sunlight based radiation gauges, for example, contrasts in a rise, incline and viewpoint because of information disseminating and to register the impact of land parameters in complex geography. Milevski et al. (2013) compared the accuracy of different DEMs available, such as 30”SRTM, 3”SRTM, 1”X-SAR SRTM, 20m DEM of ARECR. In flood mapping, channel threshold depends upon DEM resolution. If DEM resolution decreases, then the slope Manning’s value will decrease with the increase of channel threshold identified by Zhang (2016), because in flood forecasting modeling DEM provides geometries, such as, cross sections, streams, flow paths, banks for prediction and modeling of the floods done by Yarrakula et al. (2010) and Yarrakula et al. (2016). Chen (2013) found that better recognition and classification of landslide types could be obtained. Rawat (2014) analyzed the effect of DEM data resolution on sub-watershed boundaries delineation using CARTOSAT-1 (IRS-P5), SRTM, ASTER. He found that representation of major stream network and subwatershed accuracy decreases with a decrease of DEM resolution. Hence, DEM accuracy of watershed delineation depends on accuracy and quality high-resolution DEMs like CARTOSAT-1. Vaze (2007) showed that high-resolution DEMs, such as LIDAR provide very good accuracy and reliability in comparison with coarse resolution DEMs. He also highlighted the drawbacks of low-resolution DEMs. Low-resolution DEMs do not represent actual topographic features that affect the accuracy. Instead, details are lost. Therefore, the author recommended the use of high resolution DEMs. High-resolution DEMs also have drawbacks, such as model run time and handling of a large number of the grid. Therefore contour derived low-resolution DEM is preferable when compared to the high-resolution DEMs. Wolock and McCabe (2000) investigated the impact of DEM resolution on coarse DEMs and fine DEMs in the case of topographic wetness index. For the fine DEMs model, the topography was drier than for the coarse DEMs model the topography. Clarke and Archer (2007) revealed that depending on DEM resolution we can achieve the higher level of accuracy in terrain extraction. Takagi (1998) found that DEM resolution has great influence on slope inclination and drainage pattern generation because terrain analysis is the combination of the slope and inclination aspect. Bothale (2013) used high resolution Cartosat-1 DEMs of different grid sizes, such as CARTODEM (10 m, 20 m, 30 m,40 m, and 90 m). These were generated using the photogrammetric method and compared with SRTM (90 m) and ASTER (30 m). He found that high-resolution Cartosat-1 DEM provides higher accuracy of 0.42 RMSE than SRTM and ASTER DEM. Xiao et al. (2010) addressed the impact of DEM resolution (40 m, 50 m, 60 m, 70 m, 80 m and, 90 m) on stream network parameters, such as elevation, the area of sub-basins and watershed. They found that there is a correlation between the area of sub-basins and DEM grid size. Yuan (2008) analyzed the topographic attributes extraction based on grid size. He found that with the decrease of DEM resolution results in a decrease of the drainage density and increase of the area of the watershed. Wu et al. (2008) identified the sensitiveness of topographic attributes on the data resolution. They found that the watershed area is changing if the grid size is unable to cover the irregular shape of the watershed. Deo et al. (2016) validated the accuracy of high-resolution TanDEM-X DEMs with Cartosat-1 DEM. They found that TanDEM-X DEM has higher RMSE when compared with Cartosat-1 DEM due to layout and shadow effect. Vaze et al. (2010) pointed out that the higher resolution DEMs do not always work better than lower resolution since very high resolution DEMs also have artifacts that pose difficulties in understanding terrain and its analysis. The main priority should be given to DEM resolutions that are important for interpretation and analysis of the terrain features for various models.

4. Conclusions

The scientific community and industry are increasingly aware of the importance of DEM and their applications. Satellite and spaceborne missions are launched particularly to afford digital elevation data over the globe using radar interferometry and light detection and ranging (LIDAR). The present review addresses the challenges of digital elevation models and their development. This article explains Digital elevation model, DEM format and DEM development from the early stages. Also, the establishment of the name DEM is explained, as well as, the different terminologies, structure and file formats of DEM. Shortly, the overall history of DEM is presented. A comparison between traditional and recent techniques is given and a conclusion is reached that recent technologies are more appropriate than traditional. However, cloud cover is the major drawback of modern technology. Further, different techniques and patterns, such as contour lines, topographic maps, field surveys, photogrammetry techniques, interpolation techniques, radar interferometry, and laser altimetry, LIDAR with their boons and banes are explained. It is concluded that further improvement of LIDAR and InSAR techniques, generation of high-quality DEMS is needed. Errors in DEM, such as errors arising from source data, density and distribution, and errors due to interpolation methods and different techniques are discussed. It is concluded that errors and uncertainties can be quantified using analytical models, unconditioned error or conditioned error, fuzzy logic approach, simulation models, error propagation theorem, and empirical error estimation instead of RMSE. Accuracy assessment of DEM was summarized broadly using various methods, such as contour-based method, interpolation, photogrammetric survey, digital and stereo aerial photographs, Laser and DGPS, GPS techniques, InSAR radar grammetry method, and LIDAR. It is concluded that each method provides different accuracy based on the DEM and the methods employed. However, LIDAR based methods provide better accuracy than other methods. Available sources, which can serve for DEM generation, are discussed. These are: topographic maps (which are cost effective coverage for large area and low accuracy), satellite platforms (optical sensors to generate DEM, including IKONOS 2, EROS-A1, Quick Bird, CARTOSAT-1, ALOS (PRISM), EROS-B1, KOMPOSAT2, Worldview-1, Worldview-2, WorldView-3, ASTER, GeoEye-1, CARTOSAT 2, Pleiades 1B, and Pleiades 1A), and radar systems (such as, SPOT5, SPOT6, SRTM, COSMO-SkyMed, TerraSAR-X and TandemSAR-X, RadarSDat-2). It is concluded that optical satellite sensors have problems with cloud cover since they need light to record the image. Thus, they can acquire the image during daytime only. This limits the generation of a good quality and high-resolution DEM. Radar sensors and the current satellites do not have the capability to capture individual people when viewed from above because of their dimensions. Upcoming satellites mission that is scheduled to be launched in 2020, are expected to enable high-resolution DEM in the near future. Importance of DEM resolution and its influence on the improvement of the accuracy was discussed for various applications, such as hydrological models, solar radiation, landslide, soil erosion, and watershed.

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SAŽETAK

Pregled i kritička analiza digitalnih elevacijskih modela

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Danas, digitalni model uzdizanja (DEM) djeluje kao neizbježna komponenta u području daljinskog istraživanja i GIS-a. DEM reflektira fizičku površinu zemlje pomaže pri razumijevanju prirode terena pomoću tumačenja krajolika pomoću suvremenih tehnika i satelitskih slika visoke razlučivosti. Za razumijevanje i analizu prirode terena, DEM je potreban u mnogim područjima poboljšanja razvoja proizvoda i odlučivanja, svrhe mapiranja, pripreme 3D simulacija, procjene riječnog kanala i stvaranja konturnih karata za izdvajanje visine i tako dalje. DEM u raznim aplikacijama bit će korisno za repliciranje sveukupne važnosti dostupnosti svjetskih, dosljednih i visokokvalitetnih modela digitalnih elevacija. Ovaj članak predstavlja cjelokupni pregled DEM-ova, njegovog stvaranja, razvoja pomoću različitih tehnika izvedenih iz topografskih karata i satelitskih snimaka visoke razlučivosti tijekom desetljeća do danas. Korisno je razumjeti prirodu topografije, rješavati praktične probleme i popraviti ih primjenom inovativnih ideja, nadolazećih satelitskih slika i tehnika visoke razlučivosti.

Ključne riječi: DEM, visoka razlučivost, satelitske slike, topografija, točnost, terminologija, tehnike i razvoj

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