COMPARATIVE EVALUATION OF DIGITAL ELEVATION MODEL BASED ON ELEVATION DATA AND TERRAIN ATTRIBUTES LEADING TO THEIR VALIDATION

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ABSTRACT: Digital Elevation Model (DEM) is the 3D-representation of terrain surface in the discrete form and a standard tool to examine the hydrological and research application related to terrain characterization, landscape and water resources management. It helps in identifying physical features of an area, watershed delineation and stream network generation. However, several issues related to DEM's accuracy is the utmost concern for researchers. The present study is based on the comparative studies of DEMs viz., Cartosat-1, SRTM, ALOS and ASTER having the same spatial resolution of 30m each, under two different categories of elevation data and topographic attributes. The vertical accuracy of DEMs is examined by using ground control points as a reference level of elevation generated from topographic map. Analysing different sources of error in the DEMs, the RMSE and MAE based validation of elevation suggests that Cartosat-1 shows relatively high vertical accuracy (RMSE=45.2 & MAE=7.7) and ASTER shows the least (RMSE=60.5 & MAE=34.6). The grid size, spatial variation and vertical accuracy of DEM are among the prime attribute of data sources to determine the variation in basin morphometry. The study area shows a gradually undulating topography with 5th order drainage network. An inference can be made out of research study that the mean elevation values of ALOS, SRTM, Cartosat-1 are relatively lower than ASTER whereas differences in stream parameters are also observed. Mean bifurcation ratio value, which varies from 3.8-4.4, indicates that the area is structurally controlled.

1. Introduction:

Digital Elevation Model (DEM) is having the infinite sets of application in the areas of geomorphology, characterisation of watershed, ecology, surface runoff, modelling related to hydrology, soil erosion potential & agriculture etc. Significance of accurate DEM is mandatory to pursue advanced hydrologic research. Evaluating the comparison with different size of pixels' scale in DEM to generate stream network analysis and hydrologic models (Zhang & Montgomery, 1994). These streams facilitate the exact course of the channels and easy calculation of the stream order (Clarke & Burnett 2003).

The accuracy of DEM is largely dependent upon the source of DEM generation; the spaceborne DEMs or different methodologies which includes elevation data for the creation of DEM i.e. Triangulated Irregular Network (TIN), grid and contour. The essential requirements of DEM accuracy are mainly affected by the techniques of data collection, density and spacing of the sample points, break line in the horizontal scale, spatial resolution, location and topographical surfaces. TIN modelling, dense feature matching and automated strip mosaicing are used for DEM generation through GCPs (Muralikrishnan, 2006). The accuracy of DEM at any particular location is estimated through different error statistical parameters globally, viz; Root Mean Square Error (RMSE) Mean Absolute Error (MAE) and Standard Deviation (SD). Evaluation of DEM accuracy to minimize the impact of errors and voids is critical for improving the quality of posterity of DEM used globally. The horizontal control over the area is specified by X and Y whereas Z is derived from vertical control. The vertical accuracy of the satellite DEM is affected by terrain relief and vegetation type. Recently several researchers (viz., Thomas *et al.* 2014; Thomas & Prasannakumar, 2015 Elkhrachy, 2017) compared the vertical accuracy of SRTM-DEM & ASTER-DEM. Santillan *et al.* (2016) on their project based on the calculation of RMSE obtained after comparing ALOS-DSM with 274 different GCP distributed on five different LULC classes.

The major objective of the research work is to study the different attributes and compared to examine the accuracy and quality of DEMs obtained from two different sources of the satellite: 1) Optical satellite data-(a) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER Global GDEM Version2; (b) Cartosat-1 DEM, 2) Microwave satellite data-(a) Shuttle Radar Topographic Mission (SRTM); (b) Advanced Land Observing Satellite ALOS World 3D (AW3D30). The prime objective of the paper is to compare different DEMs based on - (1) Elevation attributes, in which accuracy is based on interpretation of DEMs includes a comparison of elevation values, mean values, Mean Absolute Error, Root Mean Square Error, Standard Deviation, and (2) Terrain attribute, which includes the comparison of stream network and areal analysis of DEMs.

2. Study Area:

The Asan River watershed is situated in Dehradun district, Uttarakhand State, India. The area geographically lying between 30°14' 14" N to 30°29' 54" N latitude and 77° 39' 42" E to 78° 05' 30" E longitude. Asan River is the tributary of Yamuna River flowing in the northwest of Doon valley and later joins the Yamuna River at Dhalipur. The origin point of the Asan River is from Chandrbani (spring water) in Dehradun city. This perennial river is flowing through the central portion of the area from south-west to north-east direction. The location map of the watershed is given in Figure 1. Asan is a perennial River form one of the prominent watersheds in Doon Valley at foothills of Siwalik ranges.

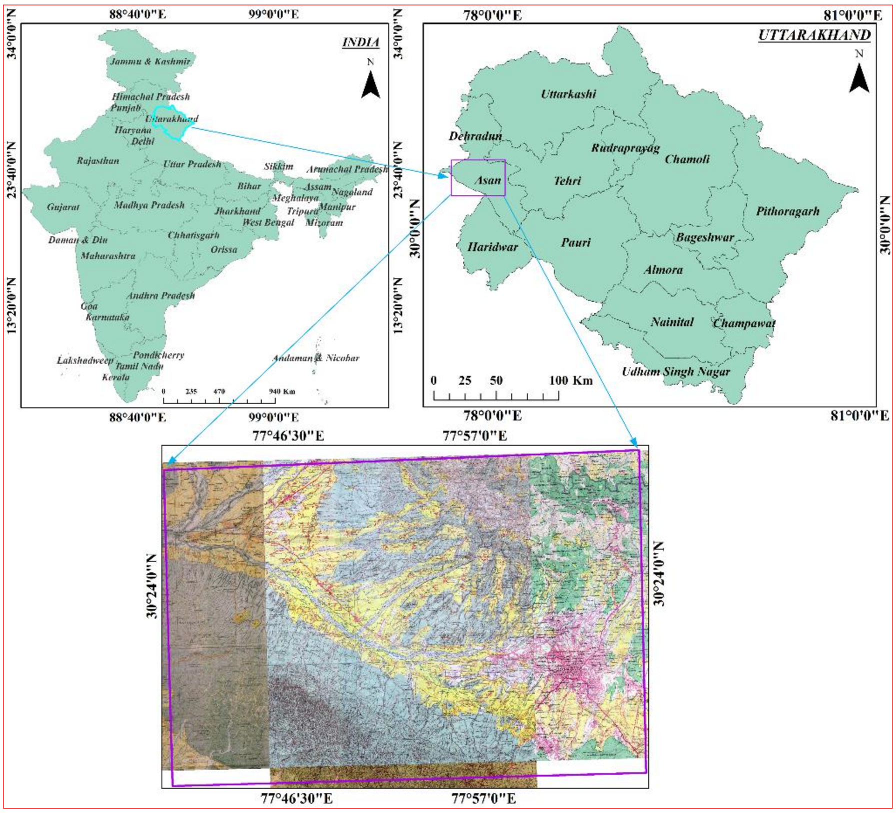
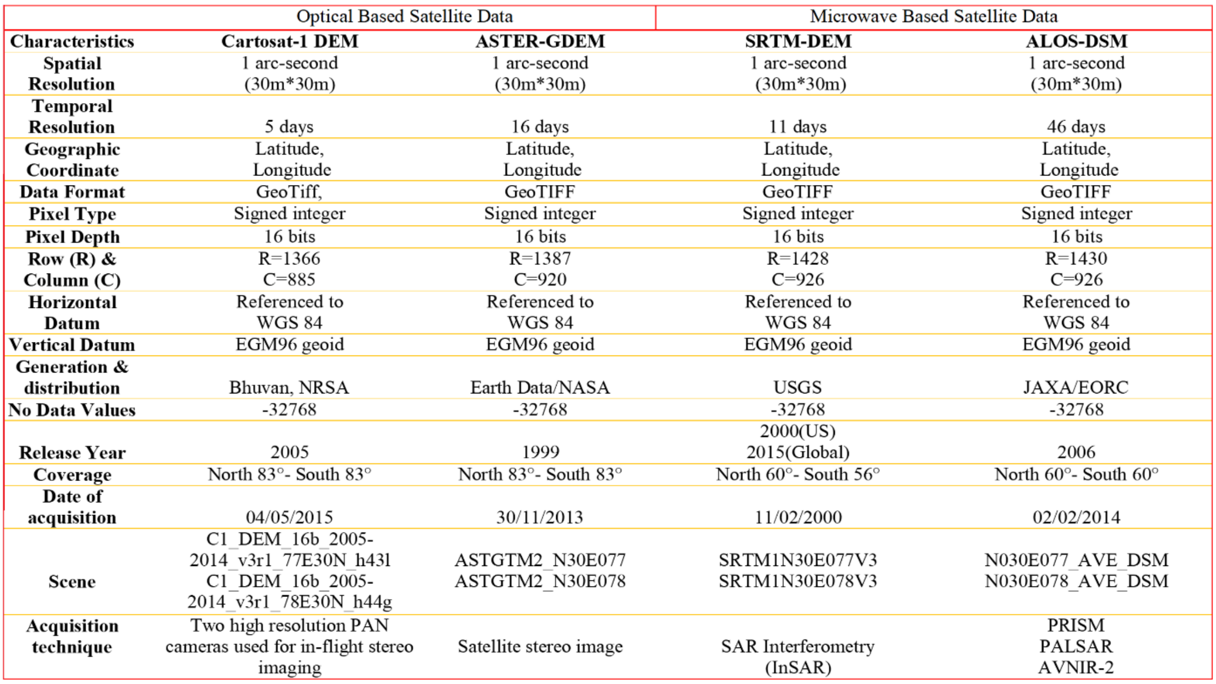


Figure 1: Study area of the Asan River Watershed

3. Methodology:

Comparative study of DEMs is carried out by determining the accuracy through elevation data, stream-based analysis and terrain derivative approach. The DEMs used for the present study are reprojected to Universal Transverse Mercator (UTM) zone 43 projection for analysis. Table 1 provides details about ortho-data and meta-information of DEMs. The use of topographic map (SoI toposheets) 53F/11, 53F/15, 53F /16, 53J/3 with RF- 1:50,000 are scanned in TIFF format, georeferenced and mosaic to real map coordinate system. The Ground Control Points (GCPs) may consider as the significant component of establishing an accurate relationship with DEMs. During fieldwork, GCPs are selected on the known location of the study area where ground coordinates i.e. Longitude and Latitude are specifying in X and Y (respectively) whereas Z coordinates indicate elevation. In the study, various landmarks and spot heights are used as GCP. For streams based analysis, the delineation of the watershed is done by using HEC-GeoHMS extension in ArcGIS v 10.3. Area and perimeter of the watershed are calculated separately and compared thereafter. Identification of minimum and maximum elevation points and the accuracy from DEMs are calculated and compared by using different error statistics.

Table 1: The characteristics of Cartosat, ASTER, ALOS and SRTM



	Optical Based Satellite Data		Microwave Based Satellite Data	
Characteristics	**Cartosat-1 DEM**	**ASTER-GDEM**	**SRTM-DEM**	**ALOS-DSM**
Spatial Resolution	1 arc-second (30m*30m)	1 arc-second (30m*30m)	1 arc-second (30m*30m)	1 arc-second (30m*30m)
Temporal Resolution	5 days	16 days	11 days	46 days
Geographic Coordinate	Latitude, Longitude	Latitude, Longitude	Latitude, Longitude	Latitude, Longitude
Data Format	GeoTiff,	GeoTIFF	GeoTIFF	GeoTIFF
Pixel Type	Signed integer	Signed integer	Signed integer	Signed integer
Pixel Depth	16 bits	16 bits	16 bits	16 bits
Row (R) & Column (C)	R=1366 C=885	R=1387 C=920	R=1428 C=926	R=1430 C=926
Horizontal Datum	Referenced to WGS 84	Referenced to WGS 84	Referenced to WGS 84	Referenced to WGS 84
Vertical Datum	EGM96 geoid	EGM96 geoid	EGM96 geoid	EGM96 geoid
Generation & distribution	Bhuvan, NRSA	Earth Data/NASA	USGS	JAXA/EORC
No Data Values	-32768	-32768	-32768	-32768
Release Year	2005	1999	2000(US) 2015(Global)	2006
Coverage	North 83°- South 83°	North 83°- South 83°	North 60°- South 56°	North 60°- South 60°
Date of acquisition	04/05/2015	30/11/2013	11/02/2000	02/02/2014
Scene	C1_DEM_16b_2005-2014_v3r1_77E30N_h43l C1_DEM_16b_2005-2014_v3r1_78E30N_h44g	ASTGTM2_N30E077 ASTGTM2_N30E078	SRTM1N30E077V3 SRTM1N30E078V3	N030E077_AVE_DSM N030E078_AVE_DSM
Acquisition technique	Two high resolution PAN cameras used for in-flight stereo imaging	Satellite stereo image	SAR Interferometry (InSAR)	PRISM PALSAR AVNIR-2

4. Result and Discussion:

4.1. Appraisal of Dem Accuracy:

The comparison among DEMs concerning reference elevation data is assessed to determine the vertical accuracy. In the first part of the objective, the evaluation of vertical accuracy through comparing the ground measured elevation values generated through DEMs at 20 locations against the spot height/landmarks present in topographic maps are digitized. The stratified random sampling method is adopted for the collection of elevation point into the watershed (Table 2). To compare and describe the accuracy of elevation values as errors, the difference between the DEM generated elevation values and reference spot heights/landmark data are evaluated using the following Equation 1:

$$\mathbf{Z_{error} = Z_{DEM} - Z_{reference}} \tag{1}$$

In which, Z_{error} = represent errors in elevation values; Z_{DEM} = represent elevation generated from different location in DEM; $Z_{reference}$ = represent reference spot heights / landmark elevation data.

The Z_{error} represent positive or negative values, positive difference represents the location where reference elevation data are preceded by DEM based elevation data and vice versa (Fugara, 2015). This universal approach which is extensively adopted by researchers around the globe to investigate the error statistics present in the elevation data is: Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Standard Deviation (SD) (Equation 2, 3 & 4). These statistics help in estimating the variation between elevations data originated from two different sources. These mathematical equations have been adopted since the late 1970s.

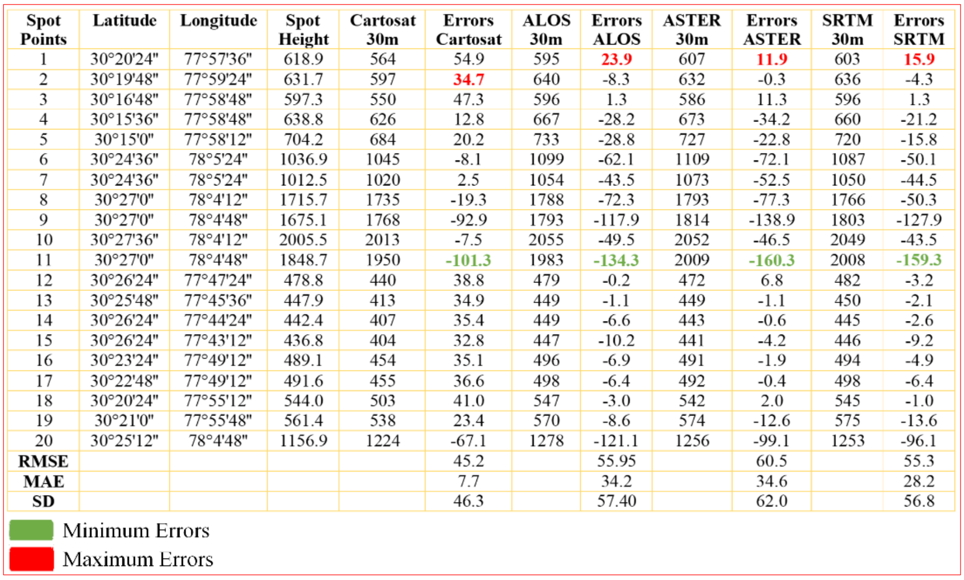
$$MAE = \frac{1}{n}\sum_{t=1}^{n}(REE_t - DEM_t) \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(REE_t - DEM_t)^2} \tag{3}$$

$$SD = \pm\sqrt{\frac{1}{n-1}\sum_{t=1}^{n}(REE_t - DEM_t)^2} \tag{4}$$

where, 'REE_t' represents the reference spot height/landmark elevation data of the 't^{th}' location, 'DEM_t' represents the DEM generated elevation data of 't^{th}' location, 'REE' represents mean of 20 reference spot height/landmark elevation data of all locations and 'n' is the total number of sample locations. The differences in vertical accuracies of satellite DEM data is correspondent to terrain complexity (Thomas *et al.* 2014).

Table 2: The coordinate of elevation data points with corresponding error's estimation



Spot Points	Latitude	Longitude	Spot Height	Cartosat 30m	Errors Cartosat	ALOS 30m	Errors ALOS	ASTER 30m	Errors ASTER	SRTM 30m	Errors SRTM
1	30°20'24"	77°57'36"	618.9	564	54.9	595	**23.9**	607	**11.9**	603	**15.9**
2	30°19'48"	77°59'24"	631.7	597	**34.7**	640	-8.3	632	-0.3	636	-4.3
3	30°16'48"	77°58'48"	597.3	550	47.3	596	1.3	586	11.3	596	1.3
4	30°15'36"	77°58'48"	638.8	626	12.8	667	-28.2	673	-34.2	660	-21.2
5	30°15'0"	77°58'12"	704.2	684	20.2	733	-28.8	727	-22.8	720	-15.8
6	30°24'36"	78°5'24"	1036.9	1045	-8.1	1099	-62.1	1109	-72.1	1087	-50.1
7	30°24'36"	78°5'24"	1012.5	1020	2.5	1054	-43.5	1073	-52.5	1050	-44.5
8	30°27'0"	78°4'12"	1715.7	1735	-19.3	1788	-72.3	1793	-77.3	1766	-50.3
9	30°27'0"	78°4'48"	1675.1	1768	-92.9	1793	-117.9	1814	-138.9	1803	-127.9
10	30°27'36"	78°4'12"	2005.5	2013	-7.5	2055	-49.5	2052	-46.5	2049	-43.5
11	30°27'0"	78°4'48"	1848.7	1950	**-101.3**	1983	**-134.3**	2009	**-160.3**	2008	**-159.3**
12	30°26'24"	77°47'24"	478.8	440	38.8	479	-0.2	472	6.8	482	-3.2
13	30°25'48"	77°45'36"	447.9	413	34.9	449	-1.1	449	-1.1	450	-2.1
14	30°26'24"	77°44'24"	442.4	407	35.4	449	-6.6	443	-0.6	445	-2.6
15	30°26'24"	77°43'12"	436.8	404	32.8	447	-10.2	441	-4.2	446	-9.2
16	30°23'24"	77°49'12"	489.1	454	35.1	496	-6.9	491	-1.9	494	-4.9
17	30°22'48"	77°49'12"	491.6	455	36.6	498	-6.4	492	-0.4	498	-6.4
18	30°20'24"	77°55'12"	544.0	503	41.0	547	-3.0	542	2.0	545	-1.0
19	30°21'0"	77°55'48"	561.4	538	23.4	570	-8.6	574	-12.6	575	-13.6
20	30°25'12"	78°4'48"	1156.9	1224	-67.1	1278	-121.1	1256	-99.1	1253	-96.1
RMSE					45.2		55.95		60.5		55.3
MAE					7.7		34.2		34.6		28.2
SD					46.3		57.40		62.0		56.8

🟩 Minimum Errors

🟥 Maximum Errors

4.2. Comparison of terrain attributes:

4.2.1. Elevation:

DEM plays a critical role to analyse the landscape and in the characterisation of the topography within the watershed. The maximum and minimum elevation of different DEMs are acquired through ArcGIS v. 10.3 for the study area (Figure 2b).

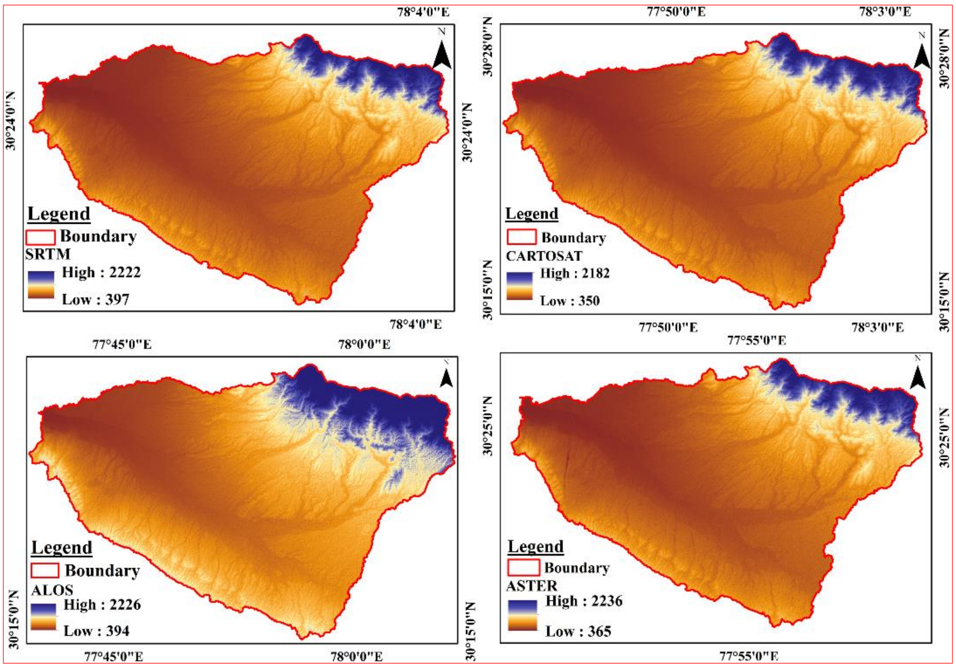


Figure 2: Comparison of different DEMs based on their respected maximum and minimum elevation and variation in the shape of the watershed boundary.

Cartosat-1 has the minimum elevation of 350m whereas ASTER, ALOS and SRTM shows 365, 394 and 397m above MSL respectively. ASTER shows the maximum elevation of 2236 followed by ALOS, SRTM and Cartosat-1 of 2226, 2222 and 2182m above MSL respectively (Table-3). Among DEMs, the value of mean elevation in the study area derived from ASTER is comparatively maximum. Because of contrasting terrain setting the distribution of elevation significantly differ. The purple and brown colour represents the hilly and the low-lying portion (respectively) of the study area (Figure 2).

Table 3: Comparison based on statistics of point elevation from different DEMs

Optical Satellite Data				**Microwave Satellite Data**			
Elevation (m)							
Cartosat-DEM		ASTER-DEM		SRTM-DEM		ALOS-DEM	
Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
350	2182	365	2236	397	2222	394	2226
Mean		**Mean**		**Mean**		**Mean**	
675.5		713.3		709.4		709.8	

4.2.2. Slope:

For hydrological and geomorphological analysis, the slope is the most important terrain attribute. Slope measures the steepness of the surface (in degrees or percent rise) at any particular location (Ballabh, 2008). The slope distribution maps (in degrees) of the watershed has been derived DEMs used in the present study (Figure 3).

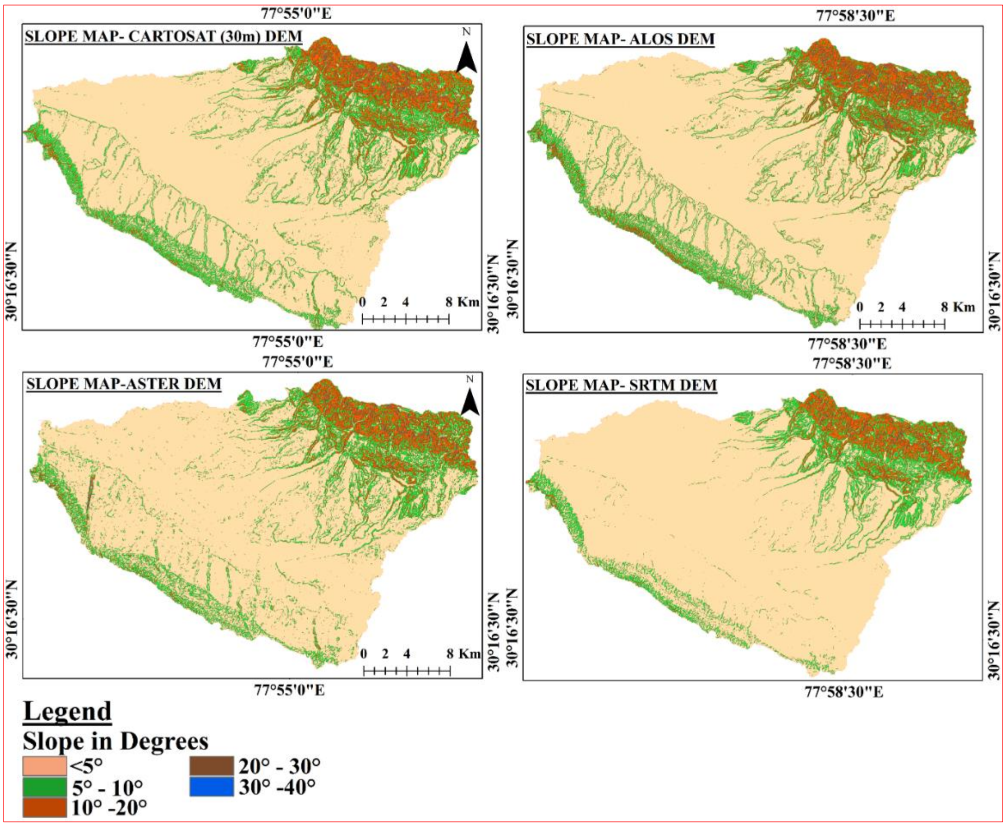


Figure 3: Slope map of the respective DEMs

The areal coverage of different slope classes for all of the DEMs are divided into Gentle (<5°), Moderate (5°-10°), Moderate steep (10°-20°), Steep (20°-30°), Very Steep (30°-40°)**.** The observed classes and values represent the slope of an area is <5°~Gentle Class for DEMs. The areal coverage of different slope classes is nearly uniform for the ASTER and Cartosat-1 of 74.6% and 73.4% respectively. SRTM shows overestimated areal coverage within <5° (about 81%) whereas ALOS shows the least of 70.8% of areal coverage.

4.3. Stream Network Analysis:

The stream generated through different DEMs in the study, facilitate with the exact course of the channels and easy calculation of stream order (Clarke & Burnett 2003). In the present study, a comparison of different morphological attributes derived which includes a comparison of stream network obtained from different DEMs having common spatial resolution and stream threshold shown in Figure 4.

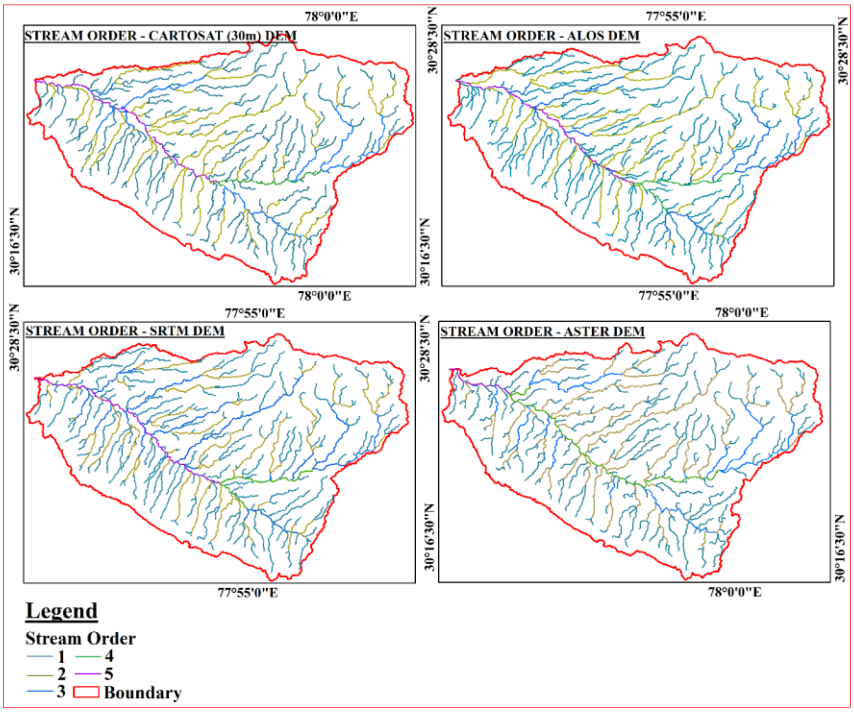


Figure 4: Drainage map derived from Cartosat-1, ASTER, SRTM, ALOS shows a variation in channel network along with watershed boundary.

The total number, length and order of streams is dependent upon the stream threshold. In contrary, it also represents the minimum upstream drainage area. In the present study, the threshold of 0.96 Km^2 or 1000 cells is applied for all the DEMs for the generation of 5th ordered stream network. The derived stream order is adopted after Strahler (1957). The number of streams generated through ALOS and Cartosat-1 shows the minimum and the maximum number of streams of different orders respectively (ALOS<ASTER<ASTER<Cartosat-1). However, while comparing the length of streams, ASTER shows minimum stream length and SRTM shows the maximum. (ASTER>Cartosat-1>ALOS>SRTM). The 5th order stream of the ASTER shows a larger deviation of least stream length while Cartosat-1 shows the longest. Variability in total stream length for each order seen in Table 4 and 5.

Table 4: Order-wise characteristics of streams from Cartosat-1 & ASTER

Optical Based Satellite Sensory Data											
		Cartosat-DEM					ASTER-DEM				
S.N.	**Stream Order**	**Stream Number**	**Stream Length**	**Mean Stream Length**	**Stream Length Ratio**	**Bifurcation ratio**	**Stream Number**	**Stream Length**	**Mean Stream Length**	**Stream Length Ratio**	**Bifurcation ratio**
1.	I	182	397.06	2.18	-	-	197	372.17	1.88	-	-
2.	II	46	204.20	4.43	2.03	3.95	51	200.30	3.92	2.08	3.8
3.	III	10	68.01	6.8	1.53	4.6	12	81.50	6.79	1.73	4.3
4.	IV	2	15.78	7.89	1.16	5	2	36.24	18.12	2.66	6
5.	V	1	28.43	28.43	3.60	2	1	8.56	8.56	0.48	2
Total		**309**	**713.48**	**49.73**	**8.32**	**15.55**	**263**	**698.77**	**39.27**	**6.95**	**16.2**
		Mean Bifurcation ratio				**3.8**	**Mean Bifurcation ratio**				**4.1**

Table 5: Order-wise characteristics of streams from SRTM & ALOS

		Microwave Based Satellite Sensory Data									
		SRTM-DEM					ALOS-DEM				
S.N.	**Stream Order**	**Stream Number**	**Stream Length**	**Mean Stream Length**	**Stream Length Ratio**	**Bifurcation ratio**	**Stream Number**	**Stream Length**	**Mean Stream Length**	**Stream Length Ratio**	**Bifurcation ratio**
1.	I	213	426.2	2.0	-	-	188	459.97	2.44	-	-
2.	II	57	187.7	3.3	1.6	3.7	45	198.28	4.40	1.80	4.2
3.	III	17	106.5	6.3	1.9	3.4	12	62.55	5.21	1.84	3.7
4.	IV	2	17.9	8.9	1.4	8.5	2	18.98	9.49	1.82	6
5.	V	1	29.5	29.5	3.3	2	1	26.96	26.96	2.84	2
Total		**290**	**767.73**	**50**	**8.2**	**17.6**	**248**	**766.74**	**48.5**	**8.3**	**15.9**
		Mean Bifurcation ratio				**4.4**	**Mean Bifurcation ratio**				**3.9**

The structural organization of the stream network is defined as a Bifurcation ratio (R_b). It is a network composition parameter given by Strahler in 1958. In the present study, the minimum and maximum values of 'R_b' ranges from 2-8.5 for SRTM, 2-5 for Cartosat-1, 2-4.3 for ASTER and 2-4.2 for ALOS (Table 4 and 5). The minimum value of 'R_b' relates to the flat region and indicates less structurally disturbed area whereas maximum value shows the influence of the structurally controlled formation of drainage pattern (Horton, 1945).

The Mean bifurcation ratio (R_{bm}) of mountainous and dissected regions is more than the basin with flat and rolling surfaces (Horton, 1945). Further, 'R_{bm}' derived from different DEMs does not show maximum deviations but in general, SRTM (R_{bm}=4.4) has a better agreement (Table 5; Figure 5a) than Cartosat-1 which shows the least (R_{bm}=3.8) (Table 4; Figure 5a). The value greater than 3.0 indicates strong structural control/structural distortions (Strahler, 1957).

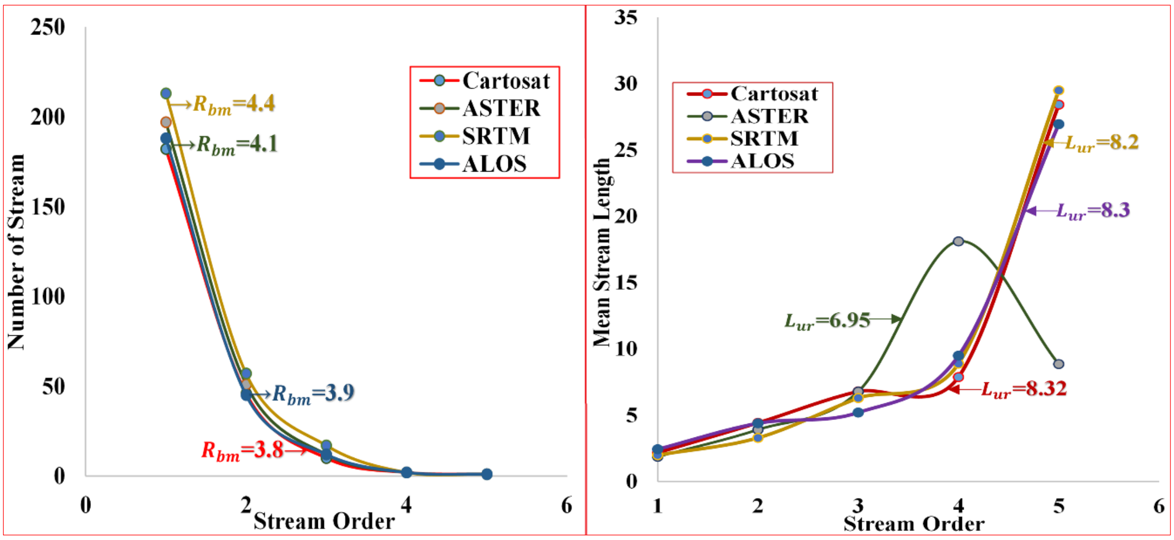


Figure 5: (a) Graph shows the relationship between Number of streams (N_u) vs Stream Order (S_u) with Mean Bifurcation Ratio (R_{bm}) & **(b)** Graph shows the relationship between Mean Stream Length (L_{um}) vs Stream Order (S_u) with Stream Length Ratio (L_{ur}).

Stream Length Ratio (L_{ur}) is the ratio of Mean stream length (L_{um}) of particular stream order (S_u) and the Mean stream length (L_{um}) of its next lower order (L_{um}-1) (Horton, 1945). It is obtained from DEMs exhibits less variation except for ASTER, but in general Cartosat-1 and ALOS show the similar value of (L_{ur}=8.3) while L_{ur} derived from ASTER show remarkable deviation (L_{ur}=6.95) as shown in Figure 5 (b).

4.4. Areal Analysis:

The total area of the watershed generated from ALOS is maximum and minimum for ASTER (ALOS>SRTM>ASTER>Cartosat-1). The perimeter of the watershed is maximum for ASTER while the minimum for Cartosat-1 (ASTER>ALOS>SRTM>Cartosat-1). The difference in an area together with perimeter found to be more in Cartosat-1 (Table 6). According to Schumm (1956), "the basin length is the longest dimension of the basin parallel to the principal drainage line". Table 6 shows basin length generated from ALOS is least, maximum for ASTER and equal for SRTM and Cartosat-1. Difference between the minimum and maximum elevation covering a watershed termed as Basin Relief. The range of basin relief derived from ASTER is maximum (1871m), similar for Cartosat-1 and ALOS (1832m) and least for SRTM (1825m) (Table 6).

Table 6: Comparison of areal attributes of the study area

		Optical Based Satellite Data		Microwave Based Satellite Data	
S.N.	**Terrain Attribute**	**Cartosat-1**	**ASTER**	**SRTM**	**ALOS**
1.	Area	677.2 Km^2	686.9 Km^2	695.3 Km^2	697.9 Km^2
2.	Perimeter	175.7 Km	181.9 Km	176.7 Km	178.2 Km
3.	Basin Relief	1832 m	1871 m	1825 m	1832 m
4.	Basin Length	35.5 Km	34.9 Km	35.5 Km	34.4Km

5. Conclusion:

The present study dealt with a comparison based on various terrain derivatives and elevation data through the DEMs having the same resolution of 30 m. Drainage map for all the DEMs produces 5th orders streams having variation in their numbers and length. With the same given threshold of 0.96 Km^2 for all the DEMs, ALOS shows the minimum number of streams as compare to others, while Cartosat-1 shows the maximum. Comparing the length of all the streams of an individual order, ASTER shows collectively more stream length while SRTM has the least. Also, highest order stream (5th order) of ASTER shows lowest individual stream length of 8.56 Km compared to stream length of main order for remaining DEMs (ranges from 26.96-29.5 Km). Bifurcation value generated from all of the DEMs suggests that the area is under the influence of the structurally controlled formation of drainage pattern. SRTM shows the maximum range of bifurcation value compares to others. While comparing the areal parameters generated from used DEMs, the Cartosat-1 shows more difference in area and perimeter together with the least value for both of the parameters. The basin relief is maximum for ASTER and minimum for SRTM. Though the slope is generated from different DEMs, it is significant that area belongs to a gentle class (gentle slope of 4-9% gradient), SRTM dominates among all DEMs in terms of areal coverage (81%) while ALOS shows the least deviation of (70%) areal coverage.

Evaluation of errors arising due to data sources is a pre-requisite for DEM's study. The study demonstrates the validation of the vertical accuracy in between DEM's elevation data and the spot heights/landmark data generated from topographic map. Among all the four DEMs used, Cartosat-1 shows comparatively lower RMSE and MAE values indicates relatively higher vertical accuracy whereas ASTER shows higher RMSE and MAE values together and indicate relatively lower vertical accuracy. Different terrain parameters which are used for the present study provide information about the surfaces which can be computed at each point on the DEM. It is observed that the Cartosat-1is suitable to provide accurate DEM for the study area as it shows the least RMSE error compares to others. The accuracy of DEMs depends on the region and type of terrain.

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