Vertical accuracy assessment of CartoDEM, SRTM and ALOS DEM's using GTS and DGPS measurement in Narmada Basin, Madhya Pradesh

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Abstract: Any hydrological, irrigation, watershed development outlook require elevation data which is a prerequisite in modelling the water movement. The free and easily available public domain DEMs are always the first choice for many engineers, researchers and modellers in the project. However, many times the elevation accuracy is either compromised or unaware by the research community. Therefore, attempts were made to assess widely used SRTM, CartoDEM, and AW3D30 DEMS for their absolute vertical accuracy for plain to hilly Kharkai Sub Basin of Narmada Basin. The elevation value derived from DGPS measurement (96 nos) and connected with SOI-GTS-BM (119 nos) were used as reference data in determining the Mean Error (ME), RMSE and LE(90). The estimated ME were 2.13(DGPS)/0.88 (GTS) for SRTM, 0.22/2.39 for CartoDEM and 1.87/3.33 for AW3D30. The RMSE estimated were 2.82(DGPS)/3.84 (GTS) for SRTM, 3.15/3.11 for CartoDEM and 3.7/3.71 for AW3D30. The LE(90) was found to be 4.22/5.07 for SRTM, 4.62/3.62 for CartoDEM and 5.54/4.97 for AW3D30. The lowest value of ME of 1.19, RMSE of 3.13 and LE90 of 4.19 was found for CartoDEM when compared with both types of GCP (DGPS+GTS). It is worth noting that the lowest value ME, RMSE and LE90 was found for SRTM for GCP with DGPS Measurement. Moreover, the CartoDEM was found to be more closer to the GTS value of elevation as compared to SRTM and AW3D30.The ME was positively skewed under both types of GCP, indicating the SRTM, CartoDEM and AW3D30 DEMs values were overestimated than the actual measurement.

Keywords: Absolute Vertical Accuracy, DEM, DGPS, GTS

1. Introduction

Digital Elevation or Surface or Terrain Model (DEM, DSM, DTM) are the mathematical representation of terrain of the earth's surface and stored the elevation value in each cell/pixel. However, Digital Surface Model (DSM) represent the elevation value of terrain and cover such as trees/building/road etc. DEM/DTM is often used for bare earth surface and required for flood/drainage modelling, land-use studies, geological, hydrological modelling. DEM/DTM/DSM term is used interchangeably among the geospatial community. The most convenient, quick and reliable way to generate the elevation data is from remote sensing-based interferometry (Sharma et al., 2010 and Marks *et al.*, 1984). The ALOS World 3D - 30m (AW3D30, Global Coverage), CartoDEM-30m (Indian and adjacent region), and SRTM-30m (Global Coverage) are DEMs that have become accessible to the world community without any charge.

The very recent release AW3D30, CartoDEM and SRTM30, calls for opportunities to conduct the localized assessment of the DEM's accuracy to test their suitability for an extensive range of applications in hydrology, watershed, basin planning and many more. On the other hand, assessments of the DEM's accuracy in various topography and land use and land cover of the world regions are critical for improving the future generation of regional/global DEMs (Suwandana et al., 2014).

Though many researcher have been carried out for accuracy assessments of DEMs in different regions of the world by utilising various kinds of reference/observed data and reference DEMs (e.g. Rawat et al., 2019; Purinton et al., 2017; Hu et al., 2017) very few have been conducted on the Indian terrain using CartoDEM (e.g. Agrawal et al., 2020; Rawat et al., 2019; Rana, 2019; Jain et al., 2018; Kumar et al., 2017; Baral, 2016; Gajalakshmi, 2015;) recently few researchers (Zhang et al., 2019; Çaglar, 2018) conducted the accuracy assessment using AW3D30. Since the AW3D30 data is available from 2016, very limited publications and validation work are available using AW3D30 (Hu et al., 2017).

Despite the fact that free and open-access DEMs are popular and contributing to various science of hydrology, geology (Cai & Wang, 2006; Chappell et al., 2006; Singh & Sharma, 2009; Paiva et al., 2011; Sharma et al., 2011; Singh et al., 2011; Wang et al., 2012), natural resource planning and management (Ficklin et al., 2010; Wu et al., 2012; Chien et al., 2013; Faramarzi et al., 2013), landside mapping (Dhakal et al., 2000), flood estimation and mapping(Sanders, 2007; Ramlal & Baban 2008; Tarekegn et al. 2010; Degiorgis et al. 2012), its accuracy is either compromised or omitted (Hu et al., 2017). Secondly, the accuracy of these datasets is often unknown and is non-uniform on region of interest (Mukherjee et al., 2012). Very limited research publication on the accuracy assessment for AW3D30 is publicly available at the time of writing this research article for the Indian region (Jain et al., 2018).

In this research quest, CartoDEM Version3.1, SRTM Version3.0, and AW3D30 Version3.1DEM data available in the public domain are utilised and accuracy evaluation for the purpose of irrigation infrastructure development, flood modelling and Dam break analysis was assessed. Traditionally, the feasibility studies of irrigation projects are prepared from Contours obtained from the Survey of India (SOI) toposheet having meter level accuracy in elevation. However, the availability of open DEM's is best suited for the preparation of feasibility reports of water resource projects with sub-meter level accuracy. Though DEM achieved sub meter accuracy in elevation, it should also be accompanied with DGPS based measurement for the preparation of Detail Project Report (DPR) of new irrigation scheme which can be further improved by a Double Fly levelling method through transfer of BM from the nearest available GTS.

The present study was conducted to find the absolute vertical accuracy of public domain DEM for use in water resource application using the standard DGPS values as well as DGPS connected with GTS measurements.

2. Study Area

The study area is the Kharkai river, which is completely within the State of Madhya Pradesh and is one of the tributaries of Narmada river, India (Figure 1.), covering 985 sq. km.Though the Narmada basin consists of diverse topography, the Kharkai Sub Basin is modestly hilly to flat terrain and elevation ranges from 148 to 400m Above MSL and slope is less than 5 degrees (Figure2).The terrains are categorised by slopes, i.e., a slope <2 degrees is considered as plain terrain , hilly with a slope between 2 and 6 degrees, and mountainous with a slope >6 degrees (Santillan et al., 2016). The land use and land cover are predominantly agricultural lands with more than 96% land cover are of the natural landscape (agricultural, forest, wasteland, scrubland) and only 7% is under the modified land-use, i.e. settlement, road/canal, waterbodies (Figure2). Since 96% of land cover is of the natural landscape, therefore DSM (AW3D30 and CartoDEM) are considered equivalent to DEM.

When the sub basin was delineated into three catchments on the basis of the direction of flow, i.e. South to North and then North-west (Figure2), it was found that the middle catchment is dominated with more forest cover compared to upper and lower catchment and average slope is 3.1 degree. The Lower catchments of 422sq km area is covered with irrigation command of Indira Sagar Project (ISP) of Narmada Valley Development Corporation (NVDA). All catchments are having a slope less than 3.2 degrees, indicating sub basin terrain plain to hilly. However, the middle catchment is a little heterogeneous compared to the upper and lower catchment with respect to the other land use, slope and topography. The brief topographical and land use characteristics of each catchment in Kharkai Sub Basin is shown in Table 1.

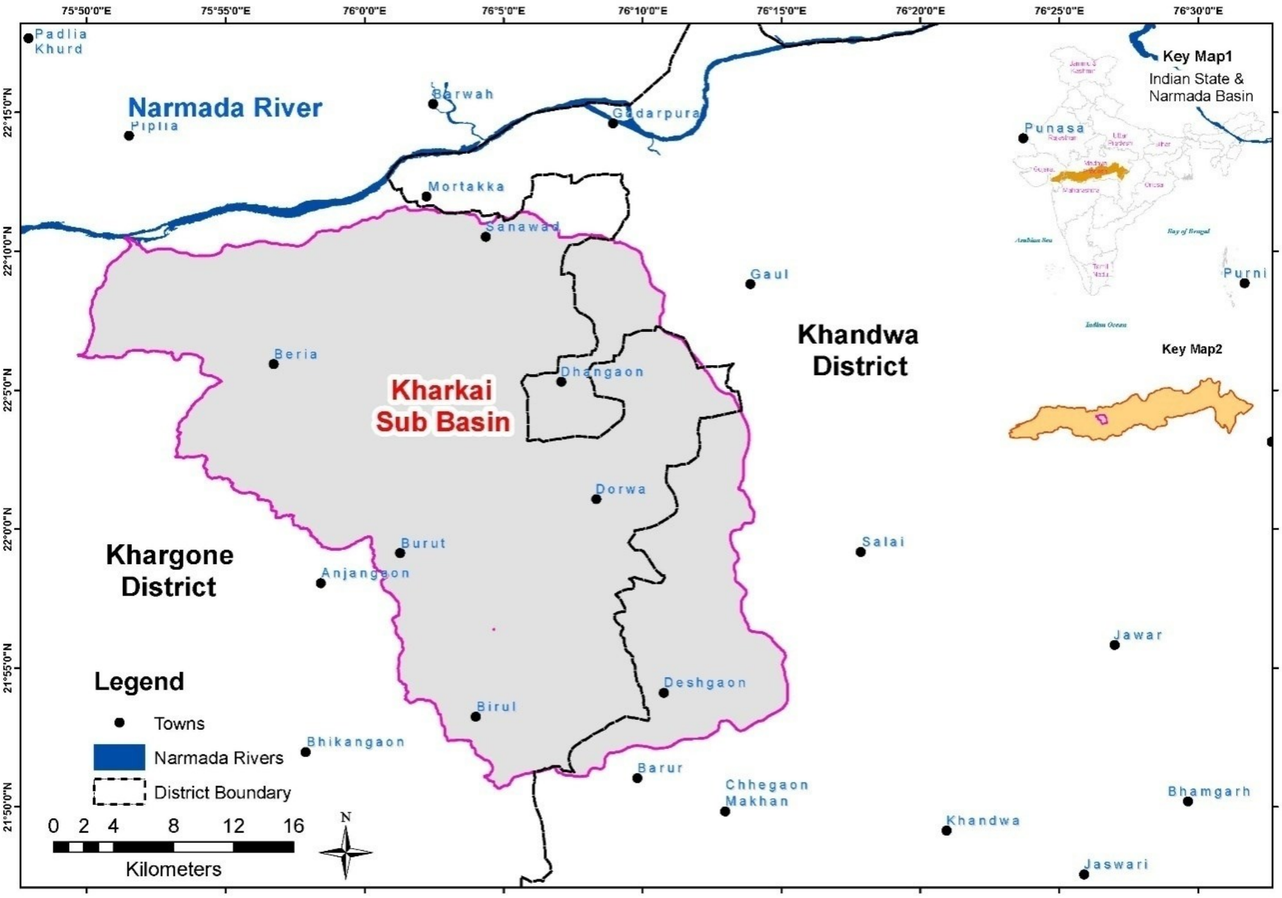

Figure 1. Location of Study Area

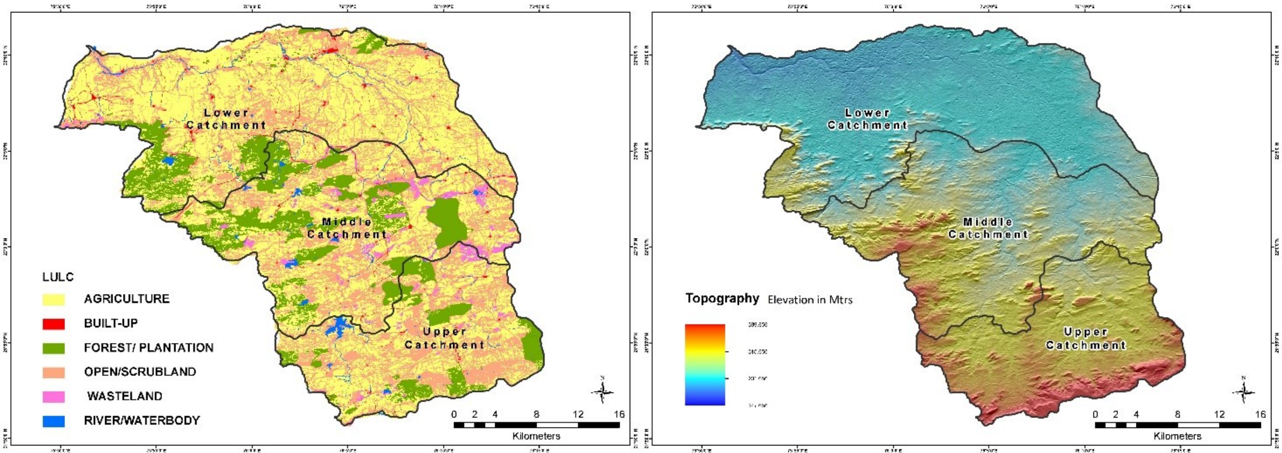

Figure 2. Land Use and Land Cover and Topography of Upper, Middle and Lower Catchments of Kharkai Sub Basin (Source: CartoDEM data and GeoEye MSS Images)

Table 1. Topographical and Land Use Characteristics of Kharkai Sub Basin

Catchments	Area sq. km	% of agricultural	%Forest/Scrubland	% of Natural Landscape	% of Modified Land Use	% of Others Land Use	Minimum Elevation (m)	Maximum Elevation (m)	Average Slope Degree
Lower Catchment	422	65%	31%	96%	2%	2%	148	312	2.8
Middle Catchment	335	64%	29%	93%	2%	5%	201	352	3.1
Upper Catchment	229	53%	43%	96%	1%	3%	242	400	2.9
Total/ Average	985	61%	34%	95%	1%	4%			

*Topographic slope and elevation are derived from CartoDEM

3. Reference Data Used

3.1 GCP Control Points

To obtain the sub meter accuracy in elevation, Ground Control Points (GCPs) established by Differential Global Position System (DGPS, GNSS), Real Time Kinematic (RTK)GPS, RTK enabled drone, airborne LIDAR, space borne LIDAR are the mostly used as observed data for assessing the accuracy of DEMs (Jain et al., 2018; Mouratidis et al., 2010; Pakoksung & Takagi,2016; Eckert et al., 2005; San &Suzen, 2005; Nikolakopoulos et al., 2006; Chirico et al., 2012; Mukherjee et al., 2012; Li P. et al.,2013; Rawat et al., 2013; Du et al., 2015).

For this study, an extensive network of ground control points (GCPs) was established with the help of dual frequency Differential Global Positioning System (DGPS) and supported with fly levelling method from known GTS Bench Marks of Survey of India (SOI) (Figure3). A GTS (Great Trigonometrical Survey) benchmarks are the permanently fixed reference survey control point, with known elevation with respect to a standard datum (mean sea level). GTS BM are established over India by the Survey of India department with highest precision.

All three DEM's elevation value was compared with GCPs collected using Double frequency DGPS Trimble equipment and GCP connected with GTS BM. There are many different methods to conduct the topographic survey for an irrigation project and each has its own advantage and limitation. It also depends on the time period available for the survey, cost of instrument and method of GCP survey (Ganesan, 2007).

3.2 Digital Elevation Model

3.2.1Shuttle Radar Topographic Mission (SRTM) Data

The very first version of SRTM-3 was made available by NASA-JPL (National Aeronautics and Space Administration-Jet Propulsion Laboratory) in 2003 and then in 2006 Version 3 of SRTM 3 was released by the CGIAR-CSI (Consultative Group of International Agricultural Research-Consortium for Spatial Information). Later in 2008, the CGIAR-CSI released improved Version 4 of SRTM 3. SRTM3 version4 is currently the best quality open-access DEM and is going to be assessed in this research. Although SRTM 30 was first released in 2003 for USA, it was after July 2015, the data is available for the other parts of the world. A detailed description of the data used is given in table2. The SRTM DEM is uses geographic coordinate system (GCS) with the WGS84 as horizontal datum and the EGM96 as vertical datum (Falorni et al., 2005).

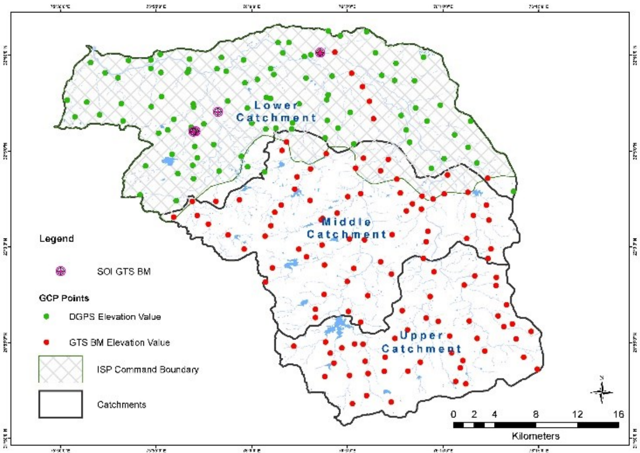

Figure 3. Distribution of, GTS BM, DGPS and Fly Levelling GCP

3.2.2 ALOS

Since 2014, the JAXA (Japan Aerospace Exploration Agency) has been developing the precise global digital 3D-30m **"ALOSWorld3D" (AW3D)** (Advanced Land Observing Satellite "DAICHI"(ALOS) having by PRISM panchromatic optical) covering the global land areas and released the AW3D30, DSM datasets with 30 meter GSD. The original datasets of e 0.15 arc sec (5 m) spacing available for commercial base, and 1arcsec (30 m) spacing are available for public. The current version of AW3D30 Ver 3.1 released in April 2020 is used in this study. The detailed description of the data used is given in Table2.

3.2.3 CartoDEM

CartoDEM is an Indian Region National DEM generated by the NRSC, ISRO from the Cartosat-1 stereo payload launched in May 2005 (Muralikrishnan et al., 2011). Augmented Stereo Strip Triangulation method (ASST) (Gupta et al., 2008) involving 500×27 km strip stereo-pairs using high precise ground control points, interactive cloud-masking, automatic dense conjugate pair generation using matching approach was used in CartoDEM generation (Radhika et al. 2007). The original output with a tile of 7.5′×7.5′ wide with DEM spacing of 1/3 arcsec is available on chargeable basis. However, the public data sets are available at 30m and 90m spacing which are generated by sub sampling the original 1/3 arcsec data (Muralikrishnan et al., 2013). The detailed description of the data used is given in Table2. It is to mention that though the horizontal resolution of resampling DEM's are the same, the original horizontal accuracy varies from 5 m to 20 m as given in Table 2. Moreover, the horizontal accuracy of DGPS and GTS measurement was less than centimetre as described in instruments and records of SOI. However, the position of DGPS and GTS was neither compared nor evaluated with any of the three DEMs, assuming the DGPS positions were within the 30 m sampling resolution of all three DEMs.

Table 2. Specifications of SRTM- 3.0, CartoDEM- 3.1 and AW3D30- 3.1 Data

	SRTM-3.0	**CartoDEM-3.1**	**AW3D30-3.1**
Acquisition Years	2000	2005	2006 to 2011
Released Years	2015	2015	2020
Agency	NASA	NRSC/ISRO	JAXA
Extent of Coverage	60deg N to 56deg S	8deg N to 39deg N and 60deg E to 98deg E	82deg N to 82deg S
Mission GSD	30 m	2.5 m	5m
Resampled Resolution	1" (30m)	1" (30m)	1" (30m)
Sensor	Shuttle Radar	PAN Stereo	PRISM
Method	InSAR	Stereo-strip Triangulation	Stereo matching
Absolute Vertical Accuracy	<9 m LE90)	<8m (LE90)	<5m (RMSE)
Reference to Vertical Accuracy	Farr et.al 2007 Rodriguez et al. 2006	Muralikrishnan, S. et.al., 2011	JAXA EORC. (2020)
Vertical Datum	EGM96	WGS84	EGM96
Absolute Horizontal Accuracy	20 m	15m	5m
Horizontal Datum	WGS84	WGS84	WGS84
Website	http://earthexplorer.usgs.gov/	https://bhuvan-app3.nrsc.gov.in/data	https://www.eorc.jaxa.jp/ALOS/en/aw3d30

4. Methods

4.1 Field Survey

High accuracy GCPs were collected on the grid of 5 km x 5km using dual-frequency base and rover (Trimble R4 receivers) (Photo1). The grid of 5 km was plotted and using the 0.5 m (IKONOS) high resolution satellite data GCP were selected within each grid. The criteria used in the selection of GCP were, it must be open to the sky, no high tension overhead electricity line, corner of permanent fencing or Hand pumps or other permanent features on the ground. The Base Station was established around known GTS BM of SOI and Fly levelling were carried out for level transfer from SOI GTS primary BM to the DGPS Base station to achieve the millimetre level accuracy consistence with existing BM available in current irrigation command. The Base Station was established 48 hours before the actual survey as reference. Other GCP's points were collected by the moving rover all over the sub basin and an Auto Level machine was put into action to transfer the elevation information from GTS to all other GCPs. Rover measurements were carried out for 40-45 minutes at each GCP with an epoch of 15 sec.The DGPS point collected in lower catchments were not connected with the primary GTS BM of SOI due to the existing irrigation command of ISP (Figure3). The GCPs were primarily established on the permanent feature on the ground such as culvert, canal crossing, road crossing, hand pumps, corner of fencing walls and man-made structures. Mukherjee et al. (2012) utilised the SOI-BM and Spot Height from SOI toposheet to validate and evaluate the CartoDEM and SRTM.

After collecting GCP points, data from the DGPS receivers (both base and rover) were downloaded and post processed with the use of differential correction method in post processing software. Then, post processed data converts into GIS format with the x, y value from DGPS processing and height information from Auto Level Fly Levelling. Total 215 GCP were collected out of which 119 GCP were connected with GTS BM elevation above MSL covering the upper and middle catchment of the sub Basin. GCP was used to extract the elevation value from each DEM under testing for determining the absolute vertical accuracy. Finally, the relative accuracy of the assessed DEMs was evaluated in terms of the elevation profile generated in each catchment within the sub basin of Kharkai.

4.1.1 Datum Conversion

The open DEM were downloaded from the authorised website as mentioned in Table2.In order to evaluate the elevation value of DEM under consideration with the referenced DGPS/GTS measurement, all the DEM and survey data should be in the same horizontal and vertical datum. Though the horizontal datum of DEM was under testing and field survey of DGPS was in WGS84, the SRTM30 and AW3D30 elevation value are based on Earth Gravitational Model (EGM96) datum while CartoDEM vertical height are reference with WGS84 datum. Therefore, CartoDEM height was determined by converting WGS84 datum measurement to EGM96to match the same vertical datum with the other two DEM for evaluation. The CartoDEM horizontal and vertical coordinates of each cell with WGS84 datum were first exported to asci file. Elevations were then transformed to ellipsoid heights relative to EGM96using a Geoid Height Calculator of the global EGM96 geopotential model jointly developed by the National Science Foundation and NASA and operated by UNAVCO (https://www.unavco.org/software/geodetic-utilities/geoid-height-calculator/geoid-height-calculator.html). The EGM96 heights in ASCII format were converted to raster geotiff format in ArcGIS and re-projected to the UTM coordinate system. Similarly, the SRTM and AW3D30 data were projected to UTM coordinate system from WGS84 with a cell size of 30 m. An EGM96 datum elevation measurement is considered to be a close approximation of MSL (Sun et al. 2003; Mukherjee et al. 2012). To determine the height of MSL following relationship between orthometric height (MSL), ellipsoidal height and geoid height is used:

$$H = h_{GPS/CartoDEM} - N \qquad (1)$$

where,
H= Orthometric height (Height above geoid ~ MSL)
$h_{GPS/CartoDEM}$= Ellipsoidal height (WGS84 datum)
N= Geoid Height/Geoid undulation (Geoid96/Geoid08).

Photo 1. Field Survey of DGPS and Double Fly Levelling

Elevation Accuracy Analysis

The absolute vertical errors of the DEMs were estimated by comparing individual test DEM elevations (*Zi*) and reference DGPS Elevation and referenced Automatic Level (Xi) at sample points (*i*) using the following metrics (Zhang et al., 2019; Höhle and Höhle, 2009; Wessel et al., 2018):

$$Error\ (E_e\ ) = Z_i - X_i \qquad (2)$$

$$Mean\ Error(ME) = \frac{1}{n}\sum_{i=0}^{n} Ee \qquad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_e\ )^2}{n}} \qquad (4)$$

$$Absolute\ Error\ at\ 90\%\ quantile\ LE90 = Q_{Ee(0.9)} \qquad (5)$$

Here,

E_e = elevation error

Z_i = elevation values of test DEM

X_i = Elevation value (elevation) of DGPS or Fly levelling

The E_e tells us whether a set of measurements consistently underestimate (negative E_e) or overestimate (positive E_e) the true/reference value. RMSE indicate an average deviation of observed values from the true value. The RMSE is a single estimates characterizing error surface, and the mean error reflects the bias of the error surface (Mukherjee et al., 2012). Linear error (LE90) is a generally accepted criterion for the evaluation of absolute elevation error of DEMs. It denotes the 90th percentile of DEM values in the group when arranged in ascending order.

For accuracy analysis, GCP measurements with and without GTS BM Elevation values were arranged and elevation values extracted from individual DEM were tested against the reference GCP. The main purpose of the study was to determine the absolute vertical accuracy of Open DEM with respect to DGPS and GTS measurement, therefore the relative accuracy was not estimated. Although the sub basin was delineated for three catchments viz, Upper, Middle and Lower, the accuracy assessment was performed on individual catchments due to the homogenous nature of the terrain and natural landscape.

5. Results

As per design sampling of GCPs, the field survey maintained the GCP collection at every 5 sq.km grid as indicated in figure4 in two delineated catchments, except middle catchment3 (5.23 sq.km). As it was found that the middle catchment is dominated with more forest cover compared to upper and lower catchment and average slope is 3.1 degree. Total 215 GCPs were collected, out of which 111 GCPs (52% of total GCP) belonging to upper and middle catchment, 8 GCPs in Lower Catchment and all were connected with GTS BM value by Double Levelling Method. The collected GCP data were sorted between DGPS derived elevation value (96 nos.) and GTS connected elevation value (119nos). The residual error and RMSE were estimated between DGPS derived value and GTS connected true elevation value. The mean error of +0.81mandRMSE of 2.66 m was observed between DGPS value and GTS value and about 80% of GCP dataset were within the residual error of +-1.5m. The LE (90) estimated to be 3.88m and about 66% DGPS measurement was found to be overestimated, indicating the DGPS derived elevation values always higher than true elevation value, i.e. GTS connected GCP.

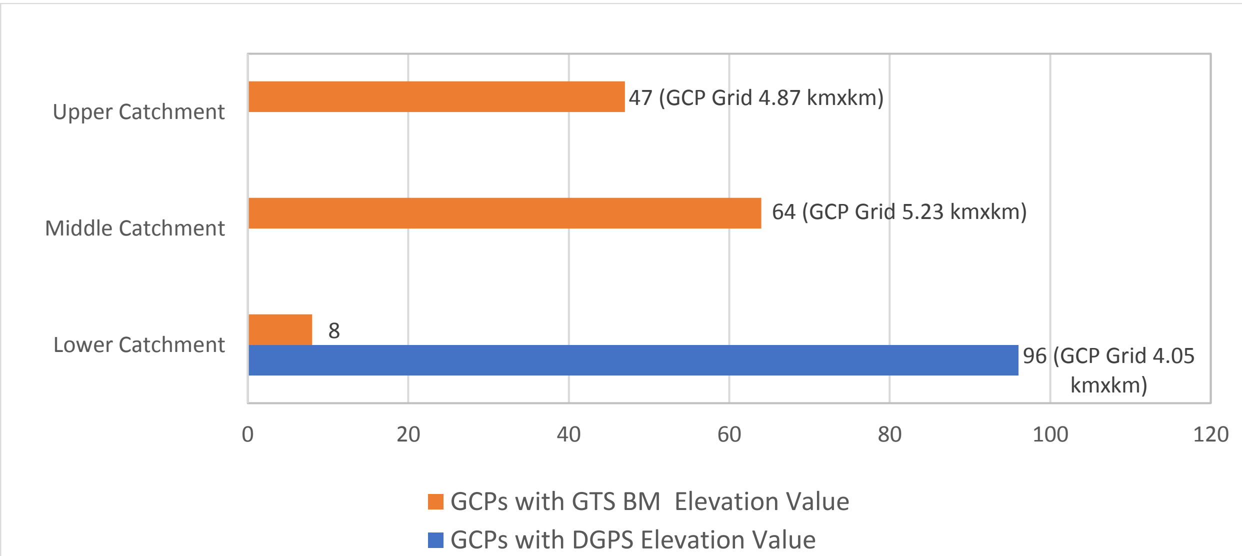

Figure 4.Catchmentwise GCPs with GTS BM and DGPS Elevation Value

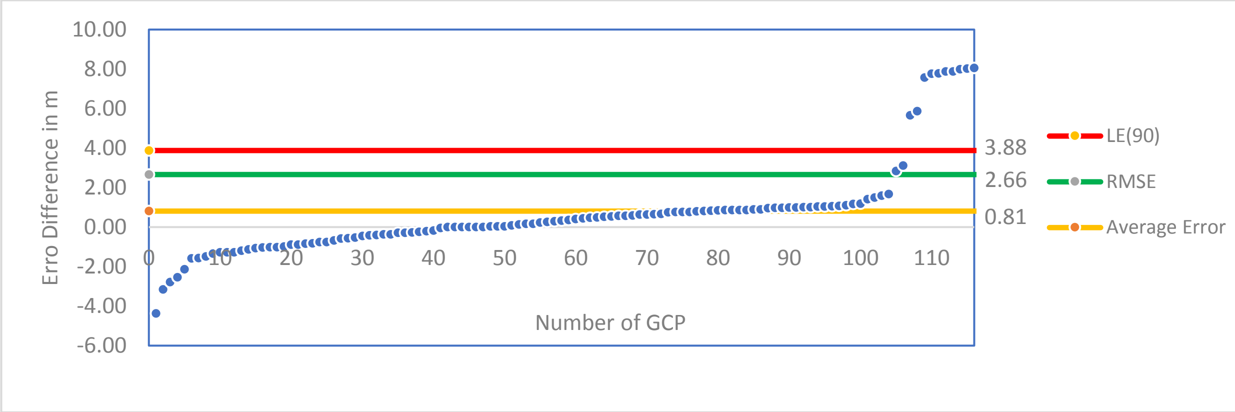

Figure 5. Residual plot of DGPS and GTS Elevation value for 116 GCPs in the sub basin

5.1 Satellite DEMvs GCPs Measurement-Absolute Accuracy

5.1.1 SRTM Vs GCP measurement

When compared with both types of GCP, the 95% confidence interval of SRTM DEM was found to be 7.55 m and -4.67 m for absolute vertical error at upper and lower limit respectively. The mean error, RMSE and LE (90) of SRTM residual error were found to be 1.44, 3.43 and 4.57. As per SRTM specifications, LE (90)is less than 16 m and relative vertical accuracy of less than 10 m, both expressed as a linear error at 90% confidence (Bamler, 1999). According to USGS, the absolute vertical accuracy is better than 9 m (Global Average), indicating that SRTM improved on its design goal of 16 m absolute by almost a factor of 2 (Farr et al., 2007). The present study reported LE (90) of 4.57, indicating a better result than the specification mentioned above.

About 44% of the SRTM dataset were within the error of +-2 m and 65% of the dataset were +-3 m. The histogram plot of residual error showed the positive biased of SRTM data since 83% of the SRTM values are overestimated (residual error greater than 0) and meagre 17% data points are underestimated (residual error less than equal 0) when compared with GCP measurement. All the accuracy indicators of the SRTM dataset are skewed to a positive scale, indicating the application of SRTM derived profile and related flood plain estimated can be overestimated with accuracy +-3.43 m height for plain areas to moderate hilly.

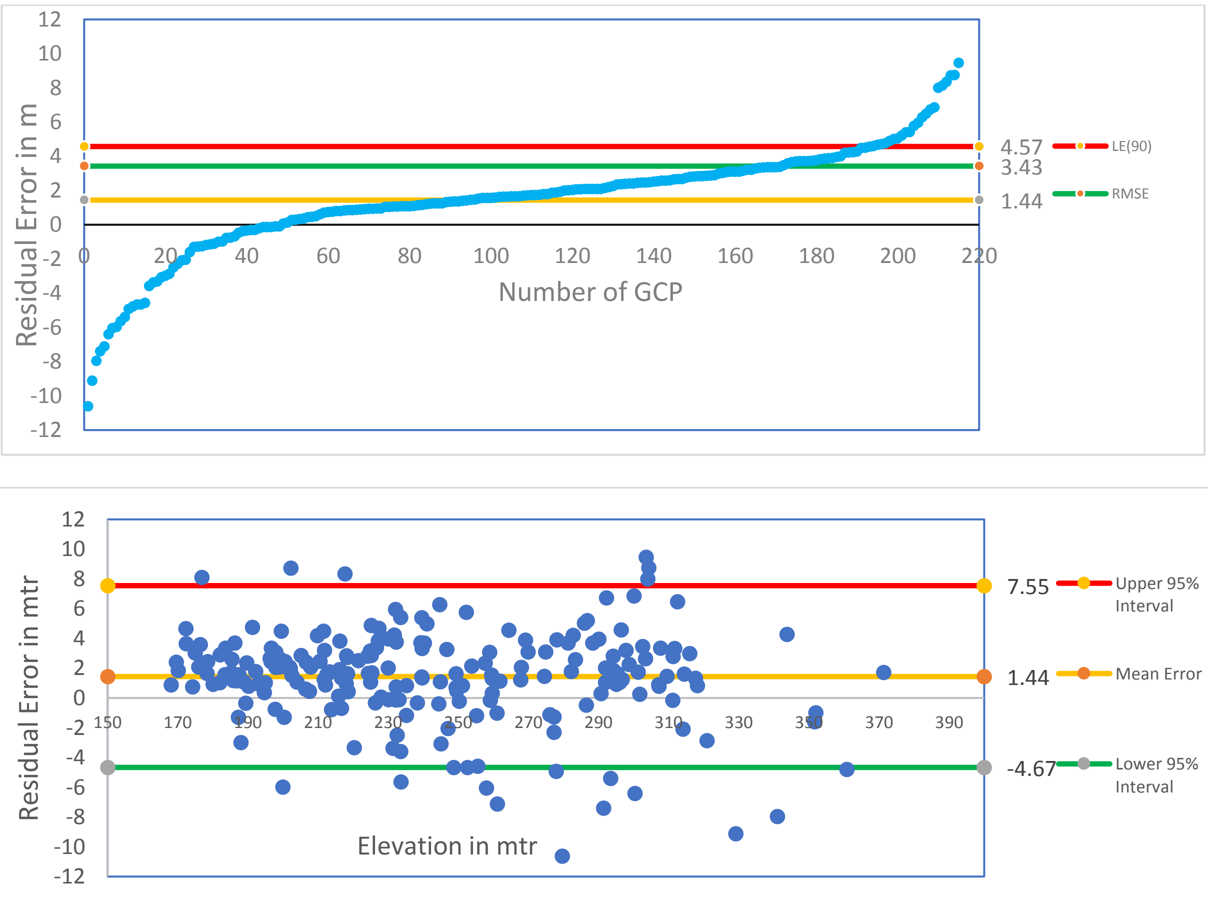

Figure 6. Residual plot of SRTM error compared with both types of GCP measurement

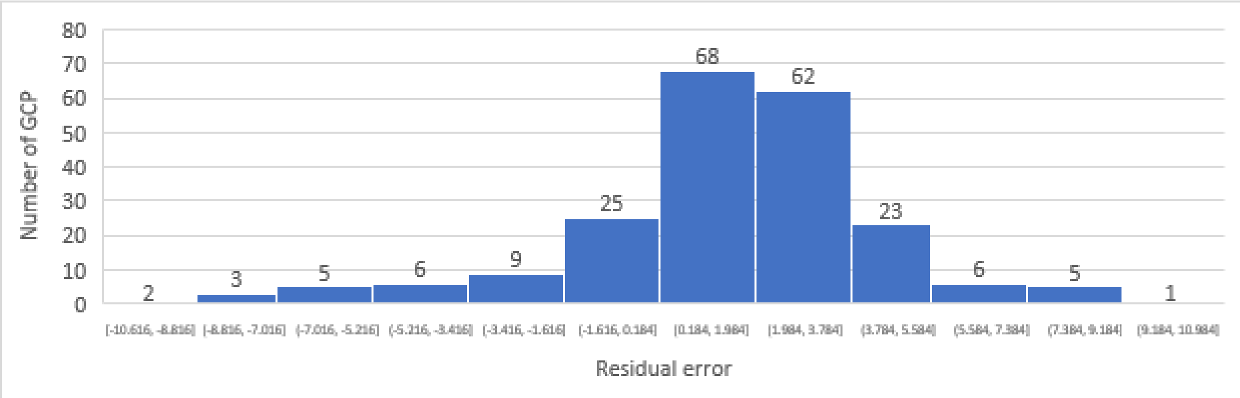

Figure 7. Histogram of residual error of SRTM data compared with GPS measurement

5.1.2 CartoDEMs GCP measurement

The absolute vertical accuracy error for CartoDEM was observed to be 6.88 m at the upper limit and -4.50 m at the lower limit at a 95% confidence interval (Figure8). Figure 8 indicated that 44% and 67% of the CartoDEM data points were within the error of +-2 m and +3 m, respectively. The positive values of CartoDEM data were due to the fact that 73% (residual error greater than 0) of the CartoDEM values are overestimated and 27% of data points are underestimated (residual error less than 0) when compared with GCP measurement (Figure9). The mean error, RMSE and LE (90) of CartoDEM were found to be 1.19, 3.13 and 4.19 m, respectively (Figure9). As per the specification of CartoDEM, the accuracy is 8m at LE90 and 15m at CE90 for data. The absolute height accuracy evaluation result shows in flat to hilly region (150 m to 650 MSL) of Alwar District in Rajasthan was 4.7m (RMSE) and LE90 of 7.3 for CartoDEM30 (Muralikrishnan et al., 2011). Accuracy of CARTOSAT DEM was evaluated at eight study sites spread over the Indian subcontinent ranging from low to mountains region and found RMSE of 1.61 m, and ME of -1.36 m for low slope terrain of Bhopal, Madhya Pradesh (Agrawal et al., 2020)

The accuracy of ICESat (V34) data was verified with respect to the CartoDEM V3R1, SRTM and ASTER DEMs over Kanpur and Unnao district located at the bank of Ganges at the plain region for about 400 points. The RMSE value of CartoDEM was varying 2.4m (fallow land) to 3.71 m (Built-up area) (Kumar et al., 2017). Another set of accuracy evaluations on the Lower Tapi Basin (very flat region less, slope 5 degrees) using 117 high accuracy ground control points (GCPs) reported the RMSE for SRTM, AW3D30, and CartoDEM-V3.1 were found to be 2.88m, 2.45m and 3.75m respectively (Jain et al., 2018). In all studies, the accuracy of CartoDEM is much better than design specification, but for flat/low terrain regions, the accuracy is much improved, as observed in the present study.

5.1.3 AW3D30 Vs GCP measurement

The absolute vertical error of AW3D30 data was observed to be 7.85 m at the upper limit and -2.80 m at the lower limit at a 95% confidence interval (Figure10). Figure 10 indicates about 22%, 44% and 69% of the AW3D30 data points were within the error of +-2 m, +3 m and +-4 m, respectively. When compared with GCP measurement, AW3D30 data points were overestimated for about 89% of data (residual error greater than 0) and 11% of data were underestimated (residual error less than 0). The mean error, RMSE and LE (90) of AW3D30 were found to be 2.52 m, 3.70mand 5.38 m, respectively Figure 10. The reported absolute vertical accuracy of AW3D30 is less than 5m RMSE (JAXA EORC 2020). A preliminary validation result of AW3D30, the absolute height accuracy of 4.40 m (RMSE) was confirmed from 5,121 Control Points distributed in 127 tiles (Tadono et al., 2016). The study presented by Caglar et al. (2018) provided similar values for RMSE ranging from 4.29 m (built-up areas) to 6.75 m (dense vegetation) based on the 274 reference points. Another study on accuracy assessments using a 307 509-measurement differential GPS dataset from the high-elevation, vegetation and cloud-free southern Central Andean Plateau (Punade Atacama) indicated the high quality of the SRTM-C, TanDEM-X, and ALOS World 3D-30m DEMs, achieved the mean residual of 2.18, -1.29, and 1.59 respectively (Purinton et al., 2017). In an independent study, the ME, SD, and RMSE of ALOS DEMs versus 5121 control points distributed uniformly on 127 image tiles were −0.44 m, 4.38 m, 4.40 m, respectively (Takaku et al., 2016). ME, SD, RMSE and LE90 of ALOS DEMs versus 95 DGPS control points distributed across flat coastal terrain of Hispaniola island was 0.92 m, 1.81 m, 2.08 m, 3.64 respectively (Zhang et al., 2019). Study on the vertical accuracy of the ALOS World 3D-30m DSM carried out using the runway method and longitudinal profile of 36 runways of the world shows AW3D30 is the most accurate DSM (Mean Difference of -0.78 m) compared with ASTER 2 (-3.6 m) and SRTM30 (-1.7) (Caglar et al., 2018). It is also comparable to the commercial product WorldDEM (RMSE 1.78 m vs 1.68 m).

For the present study area, AW3D30 data were overestimated compared to SRTM and CartoDEM (Figure 11).

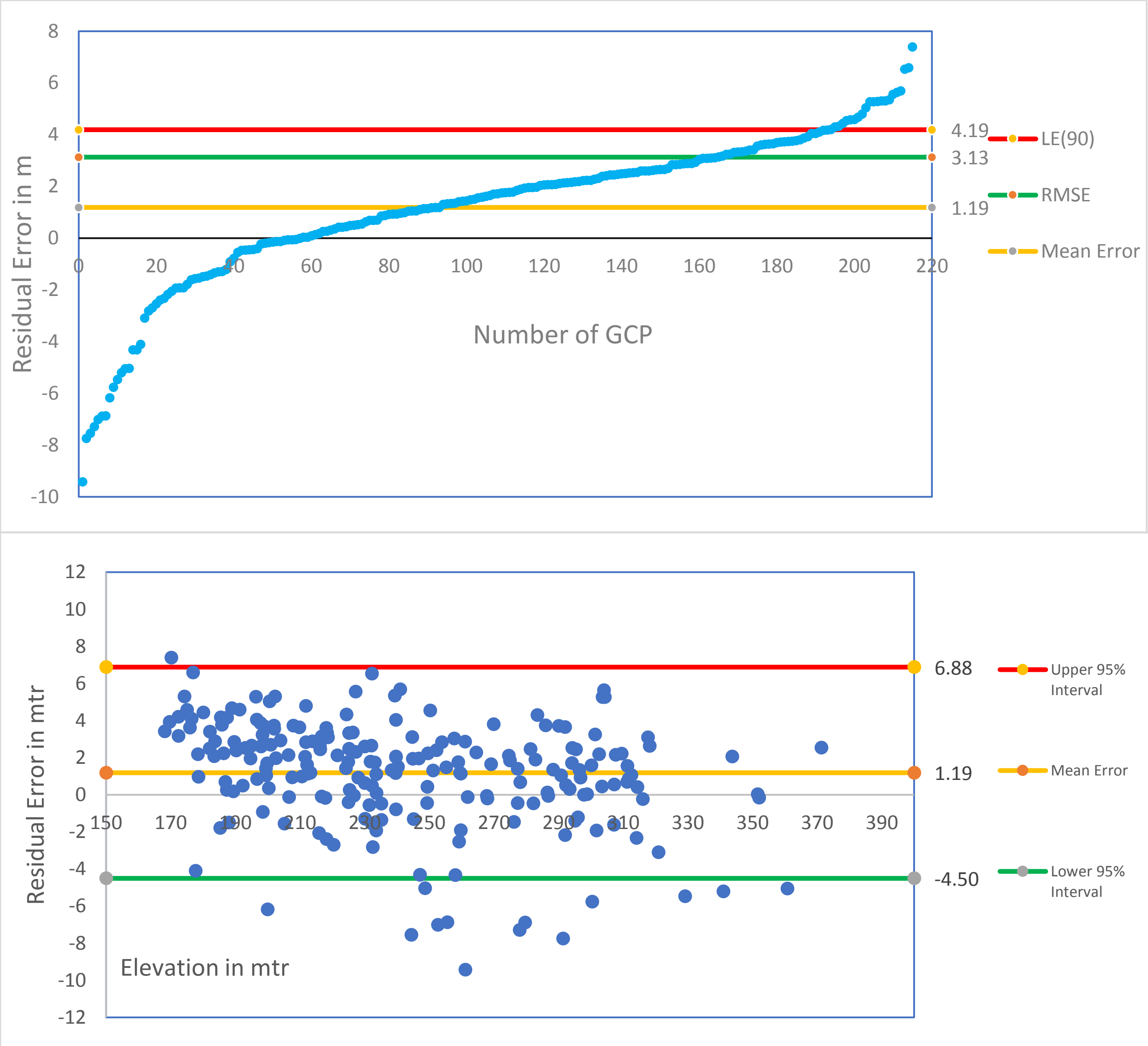

Figure 8. Residual plot of CartoDEM error compared with GCP measurement

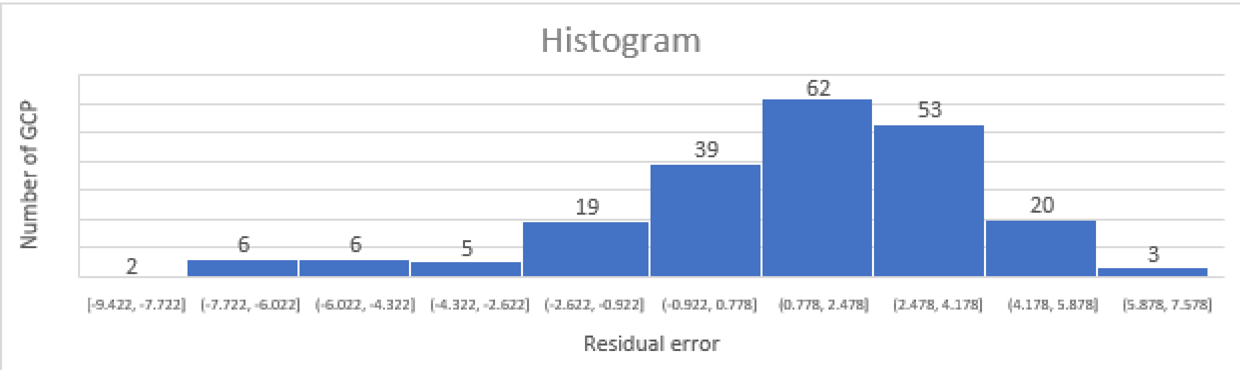

Figure 9. Histogram of residual error of CartoDEM data compared with GCP measurement

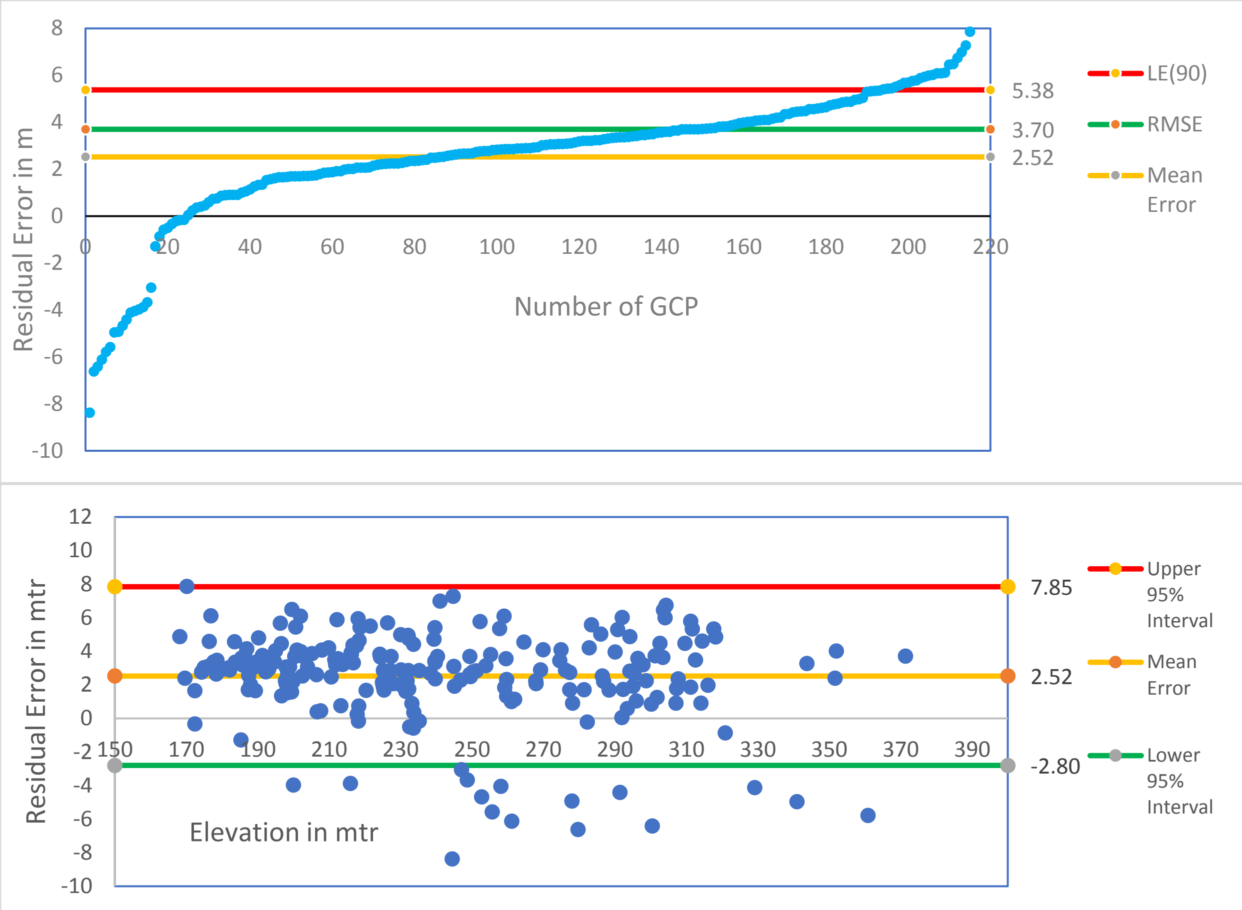

Figure 10. Residual plot of AW3D30 DEM error compared with GCP measurement

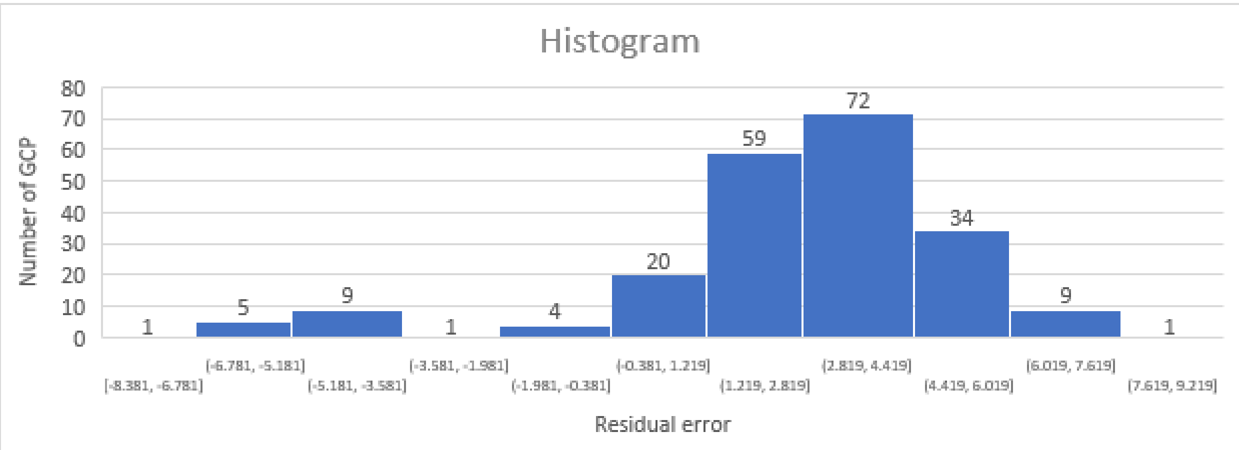

Figure 11. Histogram of residual error of AW3D30 data compared with GCP measurement

5.1.4 Overall Comparisons

The indicator of absolute vertical accuracy of DEMs (SRTM, CartoDEM and AW3D30) with reference to 96 DGPS and 119 GTS values were estimated and presented in Table 3. SRTM DEM indicated Mean Error of 2.13 m (DGPS values) and0.88 m with GTS values. Similarly, for CartoDEM and AW3D30 DEM, the ME was estimated to be 0.22 m and 1.87 m with GTS elevation value and 2.39 m and 3.33 m with DGPS elevation value, respectively. SRTM data was found to be more accurate than CartoDEM when compared with DGPS measurement. The ME is positive in both the GCP measurement for DEM under testing, indicating the SRTM, CartoDEM and AW3D30 DEM values are overestimated than actual measurement. However, the ME is very less in the case of the GTS elevation compared with DGPS elevation, this is due to the fact that GTS elevation values are far more accurate than DGPS elevation. The RMSE estimated were 2.82(DGPS)/3.84 (GTS) for SRTM, 3.15/3.11 for CartoDEM and 3.7/3.71 for AW3D30.The 90th percentile linear error (LE (90) of respective DEM value) was found to be 4.22/5.07 for SRTM, 4.62/3.62 for CartoDEM and 5.54/4.97 for AW3D30.However, the lowest value ME, RMSE and LE90 were found for SRTM DEM for GCP with DGPS Measurement.

Table 3. Statistical Comparision of Vertical Absolute Accuracy with the Ground Control Points (GCPs) for whole sub basin

Accuracy Measure	SRTM-C			CartoDEM			AW3D30		
	DGPS Derived Elevation	GTS Connected Elevation	DGPS+GTS	DGPS Derived Elevation	GTS Connected Elevation	DGPS +GTS	DGPS Derived Elevation	GTS Connected Elevation	DGPS+ GTS
Mean Error (ME),m	2.13	0.88	1.44	2.39	0.22	1.19	3.33	1.87	2.52
RMSE m	2.82	3.84	3.43	3.15	3.11	3.13	3.7	3.71	3.70
LE90 m	4.22	5.07	4.57	4.62	3.16	4.19	5.54	4.97	5.38

CartoDEM data is closer to GTS measurement and SRTM DEM data is closer to DGPS elevation measurement. ButAW3D30 data are overestimated than actual elevation value (DGPS Measurement) on the ground compared in comparison with SRTM and CartoDEM. All DEM reported overestimates the elevation value compared with GTS value and DGPS Value. However, DEM elevation values are found to be less overestimated (Positive) for GCP with GTS Elevation value. Rexer & Hirt (2014) and Satge et al. (2015) exhibits similar observation in their respective study areas. However, Zhao et al. (2011) and Li et al (2013) found a negative bias for SRTM in their research for a few region of China.

When compared with both types of GCP (DGPS+GTS), the lowest value of ME of 1.19, RMSE of 3.13 and LE90 of 4.19 was found for CartoDEM as compared to SRTM and AW3D30 DEM. Patel et.al. (2016) reported the CartoDEM RMSE of 3.49 when compared with SRTM 3.72 and concluded that CartoDEMis better performed than SRTM for the hilly region.

The smallest error in absolute vertical error in CartoDEM may be attributed to a very high horizontal resolution of CartoDEM(2.5 m Original GSD) compared to SRTM (30 m GSD) and AW3D30 (5m) DEM. Another reason for high performance may be attributed to homogeneous physical characteristics of the study area as 95% of land cover consist of natural cover with plain terrain (Jain et al., 2018). For the entire sub basin, CartoDEM has been found to be more accurate compared to SRTM and AW3D30 when comparing their RMSE values with respect to both types of GCP.

Moreover, all three DEMs' (SRTM, CartoDEM and AW3D30) absolute accuracy performance is far better than respective mission specifications on vertical accuracy (Rodriguez et al. 2006; Muralikrishnan et al. 2013; Takaku et al. 2014).It may be due to the homogenous nature of land cover within the sub basin and plain to moderate terrain slope. The mild to moderate slope and terrain did not have a significant effect on the elevation accuracy in the sub basin. The uncertainty and error in elevation can be due to the intrinsic nature of data collection (Stereo, SAR), processing (Resolutions, overlapping), method of DEM generation, validation process, algorithms used for edge matching and the number of scene (Jain et al., 2018; Li, 1992; Gong et al., 2000; Tate & Fisher, 2006; Merwade et al., 2008).

Many researchers found that the accuracy of all the DEMs degrades for terrain with slope greater than 10º. The slope of the terrain have a significant impact on accuracy of all the DTMs. Accuracy particularly improves on terrains with slope values less than 10° (Lorraine and Drew, 2009).Therefore, present research advised using of the public domain DEM/DTM for the plain to medium terrain with a slope of less than 5 degrees for a better and reliable outcome from modelling.

6. Conclusions

The CartoDEM estimated minimum error in elevation accuracy when compared with GTS connected GCPs in all accuracy indicators. However, SRTM data found minimum error, RMSE and LE (90) when compared with DGPS measurement. The CartoDEMis found to be more closed to the GTS value of elevation in the present study as compared to SRTM and AW3D30. The recently released AW3D30 data was comparatively less accurate and estimated large positive skewed value. The study concluded the use of CartoDEM for hydrology application in plain to hilly region provided the elevation values are converted to appropriate vertical datum, i.e. EGM96 which is a closed approximation to Mean Sea Level.

Regardless of what methodology approach is used, vertical datum alignment is a critical step. Before the start elevation accuracy assessment, the vertical datum of DEM and that of reference data must be checked. If the datums are different, adjustments to determine the differences should be made. A misalignment of the vertical datum can result in misleading conclusions.

7. Recommendations

Many engineers, managers and administrators are attracted to use the free and easily available DEM without paying attention to its accuracy and validation in their project during the feasibility and DPR preparation leading to inaccurate estimates. Therefore, it is imperative to assess the accuracy of DEM before its utilisation in any irrigation or water resource assessment. The present study recommends the use of publicly available DEM for hydrology, irrigation and water resource management with caution. The use of DEM for DPR preparation should be accompanied by a sufficient number of DGPS points and connected with Survey of India GTS BM to achieve the desired/recommended accuracy. However, open DEMs can be conveniently utilised for a feasibility study or general predication of flood, inundation mapping, river basin planning and watershed applications.

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