Chapter 2

RESULT AND DISCUSSION
2.1 DRAINAGE MEASUREMENT

Methodological issues collated through review of scientific discourse and the difficulties experienced during actual execution of drainage measurement in Eastern Himalayan basin under consideration can be grouped into four broad categories-

1. Identification and consideration of streams
2. Correct estimation of streams
3. Combining two sources of streams
4. Characterization of complex interconnecting streams

All these methodological issues are detailed in following sections.

2.1.1 Identification and consideration of the streams

Correct and consistent identification of drainage is of fundamental importance as it is one of the most important descriptors of basin morphometry. Identification and consideration of drainage is challenging as evidenced in the pioneering works of Horton and Morisawa\textsuperscript{3,12}. As a source of stream identification, topographical maps are the most common and have been in use right from the early days of morphometric studies\textsuperscript{3,19,87-89}. The usefulness of topographical maps in drainage delineation is that it provides streams at specific scales (1:25000, 1:50000 etc.) and its explicit marking of streams makes the possibility of missing an important drainage rare. Yet inherent difficulties remain to be overcome by researchers using topographical maps. Besides difficulties associated with use of topographical maps, there are other difficulties that one faces during drainage identification and consideration. These difficulties include discontinuous streams, unavailability of topographical maps in terms of recent temporal scale, inaccessibility of topographical maps and complex interconnecting streams.
2.1.1.1 Discontinuous streams of topographical maps

In topographical maps the features marked on the maps are commonly based on field surveys. The marked streams are classified as perennial and non-perennial with the help of blue and black lines. Some non-perennial streams are left independent as they start in the foothills and do not continue & merge with the main streams. The Gaurang basin exhibits similar patterns to streams that originate in western slopes of Chakrashila hill (Fig. 2.1a). As those streams are the part of watershed drainage system, their contribution and magnitude should get carried to river system. But due to absence of linkage with the parent channels, during stream characterization, technically they become excluded. For a solution, the independent streams of Gaurang are superimposed on LISS IV images in order to find out the existing link of those discontinuous streams. It can be clearly marked out that the overlaid independent streams join the main channel (Fig. 2.1b). So, practically there is a need to trace out the existing link of those independent streams as illustrated in Fig. 2.1c. Here it is very important to note that only the marked streams of topographical maps should be considered because the marked streams on topographical maps are the representative of streams at specific scale (in this case it is 1:50000).
Figure 2.1 (a) Discontinuous non-perennial streams of topographical map near Chakrashila hill, (b) overlaid delineated stream of topographical map on LISS IV image and (c) derived continuous stream geometry of Gaurang

2.1.1.2 Unavailability of topographical maps of recent temporal scale

Unavailability of topographical maps in terms of recent temporal scale is a major disadvantage in use of topographical streams. A major portion of Himalayan originated rivers flow through alluvial plains with weak lithology which accelerates frequent bankline adjustment. This is illustrated in Fig. 2.2a, showing the changes in stream pattern over time in Gaurang basin. It demands updating the streams with the help of recent satellite images especially for the weak lithological sections (Fig. 2.2b). Updation is tricky; as it lacks specified criteria and depends on individual judgment in considering the streams. For proper updation of streams, one needs to consider two important aspects; first, the degree of imprints of the streams in images and second, the streams of topographical map. Here the necessity of careful visual interpretation of the streams of images in conjunction with the corresponding streams of topographical maps is of central importance for consistent identification.

Figure 2.2 (a) Changes in stream pattern over time in Gaurang basin and (b) updated streams using LISS IV image

Physiographic factors like vegetation cover may create practical difficulties in the process of updation of streams. The entire stretch of foothills and adjoining areas of Himalayas is mostly covered with dense forest. This creates obstacles in the process of updation as vegetation cover does not allow satellites to provide stream information (Fig. 2.3a). DEM generated streams are also tested for one such portion (Fig. 2.3b) in
the foothills and adjoining areas of Gaurang river basin but it failed to provide satisfactory results. Vegetation cover therefore compounds operational difficulty by blocking satellite imaging and prevents field work in case of densely forested areas. In such situations, streams of topographical maps should be considered for practical purposes. It is generally understood that the streams are reasonably stable in forested areas, so the streams from topographical maps for that area can be taken into consideration.

![Figure 2.3](image)

**Figure 2.3** Inadequacy of- (a) LISS IV image in stream identification and (b) DEM in stream generation for the forested area in the plains of Gaurang

### 2.1.1.3 Intra-basin artificial streams and canals

One of the major human interferences in basin stream structure is the intra-basin artificial canals. It not only affects the drainage structure but also causes a significant impact on flow characteristics of a basin. For example, a large number of artificial channels are made on almost all major tributaries of Gaurang (Fig. 2.4a). From a morphometric point of view, two factors associated with these canals are very important, viz., the size of the canal and more importantly whether the canal rejoins the main channel or terminates in agricultural fields. The size of the canals imparts direct impact on the amount of water it removes from a tributary which in turn directly affects the magnitude of flow characteristics of a river. In case of concentration of water of canals, if an artificial canals rejoins the main stream it can serve as an anabranch whereas if it ends in agricultural fields and shows no outlet to any main stream, logically that canal cannot be considered as the drainage of the basin. In case of Gaurang, even if the water diversion due to artificial canals is causing a significant impact on flow characteristics,
logically, these canals cannot be considered as a part of drainage of the basin (Fig. 2.4b) as the canals do not have outlet to the main stream. Although the rational approach for consideration of canals is conferred, there is a strong need of insightful scientific rigour for consideration of canals as basin drainage structure.

**Figure 2.4** (a) Artificial canals made over major stream and (b) isolated natural stream of Gaurang basin

### 2.1.1.4 Inaccessibility of topographical maps

There is a common limitation regularly faced by the researchers in use of topographical maps. Topographical maps for the basin of the rivers of Brahmaputra, which shares the boundaries of two or more countries, are not accessible to the researchers because of administrative reasons. In case of Gaurang, the topographical map for the upper most portion is not accessible as it lies entirely in Bhutan (Fig. 2.5). In that case other stream information sources viz., DEM, aerial photographs and imageries are needed to be used in conjunction with topographical maps. This means use of one source for one portion of the basin and another for the rest. In this context, the methodical approach that combines the streams of two sources is vital. As the attributes of the estimated streams from different sources varies significantly, there is a definite need of methods and techniques.
that combine streams of different sources with consistency. This is an area of exploration for researchers working in drainage studies.

![Inaccessible portion of Gaurang due to administrative reason](image)

**Figure 2.5** Inaccessible portion of Gaurang due to administrative reason

### 2.1.1.5 Complex interconnecting streams

Apart from stream identification and consideration, complex intra-basin interconnection of streams is a major obstacle in stream characterization of a basin. After getting the desired drainage network, the first step in stream characterization is to number the streams following the well established defined set of rules by Horton, Strahler or Shreve. However, its execution in complex stream interconnection introduces subjective uncertainty. These fundamental rules of stream ordering were basically developed considering linear basin with simple hierarchical streams. None of the studies discussed its feasibility in complex interconnecting stream found throughout the world in the form of distributaries. The complex interconnecting streams are common drainage geometry throughout the world. **Figure 2.6** shows such complex interconnecting streams identified in Gaurang river basin. For adequate drainage characterization in case of complex...
interconnecting streams, a distinct protocol is explicitly needed keeping the fundamental rules unaltered.

Figure 2.6 Complex interconnecting streams of Gaurang river basin

Out of the five difficulties outlined in this section, first three are minor ones and can be removed by following protocols built on rationality and physical principles. Later two, inaccessibility of dataset and complex interconnecting streams, are critical and certainly demand decisive approaches to overcome it. These two critical difficulties are dealt with thoroughly in separate sections (section 2.1.3 and section 2.1.4 respectively).
2.1.2 Correct estimation of the streams

The estimation of streams from DEMs is an area of much innovation in recent years. The accessibility of DEMs coupled with availability of advanced GIS tools made it the most extensively usedgeo-informational source in drainage studies in recent decades. But as discussed in the introduction section, adequacy of the existing methods for stream estimation from DEM is an area of concern and demand exploration of effectual methods.

Responding to this issue, a novel method of stream estimation is proposed where the contemporary threshold method is compared and effectiveness of proposed method is assessed quantitatively. This method automatically generates streams from downscaled DEMs using stream order tool of ArcGIS. This stream order tool entails two inputs- (a) stream raster and (b) flow direction and performs a cell by cell correspondence of the inputs to generate streams. In this approach, flow accumulation raster is used as stream raster and with the help of flow direction raster the drainage map is derived at specific DEM scales. The suggested method is based on DEM downscaling and is demonstrated in the section 2.1.2.1.

The downscaling hypothesis is further evaluated with application of raw DEMs as stream input against flow direction derived from same surface. The basic intention of applying raw DEM as stream input is to assess whether its application further enhances the expediency of the approach. The assessment is demonstrated in the section 2.1.2.2.

2.1.2.1 Drainage estimation from accumulated surface

In the last two decades, DEM has become an extensively used tool in estimating hydrological characteristics of a surface. It generates digital representation of drainage network which is a crucial hydrological descriptor. The most convenient and widely used method of drainage extraction from a DEM surface is the d8 method which apparently allows access to all possible flow accumulation from channeled and unchanneled regions of a landscape. In actual practice this involves manual manipulation in choice of streams to decide threshold values required to categorize stream lines from accumulated flow of terrain. The element of manual choice restricts representation of stream geometry at a chosen DEM scale. This in turn highlights two main areas which detract from accuracy of assessment.
The first area concerns estimation in number and length of streams in drainage from DEM\textsuperscript{100}. Overestimation of stream numbers is inherent in high resolution DEM where channel head matching is used as threshold criteria. This arises from the visual similarities either in terms of channel head extent or in stream numbers used for determining the minimum contributing area (threshold). Channel head extent matching causes an overestimation of stream numbers whereas number matching causes an underestimation of channel lengths. Thus the problem of disagreement between the actual network and those generated from high resolution DEMs is a persistent problem for both these criteria.

The second area is associated with the estimation of the lower order streams\textsuperscript{101,102}, especially when high resolution DEM is considered. Since the stream net follows a hierarchical order for their stream segment characterization, incorrect estimation of lower order stream affects the overall stream geometry. A number of researchers have studied the effect of DEM resolution on drainage generation. Garbrecht and Martz found a relation in which the channel links and the total channel length decreases with increase in DEM grid size\textsuperscript{103}. Wang and Yin showed that low resolution DEM tends to produce less stream segments\textsuperscript{104}. A similar trend for first order streams is observed by McMaster\textsuperscript{105}. The results presented in the work of Saran et al. showed drainage density and stream frequency decrease with DEM resolution\textsuperscript{106}. All these investigations clearly indicate that coarser resolution DEM reduces the stream numbers and their extent.

Therefore, it is rational to recognize that re-sampling DEMs can be used as a practical tool for limiting the extent of stream generation. In this context it is important to note that physical properties of derived topographic features vary with re-sampled DEMs especially in terms of spatial coincidence. However, previous works on re-sampling of DEM and drainage features suggest that physical properties of topographic features become disproportionate only after many-fold downscaling\textsuperscript{103,105}. Therefore, in spite of the stated concerns, re-sampling maybe applied to find out drainage that is closest to the reference drainage.

This work therefore presents a method of automatic skeletonizing to overcome the highlighted detractors of accuracy and processing efficiency. This method processes raw flow accumulation stream information with corresponding flow direction raster to generate drainage network maximizing possible drainage geometry at the required DEM.
scale. For this purpose, stream order tool of ArcGIS 10 is utilized that works on cell correspondence of flow direction and accumulation derived from the same surface. The focal point of this method is the generation of drainage pattern without any human intervention. Beyond eliminating manual interpolation, this method successfully addresses the other two concerns of overestimation and re-sampling and concludes with due validation based on stream number (Nu) and stream length (Lu) generated from the re-sampled DEMs and stream pattern of 1:50000 topographical maps.

**Figure 2.7** Location map of test watersheds taken for demonstration of the method

Two test watersheds, denoted as test watershed1 (TW1) and test watershed2 (TW2) of lower Himalayas are taken to demonstrate the proposed approach. To get consistent result for the chosen test-watersheds and the proper validation of the findings, both the watersheds are taken from sites with identical slope and undisturbed natural vegetation cover. The chosen test watersheds are located in Southern Bhutan (Fig. 2.7).
Methodology

The method is designed to generate all possible stream geometry from accumulated raster surface without the use of threshold. For this purpose, stream order tool of ArcGIS 10 is utilized. Flow accumulation raster and corresponding flow direction are used as inputs for generating stream that conserves drainage geometry at desired DEM scale. The steps followed are detailed in the schematic diagram presented in Fig. 2.8. The methodology section is sub-divided into- (a) raster re-sampling (b) stream raster generation and vectorization, and (c) accuracy assessment.

**Figure 2.8** Design and implementation of the proposed methodology of stream generation from flow accumulated surface without the use of threshold

**Raster re-sampling**

A number of methods are available for re-sampling, viz. nearest neighbour, bilinear interpolation, cubic convolution, majority re-sample and contour interpolation. Out of these, the most commonly used one is the nearest neighbour method\(^{100,102}\). In this analysis, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
DEM with 30 meter resolution is re-sampled to coarser resolutions using nearest neighbour method in Arc GIS 10. To minimize data loss, 30m grids are transformed into grids of 60m and 90m which avoid splitting of grids. Four and nine neighbouring grids are combined to get medium (60m) and low (90m) scale DEM for the test areas.

**Stream raster generation and vectorization**

**Filling**

Re-sampling into coarser resolution combines the neighbouring pixels which may lead to propagation and formation of discontinuity in resultant DEM. So, filling is performed to ensure removal of any discontinuity produced or propagated from the raw data. Filling guarantees that each cell is part of one or more decreasing pathways of cells ending at the edge of the DEM which helps in generating a continuous stream network from DEM.

Accumulated stream order raster (A-SOR)

Flow accumulation, a commonly used drainage delineation tool, takes into consideration the pixels that serve as water storage and ignores the elevated ridges while generating flow accumulation raster. Consequently, stream geometry is produced by using threshold which defines the critical area in estimation of streams from the accumulation raster. This is commonly decided by trial and error method either by considering channel head extent or number matching. In case of high scale DEM the threshold based on channel head extent gives an overestimation of Nu (Fig. 2.9a), whereas the threshold based on Nu reduces the Lu (Fig. 2.9b). So, high scale DEM for stream estimation compromises either Lu or Nu depending on threshold criteria. In the case of low scale DEM, however, overestimation of Nu, with stream head extent as threshold, is absent but gives rise to another problem i.e., pixel clumping (Fig. 2.9c). So, subjectivity remains with the application of threshold for drainage generation. Therefore, the proposed approach estimates stream by downscaling DEM instead of using threshold. It is already recognized that DEM re-sampling can be rationally used for limiting the extent of stream generation. So, re-sampled DEM can be efficiently used for proper stream estimation with the help of stream order raster (A-SOR) that generates streams without the use of threshold.
Figure 2.9 Threshold defined accumulation raster based on- (a) head extent matching for high scale, (b) number matching for high scale and (c) head extent matching for low scale DEM

In the above context it is important to use raw accumulation raster (flow accumulation raster without threshold) for generating scale-based stream order raster. Raw accumulation raster conserves all the possible flow accumulation at the DEM scale. The stream order tool in Arc GIS 10 allows the generation of a scale-based stream order raster by using raw accumulation raster with flow direction (raster). Use of raw accumulation raster and flow direction raster as inputs generate stream without the use of threshold. The resultant stream order raster, A-SOR conserves drainage geometry at DEM scale.

Figure 2.10 A-SOR with (a) unfilled elevated ridges, background and streams, and (b) re-classed streams
A-SORs from 30m as well the other re-sampled DEMs are generated using flow direction and raw accumulation derived from the corresponding DEM surface. Since raw accumulation is the input stream raster for A-SOR generation, the resultant raster shows no value for elevated ridges, but gives a background value of the lower most class. Therefore, A-SOR is re-classed by providing zero background value for class 1 and the rest are entailed as drainage net (Fig. 2.10).

Threshold defined stream order raster (T-SOR)

Apart from A-SOR, threshold defined stream order rasters (T-SOR) are generated to compare efficacy of A-SOR. There are two common approaches for threshold determination: trial and error method and slope and area method. Practically, threshold varies with DEM scale. Therefore before generating T-SOR, thresholds for each scale were decided. For better comparison, proximity with A-SOR channel head extent is used to decide threshold for flow accumulation raster. With trial and error method, channel head proximity of accumulation raster is found to be highest at a threshold of 0.014, 0.035 and 0.079 % area for high, medium and low scale DEM respectively for TW1; and 0.034, 0.109 and 0.246 for TW2. Threshold defined accumulation is used as stream raster input for the generation of T-SOR.

Vectorization

The generated stream rasters (re-classed A-SORs) are converted into vector files using the conversion tool in GIS environment. The converted vector lines are corrected manually to get a smooth drainage pattern. The drainage maps for both watersheds - TW1 and TW2- have been prepared at all three scales. After securing the stream vectors, the stream lines are ordered following Strahler’s hierarchical system. Finally, the ordered drainage maps for TW1 and TW2 for A-SOR are prepared (Fig. 2.11). Drainages from the topographical map for the test watersheds are delineated and ordered (Fig. 2.11) to use as references for matching with those estimated from A-SORs. Survey of India topographical maps of 1:50000 scales, the most common source of drainage maps in this region, are used for this purpose.
Accuracy assessment

Accuracy assessment in various interpretations and applications of DEM is necessary to validate the outcomes. Since GIS generates streams based on the height information enclosed in each digital pixel and does not take other physiographic aspects into account, therefore it is possible that the generated streams differ from the real drainage pattern. To verify if the generated streams reflect the actual drainage pattern, it is important to check accuracy with the reference drainage maps. In this study, validation is carried out on the basis of Nu and Lu matching generated from the re-sampled DEMs with stream pattern of 1:50000 topographical maps. Since Nu and Lu are the basic parameters for evaluating drainage characteristics, they are taken as the means of accuracy measurement. Percentage accuracy of Nu and Lu is assessed for both the watersheds.

Result and discussion

A primary focal point of this work is to assess the resultant streams of the proposed method versus the threshold based approach. It is evident from the results that A-SORs for both watersheds have less pixel clumping as compared to T-SORs (Fig. 2.12). This may be due to higher cell by cell correspondence in A-SOR which is generated from raw accumulation raster that has all the possible flow accumulation and flow direction raster derived from the same surface. Whereas in T-SOR, the stream raster is threshold defined accumulation and the flow direction only orders the restricted streams. Therefore, the problem of pixel clumping continues to appear during generation of flow accumulation raster at higher level of stream head extent. Lower pixel clumping in A-SOR allows effective identification of greater stream head extent.

After affirmation of better identification of streams, the A-SOR estimation of streams at different DEM scales is further analyzed. The variations in Nu and Lu for different stream orders with DEM scale is presented in Fig. 2.13. It is found that both Nu and Lu for lower order streams, especially the first order, increase manifold from lower to higher scale DEM. These variations, however, are the least for higher order streams. This pattern of variation in Nu and Lu suggests greater dependency of lower order streams on DEM scales. Further the results of the analysis carried out at basin level and order wise for A-SOR reflects the effect of scale on stream generation. The calculated descriptors of channel network properties i.e., drainage density (Dd), stream frequency
(Fs), Nu and Lu, derived from different scale DEMs are summarized in Table 2.1. It displays Nu and Lu are the highest for finer resolution and decreases as the resolution become coarser. Similar patterns are exhibited for Dd and Fs.

Figure 2.11 Ordered drainage map extracted from A-SOR at re-sampled DEM scale and topographical map for (a) TW1 and (b) TW2
Figure 2.12 Stream raster generated by A-SOR for (a) TW1 and (b) TW2, and T-SOR for (c) TW1 and (d) TW2 at re-sampled DEM scale.
Table 2.1 A-SOR generated stream characteristics at re-sampled DEM scales

<table>
<thead>
<tr>
<th>DEM scales</th>
<th>30m</th>
<th>60m</th>
<th>90m</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW1 Stream numbers</td>
<td>643</td>
<td>342</td>
<td>199</td>
</tr>
<tr>
<td>Stream length (in km)</td>
<td>215.4</td>
<td>102.1</td>
<td>105.2</td>
</tr>
<tr>
<td>Drainage density (in km(^{-1}))</td>
<td>7.1</td>
<td>8.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Stream frequency (in km(^{-2}))</td>
<td>21.2</td>
<td>27.4</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Figure 2.13 Stream number and length variation with DEM scales using A-SOR method

In case of TW1 and TW2, quantified measures of drainage properties estimated from A-SORs and topographical maps show that out of the DEM generated drainage networks, the one closest to the reference topographical drainage is provided by the re-sampled medium scale DEM (Fig. 2.14). Both Nu and Lu estimated from medium scale DEM show high accuracy level (96.8 % and 81.5 % respectively) as shown in Table 2.2. The accuracy assessment shows greater matching of 60m DEM generated average stream lengths with those of topographical map.
One of the major problems in drainage characterization is the estimation of Nu and Lu of lower order streams. The results of the proposed method show that the A-SOR for downscaled DEM can be effectively used for closer estimation of lower order streams in terms of Nu and Lu. The use of A-SOR allows extraction of stream heads to greater stream head extent. Again, the DEM downscaling takes care of overestimation in Nu. In the present demonstration area, results reveal that lower order stream geometry extracted using A-SOR for 60m downscaled DEM shows greater matching with the reference drainages. The percentage similarity for the first order streams is as high as 81.5% and 98% for Nu and Lu respectively (Table 2.2).

A spontaneous key exercise of this work is to assess the positional mismatch that may arise due to downscaling of DEM. Process of downscaling averages the neighboring cells of higher resolution and thus it may lead to positional shift of streams derived from downscaled DEMs. In this context, evaluation is made for positional mismatching of streams of A-SORs derived from different resolution DEM. It is examined by overlay analysis of A-SORs generated from raw 30m DEM with downscaled 60m DEM (Fig. 2.15a). This appraisal shows that downscaling clusters the neighbouring channels in the upper ridges and results in loss of lower order streams but maintains the position of major streams. Further, an evaluation is made by comparing the magnitude of the tributaries of TW-2 estimated from streams of A-SORs and topographical map (Fig. 2.15b). For this purpose, seven critical locations are taken which are the confluence points of the tributaries with the mainstream. All the seven tributaries estimated from the downscaled

**Figure 2.14** Stream numbers and length at re-sampled DEM scales and topographical map for TW1 and TW2

![Stream numbers and length at re-sampled DEM scales and topographical map](image)
60m DEM and delineated from topographical map show same magnitude thus reinforcing this method and result.

**Table 2.2** A-SOR generated stream characteristics accuracy at re-sampled 60m DEM with reference to topographical map

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TW1 60 m</th>
<th>TW1 TM</th>
<th>% error</th>
<th>TW2 60 m</th>
<th>TW2 TM</th>
<th>% error</th>
<th>Mean % accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stream number</td>
<td>199</td>
<td>168</td>
<td>18.5</td>
<td>102</td>
<td>86</td>
<td>18.6</td>
<td>81.5</td>
</tr>
<tr>
<td>Total stream length (km)</td>
<td>105.2</td>
<td>103.8</td>
<td>2.3</td>
<td>51.3</td>
<td>49.4</td>
<td>3.9</td>
<td>96.8</td>
</tr>
<tr>
<td>Average length (km)</td>
<td>0.51</td>
<td>0.62</td>
<td>17.7</td>
<td>0.50</td>
<td>0.57</td>
<td>12.4</td>
<td>84.9</td>
</tr>
<tr>
<td>1st order stream number</td>
<td>154</td>
<td>131</td>
<td>17.6</td>
<td>80</td>
<td>67</td>
<td>19.4</td>
<td>81.5</td>
</tr>
<tr>
<td>1st order stream length (km)</td>
<td>67.1</td>
<td>67.0</td>
<td>0.1</td>
<td>31.7</td>
<td>33.0</td>
<td>3.9</td>
<td>98.0</td>
</tr>
<tr>
<td>Average length (km)</td>
<td>0.44</td>
<td>0.51</td>
<td>14.9</td>
<td>0.39</td>
<td>0.49</td>
<td>19.5</td>
<td>82.8</td>
</tr>
</tbody>
</table>

TM is topographical map

**Figure 2.15** Evaluation of (a) positional matching of the streams of A-SORs and (b) magnitude of tributaries estimated from 60m DEM and topographical map

The overall results show A-SORs give better identifiable stream raster than the routinely used threshold defined stream raster at greater channel head extent. The graph presenting...
Nu and Lu estimated from A-SOR clearly suggest rapid decrease in Nu compared to Lu for TW1 and TW2 (Fig. 2.16). As A-SOR identifies stream at greater head extent, it helps in maintaining the stream length even at lower resolution DEM and therefore provides opportunity to restrict the number by downscaling of DEM. So, the proposed A-SOR approach can be efficiently used for stream estimation from DEM.

**Figure 2.16** Variation of stream length and number with DEM resolution for TW1 and TW2

This method addresses a major issue of over and under estimation of streams generated from DEM by using a method of automatic skeletonizing of streams which restricts stream estimation from DEM based on downscaling. When tested on the two watersheds, the resultant A-SORs give better identifiable stream raster than the routinely used threshold defined stream raster at greater channel head extent. This method therefore allows A-SOR to be efficiently used for evaluation of basic descriptors of drainage properties resulting in closer estimation when coupled with selection of appropriate DEM resolution. One of the biggest problems associated with streams generated from DEM is the overestimation of lower order streams. The result clearly indicates that A-SOR with selection of appropriate resolution can effectively overcome the problem of lower order stream estimation. The advantages of combining A-SOR and DEM downscaling are that it allows extraction of stream to greater extent at the same time limiting the stream numbers. So, the proposed technique can be effectively used in controlling the basic drainage characteristics- stream number and length. The proposed method would provide much closer estimation of stream when finer resolution DEM is used as it provides a scope of re-sampling into smaller intervals.
2.1.2.2 Drainage estimation from raw DEM

Finding out optimum DEM resolution for drainage extraction has been a concern among scientists\textsuperscript{103,105,109-111}. To derive optimum DEM resolution for stream estimation, many authors have downscaled DEMs using different methods\textsuperscript{99,102,112,113}. Downscaling of DEM involves combination of neighbouring grids that forms coarser resolution data. But it may lead to deformation of the information retained in DEMs. The major concerns related to downscaling of DEM are - loss of details\textsuperscript{114,115} and positional shift of streams\textsuperscript{103,105,116}. The complicity of first aspect i.e. loss of details can be ruled out in its application as finer resolution DEM provides more information than required and thus results in noise at the landform scale\textsuperscript{117,118}. It is largely dependent at the scale at which one needs to extract the topographical information and to achieve the optimum DEM, re-sampling can be successfully performed to a certain extent as physical properties of topographical features become disproportionate only after many-fold downscaling\textsuperscript{103,105}. On a more positive note, DEM downscaling clusters the neighbouring channels in the upper ridges and results in loss of lower order streams but maintains the position of major streams\textsuperscript{116}.

Flow accumulation raster generated from d8 method by O’Callaghan & Mark is most commonly used for the purpose of stream estimation from DEM\textsuperscript{48}. As flow accumulation raster contains all channeled and unchanneled regions except the elevated ridges, to get the drainage, one needs to distinguish the channeled portion. It is generally achieved by Tarboton et al.’s method that uses threshold\textsuperscript{90}. But uncertainty remains with the use of threshold as it either compromises with stream number or stream length in case of high resolution DEMs whereas in case of low resolution DEM, it gives rise to the problem of pixel clumping (Fig. 2.9).

To remove this uncertainty, an automatic method of stream generation (A-SOR) has already been proposed which uses stream order tool of ArcGIS. The major advantage of A-SOR method is that it generates streams at greater head extent and thus facilitates application of downscaling approach to find out optimum DEM resolution that has appropriate details required for stream estimation at a reference scale. A-SOR method incorporates stream raster and flow direction, where raw accumulation raster is used as stream input, and their cell by cell correspondence in stream order tool automatically generates drainage pattern at different DEM scales.
The proposed A-SOR method generates all possible drainage geometry that a raw flow accumulation raster contains at a given scale. Here, it is important to note that flow direction raster derived from d8 method automatically carves out stream geometry from a base map containing stream information. This promotes application of raw DEM as a practical alternative of stream raster because raw DEM exhibits all topographical information, including stream information. The application of raw DEM as stream input is inspired by the fact that DEM exhibits more topographical information than flow accumulation raster; accumulation raster removes the cells representing elevated ridges, and therefore provides higher chances of stream generation.

With the above appreciation, a method of stream estimation using raw DEM as stream input in stream order tool is proposed. The method follows the notion of downscaling DEM for correct stream estimation where the correctness is assessed in terms of basic stream parameters i.e. stream number and length. The central motivation of this work is to evaluate the implication of the raw DEM based approach in closer stream estimation and its efficacy is tested against the drainage skeletonized from accumulated surface.

**Methodology**

For demonstration of the approach, four Eastern Himalayan small-sized test watersheds, less than 10 sq km, are taken. They are designated as TW1, TW2, TW3 and TW4 (Fig. 2.17). Smaller sized test watersheds are intentionally taken as it chiefly constitute of lower orders streams which presents majority of the disagreement during stream estimation from DEM\textsuperscript{101,102}. ASTER DEM of 30m resolution for all four test watersheds are delineated and downscaled DEMs and generated flow accumulation raster are incorporated with corresponding flow direction raster in stream order tool to generate streams at respective scales. The methodology involves is categorized as – (a) data pre-processing, (b) stream raster generation and (c) comparison, and are detailed in following sections including a schematic diagram (Fig. 2.18).
Figure 2.17 Test watersheds taken for demonstration of the method

Data pre-processing

For the purpose of DEM re-sampling, the most commonly used method of raster re-sampling i.e. nearest neighbour method is implied in GIS environment. ASTER DEM of 30 meter resolution is downscaled to 60, 90, 120 and 150 m in ArcGIS 10 for the four test basins. Then filling is performed to ensure removal of discontinuity present or induced (due to re-sampling) in DEM surface. After filling, flow direction maps are derived for all five resolution DEMs using hydrology tool of ArcGIS 10. Finally flow accumulation raster is generated from flow direction map.
Figure 2.18 Design and implementation of the methodology for stream generation from raw DEM and flow accumulated surface

Stream raster generation

After the preprocessing, DEMs of different resolution are incorporated with corresponding flow direction raster in Stream Order Tool to generate stream raster termed as D-SOR. Similarly, flow accumulation rasters are incorporated with corresponding flow direction to generate stream raster which is termed as A-SOR. Both the resultant stream i.e. D-SOR and A-SOR exhibits a background value of the lower most class. Therefore, streams are discriminated by removing the background by providing a zero value for class 1. Finally the drainages are vectorized from generated D-SOR and A-SOR as well as topographical maps.

Comparison

For the purpose of comparison of the results, the basic stream parameters i.e. Nu and Lu are taken. A test of comparison of the D-SOR and A-SOR estimated Nu and Lu are
carried out against the reference drainage delineated from 1:50000 topographical maps. With these tests, the efficacy of the D-SOR is evaluated and advantage of D-SOR method over A-SOR method is outlined.

Result and discussion

The results show large dependency of DEM generated streams on its resolution. Similar to stream generated from A-SOR\textsuperscript{116}, Nu and Lu are highest for the higher resolution DEM and it decreases with lower resolution. The comparison between D-SOR and A-SOR generated streams highlights greater streams estimation from the prior method. Both the basin drainage parameters i.e. Nu and Lu are considerably high with application of DEM as stream input (Fig. 2.19).

There is a basic difference between the two stream inputs - flow accumulation and DEM raster. Flow accumulation raster removes the cells representing elevated ridges by assigning zero value to it. Thus generated stream raster using flow accumulation as stream input contains channeled and unchanneled region without the elevated ridges. Whereas DEM as stream input exhibits all the cell information intact and thus DEM-generated streams contains only channeled and unchanneled regions without removing any information. Thus implication of DEM as stream input provides more surfaces to generate greater number of streams as compare to accumulated surface (Fig. 2.20).

Nu and Lu estimated from downscaled DEMs using D-SOR and A-SOR, and those determined from topographical maps are shown in Fig. 2.19. As mentioned earlier, D-SOR facilitates generation of higher streams, coarser resolution DEM of 90m as stream input shows highest similarity with the reference drainage of topographical map. Whereas, with application of flow accumulation raster as stream input, A-SOR method, one scale finer resolution DEM (60m) estimates streams that shows highest proximity with the reference streams of topographical maps.
**Figure 2.19** Stream number and length estimated for TW1, TW2, TW3 and TW4 with D-SOR and A-SOR method and comparison with reference drainage of topographical map
Figure 2.20 30m- (a) DEM which exhibits all cell information and (b) flow accumulation which has removed the elevated ridges by assigning zero value to it.

Accuracy assessment in application of D-SOR and A-SOR methods for stream estimation is necessary to validate their applicability. The accuracy assessment of Lu and Nu estimated from downscaled DEMs using D-SOR and A-SOR against those estimated from topographical maps are shown in Table 2.3. For all four watersheds, D-SOR shows superiority in stream estimation as compared to A-SOR. Significant increase in accuracy of estimated Nu and Lu with application of D-SOR is found. The mean percentage accuracy of Nu and Lu are found to be as high as 87.93 % and 94.5 % respectively and guarantees the efficacy of D-SOR.

The A-SOR method is based on the motivation that it identifies stream at greater head extent and therefore provides opportunity to restrict the number by downscaling of DEM. D-SOR method generates streams at even greater head extent (Fig. 2.21) thereby highlighting a practical advantage over A-SOR.
Table 2.3 Stream number and length derived using D-SOR and A-SOR methods and their percentage accuracy with reference drainage of topographical maps

<table>
<thead>
<tr>
<th>Watersheds</th>
<th>Stream numbers</th>
<th>Stream length (km)</th>
<th>Stream numbers</th>
<th>Stream length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90m DEM</td>
<td>TM</td>
<td>%error</td>
<td>90m DEM</td>
</tr>
<tr>
<td>TW1</td>
<td>25</td>
<td>22</td>
<td>13.6</td>
<td>14.3</td>
</tr>
<tr>
<td>TW2</td>
<td>33</td>
<td>30</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>TW3</td>
<td>31</td>
<td>35</td>
<td>11.4</td>
<td>16.7</td>
</tr>
<tr>
<td>TW4</td>
<td>34</td>
<td>30</td>
<td>13.3</td>
<td>21.3</td>
</tr>
<tr>
<td><strong>Mean % accuracy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>87.9</td>
<td></td>
<td></td>
<td>94.5</td>
</tr>
</tbody>
</table>

TM is topographical map; ACC is accumulation raster
One of the key features of A-SOR method is that it maintains stream length at lower resolution DEMs. It is found more so in case of D-SOR where apart from identification of streams at greater head extent, the method generated streams maintain stream length for downscaled DEMs (Fig. 2.22). This appraises higher chances of DEM downscaling to restrict Nu and certainly facilitates closer estimation of streams.
Figure 2.22 Variation in stream number and length with DEM resolution estimated with D-SOR and A-SOR

The DEM downscaling hypothesis is successfully implied in stream estimation using raw DEM as stream input in stream order tool. D-SOR estimated streams were compared with those estimated following A-SOR method in terms of Nu and Lu. On the basis of evaluated results against reference drainages, D-SOR method shows superior results in terms of both the basic stream parameters. The superior stream estimation from D-SOR method is basically due to its ability of stream generation at greater head extent which mostly sustains with downscaling and thus promotes DEM downscaling for correct estimation of Nu and Lu.
2.1.3 Combining two sources of streams

Drainage source limitation can impose major hindrance in hydrological studies. Topographical maps, aerial photographs, satellite imageries and DEMs are the major sources of stream information. Where, the factors like accessibility of data, availability in terms of their existence as well as recent time scale and competence are limiting factors in consistent and proper identification of the stream. In many cases these factors lead to situations of data limitation for a fraction of basin area which forces the researchers to use a second source to get the drainage information of entire basin. Using stream information of two or more sources lead to recognition of inconsistent and improper streams as there is no standard protocol available for their consideration.

One such example of stream source limitation is shown in section 2.1.1.5 where the topographical maps as source of drainage information for the upper most part of the basin is not accessible to Indian researchers due to administrative and security reasons. In that case, DEM is tested to generate drainage geometry of the basin, but it failed to give satisfactory results for the lower plain of the basin. The lower plain of the basin has very low gradient and therefore DEM does not generate well defined streams.

This necessitates use of two sources i.e. one for a portion of the basin and other for the rest. It demands an approach that combines streams derived for two or more sources consistently. In this regard, this section proposes an approach that combines streams derived from DEM and topographical maps, two most important sources of drainage information, properly. The stream combining method is demonstrated taking Gaurang river basin as an example. As already mentioned, for Gaurang the uppermost portion of the basin lies in Bhutan and topographical maps for the portion is not accessible to Indian researchers (Fig. 2.23).
**Dataset and methodology**

This approach combines the streams of topographical map for the available portion with the streams generated from DEM for the portion where the topographical map is not accessible. Therefore, this work includes two data sources viz., topographical maps of 1:50000 scales acquired from Survey of India and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM data of 30 meter resolution downloaded from Land Processes Distributed Active Archive Center (LP DAAC).

The prime focus of this work is to derive compatible stream geometry from two different sources. In this respect, it is important to identify the aspects that are crucial in combining streams of different sources. Stream generated from DEMs largely depend on the resolution of the data and the threshold value that separates the channeled region. Thus stream matching is a major factor that needs to be addressed before combining with the streams of topographical maps. Another factor is the positional matching of the streams derived from both the drainage sources. Thus for deriving a consistent combined stream geometry, one must assess these two crucial aspects i.e. stream matching and spatial coincidence.

**Figure 2.23** Location map of Gaurang – the basin used as an example for illustration of method combining two sources of streams
Keeping the two aspects in mind the proposed approach is organized in the sequence of (a) stream matching of the sources, (b) positional match in streams of the sources and (c) drainage and positional error calculation.

With a purpose of verification of the results, the upper portion of the basin, where the topographical maps are accessible, is divided into two parts. For convenience, the lower part of this division is termed as test-area and the upper as verification-area. Similarly, the area for which topographical map is not accessible is termed as application area (Fig. 2.24). The stream matching for both the sources are tested for the test-area, the best result is verified with the verification-area, and finally, applied in application area.

**Figure 2.24** Classified portions of Gaurang basin termed as- test, verification and application areas

*Stream matching*

D-SOR method is used for estimation of streams from downscaled DEMs and those are compared with the streams delineated from topographical maps. It is evidently found that D-SOR method facilitates generation of very close stream geometry to those of
topographical maps. Therefore, it is intentionally used for the purpose of stream matching. The steps followed for generation of streams from DEMs are arranged as – (a) re-sampling and filling and (b) drainage generation and delineation.

Re-sampling and filling

DEM downscaling method is applied for stream estimation from DEM. For this purpose, 30m ASTER DEM is re-sampled by the nearest neighbour method for linear aggregation reformed on the blocks of 2x2, 3x3, 4x4 and 5x5. It provided a series of DEMs with spatial resolution of 60m, 90m, 120m and 150m. Further, raw as well as re-sampled DEMs are filled in GIS environment to ensure removal of discontinuity present in the dataset. Filling is more important for the re-sampled DEMs as the process may produce linear artifacts in aggregation process.

Drainage generation and delineation

Stream geometries for all five resolution DEMs are generated using D-SOR method (as mentioned in section 2.1.2.2) and the drainages are vectorized for the test area (Fig. 2.25). The drainages, thus delineated, are compared with those of the topographical maps for the test area to determine the closest matching. The re-sampled DEM that provided the streams of maximum matching with that of topographical maps for the test area is further verified by using it for the verification area. After verification, stream derived from the re-sampled DEM (showing maximum matching for both test and verification area) is considered for the application area.

Stream positional matching

Spatial mismatch of the streams of topographical maps and DEM is a major concern in combining these two sources. Spatial mismatch arise as result of the subjectivity of streams generated from DEM, particularly in head-ward ends\textsuperscript{101,102} and most commonly, during transformation of co-ordinate system for uniformity which introduces planimetric shift.

For topographical mapping activities, the Everest ellipsoid has been used in India and adjacent countries, whereas DEM possesses geographic co-ordinate system of WGS-84. To combine the streams of both the sources, one needs to bring them into uniform co-
ordinate system. For this, topographical maps are projected with the projection system of DEM. Transformation of Datum/co-ordinate system of the topographical maps introduces geometric error in terms of planimetric shift\textsuperscript{119,120}. An alternative source of transformed WGS co-ordinate system (with UTM projection) is Open Source Maps (OSM). However, mathematically transformed sources produce lot of mismatching\textsuperscript{121}.

For reducing the positional shift of the streams, GCPs of the nodal points of major tributaries of DEM are taken as the references for geo referencing of topographical maps. The method imports DEM’s projection to the topographical maps with less stream spatial mismatch.

**Calculation of drainage and positional errors**

Streams delineated from DEMs of all five resolutions are compared with those of topographical maps. The accuracy of matching in number (\(N_u\)) and length (\(L_u\)) of streams is estimated statistically to choose the best representing stream derived from DEMs.

Similarly, accuracy matching for the verification area is also done to ensure that resultant streams can be considered for the application area. To calculate the positional mismatch, the major tributaries of topographical maps as well as DEM are used as the reference features. Systematic sampling points at a distance of 2 km from the end point of major tributaries are taken to calculate the areal displacement of the streams (Fig. 2.26a).
Figure 2.25 Ordered drainages estimated from re-sampled DEMs


Result and discussion

The primary focus of this section is to find the closest matching of the streams of the DEMs with that of topographical maps. Matching is carried out on the basis of Nu and Lu generated from the re-sampled DEMs with stream pattern of 1:50000 topographical maps. Since Nu and Lu are the basic parameters for evaluating drainage characteristics, they are used as the means of matching. The drainage maps generated from DEMs of different resolution is presented in Fig. 2.25. A comparison of Nu and Lu is presented in Table 2.4.

Table 2.4 Attributes of streams estimated from re-sampled DEMs and topographical map

<table>
<thead>
<tr>
<th>DEM resolutions</th>
<th>TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>30m</td>
<td>60m</td>
</tr>
<tr>
<td>Stream number</td>
<td>2721</td>
</tr>
<tr>
<td>Stream length (km)</td>
<td>693.3</td>
</tr>
</tbody>
</table>

TM is topographical map

Drainage of test area derived from different resolution DEMs show large fluctuations in streams. It varies with resolution and shows a pattern of rapid decrease with coarser resolution which is in agreement with the general observations. In our case, 90m resolution DEM stream geometry has the closest matching for the test area (Table 2.4). Both Nu and Lu show a great degree of matching for the streams of 90m DEM with those of topographical maps. The percentage accuracy is found to be 86% and 99% for Nu and Lu respectively (Table 2.5). The result is further verified with the verification area. 90m DEM generated streams of verification area show a similar result. The accuracy is found
to be as high as 95% and 96% (Table 2.6) in terms of Nu and Lu respectively. Based on the results 90m DEM is considered for generating the streams for the problem area where the topographical information is absent.

**Table 2.5** Percentage accuracy of stream matching in terms of number and length estimated from 90m DEM for the test area taking streams of topographical maps as reference

<table>
<thead>
<tr>
<th>Sources</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90m DEM</td>
</tr>
<tr>
<td>Stream number</td>
<td>450</td>
</tr>
<tr>
<td>Stream length (km)</td>
<td>230.84</td>
</tr>
</tbody>
</table>

TM is topographical map

**Table 2.6** Percentage accuracy of stream matching in terms of number and length estimated from 90m DEM for the verification area taking streams of topographical maps as reference

<table>
<thead>
<tr>
<th>Sources</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90m DEM</td>
</tr>
<tr>
<td>Stream number</td>
<td>454</td>
</tr>
<tr>
<td>Stream length (km)</td>
<td>255.45</td>
</tr>
</tbody>
</table>

TM is topographical map

To minimize the spatial mismatch, the second critical aspect in such operations, topographical maps are georeferenced using GCP’s of DEM generated streams. The shifting pattern of the streams of topographical maps is shown in Fig. 2.26b. The geospatial mismatch of the 40 reference stream points from streams of DEM has an average of about 0.5 pixels in planimetry. Visual assessment reveals that streams of DEM provide relatively accurate depiction of main streams in terms of its spatial co-incidence with the streams of topographical maps. However, spatial mismatch is relatively high for the streams near to the edge of the basin. The subjectivity of streams of DEM in headward ends (lower order streams) is largely responsible for this mismatch. In spite of this subjectivity, GCP operation has restricted the spatial mismatch to well less than a pixel size.
Highlighting the two major constraints—stream matching and spatial mismatching—associated with source combining, this section suggests an approach for combining streams of two sources. In this work stream matching in terms of Nu and Lu is controlled by a method of automatic stream generation from downscaled DEM. In this illustration, stream geometry of 90m resolution DEM has the maximum matching with that of topographical maps. GCPs are commonly used for spatial accuracy; the GCPs of the nodal points of major tributaries of DEM have restricted the positional mismatching to less than a pixel size. With the consent of both the aspects i.e. stream matching and positional matching, the streams derived from 90m DEM is considered to combine with the stream of topographical maps to get the drainage map of entire basin (Fig. 2.27).

Figure 2.27 Entire drainage geometry of Gaurang basin
2.1.4 Characterization of complex interconnecting streams

In hydrological studies, ordering tributaries or stream segments in a river network is commonly used to study and measure the size of the waterways. It is unanimously accepted that the foundation for modern stream ordering was provided by R. E. Horton in his epoch-making paper on river morphometry in 1945 “where he brought together the early threads of enquiry”1. The most widely used method- the Strahler’s method of stream ordering which is “slightly modified from Horton”, follows a system of smallest fingertip channels as 1st order and further 2nd order segment formed by the junction of any two first order segments and so on6. Shreve realized that the Horton-Strahler system of stream ordering ignores lower order streams that flow into higher order streams; therefore he proposed an ordering system which considered all tributaries where the order of a segment is result of the contribution of all previous segments14.

The stream classification systems of Horton, Strahler and Shreve categorize streams into different segments following defined sets of rules for stream ordering. In Horton’s system every single main tributary belongs to a single highest order and follows a back chronological order whereas in Strahler’s system all fingertip tributaries are of 1st order and the segment beyond the confluence point of two 1st order tributaries is 2nd order which continues till the junction of another 2nd and so forth. On the other hand, Shreve classifies every segment placed between two junctions of any order of streams. Therefore, an order number of stream segment, classified by stream classification system of Horton, Strahler and Shreve, not only specifies its order but also signifies its corresponding segment length.

Thus it is quite relevant to mention that all classification systems fundamentally vary in two aspects viz., stream orders and their corresponding lengths. Taking these two aspects as basis of classification, the classification systems work well for simple linear watershed having independent stream segments. Riverine systems in many cases form complex network which brings ambiguity in applying these classification systems. Except circuited and braided networks69-73, application of these classification methods in complex distributary conditions is rarely attempted which is definitely an area of research exploration. Gaurang exhibits such stream interconnections where the distributaries receive exterior streams of different orders and presents subjectivity in applying basic rules of stream classification (Fig. 2.28).
Keeping these complexities in mind, this exercise evaluates of the possible method of stream numbering and their extent consideration for complex distributaries condition. Taking clue from the complex situation witnessed in case of Gaurang, three complex distributary conditions are modeled. Strahler’s and Shreve’s methods of stream ordering are applied in modeled distributary conditions. Concurrently, the methods are tested in real river situation exhibiting complex stream interconnection.
Methodology

Three sets of complex distributary conditions are drawn representing- (a) simple anabranching condition with two anabranches of \( n \)th order main stream (b) relatively complex situation where an exterior channels of same \( n \)th order joining the left bank anabranch and (c) two independent channels of \( n \)th order joining both right and left bank anabranches which further complicates the stream structure (Fig. 2.29). This paper advocates idea of main flow anabranch for correct stream numbering in application of Strahler’s classification for complex stream interconnections. With the conception of primary and secondary flow, this work promotes reduction of stream number for the secondary flow which can be decisive in designating correct stream number in complex stream interconnections. In this paper the left branch is assumed as the primary one. However, this assumption is for the sake of illustration, not by rule (one can take right bank anabranch as primary one and apply the method in the same way), because it can be either of the branches in real world.

Figure 2.29 Outlined anabranching conditions- (a) simple anabranching with two anabranches of main stream, (b) complex situation where exterior channel of \( n \)th order joins left bank anabranch and (c) two exterior streams joins both the anabranch making the situation more complicated

The two most widely used stream numbering methods- Strahler’s (Fig. 2.30a) and Shreve’s (Fig. 2.30b) systems are used for the outlined anabranching conditions. Taking the fundamental basis of these classifications, the possible characterizations of the
anabranches are evaluated keeping the rationality of the physical significance of the classification systems in mind.

![Figure 2.30](image)

**Figure 2.30** (a) Strahler’s and (b) Shreve’s stream classification systems

Further, for validation, the approach is scrutinized in real river situation exhibiting complex system taking an example of a river from eastern Himalaya. The idea of main flow anabranch is applied to verify the effectiveness of the proposed approach in assigning correct stream number in real world situation.

**Result and discussion**

*Stream laws of Strahler’s system and anabranching conditions*

Strahler’s hierarchical system is the most widely used classification system that gives a hierarchical ranking to the stream segments. The method is based on arrangement of the preceding streams and refers only to interconnections\(^{14}\). Since Strahler’s stream segment number represents the arrangement of interconnection in head ward streams, it is the same for the anabranches of a particular stream as well. The hierarchy of a particular stream therefore carries the same number for its anabranches. It gives agreement to an approach that anabranches should be numbered the same as the parent stream\(^{73}\). If one applies Strahler classification in anabranching situation, as represented by **Fig. 2.31a**, there is
least complexity in stream consideration as it confines two individual bifurcated distributaries which rejoin in downstream. The stream therefore retains its stream order with reference to the parent however the bifurcation causes increase in stream segments. In **Fig. 2.31a**, the modeled stream net starts at A and finishes at B. The anabranches of the stream net form two nodes i.e. a and b that creates dividing points for segments. Since segments are anabranches of a single main channel so during segment consideration, minimum modification should be the prime target. The necessity of the minimum modification is rooted in the fact that it contributes to minimum alteration in the measurement of morphometric parameters associated with the drainage. Minimal modification can be achieved by considering the least number of stream segments. In the case of **Fig. 2.31a**, the minimum number of segments is two, which can be any set of - AB<sub>L</sub> & ab<sub>R</sub>, AB<sub>R</sub> & ab<sub>L</sub>, Ab<sub>L</sub> & aB<sub>R</sub> and Ab<sub>R</sub> & aB<sub>L</sub>, where, subscript L and R represents stream segment through left and right anabranch respectively. For eliminating this subjective uncertainty, a procedure is required that furnishes the basis for stream segmentation and selection. In this regard, consideration of main flow anabranch can be very effective in eliminating the dilemma in stream characterization. It is noteworthy that in general, one anabranch carries the main flow and the rest just serves as lean distributaries which rejoin downstream. So, taking main flow anabranch as continuous channel in case of anabranching rivers is judicious from the hydrological point of view. Applying the main flow anabranch criteria in anabranching condition of **Fig. 2.31a**, the two stream segments will be- the continuous stream segment AB through left bank anabranch (AB<sub>L</sub>) and the segment will lie between the nodes a and b (ab<sub>R</sub>). Considering main flow anabranch as continuous segment also fits well in case of more complex situation which is discussed in the succeeding sections.

Coming to more complex situations, **Fig. 2.31b** has greater complexity in terms of drainage composition where an exterior stream of n<sup>th</sup> order joins the left bank (main flow) anabranch. In that case, according to Strahler’s system, addition of the exterior stream of n<sup>th</sup> order to primary anabranch causes increase in stream order (n+1). The resultant n+1 stream confluences with right bank anabranch (n-1<sup>th</sup> order) at b and the succeeding channel continues with the same number. The most complex situation is demonstrated in **Fig. 2.31c**, where two exterior streams of n<sup>th</sup> order join both left and right bank anabranches. **Figure 2.31c** has three n<sup>th</sup> order streams – the anabranched n<sup>th</sup> order main stream and two additional exterior n<sup>th</sup> order streams. Gleyzer et al. (2004) urges that that if
one stream splits into distributaries, all diverted streams have same order number due to coming from the same upstream. He also noted that if the distributaries join exterior streams at an additional articulation point, the downstream will be affected and can change their order. This change holds Strahler’s philosophy which says changes in order of a stream segment is a result of junction of two streams having immediate lower stream orders. Based on these rules, both the anabranches in Fig. 2.31c, after joining with exterior nth order streams should continue with n+1. This results in an n+2 order stream after rejoining at ‘b’.

![Figure 2.31](image.png)

**Figure 2.31** Strahler’s classification for three outlined anabranching conditions

In the pioneering work of Horton (1945) and the subsequent commentaries of Gardiner and Park (1978) on Horton-Strahler’s classifications, it becomes apparent that the main intention of stream number is to measure the size and magnitude of waterways. In that perspective the secondary anabanch cannot represent the same order. Again, according to Strahler’s classification, three same order segments- one main stream and two exterior streams- can only form resultant n+1 order stream at all possible interconnections. Thus, Gleyzer et al.’s (2004) method, which assigns same order to all braided channels, irrespective of the size and magnitude (of the channels), can cause exaggeration of stream number compared to the reality.

As mentioned in methodology section, taking main stream anabranch criteria fits well for Strahler’s classification in such complex anabranching situation by conserving the resultant stream order in this condition. The primary or the main flow branch (in our case the left anabanch) provides streams of nth order that can form a n+1 order stream after
combining with the exterior nth order stream. Whereas, the stream number of the secondary flow (in our case the right anabranch) is reduced to n-1. Thus, the other exterior stream that joins right bank anabranch retains its stream number (nth). Further combination of the both the resultant stream gives a final n+1 stream.

In this approach the minimum number of segment consideration with main flow anabranch conserves Strahler’s hierarchical stream number with minimal modifications in drainage parameters. In more complex situations where the main channel splits into more than two distributaries, the idea of primary and secondary distributaries can be adopted in applying Strahler’s classification to void ambiguity.

**Stream laws of Shreve’s system and anabranching conditions**

It is also attempted to apply Shreve’s philosophy of stream classification to the anabranching models. Shreve’s method takes all tributaries and provides a realistic picture of a size of basin in terms of number of stream segment it contains. As Shreve’s segment changes its magnitude after each and every node of two streams the operation can be practically used for all anabranching rivers. During anabranching the main stream gets divided into two or more segments, this divides the magnitude of the stream which can be taken as n/x of magnitude, where n is the magnitude of main stream and x is the number of divides from a single point of the stream.

As shown in Fig. 2.32a, the anabranches of the main channel divides the magnitude into n/2 and it regains the nth magnitude after rejoining at the point b. Figure 2.32a presents straight anabranching condition that forms two nodes (a, b). As Shreve’s system of stream magnitude divides the stream between each node, it forms four individual segments in this anabranching condition (Fig. 2.32a). In case of more complex situations as shown in Fig. 2.32b and 2.32c, Shreve’s classification shows good compatibility. In Fig. 2.32b, according to Shreve’s rule, the left bank anabranch of magnitude n/2 adds the magnitude of the exterior stream and the resultant stream gets a magnitude of n+n/2. Further the right bank anabranches of magnitude n/2 confluences at the point b and the final stream gets the magnitude of two. In (Fig. 2.32c), the addition of nth order streams to both the anabranches result in two n+n/2 magnitude streams which joins at b to form final stream of magnitude 3n. In Fig. 2.32b and 2.32c, there are two and three nth order streams that have the potential to form 2n and 3n magnitudes stream. The application of Shreve’s rules
in both situations, gives the consistent final stream, proving its efficiency in river characterization in complex situations.

Figure 2.32 Shreve’s classification for three outlined anabranching conditions

Further, more complex situations where one stream forms more than two distributaries are drawn in Fig. 2.33. In Fig. 2.33a, the main stream forms three distributaries at a single point, in Fig. 2.33b the main stream forms two distributaries which further split into sub-distributaries and in Fig. 2.33c one of the two distributaries of the main channel joins a neighboring stream of n\textsuperscript{th} order. Shreve’s philosophy is further tested in more complex distributary conditions (Fig. 2.33). As Shreve’s method divides the magnitude of the main stream equal to the number of divides (distributaries) at a single point, the operation results a magnitude of n/3 to each distributary in Fig. 2.33a. If a distributary is further split, the magnitude consequently gets sub-divided in the same way (Fig. 2.33b). When split distributaries join another neighboring channel, the resultant stream earns a magnitude equal to the total magnitude of both the streams.
Figure 2.33 Shreve’s classification in more complex situations

Suggested approaches in real world situation

Figure 2.34 shows real world example of complex stream interconnection which exhibits distributary as well as sub-distributary situations. It is clear from the figure that the stream-net has three 3rd order streams where the main stream in upper part of the stream-net splits into two and carries the same (3rd) order following and thus resulted into 4th order after joining two exteriors streams of 3rd order. Finally, both 4th order streams join to form a 5th order final stream. As three 3rd order streams can only form a 4th order stream at all possible joining and combination, Gleyzer et al.’s method which assigns same order to all braided channels, therefore, leads to exaggeration in order number of final stream (Fig. 2.34a).

To remove this exaggeration, based on flow characteristics of the streams, the idea of primary and secondary anabranches are applied in the stream net (Fig. 2.34b). Following our approach for Strahler’s classification designates 2nd order to the right anabranch as it has the secondary flow (split at ‘a’). Further, the primary anabranch again splits and continues left anabranch as primary flow (at ‘b’). Thus it carries 3rd order whereas both the distributaries carry a reduced stream number i.e. 2nd order. When two exterior streams having 3rd order join right anabranch and middle anabranch (at ‘e’ and ‘c’), it continues as 3rd order as both the secondary anabranches carry 2nd order. Later middle anabranch joins the primary anabranch in lower reach to form 4th order stream (at ‘d’) and continues the same after joining the combined right anabranch at ‘f’. Thus the final stream possesses 4th
order. Reducing stream number of secondary anabranch succeeds in maintaining “three streams of 3rd order” and thus facilitates in correct stream numbering in final stream (Fig. 2.34c).

![Diagram](image)

**Figure 2.34** (a) Illustrating exaggeration in stream number when used Gleyzer et al.’s method for braided systems, (b) indicates primary and secondary anabranch used for succeeding illustration [ at (c) and (d)], and (c) & (d) application of proposed approach in real world complex interconnection stream systems following Strahler’s and Shreve’s philosophy respectively.

Application of the idea of primary and secondary anabranches into Shreve’s philosophy classification system is also scrutinized in real world situation using the same real world example. As Shreve’s stream magnitude changes after each and every node of two streams, it works well in the demonstrated this situation. The main stream here (Fig. 2.34d) has a magnitude of 14 which splits into two anabranches at ‘a’ and both the anabranches carries a magnitude of 7 each. The right anabranch joins single magnitude stream on its left bank to get a magnitude of 8. Further, the anabranch splits again and flows as streams of 4 magnitudes each (at ‘b’). Both the streams continue receiving different streams of various magnitudes and finally meet left anabranch at ‘f’ to form 67 magnitudes. It again receives one more single magnitude streams and the eventual stream
gets a magnitude of 68. This splitting magnitude approach yields precise result as the main stream (above ‘a’) has 14 magnitude and it receives 54 single magnitude streams on its way to the last point (below ‘f’) which ultimately gives a Shreve number of 68.

The central focus of the work is to outline a set of protocols to order complex networks retaining the fundamental premises of the prevailing classification system. Application of Strahler’s and Shreve’s philosophy clearly reveals that Shreve’s method efficiently works for river characterization in complex drainage situations, whereas minimum number of segment consideration with main flow anabranche conserves stream characteristics in case of Strahler’s classification system.
2.2 WATERSHED DELINEATION

As far as watershed delineation is concerned, researchers regularly face difficulties but commonly ignore them as they are difficult to resolve effectively. In recent times, availability and accessibility of high quality data along with advanced analytical tools has enabled researchers to measure the earth features more precisely and accurately, thereby opening the door to better identification of those difficulties and pitching solutions to it.

With the help of the Eastern Himalayan river- Gaurang, the operational difficulties associated with watershed delineation are identified and probable solutions are suggested in this section.

2.2.1 Identifying water divide in plains

The features that are critical in deciding the watershed boundary are stream ends, contour lines and Triangulated Irregular Network (TIN) generated from elevation data. DEM is predominantly used for extraction of these features in order to find out watershed boundary throughout the world. With the application of DEM one can generate contour lines at desired intervals and other features that can identify the watershed boundary can be easily generated with the use of GIS tools.

But application of DEM is rather restricted in plain areas where the gradient become very low and subsequently leads to large amount of deformities in generated features. One such example is shown in Fig. 2.35a, where very low to nearly level gradient of the plains of Gaurang escalates difficulties in identifying watershed divide. The most important feature of watershed boundary demarcation i.e. contour lines generated from medium scale DEM (30m resolution) do not provide any distinct line of boundary separation due to minimum vertical and lateral relief in the plains.

The difficulty of identifying watershed divide in low relief plains can be effectively overcome by the systematic utilization of geo-information resources. In order to locate an unambiguous watershed boundary, an approach is exercised using multiple geo-information sources. The approach follows a protocol that includes following steps-demarcation of watershed zone, updating the zone, location of the tentative watershed dividing line and finalization of the watershed boundary.
The approach begins with demarcation of watershed boundary zone using stream ends of adjacent watershed from topographical maps (Fig. 2.35b). It is followed by updating the zone with the help of recent satellite images. This update is essential especially in the lower plains which have weak lithology coupled with very low lateral relief separating watersheds. These factors accentuate the possibility of watershed boundary reorganization. Besides updating, the use of high resolution satellite images is effective in narrowing the watershed boundary zone as it facilitates identification of stream heads to a greater extent (Fig. 2.35c). Further the updated boundary zone can be used for identification of tentative watershed boundary. As the elevated ridge line that divides contiguous watershed lies within the demarcated boundary zone, it can be a guide to locate the DEM pixels that represents the elevated ridges. For the purpose, the updated watershed boundary is imported over DEM, then parallel lateral lines are drawn on updated watershed zone and finally highest elevated pixels of the lateral lines are stringed into line to get the tentative watershed boundary as shown in Fig. 2.35d. The identified tentative watershed boundary is now commensurable for use as reference to the contour lines drawn from DEM for finalization of the water divide. To get the final watershed boundary, the tentative boundary is overlaid on contour map (Fig. 2.35e) and the nearest highest elevated contours curves are conjoined (Fig. 2.35f).

Even with application of high resolution DEMs, the possibility of localized error is very high in the areas of very low gradient. It may lead to identification of erroneous watershed divide which may be significantly different from ground truth. Concerning this subjectiveness, the protocol here is an effective practical solution as it takes care of issues involved.
Figure 2.35 (a) Insufficiency of DEM generated contour lines in watershed delineation in plains and (b-f) systematic multi geo-information data utilization approach for watershed delineation

It is quite relevant to mention that stream ends of topographical maps provide an initial guide in watershed boundary delineation especially in plains. But, presence of inter-basin streams and canals spread over neighbouring watersheds may create a dilemma as to which streams ends are to be considered for watershed delineation. In general watershed inter-basin streams are rare in nature. But human activities, predominantly irrigation,
dissect the landscape and create artificial streams and canals that spread over two watersheds. Two such examples are depicted in Fig. 2.36. The first example presents one artificial canal that emerges from Gaurang near Saralpara and dissects the watershed area to meet the contiguous Champamati watershed. The second example shows the artificial canals that emerge from the check dam made over Champamati river and spread over the watershed of Gaurang. As the stream ends of these artificial canals or stream do not provide guidance in identifying watershed boundary, it is logical that these inter-basin streams and canals should not be included during watershed delineation. Here careful identification of those streams and canals is pivotal in diminishing the chances of error in watershed delineation.

![Figure 2.36](image.png)

**Figure 2.36** (a) Artificial stream of Gaurang that run across to Champamati watershed and (b) artificial canals emerged from the check dam of Champamati river and spread over the Gaurang watershed.

Gradient variation is a significant factor in the lower mouth section where the gradient is almost zero. Due to nearly level gradient, the area between two individual watersheds always tends to form individual micro watersheds. In case of Gaurang, two micro watersheds are identified on the eastern side near the confluence point with Brahmaputra (Fig. 2.37). Discriminating the boundary between those micro watersheds and any basin under consideration using geo-information data is impractical as it does not provide recognizable stream feature or contour lines that are prime in watershed delineation. Therefore it is fairly well understood that the final method of choice to decide the watershed boundary in mouth section is by field visits. In case of Gaurang, field visits
identified a dirt tract (Kacha road) on the southern side of Machhaner Alga village that serves as the water divide between micro watershed-1 and Gaurang.

Figure 2.37 (a) Two micro watersheds in the eastern side of Gaurang near confluence point and (b) identified watershed boundary in the mouth section by field appraisal

It is found that the major hindrance in watershed boundary delineation is the low gradient. Practically single geo-information does not provide useful guides like stream feature, contour lines or other features. This inevitably supports a multi-geo-informational approach for unambiguous watershed boundary identification.
2.3 BASIN LENGTH MEASUREMENT

Basin length is a fundamental descriptor of basin size and shape. In contemporary usage, it is the principal input required to compute two basic shape parameters viz., form factor and elongation ratio. These parameters govern a large number of practical applications in assessing river function and behaviour. Researchers till date determine the basin length by general manual measurement of the maximum line drawn from the mouth to the most distant point following basic laws which in principle laterally bisects the basin. In practice these methods are hamstrung by subjectivity associated with manual recognition of basin length. Lack of clearly defined measurement techniques and methodology has long been recognized. The method of determining basin length is not explicit, and it is difficult for two investigators to come with identical results in a chosen basin. It inevitably categorizes the basin length measurement techniques approximate in nature. This approximate method of establishing basin length may lead to loss of accuracy.

In practice, basin length is measured by drawing the maximum line from mouth to the most distant point that passes through the mid points of the basin’s lateral outlines. With this manual operation, basin length cannot be measured with precision as smaller bends and irregularities gets always neglected thereby leading, inevitably, to underestimation of basin length. Basin length not only varies due to subjectivities in manual measurements, but also with scale of the basin perimeter. The scale effect on basin perimeter has long been recognized by researchers. Therefore, depending on scale, the magnitude of underestimation can be large. As the basin shape parameters are the function of basic indices viz., area, perimeter and length, the inaccuracy in length is a shortcoming. In view of these shortcomings, a precise basin length measuring technique is fundamental. Basin length is central input along with area and perimeter, which are defined for an outlined basin, in computation of shape parameters. Its precise measurement for an outlined basin can be cardinal in consistent measurement of shape parameters.

In the context of this long standing ambiguity, this work suggests a categorical numerical approach that calculates the maximum length of a basin by dividing it laterally into two equal halves. Consequently an equation that estimates basin length is derived from a mathematical relationship between the increased perimeter and the corresponding increase in length using a set of modeled watersheds. Subsequently, the efficacy of the proposed
method is validated against manually measured basin lengths, following Ogievsky’s lateral line method\(^{38}\), of three natural test watersheds. This proposed mathematical approach is decisive and accurate without negating the basic conceptual premises of basin length measurement.

**Methodology**

This work takes clue from Miller’s circulatory ratio where he introduced a criterion of the ratio of a basin area to the area of a circle having a circumference equal to the perimeter of the particular basin to interpret the shape of the basin\(^ {31}\). In this work, the change in perimeter with respect to a circular basin of the same area is used to measure basin length.

The basis for the measurement of the basin length is taken from the premise that any increase in perimeter physically increases the length of a basin irrespective to its orientation. Using this principle, a mathematical relationship between the increased perimeter of basins and its corresponding length is drawn. In nature the most common sizes of basins vary from 10-10000 sq km, so to present the natural cases, first, four perfect circular basins of sizes ranging from 10 to 10000 sq km are drawn. Then the basins are lengthened symmetrically by 1.5, 2, 2.5, 3, 3.5 and 4 times keeping the area constant (Fig. 2.38). Constant area allows us to derive the relationship between increased perimeter and corresponding increased length while maintaining symmetry; thereby eliminating the chances of error in the calculation of basin length.

For validation, numerical approach is tested in three natural test watersheds (TW1, TW2 and TW3) of irregular sizes and shapes. For this purpose, equidistant lateral lines of intervals 20, 10, 5 and 1 km are drawn for all the three basins taking confluence as reference point. The basin lengths are then measured by joining the mid-point of lateral lines (Fig. 2.39). The efficacy of the length calculated with proposed approach is evaluated against these measured multi-interval basin lengths.

Further, shape parameters (form factor, circulatory ratio and elongation ratio) that are dependent on length and perimeter are computed using the manually measured basin length and the consistency of the results are evaluated against those derived mathematically for all the three test watersheds.
Figure 2.38 Modeled watersheds, circular as well as lengthened, of size (a) 10, (b) 100, (c) 1000 and (d) 10000 sq km
Figure 2.39 Three test natural watersheds and drawn equidistant laterals at 1 km interval from reference point (confluence point with mainstream of Manas River) for validation of the proposed approach

Result and discussion

It naturally follows that an increase in perimeter leads to lengthening of the shape when the size remains constant. To evaluate this relationship between lengthening factor (Lf) and percentage increased perimeter (P%) the simplest case i.e. first order equation is plotted. Although the equation gave a significant positive relationship, a swing is observed between trend line and the plotted data points towards the origin. This retarded the efficacy of straight line equation in predicting appropriate basin length. As the major target of this work is to remove the approximations in basin length measurement, a second order equation is therefore drawn. The results clearly showed nearly perfect positive relationship (Fig. 2.40a-d) with plotted data point falling nearly or on the trend lines and thus providing proximity appropriate for basin length calculation.
Figure 2.40 Relationship between percentage-increased perimeter and their corresponding increase in length (lengthening factor) for modelled watersheds size of – (a) 10, (b) 100, (c) 1000 and (d) 10000 sq km; and (e) generalized second order equation with averages of percentage increase in perimeter against lengthening factor.

A close look at the graphs of considered four models show a marginal difference in the lengthening $L_f$ - $P\%$ relationship. To diminish this minimal difference and generalize the relationship, averages of the $L_f$ and $P\%$ are taken to plot the final equation (Fig. 2.40e).

The equation that represents the $L_f$ - $P\%$ relationship is:

$$L_f = -3 \times 10^{-5} P\%^2 + 2.29 \times 10^{-2} P\% + 1.1076$$

$P\%$ for a basin under consideration can be calculated by determining the difference between perimeter of the basin ($P$) and perimeter of a perfect circular basin ($P_c$) having same area as to the particular basin. The common relationship between area and perimeter of a perfect circular basin is $P_c = (4\pi A)^{1/2}$; where $A$ is the area of the basin. And thus increased perimeter ($P_i$) can be expressed as $P_i = P - (4\pi A)^{1/2}$. 
Consequently, the percentage increase in perimeter is-

\[ P\% = \left\{ \frac{P}{(4\pi A)^{1/2}} - 1 \right\} \times 100 \] (2)

From equation (1) and (2),

\[ L_f = -3 \times 10^{-5} [\{ \frac{P}{(4\pi A)^{1/2}} - 1 \} \times 100]^2 + 2.29 \times 10^{-2} [\{ \frac{P}{(4\pi A)^{1/2}} - 1 \} \times 100] + 1.1076 \]

\[ = -0.3(0.28P/\sqrt{A} - 1)^2 + 2.29(0.28P/\sqrt{A} - 1) + 1.1076 \] ………………… (3)

To find the length of a particular basin one needs to multiply \( L_f \) with the diameter- \((4A/\pi)^{1/2}\) of a perfectly circular basin of same area. Therefore, the equation that emerged for basin length (L) measurement is-

\[ L = (4A/\pi)^{1/2} [-0.3(0.28P/\sqrt{A} - 1)^2 + 2.29(0.28P/\sqrt{A} - 1) + 1.1076] \]

\[ = -0.33\sqrt{A}(0.28P/\sqrt{A} - 1)^2 + 2.58\sqrt{A}(0.28P/\sqrt{A} - 1) + 1.25\sqrt{A} \] ……………… (4)

The derived Eq. (4) therefore can be used to calculate length of a basin with the help of the basic inputs i.e. its area and perimeter.

As mentioned in methodology section, a test for validating the efficacy of the proposed approach in asymmetric basin conditions is carried out in three natural watersheds (Fig. 2.41). The comparison of manual measured basin lengths following a systematic multi-interval lateral line method and the basin lengths calculated by the proposed method is presented in Table 2.7. It is found that measured length of test watershed varies widely with frequency of lateral lines. The measured lengths with finest interval (1km) of all the three natural test watersheds provides maximum proximity with those of mathematically calculated (Table 2.7). In spite of the closer estimation with 1km interval, the measured lengths of test watersheds are shorter as compared to those of mathematically calculated (Table 2.7). The problem of underestimation is inherent with manual measurement as it considers the line by joining the midpoint of lateral lines which practically leaves out the curves between the lateral lines and results in smaller basin lengths. The proposed method calculates basin length to a finer level as compared to manually calculated finest level (1 km) lateral line and guarantees its efficiency in length measurements.

The possibility of underestimation in manual basin length measurement is magnified in irregular basins. It is because irregular shapes form more curves and thus with fixed
lateral lines it multiplies the chances of missing curves. Among the considered three natural test watersheds, TW1 has the most irregular shape; hence measurements by the manual method show considerable deviation in comparison to mathematical measurements. This highlights the insufficiency of the manual method for irregular basin and thus strongly supports the proposed mathematical method in calculating to the finest level.

![Diagram of basin length measurements](image)

**Figure 2.4** Multi-interval manually measured basin length of the three natural watersheds

The uniformity in perimeter dependent (circulatory ratio) and length dependent (form factor and elongation ratio) shape parameters would decide how precisely and consistently basin length measurements are made for a determined basin boundary. Of the manually measured basin lengths, shape parameters shows highest consistency with the length measured using finest interval (1km) lateral lines (**Fig. 2.4a-d**). This is obvious because the basin length measured with finer interval provides more accurate measurement as it leaves out least curves between the lateral lines. This consistency increases significantly with mathematically calculated basin length highlighting the efficacy of the proposed approach (**Fig. 2.4e**).
Table 2.7 Comparison between calculated basin lengths using mathematical and manually approaches

<table>
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<tr>
<th>Basins</th>
<th>Area (km²)</th>
<th>Perimeter (km)</th>
<th>Mathematically Calculated</th>
<th>Systematic manual measurement</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>With 20 km lateral line</td>
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<td></td>
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<td>275.8</td>
<td>120.5</td>
<td>96.0</td>
</tr>
</tbody>
</table>

Figure 2.42 Shape parameters estimated from basin length calculated- (a-d) manually with 20km, 10km, 5km and 1 km interval lateral line respectively, and (e) mathematically with the proposed method
This work presents an unequivocal numerical approach to counter issues associated with practical execution of basin length. The proposed mathematical approach calculates basin length to the finest level which is unattainable with manual measurements especially in asymmetric basin condition. It provides unambiguous measurement of basin length which is fundamental input in basin characterization and its hydrological implications. Besides accuracy, the mathematical approach lends consistency in deriving shape parameters as it removes approximation associated with manual recognition of basin length.