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Determination of parameters for watershed delineation using various satellite derived digital elevation models and its accuracy

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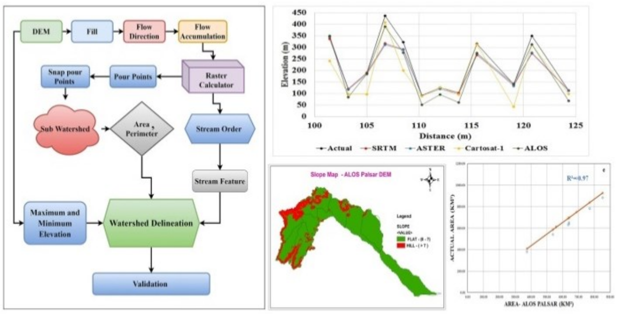
Graphical abstract



Abstract

Digital Elevation Model (DEM) is an inevitable tool for many applications, such as natural resource management. At present scenario, it is available with various resolutions from meter to sub-meter accuracy. These data are used extensively to explore the river basin's physical features by detecting and extracting watershed boundaries, elevation points, drainage networks, flow directions, and morphological parameters. Although many researchers have used DEMs to delineate the watershed boundaries of the river basin, accuracy makes the significant distinction and usage of various DEMs. In this study, the accuracy of watershed delineation derived from various open-source DEMs such as Shuttle Radar Topographic Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Cartosat-1, and ALOS Palsar, in the vaigai river basin have been observed. The Arc SWAT hydrological modeling tool was used to delineate the watershed boundary using the DEMs mentioned above. Eventually, the outcome is validated with the help of base data received from TN-PWD (Tamilnadu Public Work Department). The results attained from the extraction of watershed boundary from various DEMs reveals that the watershed boundary delineated from ALOS – Palsar is closely matching with actual boundary of vaigai river basin. The regression analysis of the watershed on area and perimeter obtained from the ALOS Palsar DEM yielded R^2 as 0.97 and 0.99. This R^2 exhibits the close fitness of the predicted value with data obtained from TN-PWD data. The ALOS Palsar DEM provided low vertical errors and high vertical accuracy compared to other DEMs. Overall the ALOS Palsar DEM generated outcome exhibited comparatively better results than the rest of the DEMs.

Keywords: Watershed delineation, morphometric analysis, vertical error, perimeter – area accuracy, ALOS Palsar, high resolution DEM, ArcGIS, vertical error

1. Introduction

A Watershed is an area that drains all the rivers into a common outlet. It requires an integrated approach to analyze and model the data. In watershed management studies, the accurate delineation of watershed boundary is a challenging task to calculate the area of the watershed. Nevertheless, only a few studies on watershed delineation have been conducted, mainly at large scales. The development of remote sensing and Geographical information system have appropriate tools to make a digital illustration of hydrological modeling of the watershed.

In addition, the Digital elevation model (DEM) have been used extensively in the watershed analysis and management studies due to recent developments (Prastacos, 2018). It is efficient to portray the ground surface and allow for the automated extraction of hydrological features. Therefore, it benefits processing time and cost compared to traditional techniques based on topo sheets. Over the past decade, DEM with high resolutions of 30m resolution became accessible from open-source satellite data from the SRTM, ASTER-V2, Cartosat-1, and ALOS Palsar DEM of 12.5m resolution a faster, inexpensive way for analysis (Aher *et al.*, 2014), (Ozdemir & Bird, 2009), (Vishwas, 2021). All the DEM data are processed in geospatial software (ArcGIS) to delineate the watershed based on morphometric parameters of the river basin.

An analysis of morphometric parameters provides an idea about the drainage network process in the watershed (Prasannakumar *et al.*, 2013). It has primary significance in watershed management studies (Ozdemir & Bird, 2009). Step by step morphometric analysis using GIS helps understand the watershed's linear, areal, and relief parameters. It helps distinguish the watershed based on the different topographical features. Watershed boundary and river networks are manually delineated from topo sheets and digitized with ArcGIS software (Sreedevi *et al.*, 2013)(Bassey Eze & Efiong, 2010), where the data gathered are always relative to the scale factor (Karabulut & Özdemir, 2019). Topo sheets with the scale of 1:25000, 1:50000, and 1:250000 have been extensively used in morphological analysis (Ozdemir & Bird, 2009).

In the recent past, many watershed drainage network extraction studies have been prepared using various DEMs. (Samal *et al.*, 2015), (Kaliraj *et al.*, 2015), (Al-Saady *et al.*, 2016), (Dinagara Pandi *et al.*, 2017) in their exploration, the ASTER DEM and topographic sheets were used for morphometric analysis. From their inference, the ASTER DEM is a sufficient source for watershed drainage morphological study (Sreedevi *et al.*, 2009), (Ansari *et al.*, 2012), (Patel *et al.*, 2013), (Prabu and Baskaran, 2013), (P. Singh *et al.*, 2014), and (Samal *et al.*, 2015) used DEMs derived from SRTM 90m resolution DEM and along with topo sheets for extraction drainage network. The SRTM 30m resolution DEM was used for morphometric analysis along with topo sheets in many studies (Radwan *et al.*, 2017), (Arulbalaji and Gurugnanam, 2017), (Choudhari *et al.*, 2018). The result concludes that the SRTM 30m is considered as appropriate data for extraction stream network and morphometric analysis. However, the SRTM DEM delivered accurate results compared to ASTER DEM. (Forkuor and Maathuis, 2012). Very few studies compared watershed parameters extracted from two or more DEMs (Gopinath *et al.*, 2014),(Thomas and Prasannakumar, 2015), (Karabulut & Özdemir, 2019), (Niyazi *et al.*, 2019), (Gajjar *et al.*, 2018), (Tesema, 2021).

The delineation of watershed is essential work for several activities such as river basin planning and management, identification of groundwater potential, Land use mapping, and geomorphological research. After the arrival of geospatial techniques, Geographers prefer creating opportunities and getting things done in a more efficient and precise manner than before. For researchers working in drainage basin or catchment basis activities such as catchment hydrology, fluvio-geomorphic analysis, water and sediment discharge dynamics, river bank erosion and deposition, etc., the accurate delineation and perfect mapping of catchments is a key work. Basin parameters like shape, area and size factors of various studies which cannot be ignored. More studies available in watershed delineation from various open-source DEMs, (Shahimi *et al.*, 2021). (Mashimbye *et al.*, 2019) (Rana and Suryanarayana, 2019)(Rai *et al.*, 2020)(Rusli *et al.*, 2014), (Anornu *et al.*, 2012) From their inference, The SRTM DEM is the viable source for watershed delineation compared to ASTER, and the DEM is feasible in delineating the watershed in flat terrain.

The quality of DEMs has been researched extensively in order to assess their broad spectrum of applications, and the majority of these studies compare the data generated from DEMs to a set of reference data commonly referred to as control points (Athmania and Achour, 2014) (Elkhrachy, 2018), (Kasi *et al.*, 2020),(Jain *et al.*, 2018a),(Rana and Suryanarayana, 2019). From these authors, this comparison, which is based on accuracy statistical measures including mean difference, standard deviation, and root mean square error, is essential for evaluating DEM positional accuracy and helps in the improvement of mapping methodologies. Furthermore, to verify the data collected from a DEM is accurate. It is vital to have relatively accurate information about the DEM's coordinate system, cartographic projection, and datum, as well as to keep in mind that horizontal positional accuracy mistakes might result in significant vertical errors in the DEM, especially in steep slope areas (Yap *et al.*, 2019). Many studies dealt DEMs accuracy calculation (Rawat *et al.*, 2013) (Mesa-Mingorance and Ariza-López, 2020), (Singh *et al.*, 2016)(Nikolakopoulos, 2020), However, there have been no studies that particularly evaluated the ALOS PALSAR's vertical accuracy.

In this study, the primary purpose is to delineate the watersheds from drainage network using DEMs derived from high resolution satellite data such as ALOS Palsar with 12.5m, SRTM, ASTER, and Cartosat-1 (all with 30 m resolution). This study involve (i) Extraction of drainage network using Arc SWAT from all mentioned above DEMs (ii) Delineation of the watershed for the study area using DEMs mentioned above and the validation. (iii) Assessment of vertical accuracy of open source DEMs used in the study area. However, In Tamilnadu state many researchers have been working with DEMs for morphometric studies and Groundwater studies, but very few studies are concerned with the delineation of watershed boundary.

The Vaigai river basin is situated very close to the Madurai city, one of the ancient cities of India with high population density and is called “No sleep city” (*thoongaa Nagaram* in tamil) due to its dynamic activities throught day and night. In recent years the city and and area within districts of Theni, Dindigul, Sivaganga, Ramanathapuram and Madurai under the Vaigai river basin is undergoing severe water crisis and drought. The 289 km long river basin from western ghat near Kerala state to bay of Bengal near Ramanathapuram, isn’t been managed properly. The cultivable land in this area are forced to manage with recycled sewage water from the treatment plant by the city to some extent. However no water resources management attempt has been made in this study area for the past few decades. Accurate delineation of a watershed plays an important role in the management of the watershed. The delineated boundaries form the core information with that the water resources management efforts such as land use, land change, soil types, geology and river flows are analyzed and appropriate conclusions could be arrived at. In this vaigai river basin, no study has been attempted using DEMs to accurately delineate the watershed parameters. Hence, this study targets using open-source DEMs for the vaigai river basin to extract drainage network using Arc SWAT, delineate the watershed boundary, and determine the parameters such as elevation, slope, area, and perimeter.

2. Study area

The vaigai river basin is considered one of the vital river basins in Tamil Nadu. It has an aerial extend of 7009.13 km2 and has high relief and a steep gradient surface of the Western Ghats. It has ten sub-basins. It lies between the geographical coordinates $9^{0}15$'N to $10^{0}20$'N latitude and $77^{0}10$'E to $79^{0}15$'E longitudes. The study area is covered in the 58F, 58G, 58J, and 58K Toposheets provided by the Survey of India. The river vaigai originates on the eastern slope of the V*arusanadu* hills and ends in the *Bay of Bengal*, drains through *Theni, Dindigul, Madurai, Sivaganga*, and *Ramanathapuram* districts as depicted in (Figure 1). The study area characteristics are hard crystalline rocks, hot and humid climate, and low rainfall during the southwest monsoon in the mountainous area. Occasionally, there will be more rainfall over the *Bay of Bengal's* coastline areas during the northeast monsoon, and it receives an average rainfall of about 850mm.

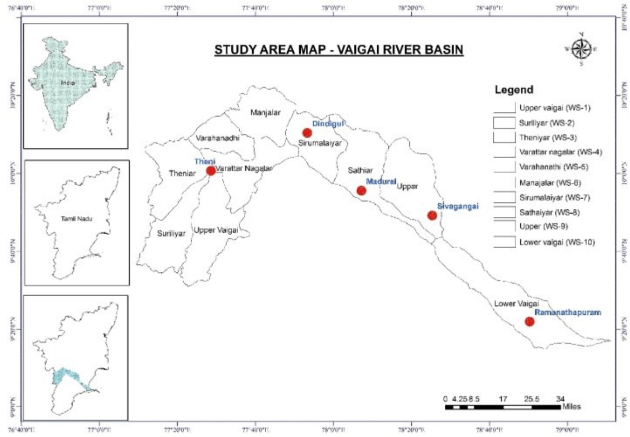


Figure 1. Study area map – vaigai river basin

3. Material and methods

3.1. Data and sources

In this research, four open-source DEMs such as SRTM, ASTER, Cartosat-1, and ALOS Palsar DEM were used for watershed delineation studies. Data and its sources are depicted in (Table 1).

Table 1. Details of data used and its source

S.no	Data authority	Data description	Spatial/ Scale details
1	NASA,USA	SRTM DEM – 1 arc second version3	30m
2	NASA,USA	ASTER DEM – version 3	30m
3	NRSA-ISRO	Cartosat 1 – version3	30m
4	JAXA	ALOS Palsar DEM – 1 arc second	12.5
5	Survey of India	Topo sheets: 58F4, 58F8, 58F11, 58F12, 58F15, 58F16, 58G1, 58G2, 58G5, 58G6, 58G9, 58G10, 58G13, 58G14, 58J4, 58J8, 58K1, 58K2, 58K3, 58K5, 58K6, 58K7, 58K10, 58K11, 58K15.	1:50000
6	TN-PWD	Details of vaigai river basin from the Tamilnadu water resource department	

3.2. Methods

The following flow chart (Figure 2), depicts the methodology adopted for the study.

3.2.1. Data collection

As shown in the flow chart, the methodology adopted for the study involves boundary demarcation, DEM generation, watershed delineation, morphometric analysis, and the same comparison of results obtained from various DEMs sources.

Nearly 25 topo sheet listed (58F4, 58F8, 58F11, 58F12, 58F15, 58F16, 58G1, 58G2, 58G5, 58G6, 58G9, 58G10, 58G13, 58G14, 58J4, 58J8, 58K1, 58K2, 58K3, 58K5, 58K6, 58K7, 58K10, 58K11 and 58K15) are georeferenced and mosaic for the study area boundary demarcation.

The Advanced Land Observing Satellite (ALOS) is a global dataset developed from imageries using Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) to attain cloud-free data. It was established in 2006. The Phased Array type L-band Synthetic Aperture Radar (PALSAR) is an open-source DEM having a 12.5m resolution developed in ALOS.

Eventually, the DEMs derived outcomes are validated with the help of source data from the field and TN-PWD source information.

3.2.2. Data processing

Stream sections have been extracted from the fill DEMs based on the stream ordering method. The extraction of drainage networks from DEMs follows a structure of organized GIS processes such as filling the pixels, calculating flow direction, flow accumulation, and calculating water drains contribution into an outlet cell (Tarboton and Matthew E. Baker, 2008). SRTM, ASTER DEM datasets gives altitude value with reference to EGM96 datum, and it is considered to be a close approximation of MSL (Sandip Mukherjee *et al.*, 2012). and the cartosat DEM gives elevation value with reference to WGS84 (Ward *et al.*, 2006). Altitude with reference to EGM96 datum is considered It is important to note that the data acquired for different DEMs are transformed to the same datum (WGS84) to eliminate any errors caused by differences in the datum. It is done through projection and transformation tool in arcGis.

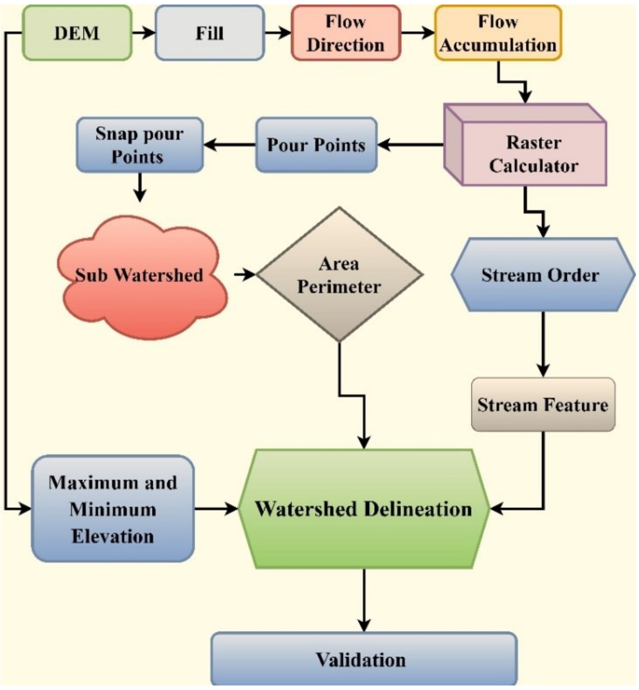


Figure 2. Methodology

3.2.3. Watershed delineation

Watershed delineation is the identification of watershed boundaries using geospatial software. The soil water assessment tool (SWAT) has a delineation tool that can be integrated with ArcGIS geospatial software. The researchers were able to integrate more physical data into the Arc SWAT model than the Arc Hydro model, resulting in a more realistic representation of the watershed (Ray*et al.*, 2018). Furthermore, Arc SWAT is more user-friendly for researchers with limited GIS familiarity Arc SWAT is a free, open-source hydrological model with various applications used in watershed analytical research (Shahimi *et al.*, 2021),(Gopinath *et al.*, 2014).

The linear regression method can be used to investigate the relationship between actual and predicted variables. It helps to observe changes in the distribution of watersheds (Suwandana *et al.*, 2012),(Ibrahim *et al.*, 2020).

In this study, the watershed delineation is the most crucial phase. It is carried out in Arc SWAT tool using SRTM, ASTER, Cartosat-1, and ALOS Palsar DEM. The regression analysis of 10 sub-basins area, perimeter and its accuracy analysis have been performed using a statistical approach to evaluate the DEMs influence in watershed delineation.

In the process of watershed delineation with SWAT analysis of Vaigai river basin, the ArcSWAT (Arc GIS-SWAT) is used. It perform as an interface between the ArcGIS and the SWAT model. The DEMs derived from various satellite data of ASTER, Cartosat, ALOS Palsar and SRTM) are the primary input for the SWAT model. The other data soil, and land use are used in the processing phase and fed into the SWAT model through the interface. Soil and land cover made important responding units, which the SWAT model used in subdividing the catchment into Hydrologic Response Units (HRU), having unique land use soil combinations during the process of runoff generation. For the model setup and watershed simulations, SWAT requires an assortment of input data layers. The Digital Elevation Model (DEM) defines the topography of the watershed and it is used to calculate sub-basin parameters, such as slope, and to define the stream network. The soil data define soil characteristics while the land use data provide vegetation information. After soil data processing, the next step is assigning slope attributes to each HRU. To keep the process simple, the single slope option in the soil discretization frame is used , and then classification / reclassification is performed. This will complete the processing of landuse, soil and slope data for HRU analysis. Finally, by overlaying individual themelayers a combined information on land use, soil type and slope is created, which will then be used to create HRU. After all geo-processing is done on DEM, land use, and slope data the sub-basins and HRUs are generated. Then weather data such as temperature, relative humidity, solar radiation, wind speed and rainfall data will be applied to run the simulation of SWAT model.

3.2.4. Morphometry parameter assessment

Extraction of drainage network and assigning the stream order were obtained using both the satellite imageries and topographic map of the study area , as listed in Table - 1, published by the Survey of India Organisation. As the extraction from geo-referenced satellite data for a large area is a difficult and time consuming process, automatic extraction techniques have been used for evaluating the morphometric parameters of the Vagai river basin such as extraction of River basin, watershed boundary and extraction of drainage and stream network from the Vaigai River basin. For the process of extraction of stream orders, the Hydrology tool from spatial analyst Arc toolbox is used and eight direction (D8) Flow Model was adopted from the ArcGIS Software. The DEMs, derived from Cartosat-1, ASTER, SRTM and ALOS Palsor, and the pour point are the two inputs parameters required for the extraction function. A pour point is the user supplied-point to the cells wherein the flow accumulation is a maximum. To evaluate the drainage basin morphometry, various parameters such as stream number, stream order, stream length, stream length ratio, bifurcation ratio, basin length, basin area, relief ratio, elongation ratio, drainage density, stream frequency, form factor and circulatory ratio, etc., have been analysed using the mathematical relationships as summarised by Ramesh L. Dipkal *et al.*, 2017. The aspect of slope and slope map is detailed in the section 3.2.5 below under slope analysis.

3.2.5. Elevation and altemetric error

The accuracy of elevation data and its error distribution accuracy analysis were done for the different DEMs with reference to TN-PWD data. The height of ground reference points gathered from the TN-PWD data has been taken into account. Assuming that the elevation values from TN-PWD values are the most accurate of all the data sources. The elevation values from the DEM were extracted from 149 locations, as shown in (Figure 3). The altitude values from the various DEMs were retrieved using the Surface information tool in ArcGIS.It is important to note that the data acquired for different DEMs are transformed to the same datum (WGS84) to eliminate any errors caused by differences in the datum.

The coefficient of determination (R^2) was calculated to know the linear relationship between the actual elevation and measured elevation. In this, the R^2 was measured using the statistical tool for each DEM. The R^2 value varies from 0 to 1. If the R^2 is 0, the measured data is not fitted with actual data, and if the value is 1 the measured is linearly fitted with actual data.

To quantify the elevation data's accuracy, the altimetry error between the actual and DEMs elevation were analyzed. The altimetry error is the difference between the actual elevation and elevation measured using DEMs. In addition to the descriptive statistical parameters such as, Mean error (ME), Root mean square error (RMSE), Standard deviation (S), skewness, and kurtosis was calculated for each DEM (Table 3). The ME shows whether the predicted measurements is over estimated (+ ME) or under estimated (- ME). The RMSE exhibits the spreading of data from the fitting line, and a high RMSE value shows the data is how far deviation with actual data. If the more RMSE value shows more deviation and less RMSE value show less deviation of predicted measurements from actual data. Similarly, the S shows the distribution of data from the mean. (Sandip Mukherjee *et al.*, 2012) The skewness shows the amount of distortion of the elevation data from the normal distribution. Positive skewness indicates a tail is longer in the left and the observed histogram balancing on the left. Similarly, negative skewness refers to a longer tail in the right and the observed histogram balancing on the right. The kurtosis is used to identify the outlier with reference to peakness, more kurtosis value shows more peakness and more outliers, if peakeness is low the data having less outliers, the measured data is closely fitted with actual data(Jain *et al.*, 2018b).

$$RMSE = \sqrt{\frac{\sum(Acutual\ Data - Forecast\ data)^2}{N}}$$

$$MAE = \sum_{i=1}^{N}\sum\left|DEMelevation - Actualelevation\right| / N$$

$$S = \sqrt{\sum(x-\overline{X})^2/(N-1)}$$

$$R^2 = 1 - (Sum\ of\ square\ of\ residuals / Total\ sum\ of\ squares)$$

Where x is the difference between actual and DEM elevation, $\overline{X}$ is the Mean error and N is the number of samples. Based on statistical metrics (RMSE, MAE, S, and R^2) in (Table 3) the vertical error distribution and elevation accuracy were found.

3.2.6. Slope analysis

The Slope analysis is essential to understand the inclination of topographical structure, and it is used to find the catchment's morphometric characteristics (Sreedevi *et al.*, 2005). In this study, the slope area was derived from DEM using the following steps. The contour map is generated using a spatial analysis tool with a contour interval of 100m. From the derived contour, the triangular irrigated network is generated using a 3D analysis tool and is converted to a raster image. With the use of generated raster image, the slope map is generated using a spatial analysis tool in ArcGIS software.

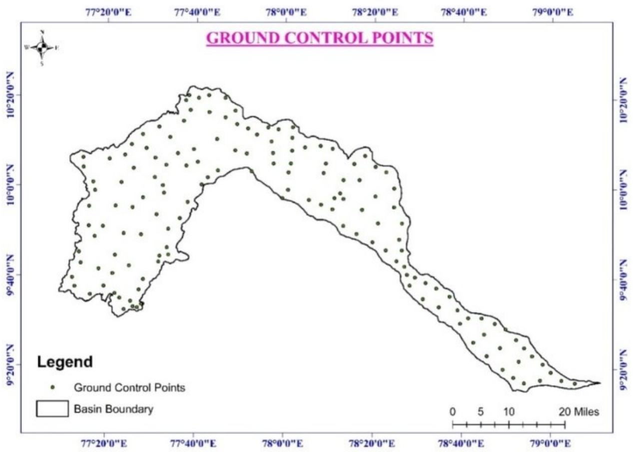


Figure 3. Location of ground control points

3.2.7. Regression analysis – area and perimeter

The regression analysis helps us to understand the linear relationship between the actual value and measured values. It makes use of a model that uses a simplified mathematical form to express the relationship between the variables. The coefficient of determination R^2 shows the fitness of measured data with actual data. The R^2 varies from 0 to 1. If the R^2 is 0, the measured data is not fit linearly with actual data, and 1 stands for perfectly matching. In this study, the measured area and perimeter of the vaigai river basin using various DEMs were analyzed with the actual measurement obtained from TN-PWD using a linear regression analysis tool.

4. Results and discussion

4.1. Delineation of watershed

In this study, the actual watershed boundary provided by TN-PWD, is shown in (Figure 4), was compared with delineated watershed boundaries from various DEMs such as ASTER, SRTM, Cartosat-1, and ALOS Palsar. The watershed parameters (area and length) were derived using various DEMs for the study area (Table 2). The actual watershed area and perimeter provided is used as a base to compare the parameters of the watershed.

Figures 4a & 4b shows the watershed boundary delineated by various DEMs with respect to the actual area. The ALOS Palsar, Cartosat-1, ASTER and SRTM derived DEMs have delineated the watershed with an accuracy of 87.22%, 82.99%, 80.08% , 77.92 % respectively with respect to the actual area of 7009.13 km^2 . Similarly, ALOS Palsar, Cartosat-1, ASTER and SRTM derived DEMs predicted the watershed perimeter with an accuracy of 97.60%, 94.04%, 90.34% and 88.96% respectively against the actual perimeter of 783.45 km.

Table 2. Area and length of delineated watershed from various DEMs

Perimeter (km) / Area(km2)	Perimeter / Area derived from various DEMs			
	SRTM	ASTER	Cartosat-1	ALOS
Perimeter = 783.45	696.88	707.72	736.70	764.58
Difference in perimeter (%)	-11.04	-9.66	-5.96	-2.40
Area = 7009.13	5460.97	5612.25	5816.69	6112.92
Difference in area (%)	-22.08	-19.92	-17.01	-12.78

The results revealed that the ALOS Palsar DEM efficiently delineate the watershed boundary at 97.60% accuracy in predicting the perimeter, 87.22% accuracy on predicting the area. The outcomes are more precise than the rest of the DEMs used in this study. (Arabameri *et al.*, 2019),(Rabby *et al.*, 2020) revealed similar performance of ALOS palsar DEM and concluded that ALOS was the best in delineation of watershed compared to other DEMs in their study.

The SRTM and ASTER closely under predicted the perimeter length with 11.04% and 9.66% difference. The similar results found in the study by (Pasha and Sathian, 2021) on perimeter and area using SRTM and ASTER data.

4.2. Elevation accuracy and error analysis

4.2.1. Elevation and Altemetric error

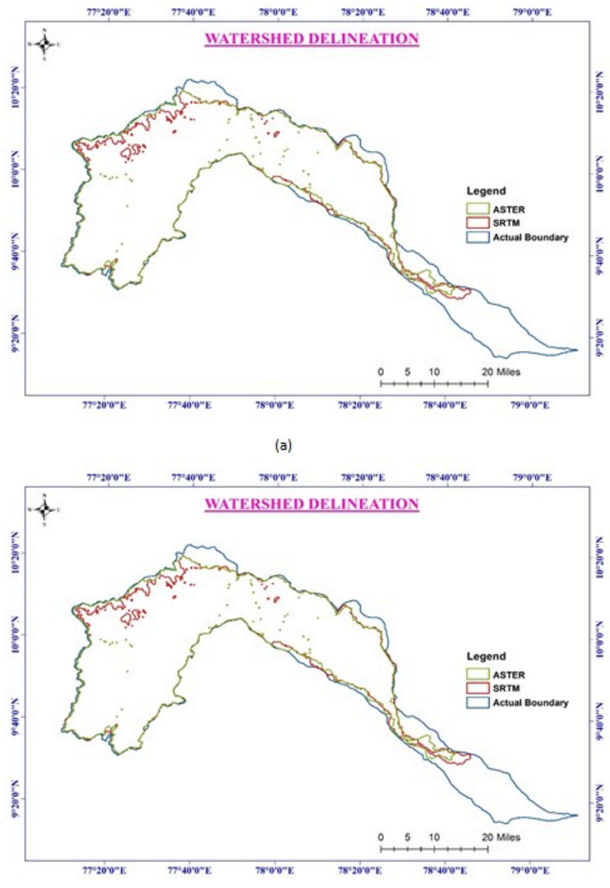
In this work, 149 elevation points from the study area provided by the government of India have been compared. The maximum (Z) and minimum (z) of elevation data are shown in (Table 3), and (Figures 5a to 5h) shows the variations in surface elevation obtained from various DEMs at 25km longitudinal interval. In that elevation profile out of 149 points 99 points are considered, in longitudinal direction as rest of the 50 points in transverse direction could not be shown in longitudinal profile.

Figures 5a to 5c shows the difference in elevation at the upper most area of the study, which is in the hilly region. It is observed that all the DEMs have predicted , the elevations nearer to the actual value and there is not much variation. In a recent study carried out by (Shetty *et al.*, 2021) , (Ibrahim *et al.*, 2020) and (Das *et al.*, 2016) found that the SRTM and ASTER showed the similar results in the hilly area of their study.

Figures 5d to 5e shows the elevation variation from 75 km to 125 km in the study area, this area is mainly composed of urban settlements, in that from 75-79 km, the cartosat-1 DEM under predicted the elevation in most of the range considered. Further ASTER and SRTM predicted close to the actual elevation. (Rawat *et al.*, 2019) found similar performance of ASTER and SRTM derived DEMs.

Figures 5f and 5g shows the elevation variation from 125km to 175km in the study area. In this the ASTER over predicted the elevation values nearby water bodies.

Figures 5h, shows the altitude variation at the outlet of the vaigai river basin from (175-225km). From the results at the outlet the Cartosat-1 again under predicted the elevation value compared to the actual. The SRTM over predicted the elevation value compared to the actual value. (Rawat *et al.*, 2019) found similar results in their study.



(b)

Figure 4. (a) Delineated watershed boundary using SRTM and ASTER. (b) Delineated watershed boundary using Cartosat-1 and ALOS Palsar

Figure 6 shows the regression analysis for overall length between the actual data and predicted data from DEMs. In that the Cartosat-1 is having R^2 value of 0.996 and little high compared to SRTM and very similar to ASTER as shown in Figure 6. The DEMs derived from Cartosat-1 demonstrated as an accurate DEM in determining the elevation. The result obtained from the following studies using Cartosat-1derived DEMs (Rana and Suryanarayana, 2019),(Rawat *et al.*, 2019),(Samadrita Mukherjee *et al.*, 2015) (Gajalakshmi and Anantharama, 2015), confirms with the result of the present study.

In the entire longitudinal range, it is observed distinctly that the ALOS Palsar derived DEM predicted very close to actual elevation than other DEMs. Among the all DEMs ALOS Palsar predicted with R^2 = 0.998, and the rest of DEMs have also predicted significantly close to the actual with (R^2 = 0.992, 0.996) in the entire longitudinal direction. Since the ALOS high resolution data of 12.5m is significant in surface feature (i.e. horizontal features) detection, and it couldn't enhance elevation accuracy significantly compared to other DEMs.

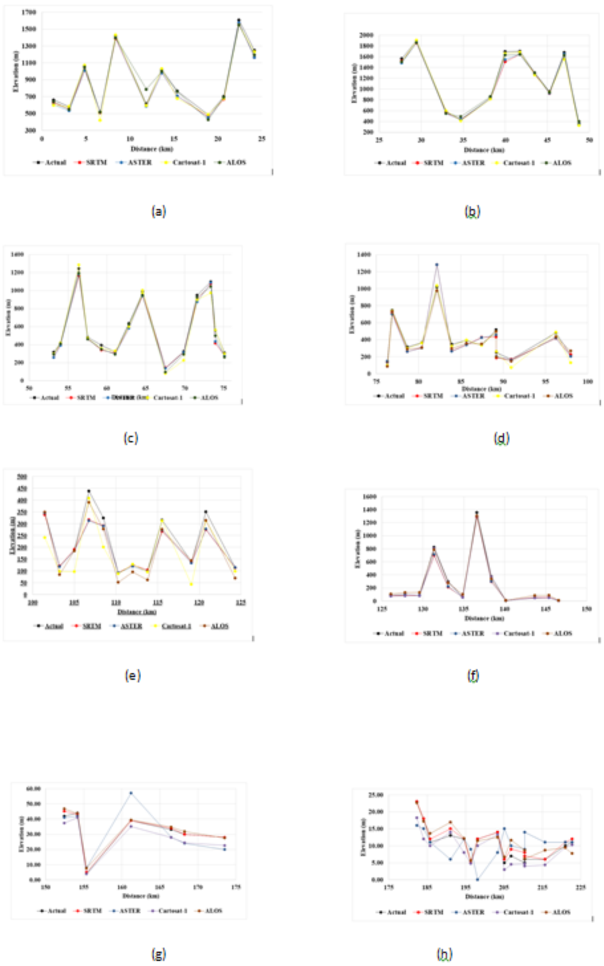


Figure 5. (a) Elevation profile from 0 to 25 km for various DEMs. (b) Elevation profile from 25 to 50 km for various DEMs. (c) Elevation profile from 50 to 75 km for various DEMs. (d) Elevation profile from 75 to 100 km for various DEMs. (e) Elevation profile from 100 to 125 km for various DEMs. (f) Elevation profile from 125 to 150 km for various DEMs. (g) Elevation profile from 150 to 175 km for various DEMs. (h) Elevation profile from 175 to 225 km for various DEMs

4.2.2. Vertical error and accuracy analysis.

The statistical analysis for vertical error has been performed for all of the DEMs (SRTM, ASTER, Cartosat-1, ALOS Palsar DEM) with reference to 149 ground control points provided by government of india in the study area (Table 3). It shows a high mean error of 27.50m for SRTM, and ALOS Palsar DEM has a low mean error of 19.20m with actual elevation. The same results obtained in (Rawat *et al.*, 2019),(Jain *et al.*, 2018b) with the mean error higher in SRTM. The RMSE shows the deviation of elevation data from actual data, the RMSE of SRTM is 51.79, showing that the elevation from SRTM is more spread out from the fit line compared to other DEMs. The standard deviation shows the deviation of elevation data obtained from various DEMs with actual elevation. In this study, the standard deviation between actual data and SRTM is 44.03, for ASTER 42.03, cartosat-1 38.35 and ALOS palsar DEM 33.27. It reveals that the ALOS palsar DEM having very less deviation with actual elevation and predicts closely compared to other DEMs, In a recent study by (Shetty *et al.*, 2021) on Shurbulak water reservoir project, the DEM derived from ALOS palsar shows similar results in comparison with ASTER and SRTM derived DEMs.

The spatial error distribution between actual elevation and measured elevation from DEMs shown in (Figure 7). In that Figure 7a shows the error distribution of SRTM with the skewness of 1.24 and the kurtosis of 13.01, further it reveals that the histogram balancing on the left side, and the tail is longer on the right side (positive skewness), and the high kurtosis indicates peaked distribution. The mean error of SRTM is -27.50. It reveals that the SRTM is mostly under predicted the elevation.

Similarly, the ASTER also positively skewed with the skewness of 1.78, and the mean error was -27.49. It reveals that the ASTER mostly under predicted the elevation . Similar results have been arrived in the study by (Li *et al.*, 2013) wherein ASTER and SRTM derived DEMs revealed similar performance.

The Cartosat-1 DEM has negatively skewed with skewness -1.40, and it has mean error of -25.93. It reveals that the Cartosat-1 has under predicted the elevation. In a study by (Jain *et al.*, 2018b) similar performance is observed.

In ALOS Palsar DEM, skewness and kurtosis are low i.e. 0.98 and 0.02 respectively and it reveals that the ALOS Palsar DEM predicted the elevation very close to actual elevation measurements. Hence the ALOS Palsar DEM is more accurate in predicting the elevation in comparison with other satellite derived SRTM, ASTER and Cartosat-1 derived DEMs.

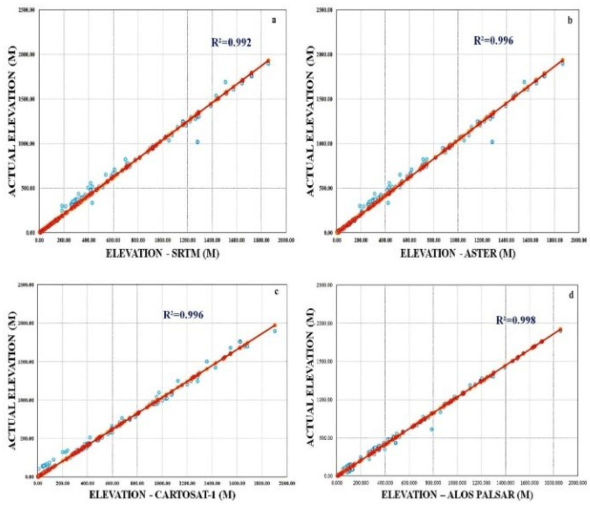


Figure 6. R^2 value for vertical accuracy obtained using various DEMs

4.3. Slope-area analysis

The amount of slope represents the variation in surface value with respect to distance. It is denoted as degrees or percentages. The range of slope varies from 0^0 to 30^0. The slope area distribution is categorized as plain area when the slope is less than 8^0 and more than 8^0 comes under hilly area. In this study, the slope maps were generated for each DEM using geospatial techniques, as shown in (Figure 8). The slope area of for all 10 sub-basins in the study area were derived using various DEMs (Tables 4 and 5) and compared with actual sub-basins wise data provided by the Tamilnadu public works department.

Table 3. Statistical measures of vertical error from various DEMs

S.no	Statistical parameters	SRTM	ASTER	Cartosat-1	ALOS-Palsar
1	ME	-27.50	-27.49	-25.93	-19.20
2	RMSE	51.79	50.11	46.19	38.32
3	Standard Deviation	44.03	42.03	38.35	33.27
4	Skewness	1.24	1.78	-1.40	0.98
5	Kurtosis	13.01	15.25	1.09	0.02
6	R^2	0.992	0.996	0.996	0.998
7	Maximum (Z)	2556	2545	2433	2555
8	Minimum (z)	-9	3	1	1

Table 4. Slope area analysis from various DEMs for plain area

Sub Basins	Plain area derived from various sources				
	Actual	SRTM	ASTER	Cartosat-1	ALOS Palsar
Upper Vaigai	263.05	259.03	260.74	261.02	261.92
Suriliyar	422.15	413.24	417.02	418.46	421.24
Theniar	340.81	334.81	335.49	340.07	339.92
Varahanadhi	179.65	178.28	176.48	176.28	179.00
Varattar Nagalar	400.51	393.09	395.66	397.07	400.27
Manjalar	303.06	296.82	300.41	297.39	302.58
Sirumalaiyar	337.18	334.21	336.44	334.21	336.98
Uppar	860.94	841.83	853.40	853.62	855.52
Sathiar	663.47	647.28	659.75	657.76	662.61
Lower Vaigai	1063.88	1061.11	1061.11	1060.21	1061.20
Total area	**4834.70**	**4759.71**	**4796.50**	**4796.11**	**4821.23**
Accuracy in %		**98.44**	**99.20**	**99.20**	**99.72**

Table 5. Slope area analysis from various DEMs for hilly area

Sub Basins	Hilly area derived from various source				
	Actual	SRTM	ASTER	Cartosat-1	ALOS Palsar
Upper Vaigai	558.97	559.45	556.92	542.91	557.09
Suriliyar	217.95	220.46	216.79	207.37	216.09
Theniar	310.84	315.26	306.36	292.93	309.22
Varahanadhi	200.63	200.19	199.18	188.89	198.92
Varattar Nagalar	231.31	228.74	229.08	223.86	229.54
Manjalar	309.68	306.23	307.81	298.60	308.87
Sirumalaiyar	204.41	202.84	201.53	191.06	203.23
Uppar	21.35	20.97	20.68	20.76	21.19
Sathiar	119.29	117.05	115.86	115.86	118.51
Lower Vaigai	0	0.00	0.00	0.00	0.00
Total area	**2174.43**	**2171.19**	**2154.23**	**2082.24**	**2162.67**
Accuracy in %		**99.85**	**99.07**	**95.76**	**99.45**

The slope area estimated by SRTM, ASTER and Cartosat-1 in the sub-basins under hilly area of *Upper vaigai, Surliyar, Theniar,* are very close to the actual area. In Uppar sub basin, the SRTM, ASTER and Cartosat-1 under predicted with actual slope area. The slope area of plain surface predicted from Cartosat-1 is nearer to actual data in all sub-basins but in contrast in hilly area Cartosat-1 under estimated (2.87%) in *upper vaigai,* (4.85%) in *surliyar* sub-basin, (5.76%) in *theniyar* sub-basin, and (5.85%) in *varahanadhi* sub-basin. Compared to all other 30m resolution DEMs, the ASTER predicts the plain area very close to actual data. In previous study done by (Kumar Rai *et al.*, 2017) using ASTER DEM found similar performance of DEMs. Overall, in this study the ALOS Palsar predicted the slope area of the watershed in both plain (99.72%) and in the hilly (99.45%) region accurately in comparison with rest of the DEMs studied. Studies carried out by (Ahirwar *et al.*, 2019), (Sreedevi *et al.*, 2009) showed similar results in their study.

4.4. Area and perimeter

The performance of watershed boundary delineation drawn from SRTM, ASTER, Cartosat-1, and ALOS Palsar

DEM have been examined and a statistical analysis have been performed. Watershed area and perimeter were compared with the actual data provided by TN-PWD. The regression coefficient $R^2$and other statistical parameters, were analyzed and the results were shown in (Figure 11 and 13). In this study, area and perimeter of 10 sub-basin of the *vaigai* river basin have been predicted from DEMs. Derived from ASTER, ASTER, Cartosat-1 and ALOS Palsar satellites. The R^2 shows the strength of association between actual measurements and predicted values for area and perimeter.

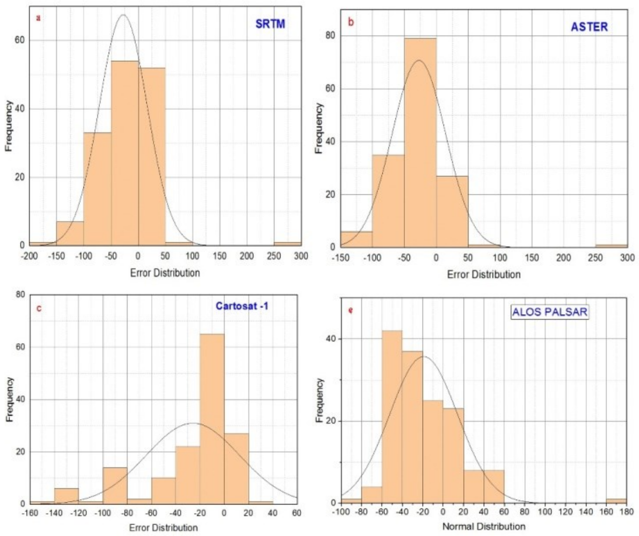


Figure 7. Vertical error distribution of various DEMs

4.4.1. Area

The area of *vaigai* river sub-basins from various DEMs were compared (Table 6) with actual data and the difference in area predicted is shown in (Figure 9).

The SRTM DEM had predicted less area 120.21 km^2 against actual area of 1063.88 km^2 in *lower vaigai* sub basin, this may be due to the SRTM and ASTER delineated less number of streams due to huge gap found between streams in the process of delineation, and as it couldn't connect with main stream. In *surliyar* sub basin SRTM predicts 205.79 km^2 which is 32.14% more than the actual area. The ASTER DEM predicted an area of 922.61 km^2 which is 86.72 % area lesser than the actual area in *lower vaigai* sub-basin, and 207.91km^2 area more than actual in *surliyar* sub-basin. Compared to actual data, the Cartosat-1 predicted (-) 655.01 km^2 area in *lower vaigai* sub-basin and (+) 231.57 km^2 area in *surliyar* sub basin. The ALOS Palsar predicted (-) 376.02 km^2 against the actual area of *lower vaigai* sub-basin and (+) 2.91km^2 against the actual area in *varattar nagalar* sub basin. From the total area of 7009.13 km^2 the area predicted by SRTM is 77.88% , ASTER is 80.14% ,Cartosat-1 84.65% and area predicted by ALOS Palsar DEM is 92.79%. Thus the ALOS Palsar DEM derived area of the watershed is nearly equal i.e. 92.79% of the actual area compared to other DEMs. Previous study by (Ouerghi *et al.*, 2015),(Freitas *et al.*, 2016), (Gajjar *et al.*, 2018) reveals that similar results on delineated area and perimeter by ALOS DEM. In this study the ALOS derived delineated area is close to actual area.

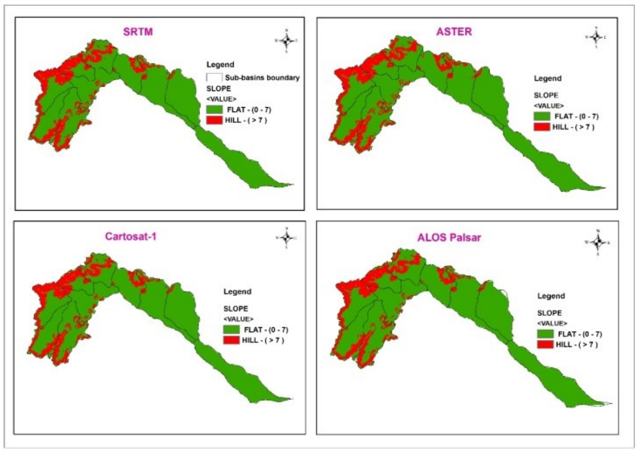


Figure 8. Slope area analysis from various DEMs

Table 6. Sub basins area derived from various DEMs

Sub Basins	Actual	SRTM	ASTER	Cartosat-1	ALOS Palsar
Upper vaigai	822.02	803.82	801.99	802.48	807.15
Suriliyar	640.10	845.89	848.01	871.67	639.47
Theniar	651.65	359.81	430.39	415.78	640.52
Varahanadhi	380.28	330.39	340.78	372.07	374.26
Varattar nagalar	631.82	576.39	620.68	558.37	634.73
Manjalar	612.74	390.29	432.95	463.28	558.62
Sirumalaiyar	541.59	663.33	662.22	391.14	538.14
Uppar	882.29	717.96	538.13	813.78	852.45
Sathiar	782.76	650.69	800.78	835.88	770.79
Lower vaigai	1063.88	120.21	141.27	408.87	687.86
Total area	7009.13	5458.79	5617.18	5933.31	6503.99

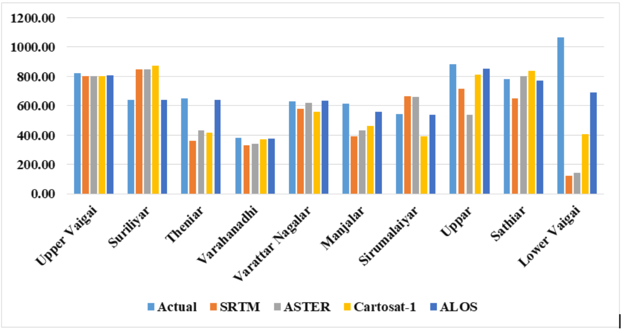
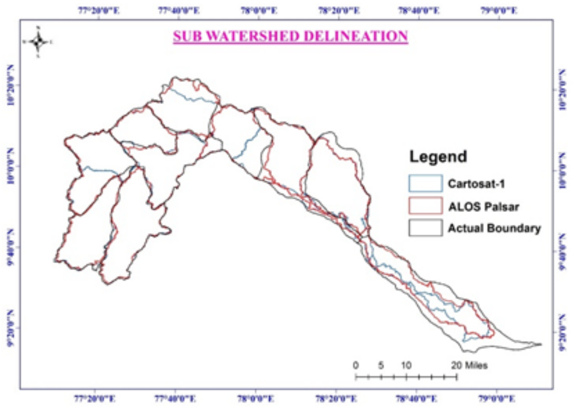
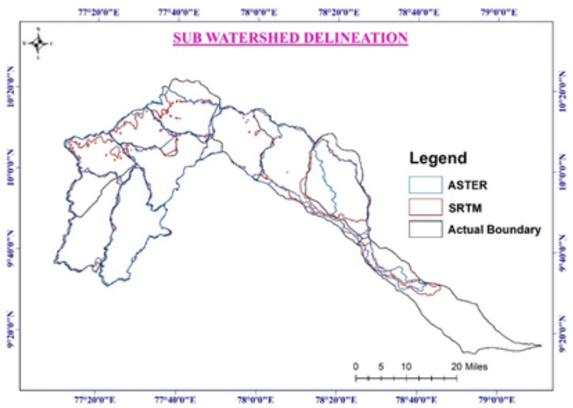


Figure 9. Area difference in various DEMs with actual data



(a)



(b)

Figure 10. (a) Sub-watershed delineation of vaigai river basin using Cartosat-1 and ALOS palsar. **(b)** Sub-watershed delineation of vaigai river basin using SRTM and ASTER

The statistical analysis conducted for the 10 sub-basins on actual area and predicted area using DEMs is shown in.(Figure 11). It reveals that the sub-basin area measured using ALOS Palsar DEM has predicted very close to the actual area of 10 sub-basins of vaigai river with R^2=0.974, compared to other DEMs. The other DEMs using SRTM, ASTER, Cartosat-1 were predicted with R^2 Value as shown in Figure 11. Hence ALOS palsar DEM has predicted the area more accurately than the other DEMs used.

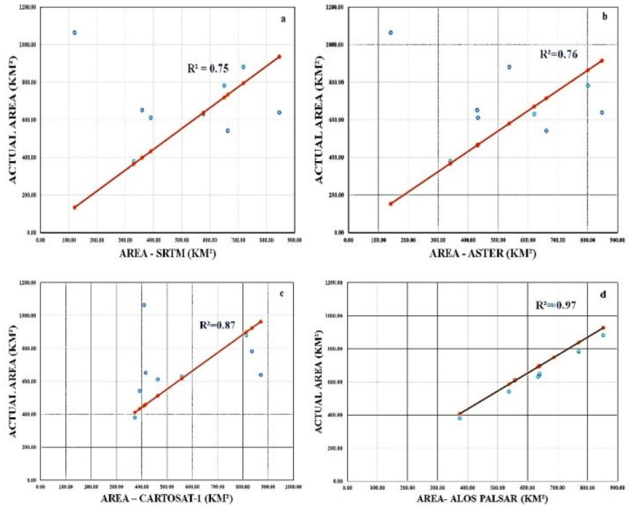


Figure 11. R^2 value for sub-basin area obtained using various DEMs

4.4.2. Perimeter

The perimeter of *vaigai* river sub-basins from various DEMs have been compared (Table 7) with actual data to find the perimeter difference and is shown in (Figure 12). The SRTM DEM had a difference in perimeter of (-143.12) km in the *lower vaigai* sub-basin and (+55.94) km more than the actual area in the *surliyar* sub-basin. ASTER, predicted with a difference in perimeter of (-118.83) km against the actual perimeter in lower vaigai, and (+10.14) km is more than actual in manjalar. The Cartosat-1 predicted perimeter with (-83.30) km shortage in lower vaigai and (+32.14) km excess in surliyar. ALOS Palsar DEM predicted the perimeter with a (-36.06) km, in lower vaigai and (+13.85) km extra area in the uppar basin. With the actual total perimeter of 1558.42 km, the perimeter predicted from SRTM is 1363.50 km, (87.49%), from ASTER 1425.70 km, (91.48%), from Cartosat-1 1462.15 km, (93.82%), and perimeter predicted by ALOS Palsar is 1510.99 km, (99.60%) of the actual. It demonstrates that the ALOS Palsar DEM provided perimeter nearly equal to actual data compared to other DEMs.

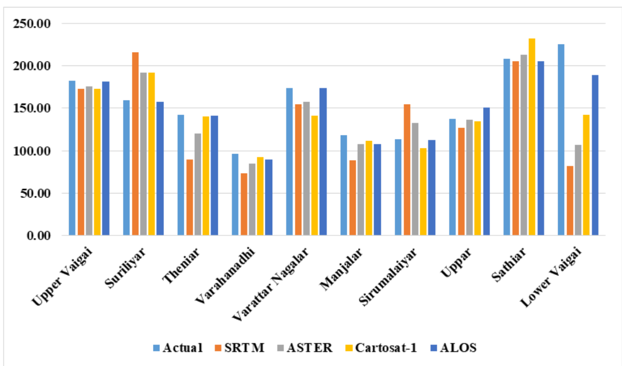


Figure 12. Perimeter difference in various DEMs with actual data

Further it is observed from the statistical analysis that the ALOS Palsar provided th13e closest perimeter for 10 sub basins of *vaigai* river (Figure 13) with R^2=0.99. The other DEMs using SRTM, ASTER, Cartosat-1 predicted with R^2 (),value as shown in Figure 13. Thus ALOS Palsar DEM has predicted the perimeter of the sub-basins more accurately than the other DEMs considered in this study. Earlier studies by various authors (Rawat and Mishra, 2016),(Freitas *et al.*, 2016),(Elewa *et al.*, 2016), also found similar results from ALOS Palsar derived DEM in comparison with other DEMs.

4.4.3. Over all accuracy of various DEMs

The accuracy of parameters derived from various DEMs have been computed based on regression analysis and is shown in (Table 8).

Table 7. Sub basins perimeter derived from various DEMs

Sub Basins	Actual	SRTM	ASTER	Cartosat-1	ALOS Palsar
Upper vaigai	182.74	172.60	175.48	172.98	181.54
Suriliyar	159.86	215.80	192.23	192.00	157.24
Theniar	142.04	89.98	119.85	140.23	141.34
Varahanadhi	96.71	73.21	84.49	92.96	89.67
Varattar nagalar	173.91	154.41	157.19	141.29	174.125
Manjalar	118.32	88.23	108.18	111.24	108.2
Sirumalaiyar	113.67	155.06	132.78	103.21	112.95
Uppar	137.36	127.05	136.38	134.23	151.214
Sathiar	208.52	204.98	212.64	232.00	205.47
Lower vaigai	225.30	82.18	106.47	142.00	189.24
Total perimeter	1558.42	1363.50	1425.70	1462.15	1510.99

Table 8. Comparison R^2 value for all parameter from each open source dem

	Regression coefficient obtained from various DEMs			
Parameters	**SRTM (R^2)**	**ASTER (R^2)**	**Cartosat-1 (R^2)**	**ALOS Palsar (R^2)**
Sub watershed perimeter	0.86	0.92	0.95	0.99
Sub watershed area	0.75	0.76	0.87	0.97
Slope area (Plain and Hilly)	0.99	0.99	0.99	0.99
Elevation	0.992	0.996	0.996	0.998

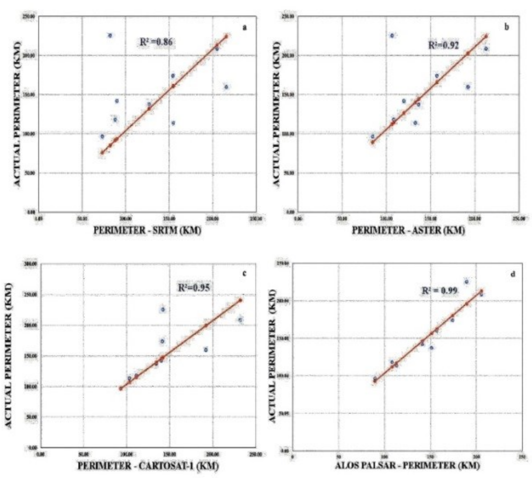


Figure 13. R^2 value for sub-basin perimeter obtained using various DEMs

4.4.3.1 ALOS Palsar DEM

The ALOS Palsar DEM is found better, both in extraction of drainage network and watershed boundary delineation than other DEMs. The vertical error distribution, which is near normal proves it vertical accuracy. It has extracted the watershed boundary very close to the actual shape and area. As seen in (Table 8) with high R^2 value for all the parameters, the ALOS Palsar proved to be an accurate data source, due to its high spatial resolution (12.5m), to estimate area, perimeter, slope area and elevation of the watershed studied and hence it is ranked first in the performancanalysis .

4.4.3.2 Cartosat-1 DEM

The Cartosat-1 extracted more number of streams than SRTM and ASTER, and it delineate the catchment boundary nearer to actual boundary. It has under estimated the elevation at hilly region, urban settlements and at outlet of the river basin but overall elevation accuracy was very close to actual (R^2 =0.996). Slope area predicted by Cartosat -1, SRTM and ASTER is almost similar and close to actual area (same R^2). However , overall the Cartosat-1 has predicted the slope area, area and perimeter of the watershed better than SRTM and ASTER, and hence ranked second in the performance analysis.

4.4.3.3 ASTER DEM

In watershed delineation ASTER DEM delineated the catchment boundary with less number of streams and watershed area than Cartosat-1. In elevation aspects ASTER over predicted higher values near to water bodies and basin outlets and in other area the performance is similar with other DEMs. In estimation of the slope area, the ASTER, SRTM, and Cartosat-1performed very similar (R^2 =0.99 for all). In delineation of sub watershed area and perimeter estimation ASTER performed better than SRTM, and hence ranked third in the performance analysis.

4.4.3.4 SRTM DEM

While delineating the watershed the SRTM under estimated the number of streams and failed to connect with main channel. The accuracy of estimating the elevation and slope area is generally similar to other DEMs. However it has predicted less in perimeter and area than the other DEMs studied, and hence ranked fourth in the performance analysis.

5. Conclusion

This investigation successfully delineated the watershed boundaries using DEMs derived from free open access satellite data. This watershed delineation study in which various parameters such as area, perimeter, slope, elevation, drainage net work extraction and shape etc. have been determined accurately. The use of satellite imagery based Digital Elevation Models (DEM) in an Arc GIS platform, has very well established its robustnous and ease with which the parameters could be determined precisely. The analysis have enabled us to understand how the correlation/association between the predicted parameters watershed area, perimeter, elevation, and slope of the vaigai river basin and the data kept as actual with the Govt. organaisations. . The results show that ALOS Palsar DEM is the best and stand first in the order of accuracy , in delineating the watershed boundaries and in estimating the elevation, area and perimeter of the watershed. . The Regression analysis confirms that the ALOS Palsar high-resolution DEM is the best prediction model among all the DEMs studied. Further it is evident that the ALOS Palsar DEM can be recommended in watershed management as a tool to analyze the watershed parameters.

The Cartosat-1 derived DEM has predicted most of the parameters better than ASTER and SRTM and stand second in order in this process of watershed parameters delineation. ASTER based DEM has predicted the Elevation and slope area very close to the actual, and stand third in the order. Inspite the SRTM based DEM has predicted Elevation and slope area, similar to ASTER its performance in prediction of other parameters make its stand in fourth order, in accurately delineating the watershed parameters.

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