GIS Application on Drainage Network Extraction

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Abstract

Although field mapping is acknowledged as the most accurate way to determine channel or drainage networks, it is often impractical, especially for the large and remotely situated mountainous watersheds. Topographic maps, providing a useful surrogate for drainage networks, are the fundamental source for the drainage analysis. But, drainage analysis by manual delineation on topographic maps requires time and expertise, and subjectivity judgments. Furthermore, extracted and mapped data from the topographic maps are not in digital from, thus; requires additional works in order to incorporate with other Remote Sensing (RS) and Geographic Information Systems (GIS) outcomes. In this study, drainage network delineation was performed using two methods: 1) Traditional method by hand delineation on 1/25,000 topographic map; and 2) Using TauDEM (Terrain Analysis Using Digital Elevation Models) model in ArcGIS 9.0 environment using different resolution and sources of DEMs. We compare and examine these two methods with their drainage network extraction, and results obtained were tested statistically. This study attempts to investigate the consistency of the outcomes obtained from these two different methods using different sources of DEMs.

Keywords: Channel/drainage network, constant drop analysis (CDA), geomorphometric values, drainage density, TauDEM

Introduction

While performing drainage analysis of a watershed, determining geomorphometric parameters: drainage area, stream length, stream drop and stream frequency become essential; thus, incur extraction of channel networks. Although field mapping is acknowledged as the most accurate way to determine channel networks, it is often impractical, especially for the large and remote watersheds situated in the high altitude mountainous regions. Topographic maps have been a fundamental source for the drainage analysis using a traditional method due to its availability, simplicity and cheapness. However, channel networks extraction and watershed delineation from topographic maps require tedious time, and expertise in cartography providing subjective decision. Furthermore, as extracted or mapped data from the topographic maps using traditional method (hand delineation) are in non-digital form; thus, requires additional works to incorporate with other Remote Sensing (RS) and Geographic Information Systems (GIS) outcomes.

The advent of GIS tools and technology, and digital elevation models (DEMs) have resulted in the evolution of procedures to automatically map or derive channel networks from DEMs. Due to the developments on these, much of the information that we gather from the topographic maps can now be gathered electronically using GIS. DEMs that derive flow networks then provide a useful surrogate for channel or drainage networks have been a useful data source for the automatic delineation of channel networks and sub-watersheds. GIS based methods are being used increasingly to delineate channels and watersheds and automatically extract geomorphometric parameters for use in hydrologic models. However, care needs to be exercised to ensure that networks are extracted from DEMs at an appropriate scale. This scale should correspond to the networks obtained by more traditional methods, such as from high-resolution topographic maps or fieldwork (Tarboton et al., 2001).

In this study, channel network extraction and watershed delineation were performed using two methods: 1) Traditional method by hand delineation on the 1/25,000 topographic map; and 2) Using TauDEM (Terrain Analysis Using Digital Elevation Models) model in ArcGIS 9.0 environment using different resolution and sources of DEMs. The geomorphometric values: drainage areas, stream lengths and stream drops obtained from the methods with different DEM data sources were compared and tested statistically. We attempted to investigate the consistency of the outcomes obtained from the traditional and GIS methods in the context of drainage analysis using different DEM data sources.

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Materials and methods

Study area

Four watersheds, each two from different regions were selected as the studied areas. Two watersheds: Thado khola and Chure khola are from the Siwalik Hills; and Manahari khola and Jhirke khola are from the Mahabharat Range located in Makwanpur district of the Central Development Region (CDR) of Nepal (Fig. 1). These two regions are significantly distinct from their geological and morphological aspects (Shrestha et al., 2005a,b). Furthermore, the topographic textures between the regions are significantly different; Siwalik Hills watersheds have coarse topographic textures (moderately confined or unconfined contour lines), whereas, Mahabharat Range watersheds have fine topographic textures with confined contour lines (Fig. 2). Contours of the Mahabharat watersheds are more crenulated than the Siwalik Hills'.

Data preparation

Digital data (Aster DEM and contour based DEM) and non-digital data (1/25,0000 topographic maps) were used to extract channel networks. An extraction of channel network from digital data was carried out in the ArcGIS 9.0 environment using TauDEM (Terrain Analysis Using Digital Elevation Models) software. TauDEM incorporates the DEM analysis tools and functions developed by David G Tarboton at Utah State University for hydrologic digital model analysis and watershed delineation (http://www.engineering.usu.edu/dtarb/taudem/). Aster DEMs (30m resolution) were obtained from the U.S. department of the interior U.S. geological survey

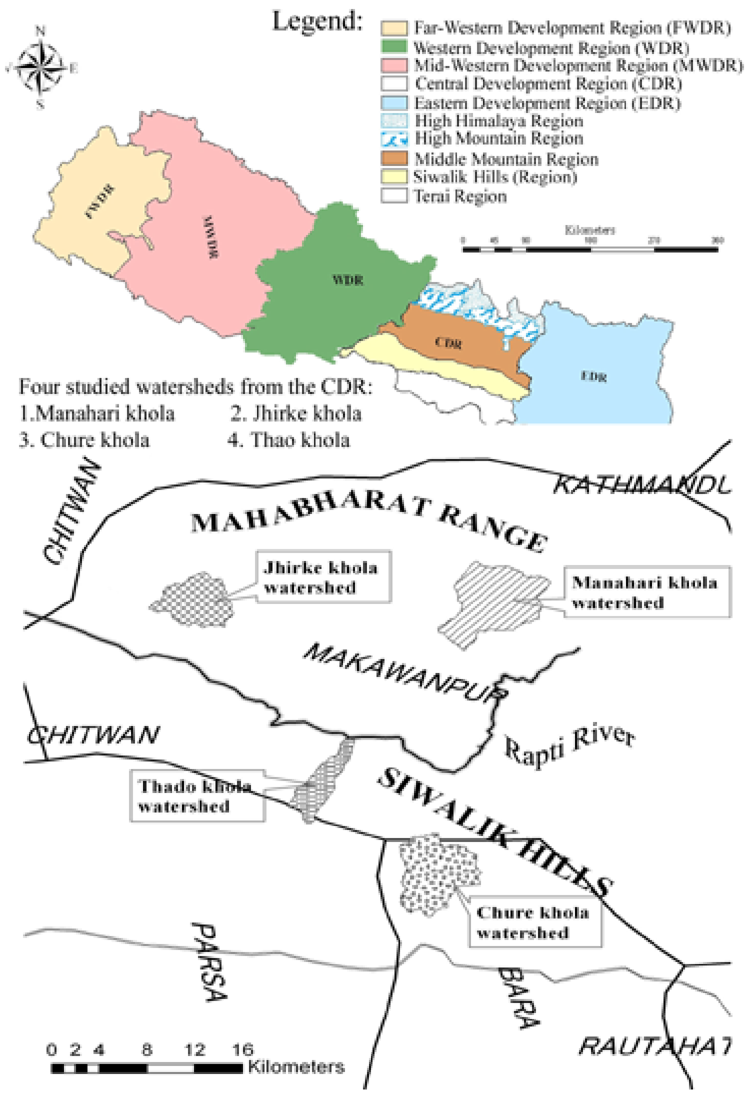

Fig. 1. Map of Nepal and location of the studied watersheds

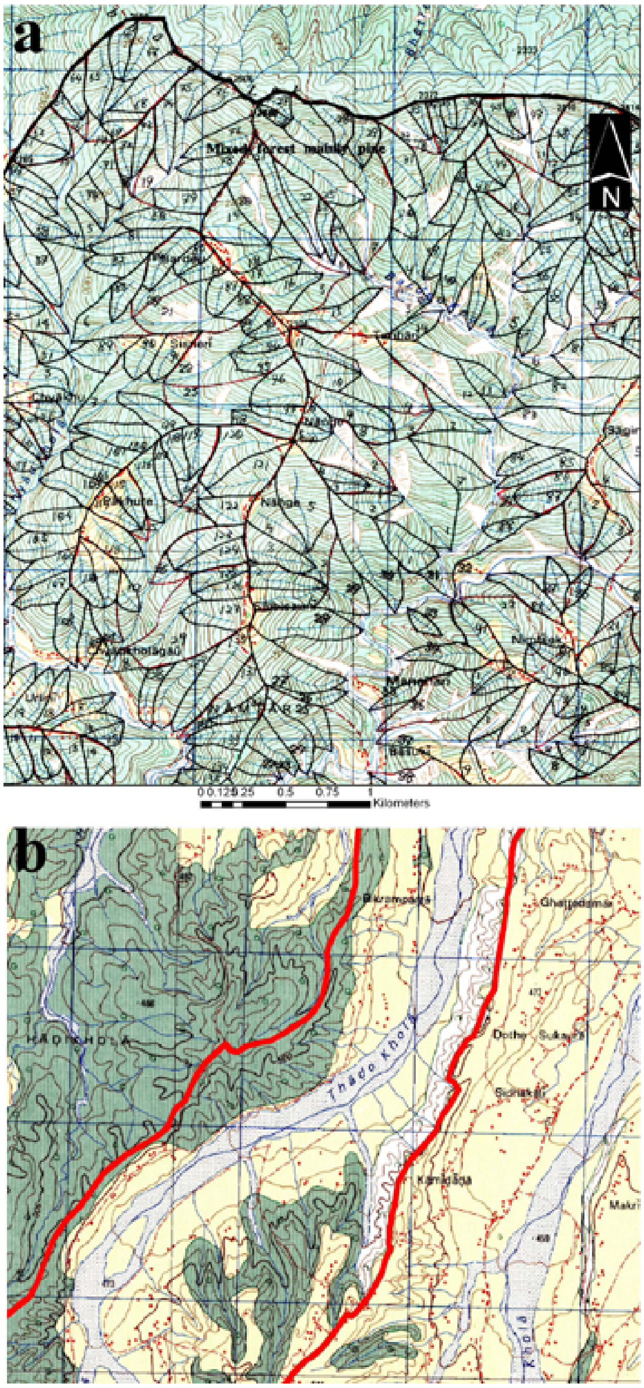

Fig. 2. Topographic textures of the two different regions. a: Manahari khola watershed (Mahabharat region), b: Thado khola watershed (Siwalik region).

(USGS; http://www.usgs.govt/), and contour based DEM and 1/25,000 scale topographic maps (topo-maps) were purchased from the HMG/Nepal Survey Department.

In the TauDEM, grid digital elevation model data is used. Grid DEMs are distinct from other DEM representations such as triangular irregular network (TIN) and contour-based data storage structures (Tarboton et al., 2001). In this study, both Aster and contour based data were converted into the grid data and performed channel extraction using TauDEM. Before converting into the grid form, both Aster DEM (HDF-EOS format) and contour based data (arc coverage format), were first converted into the Imagine file (img.file) in Erdas Imagine software. The image files were then re-projected over a Universal Transverse Mercator (UTM zone-45) grid as a cartesian reference frame with a horizontal resolution of 30m, then transformed into the grid data, and used in the drainage analysis. Regarding contour based DEM, conversion of arc coverage data into Image files were performed by surfacing using Linear Rubber Sheeting method in the Erdas Imagine.

SChannel networks extraction and watersheds delineation

There are a variety of approaches to delineating flow networks, using different algorithms such as single (drainage to a single neighboring cell) and multiple (partitioning of flow between multiple neighboring cells) flow direction methods for the computation of contributing area and local identification of upwards curvature (Tarboton et al., 2001). TauDEM is a method for the delineation of drainage networks based on the weighted accumulation of upwards curved grid cells. This method is adaptive to spatial variability in drainage density. The weighted support area threshold is chosen objectively using a t-test to select the highest resolution drainage network with mean stream drop of first order streams not significantly different from the mean stream drop of higher order streams. In this way a drainage network consistent with geomorphology is delineated without the need to subjectively choose a support area threshold parameter (Tarboton et al., 2001).

In this study, channel network extraction and watershed delineation was performed using "DEM Curvature Based" algorithm, one of the algorithms available in the TauDEM functions, because it is recommended for the places where streams are not present. Streams of the studied areas, especially from the Siwalik Hills, are wadji and generally do not present; surface flows are only visible during high and intense rainfall (Shrestha et al., 2005a,b). Furthermore, when determining stream orders, intermittent streams (those that do not flow continually), which are predominant in the Siwalik Hills, usually not included while delineating channel and watersheds in traditional method. In "DEM Curvature Based" algorithm, TauDEM default setting that automatically does a constant stream drop analysis using an upwards curved drainage area threshold (number of grid cells) to map the channel network. The smallest threshold searched by "Constant Stream Drop Analysis (CDA)" with absolute value of the t-statistic less than 2 is selected. This is done automatically during the process. For the science behind the constant drop property (analysis) see Tarbotom et al. (1991, 1992), and more details for the TauDEM procedures see (http://www.engineering.usu.edu/dtarb/taudem/).

TauDEM extracts channel networks according to the Horton-Strahler branch ordering method. After the channel network extraction, sub-watersheds were reorganized according to the each stream order. Similarly, sub-watersheds on the 1/25,000 scale topo-maps were also delineated according to the Horton-Strahler branch ordering method. Maximum and minimum elevations, drainage areas and stream lengths were measured directly from the topo-map. Digital planimeter (X-PLAN 360) was used for drainage area and stream length measurements. In this study, delineation of watershed on 1/25,000 topo-map by traditional method will refer as "Traditional Delineation (TRD)", and by TauDEM using Aster DEMs and contour based DEMs will refer as "TauDEM Aster Delineation (TAAD)" and "TauDEM Contour Based DEM Delineation (TACD)", respectively.

Results and discussion

Geomorphometric values with different delineation methods

Studied watersheds delineated from the three methods: TRD, TAAD and TACD have shown similarity in their shape of the watersheds (Fig. 3). However, their watershed areas differ slightly correspond to the methods and data used (Table 1). Contrast to the watershed area, total stream lengths differed significantly among the methods. For an example, total stream lengths obtained from the TRD using 1/25,000 topo-maps are: 65.50 km for Thado khola; 261.36 km for Manahari khola; 157.40 for Chure khola; and 95.89 km for Jhirke khola watersheds. These values are larger than the values obtained from the TAAD and TACD; excluding values obtained from the TACD using 15 m DEM with thresholds 8 and 5 for Chure khola watershed (Table 1). More specifically, Table 1 corroboratively illustrates that higher threshold values extract shorter stream lengths, whereas, their watershed areas remain almost constant. As higher threshold value delineates less numbers of 1st order streams; thus, have less network order, which ultimately reflects less in total stream lengths (Fig. 4).

Nevertheless the shape and size of the entire watershed showed similarity among the methods and data used, the geomorphometric values obtained for 1st, 2nd and 3rd order streams have shown statistically significant among the methods (Table 2). The values of stream lengths, drainage areas and stream drops (difference in elevation between the beginning and end of Strahler streams) obtained for 1st, 2nd and 3rd order streams differ among each delineation method, and their mean values differ significantly at the 0.01 level (Table 2).

At 1st order sub-watershed, the longest mean stream length was obtained for the TRD, and showed statistically different with the values found from other two methods. Contrary to this, mean drainage area obtained from the TACD has the largest area, and is statistically different (significant at the 0.01 level) with the mean values obtained from the TRD and TAAD methods. Similarly, the mean elevations (max. and min. elevations) obtained from the TAAD showed the lowest among all, and found statistically different with other

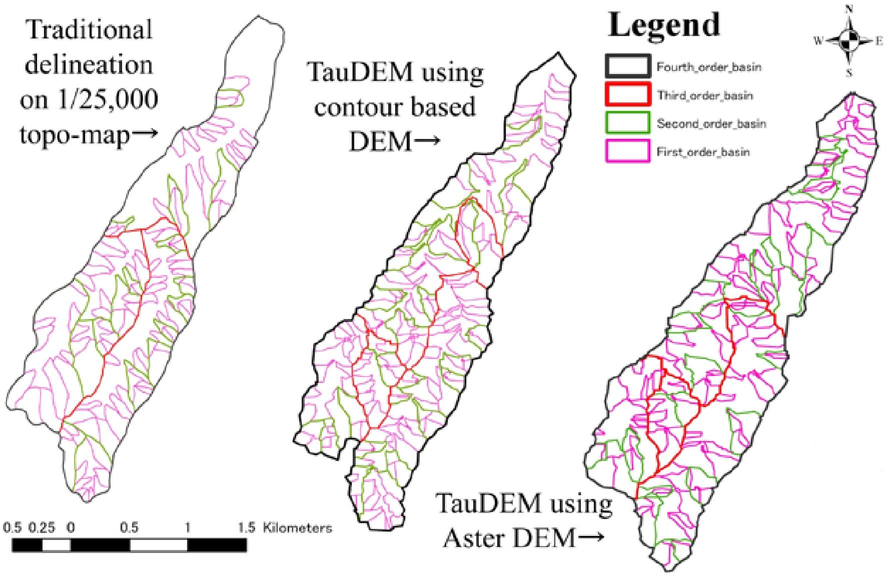

Fig. 3. An example of channel network and watersheds delineation for Thado khola watershed

Table 1. Descriptive statistics of the geomorphometric values obtained from the different delineation methods

Watershed Name	Method	Data source	Threshold	Total stream length (Km)	Watershed area (km^2)
	TACD	Contour based DEM (30m)	CDA (5)	60.92	13.79
	TAAD	Aster DEM (30m)	CDA (5)	50.55	14.17
Thado khola	TRD	1/25,000 topo-map	-	65.50	13.90
	TACD	Contour based DEM (30m)	10	97.72	35.38
	TACD	Contour based DEM (30m)	8	111.06	35.37
	TACD	Contour based DEM (30m)	5	143.27	35.36
	TACD	Contour based DEM (30m)	CDA (108)	38.57	35.40
	TACD	Contour based DEM (15m)	10	148.17	35.16
	TACD	Contour based DEM (15m)	8	165.56	35.16
	TACD	Contour based DEM (15m)	5	209.98	35.16
	TACD	Contour based DEM (15m)	CDA (108)	36.57	35.17
	TAAD	Aster DEM (30m)	5	117.47	33.94
	TAAD	Aster DEM (30m)	CDA (65)	41.48	33.95
Chure khola	TRD	1/25,000 topo-map	-	157.40	32.87
	TACD	Contour based DEM (30m)	10	94.20	40.53
	TACD	Contour based DEM (30m)	5	132.92	40.53
	TACD	Contour based DEM (30m)	4	146.13	40.53
	TACD	Contour based DEM (30m)	3	165.95	40.52
	TACD	Contour based DEM (30m)	CDA (65)	39.10	40.55
	TAAD	Aster DEM (30m)	5	102.25	35.52
	TAAD	Aster DEM (30m)	3	138.34	35.52
	TAAD	Aster DEM (30m)	CDA (65)	31.20	35.54
Manahari khola	TRD	1/25,000 topo-map		261.36	40.64
	TACD	Contour based DEM (30m)	5	22.04	21.56
	TACD	Contour based DEM (30m)	10	53.48	21.54
	TACD	Contour based DEM (30m)	CDA (5)	76.45	21.54
	TAAD	Aster DEM (30m)	5	77.63	22.04
	TAAD	Aster DEM (30m)	10	48.13	22.05
	TAAD	Aster DEM (30m)	CDA (39)	23.43	22.06
Jhirke khola	TRD	1/25,000 topo-map	-	95.89	21.18

TRD: Traditional method using 1/25,000 topo map; TACD: TauDEM method using contour based DEM (30m); TAAD: TauDEM method using Aster DEM (30m); CDA: Constant Drop Analysis. An automated threshold values calculated from the CDA are shown in the parenthesis.

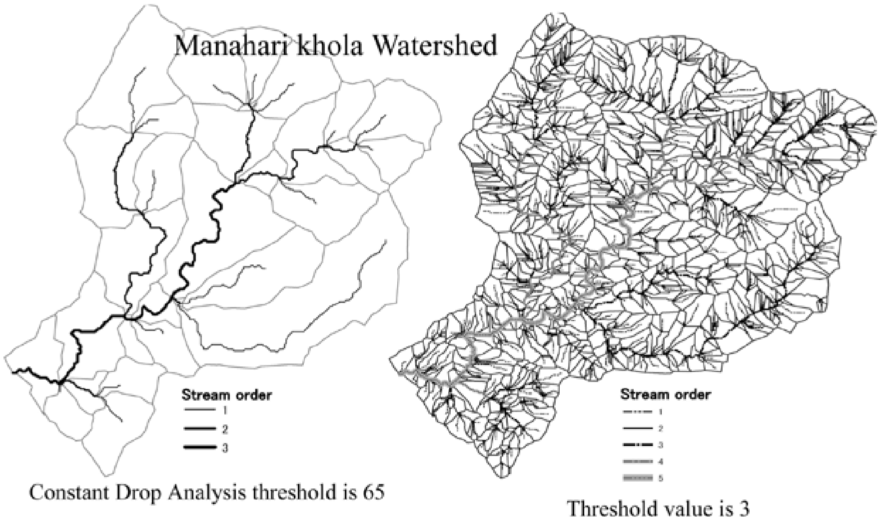

Fig. 4. Channel extraction according to different threshold values

two methods (significant at the 0.01 level). Furthermore, the mean values for stream drops obtained from each method differs significantly (0.01 level). In comparison to 1st order sub-watersheds, all the gemorphometric values (excluding elevations for TAAD) at 2nd and 3rd order sub-watersheds are insignificant among the three methods. These outcomes suggest that the geomorphometric values of a watershed differ significantly according to the methods and data used, especially in the lengths along streams. A stream's length on the topo-map is referred by the magnitude of the blue lines, which are drawn by the cartographer, are longer than those extracted form the DEMs. Delineation of a stream length (blue lines) on 1/25,000 scale topo-maps usually involves some subjective judgments by the cartographer, and could be a cause for accounting longer stream lengths.

Similarly, mean drainage areas of 2nd and 3rd order sub-watersheds obtained from topo-maps are larger than those obtained from the DEMs. However, their mean values do not differ significantly. Among all the geomorphometric values, only elevation values showed statistically different at the 0.01 level. Aster DEM represented significantly less elevations than that of contour based DEM and topo-map. For an instance, Aster DEM showed the minimum elevation of 31m at 1st order sub-watersheds, which is more than 300m less than contour based DEM and topo-map elevation. The reason for the low elevation representation from the Aster DEM is believed to be due to the algorithm used during the data processing. ASTER relative DEM data products are generated from ASTER Level-1A data by the Aster DEM data processing algorithm. Aster DEM products used in this study (Granule ID: AST14DEM) in HDF (Hierarchical Data Format) is raw elevation data derived from the ASTER Level-1A stereo data (VNIR 3N and 3B images; N = nadir looking, B = backward-looking) without GCPs. The coordinate of Aster DEM data is based on ECR (Earth centered rotating), and elevations are measured at every other pixel of Level-1A VNIR 3N image (Earth Remote Sensing Data Analysis Center; http://www.eoc.nasda.go.jp/). Thus, it could be recommended that Aster DEMs (USGS products) need to be checked or, need to be corrected with precise and actual elevation data before using them. Representation of elevations in the contour based DEM showed consistency with the topo-maps. The slight difference in elevations between TRD and TACD outcomes is due to the limitation of readable elevation values from the topo-maps. It is an adversity of topo-maps having contours with a 20m interval to measure accurate elevation. The max. and min. elevations measured from the topo-maps represent the values of the contours that intersect or runs very closer to the watershed boundaries. Contrary to topo-maps, contour based DEM provides more precise and accurate values of a call as they represent raster data (grid data) having a single value that can be either an integer or a decimal number. This number may represent the average value of the cell or the value at the cell's center for the variable described by the grid.

Channel networks extraction with different support area thresholds

Most of the methods for delineation of drainage networks from digital elevation model data require the selection of some parameter that controls the form of network extracted and the resulting drainage density scale (Tarboton et al., 1991). In TauDEM, the weighted support area threshold is chosen objectively using the constant stream drop property of channel networks. The constant stream drop property is an empirical

Table 2. Descriptive statistics of the geomorphometric values obtained for Thado khola watershed

Stream orders	Geomorphometric values	Method	N	Mean	Minimum	Maximum	Std. deviation	Std. error
First order watershed	Stream length (km)	TRD	101	0.45*	0.13	1.72	0.24	0.02
		TACD	131	0.28	0.03	0.95	0.19	0.02
		TAAD	113	0.25	0.03	1.04	0.20	0.02
	Drainage area (km^2)	TRD	101	0.08	0.02	0.74	0.06	0.10
		TACD	131	0.64*	0.11	2.83	0.56	0.72
		TAAD	113	0.07	0.01	0.35	0.06	0.08
	Max. elevation (m)	TRD	101	629.50	490	740	617.36	641.63
		TACD	131	617.26	460	800	606.06	628.46
		TAAD	113	435.27*	77	711	407.96	462.58
	Min. elevation (m)	TRD	101	541.58	400	700	528.26	554.91
		TACD	131	544.66	382	697	531.97	557.34
		TAAD	113	314.85*	31	582	287.75	341.95
	Stream drop (m)	TRD	101	87.91*	40	173	83.58	92.24
		TACD	131	72.60*	28	140	68.68	76.52
		TAAD	113	120.42*	44	226	113.30	127.55
Second order watershed	Stream length (km)	TRD	17	1.90	0.65	9.08	2.01	0.49
		TACD	26	1.13	0.27	2.97	0.70	0.14
		TAAD	19	1.01	0.23	1.96	0.53	0.12
	Drainage area (km^2)	TRD	17	0.35	0.07	2.12	0.48	0.12
		TACD	26	0.23	0.07	0.62	0.15	0.03
		TAAD	19	0.25	0.09	0.56	0.14	0.03
	Max. elevation (m)	TRD	17	640.59	510	740	59.61	14.46
		TACD	26	634.38	500	800	65.96	12.94
		TAAD	19	536.11*	379	711	106.08	24.34
	Min. elevation (m)	TRD	17	527.06	410	630	55.43	13.44
		TACD	26	533.73	400	635	71.24	13.97
		TAAD	19	355.95*	141	573	133.69	30.67
	Stream drop (m)	TRD	17	113.53	60	180	25.91	6.28
		TACD	26	100.65	60	165	29.30	5.75
		TAAD	19	180.16*	126	291	49.85	11.44
Third order watershed	Stream length (km)	TRD	2	24.02	22.12	25.92	2.68	1.90
		TACD	4	9.10	3.62	20.37	7.82	3.91
		TAAD	3	8.56	3.26	15.03	5.97	3.45
	Drainage area (km^2)	TRD	2	4.52	4.51	4.52	0.01	0.00
		TACD	4	1.96	0.75	4.26	1.62	0.81
		TAAD	3	2.47	0.89	4.55	1.88	1.09
	Max. elevation (m)	TRD	2	740.00	740	740	0.00	0.00
		TACD	4	694.00	600	800	86.01	43.00
		TAAD	3	623.00	543	711	84.29	48.66
	Min. elevation (m)	TRD	2	480.00	480	480	0.00	0.00
		TACD	4	501.25	442	540	47.77	23.89
		TAAD	3	288.33*	247	309	35.80	20.67
	Stream drop (m)	TRD	2	260.00	260	260	0.00	0.00
		TACD	4	192.75	116	317	86.98	43.49
		TAAD	3	334.67	234	464	117.65	67.92

*: Significant at the 0.01 level; N: Numbers of streams; TRD:Traditional method using 1/25,000 topo map; TACD: TauDEM method using contour based DEM (30m); TAAD: TauDEM method using Aster DEM (30m). An automated threshold calculated from theCDA is 5 for both contour based DEM and Aster DEM.

geomorphological attribute of properly graded drainage networks that has a physical basis in terms of geomorphological laws governing drainage network evolution (Tarboton et al., 1992). The smallest weighted support area threshold that produces a channel network where the mean stream drop in first order streams is not statistically different from the mean stream drop in higher order streams is selected (Tarboton et al., 2001). By using the smallest weighted support area that produces networks consistent with the constant stream drop property TauDEM extracts the highest resolution drainage network statistically consistent with geomorphological laws. However, it is important that the networks extracted from the automated procedure be close to what traditional methods using topo-maps or fieldwork would regard as channel networks. We will try to investigate this issue with following results.

Results of extractions of drainage networks with different thresholds for the studied watersheds are shown in Tables 3 to 5. In Table 3, geomorphometric values obtained with different threshold values for contour based DEM and Aster DEM showed discrepancy and statistically insignificant. Both TACD and TAAD with thresholds of 65 calculated using constant drop analysis have extracted extremely few numbers of 1^{st} order streams in compare to TRD. Furthermore, their mean stream length and mean drainage areas are four and forty times larger than that of the TRD's, respectively, and significantly different (0.01 level). However, their mean stream drops showed resemblance and are statistically insignificant. To have resemblance numbers of 1^{st} order streams correspond to topo-map (TRD) for Manahari khola watershed it is better to select a threshold having less or equal to 3 for both contour based and Aster DEMs (Fig. 4).

In the case of Jhirke khola (Table 4), the numbers of 1^{st} order streams extracted from TACD with

Table 3. Descriptive statistics of the geomorphometric values obtained for Manahari khola watershed

	Method	Data source	N	Threshhold	Mean	Minimum	Maximum	Std. deviation	Std. error
Stream length (m)	TACD	Contour based DEM (30m)	138	10	347.84 *(a)*	30	1208	264.82	22.54
	TACD	Contour based DEM (30m)	268	5	256.8 *(bcde)*	30	891	197.25	12.05
	TACD	Contour based DEM (30m)	316	4	241.05 *(bfg)*	30	964	181.73	10.22
	TACD	Contour based DEM (30m)	418	3	210.2 *(cfhi)*	30	969	170.22	8.33
	TACD	Contour based DEM (30m)	16	CDA (65)	1193.75 *(j)*	162	6181	1410.37	352.59
	TAAD	Aster DEM (30m)	224	5	224.57 *(dghk)*	27	988	198.35	13.25
	TAAD	Aster DEM (30m)	404	3	175.78 *(ik)*	27	948	154.46	7.68
	TAAD	Aster DEM (30m)	14	CDA (65)	1156.64 *(j)*	65	6064	1533.19	409.76
	TRD	1/25,000 topo-map	577	-	290.96 *(ae)*	42.16	845.71	124.96	5.2
Stream drop (m)	TACD	Contour based DEM (30m)	138	10	135.1 *(ab)*	0	549	110.39	9.4
	TACD	Contour based DEM (30m)	268	5	118.58 *(acd)*	0	508	94.29	5.76
	TACD	Contour based DEM (30m)	316	4	116.98 *(bce)*	0	536	88.8	5
	TACD	Contour based DEM (30m)	418	3	107.13 *(def)*	0	558	88.63	4.34
	TACD	Contour based DEM (30m)	16	CDA (65)	249.38 *(gh)*	15	927	220.28	55.07
	TAAD	Aster DEM (30m)	224	5	93.52 *(fi)*	0	499	96.53	6.45
	TAAD	Aster DEM (30m)	404	3	82.26 *(I)*	0	450	83.98	4.18
	TAAD	Aster DEM (30m)	14	CDA (65)	252.43 (gj)	0	938	245.91	65.72
	TRD	1/25,000 topo-map	577	-	255.86 *(hj)*	70	580	90.38	3.76
drainage area (m^2)	TACD	Contour based DEM (30m)	138	10	175808.2	35971.31	676907.2	125978.13	10723.97
	TACD	Contour based DEM (30m)	268	5	83706.52 *(ab)*	7200	401328.5	66384.23	4055.06
	TACD	Contour based DEM (30m)	316	4	67385.34 *(acdef)*	5400	401328.5	53257.78	2995.98
	TACD	Contour based DEM (30m)	418	3	50168.65 *(cghi)*	3294.14	401146.7	45580.3	2229.41
	TACD	Contour based DEM (30m)	16	CDA (65)	1528197.07 *(j)*	566513.5	6087883	1365404.23	341351.06
	TAAD	Aster DEM (30m)	224	5	83082.45 *(bdg)*	7896.55	341913.3	65866.09	4400.86
	TAAD	Aster DEM (30m)	404	3	44623.47 *(ehk)*	2916	225020.6	39986.78	1989.42
	TAAD	Aster DEM (30m)	14	CDA (65)	1598439.16 *(j)*	589313.1	6133630	1447930.21	386975.63
	TRD	1/25,000 topo-map	577	-	39859.62 *(fik)*	8000	224000	25530.54	1062.85

In mean value column, same letter in the parenthesis refers statistically insignificant.

Table 4. Descriptive statistics of the geomorphometric values obtained for Jhirke khola watershed

	Method	Data source	N	Threshold	Mean	Minimum	Maximum	Std. Deviation	Std. Error
Stream length (m)	TACD	Contour based DEM (30m)	21	50	503.19 *(a)*	42	2303	555.8	121.29
	TACD	Contour based DEM (30m)	89	10	301.31 *(bcd)*	30	1001	238	25.23
	TACD	Contour based DEM (30m)	163	CDA (5)	252.98 *(bef)*	30	989	203.63	15.95
	TAAD	Aster DEM (30m)	19	CDA (39)	535.79 *(a)*	27	1744	469.68	107.75
	TAAD	Aster DEM (30m)	84	10	272.32 *(cegh)*	27	1007	210.04	22.92
	TAAD	Aster DEM (30m)	196	5	214.68 *(fg)*	27	1142	192.84	13.77
	TRD	1/25,000 topo-map	178	-	331.56 *(dh)*	100.26	1246.24	172.55	12.93
Stream drop (m)	TACD	Contour based DEM (30m)	21	50	88.57 *(abcde)*	0	445	103.31	22.55
	TACD	Contour based DEM (30m)	89	10	91.17 *(afghi)*	0	455	89.66	9.5
	TACD	Contour based DEM (30m)	163	CDA (5)	89.96 *(bfjkl)*	0	452	89.52	7.01
	TAAD	Aster DEM (30m)	19	CDA (39)	122.75 *(cgjmn)*	0	339.61	103.83	23.82
	TAAD	Aster DEM (30m)	84	10	84.43 *(dhnmo)*	0	302.45	78.53	8.57
	TAAD	Aster DEM (30m)	196	5	78.87 *(eilno)*	0.3	452.05	79.96	5.71
	TRD	1/25,000 topo-map	178	-	269.82	20	800	132.27	9.91
Drainage area (m^2)	TACD	Contour based DEM (30m)	21	50	685006.57 *(a)*	289535.6	2617841	517212.92	112865.11
	TACD	Contour based DEM (30m)	89	10	149543.91 *(b)*	32855.82	479675.4	85147.45	9025.61
	TACD	Contour based DEM (30m)	163	CDA (5)	81902.42 *(cd)*	8100	331238.8	61641.44	4828.13
	TAAD	Aster DEM (30m)	19	CDA (39)	605565.17 *(a)*	257971.3	1286053	286090.9	65633.75
	TAAD	Aster DEM (30m)	84	10	151303.07 *(bc)*	27056.65	411933.2	95251.64	10392.81
	TAAD	Aster DEM (30m)	196	5	66411.5 *(de)*	5103	411284.4	61658.45	4404.18
	TRD	1/25,000 topo-map	178	-	63404.49 *(e)*	11000	337000	47778.73	3581.17

In mean value column, same letter in the parenthesis refers statistically insignificant.

Table 5. Descriptive statistics of the geomorphometric values obtained for Chure khola watershed

	Method	Data source	N	Thershold	Mean	Minimum	Maximum	Std. deviation	Std. error
Stream length (m)	TACD	Cotour based DEM (30m)	159	10	278.77 *(abc)*	30.00	986.00	205.59	16.30
	TACD	Cotour based DEM (30m)	200	8	266.66 *(adef)*	30.00	1001.00	189.55	13.40
	TACD	Cotour based DEM (30m)	322	5	233.73 *(bdghij)*	30.00	1061.00	175.04	9.75
	TACD	Cotour based DEM (30m)	13	CDA (108)	1467.62 *(kl)*	234.00	2977.00	1046.30	290.19
	TACD	Cotour based DEM (15m)	351	10	223.94 *(egmno)*	15.00	1378.00	186.34	9.95
	TACD	Cotour based DEM (15m)	430	8	202.28 *(hmpq)*	15.00	1399.00	168.38	8.12
	TACD	Cotour based DEM (15m)	719	5	158.35 *(inpr)*	15.00	989.00	174.66	21.03
	TACD	Cotour based DEM (15m)	12	CDA (300)	1613.08 *(k)*	21.00	3013.00	967.55	279.31
	TAAD	Aster DEM (30m)	290	5	199.93 *(joqr)*	27.00	968.00	177.74	10.44
	TAAD	Aster DEM (30m)	15	CDA (65)	1266.4 *(l)*	65.00	3307.00	1075.29	277.64
	TRD	1/25,000 topo-map	309	-	311.33 *(cf)*	0.00	1230.00	157.86	8.98
Stream drop (m)	TACD	Cotour based DEM (30m)	159	10	29.12 *(abcde)*	0.00	120.00	26.44	2.10
	TACD	Cotour based DEM (30m)	200	8	30.21 *(afghi)*	0.00	125.00	27.14	1.92
	TACD	Cotour based DEM (30m)	322	5	31.89 *(bfjkl)*	0.00	143.00	28.43	1.58
	TACD	Cotour based DEM (30m)	13	CDA (108)	67.38 *(m)*	10.00	140.00	48.81	13.54
	TACD	Cotour based DEM (15m)	351	10	31.18 *(cgjno)*	0.00	150.00	28.32	1.51
	TACD	Cotour based DEM (15m)	430	8	30.42 *(dhknp)*	0.00	161.00	26.78	1.29
	TACD	Cotour based DEM (15m)	719	5	23 *(eilop)*	0.00	87.00	23.10	2.78
	TACD	Cotour based DEM (15m)	12	CDA (300)	72.75 *(mq)*	1.00	140.00	45.31	13.08
	TAAD	Aster DEM (30m)	290	5	41.43	0.00	339.18	50.13	2.94
	TAAD	Aster DEM (30m)	15	CDA (65)	101.2 *(qr)*	0.00	316.51	91.10	23.52
	TRD	1/25,000 topo-map	308	-	114.35 *(r)*	25.00	245.00	35.94	2.05
Drainage area (m^2)	TACD	Cotour based DEM (30m)	159	10	113264.5 *(a)*	28756.60	460466.50	71312.04	5655.41
	TACD	Cotour based DEM (30m)	200	8	93260.08 *(a)*	16334.26	460466.50	56349.57	3984.52
	TACD	Cotour based DEM (30m)	322	5	62281.88 *(bcdef)*	9426.05	461199.30	47252.86	2633.30
	TACD	Cotour based DEM (30m)	13	CDA (108)	1621820.69	537073.50	3016692.00	885930.19	245712.83
	TACD	Cotour based DEM (15m)	351	10	56103.27 *(bghij)*	2250.00	435667.80	41709.98	2226.31
	TACD	Cotour based DEM (15m)	430	8	44343.62 *(cgklm)*	2250.00	224711.30	31846.98	1535.80
	TACD	Cotour based DEM (15m)	719	5	31171.09 *(dhkno)*	2250.00	139562.80	29588.61	3562.05
	TACD	Cotour based DEM (15m)	12	CDA (300)	1749915.88	794098.30	2784980.00	726281.90	209659.53
	TAAD	Aster DEM (30m)	290	5	59074.18 *(eilnp)*	6010.30	426641.30	46498.84	2730.51
	TAAD	Aster DEM (30m)	15	CDA (65)	1133925.35	451385.60	2784752.00	810590.75	209293.63
	TRD	1/25,000 topo-map	309	-	46996.76 *(fjmop)*	0.00	252000.00	33341.84	1896.75

In mean value column, same letter in the parenthesis refers statistically insignificant.

threshold 5 resembles with the TRD's outcomes; however, their gemorphometric values differ significantly (0.01 level). Similarly, geomorphometric values obtained from the TAAD and TACD showed consistency for threshold 5, and are statistically insignificant. Here, the threshold for TAAD should be selected 5 instead of 39 in order to have similar outcomes. One of the probable reasons for selecting different CDA threshold values for TAAD (39) and TACD (5) could be because of their different sources of DEM data; contour based DEM is derived from contour maps (topo-map) and Aster DEM is from stereo images (photogrammetrically). Furthermore, as shown in Table 5, the thresholds calculated using CDA for TACD is 108 and that for TAAD is 65. Even though their thresholds differ, the numbers of 1st order streams are very close, and mean streams lengths between them are statistically insignificant. Therefore, from Tables 4 and 5, it could be suggested that extracting 1st order streams similar in numbers to that of topo-map's could be achieved by selecting different thresholds rather than selecting the one computed by the constant drop analysis. In this case, an appropriate threshold value would be 5 for the Mahabharat watersheds. In making this judgment it is best to consider many things, like sample sizes (is the *t*-statistic robust), the visual impression in comparison to contour crenulations, and the drainage density that would result from a slope versus area plot as discussed in (Tarboton et al., 2001,

Table 6. Test of significance in drainage density and stream drops at Thadokhola watershed

Watershed name	Stream order	N	Drainage density (km-1)	Stream drops (m)
Thadokhola	First order	101	7.65	87.91*
	Higher order	19	6.64	128.95*
Chure khola	First order	307	7.84*	114.4*
	Higher order	88	6.76*	188.52*
Manahari khola	First order	578	8.21 *	255.68*
	Higher order	167	7.53*	488.53*
Jhirke khola	First order	178	6.6*	269.82*
	Higher order	61	5.68*	501.65*

*: *The mean difference is significant at the .05 level.*

*: The mean difference is significant at the 0.05 level

Table 7. Drainage density of the all studied watersheds

	Watersheds											
Stream order	Thado khola			Chure khola			Manahari khola			Jhirke khola		
	N (TRD)	Dd (TRD)	Dd (TAAD)	N (TRD)	Dd (TRD)	Dd (TAAD)	N (TRD)	Dd (TRD)	Dd (TAAD)	N (TRD)	Dd (TRD)	Dd (TAAD)
1	101	4.1	4.5	308	7.8	1.0	576	8.2	0.6	178	6.6	1.0
2	17	4.3	5.0	69	7.1	1.2	130	7.8	0.8	46	6.0	1.4
3	2	3.6	4.1	14	5.9	1.2	29	7.0	0.9	11	4.9	1.3
4	1	3.6	4.4	5	4.5	-	5	7.8	-	4	4.5	1.4
5	-	-	-	1	4.8	-	1	6.4	-	1	4.5	-

TRD:Traditional method using 1/25,000 topo map; TAAD: TauDEM method using Aster DEM (30m) N: Numbers of streams. Dd: Drainage density (km-1).

1991, 1992).

To investigate automated threshold selections for different DEM resolutions, a 15m resolution contour based DEM (DEM-15m) was prepared from the 30m resolution contour based DEM (DEM-30m) by interpolation method in Erdas Imagine. The threshold values obtained for 30m and 15m DEMs are 108 and 300 by using CDA, respectively (Table 5).

Numbers of 1st order streams extracted for 30m and 15m DEMs are 13 and 12, respectively, and differences in their mean stream lengths and stream drops are statistically insignificant. The results suggest that there is a relevancy in drainage network extraction between 15m and 30m resolution DEMs. Having same threshold values, numbers of 1st order streams extracted from the 15m DEM are more than a double to that extracted from 30m DEM. For an instance, numbers of 1st order streams extracted from 15m DEM are, 351, 430 and 719, whereas, that for 30m DEM are 159, 200 and 322, for the thresholds 10, 8 and 5, respectively (Table 5). This outcome implies that high-resolution DEM extracts more 1st order streams than low resolution DEM, and their mean stream length and drainage area differ significantly at the level of 0.01 (in this case for thresholds: 10 and 8).

The aforementioned results depict that the extraction and delineation of lower order streams from TauDEM using DEMs differ with the traditional method using topographic maps; as a result, their geomorphometric values differ accordingly.

However, TauDEM delineates the entire watershed with similar shape and size as delineated from the topo-maps. The most apparent reason for the difference between TauDEM and traditional methods in extracting and delineating lower order streams is due to the algorithm incorporated into the TauDEM program. In TauDEM, a smaller weighted support area threshold would result in drainage networks with first order stream drops inconsistent with the rest of the drainage network (Tarboton et. al., 2001). But, this is not the case for the TRD outcomes. Difference in mean stream drops between 1st and higher order stream is found statistically significant (0.05 level) for all the studied watersheds (Table 6). These results do not comply with the constant stream drop property; therefore, traditional and TauDEM methods might have attributed different outcomes. Another explanation for different outcomes between traditional and TauDEM methods, is probably due to the variation of drainage density (*Dd*: total stream length divided by total drainage area) within the watersheds. *Dd* calculated from the topo-map varies within the watershed, i.e. lacks consistency between lower and higher order watersheds (Table 7). In contrast, drainage density obtained from the TauDEM showed spatially uniform as it extracts channel network statistically consistent with geomorphological laws.

As shown in Table 6, excluding Thado khola watershed, all the watersheds have high drainage densities and their mean differences between 1^{st} and higher order streams lack consistency (significant at the 0.05 level). Higher drainage density for TRD is due to the extraction of blue lines (stream lenght) on topo-maps. It is very interesting to note that drainage density obtained from TRD resembled with that of TAAD for Thado khola, and geomorphometric values obtained from TRD, TACD and TAAD with same CDA threshold (5) showed much consistency in comparison to other studied watersheds (Table 2). It is not evident whether this coincidence is responsible for the constant drop property or is due to it. Further investigations are needed to clarify it.

Conclusion

Extracting channel networks, delineating sub-watersheds and measuring geomorphometric parameters from topo-maps require time; precise workmanship and judgments of a cartographer; and fully depended upon the resolution of topo-maps. In contrast, an automated delineation using TauDEM is more sophisticated, convenient, and can be circumvented the efforts on digitizing to incorporate with other GIS data. It extracts the highest resolution channel network statistically consistent with geomorphological laws by using the smallest weighted support area threshold calculated from the constant drop analysis. However, TauDEM attributed geomorphometric values are not resemblance with the outcomes obtained from the 1/25,000 topographic maps, TauDEM is still advantageous to use as drainage analysis tool. But, it should be kept in mind that the automated procedure is not completely foolproof and some degree of judgments and subjectivity is required.

As DEM is numeric or digital representation of the elevations of all or part of a planetary surface (Tarbotom et al., 1991), it is advantageous in using drainage analysis purposes. However, it is highly recommended to use same DEM domain with same resolution in order to avoid discrepancies while performing drainage analysis for a watershed or among watersheds. It is undesirable to compare drainage analysis results within or among the watersheds that is obtained from different methods; traditional method with topographic maps and using TauDEM with different DEMs.

Acknowledgements

We gratefully acknowledge the financial support from the Japan Society for the Promotion of Science (JSPS) for purchasing computer machine, GIS software and DEMs for carrying out this work.

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