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Analysis of alluvial fan surface coefficients to understand the Himalayan foothill instability in the Koshi-Mahananda interfluve area, East Nepal

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Abstract

The foothills of the eastern Nepal Himalayas form a colony of alluvial fans. The fan surfaces are extensively used for tea plantations and their associated land use, like dense settlements and intensive crop cultivation. Dynamic surfaces of the fans are unfavorable for a stable land use pattern and hamper human life. It is necessary to identify the dynamic natures and their cause over the fan surfaces to avoid unfavorable circumstances and for preventive measures. Fan surface coefficients show that most of the alluvial fans of the study area are highly unstable. The perennial stream supplies huge sediments in a wet climatic environment, which causes an alluvial fan instability in the eastern Nepal Himalayan foothills. The studied fan areas are derived from small river basins (2nd order) that supply a relatively low amount of sediments, but the fans are highly dynamic. This study reveals that frazil surface due to huge deforestation of geological structures under high neotectonics and high stream competency due to wet climate are responsible for this instability.

Keywords: Surface Geometry; Instability; Stage of development; Ideal shape; Controlling factors

1. Introduction

The study area is located in the Koshi-Mahananda interfluve area at the foothills of the eastern Nepal Himalayas. It is extended from 87°E to 88.5°E and from 26°N to 27°N (Fig 1). This area's hot and humid climate (Shrestha and Aryal, 2011) forms a colony of alluvial fans that covers an area of about 1706 km^2. The fans favor the luxurious growth of natural vegetation. They are attractive for agriculture and associated land use of settlements and roads due to their high moisture, and fertile soil. But, the area shows a great variation in land cover and land use. Fan surface instability is responsible for such variation. The instability also causes hazards like soil erosion and flash floods. Understanding the instability of the fan surfaces is the main focus of this study, to find out the solution of this hazard problem. For this purpose, coefficients are measured in different ways. To understand the controls of the instability, geology and geotectonics, drainage, land use and land cover are studied, which are the objectives of this research.

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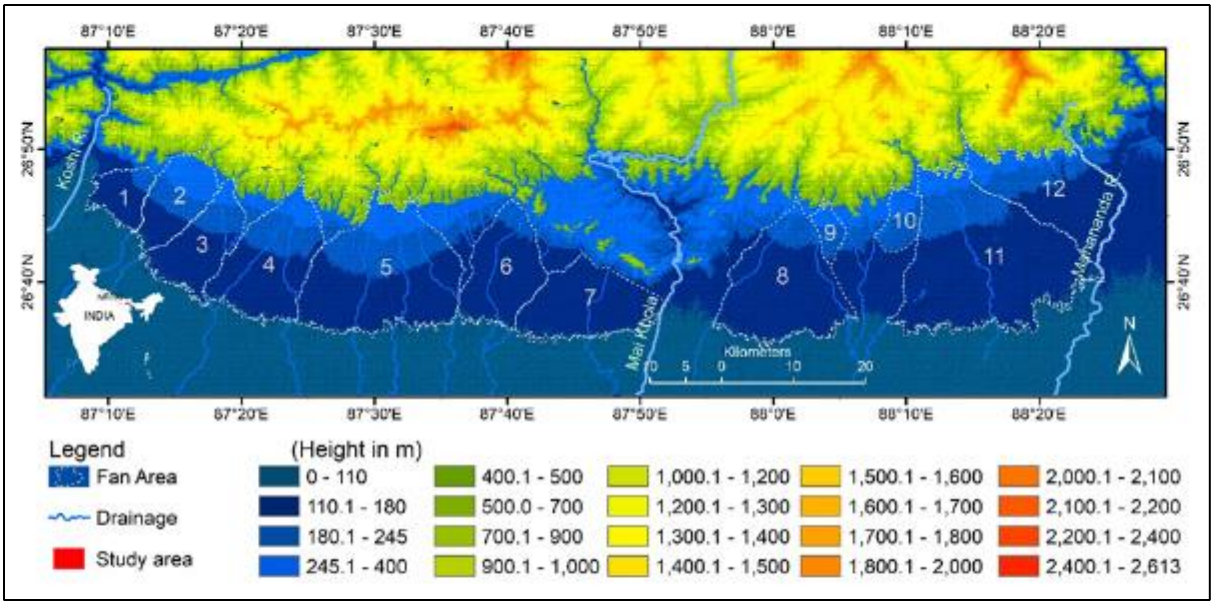

Figure 1 Location of the study area

2. Methodology

This research work has been completed in different steps (Fig 2). The alluvial fan surfaces and their different geomorphic areas and geometric surfaces are identified to measure the coefficients (Table 1). For this purpose, geometric points A, B, C, D, M and N are placed over the fan surface (Fig. 3). Line *BC* shows the maximum width of the fan surface, with point *A* being the fan head and *D* being the center of line *BC*. The lines *AM* and *AN* represent the maximum distance between the head and the distal part of the alluvial fan. The fan area above the line *BC* is identified as a *no-serve zone* and below the line *BC* is identified as a *serve zone* (Table 1; Fig 3). The *ΔABC* is the ideal triangular geometric surface of the fan and the half circle with the radius *BD* or *CD* is the ideal semi-circular geometric surface of the fan (Table 1; Fig 3). The sector *AMN* of a circle with a radius *AM* or *AN* is a perfect conical shape of the fan. Here, the fan is placed exactly within the sector *CMN*. The drainage and hydrology, geology and geotectonics, and land use and land cover are studied to understand the other factors of fan dynamics. The data are collected from different secondary sources and are measured, analysed and interpreted with the help of Different RS and GIS softwares (Table 2).

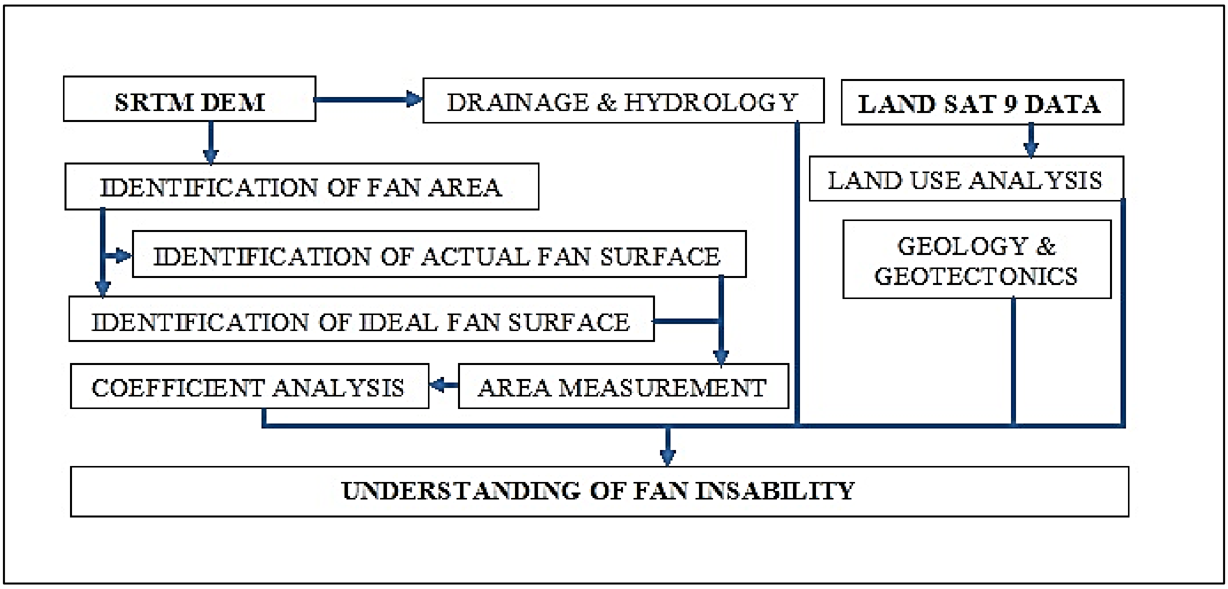

Figure 2 Methodological flow chart

Table 1 Coefficients of Alluvial fan

Description		**Remarks**	**Source**
Different Fan Surface Areas	Actual area of No-serve zone (AaNsz)	Area of fan above maximum width with restricted or no fan propagation.	SRTM DEM
	Actual area of Serve zone (AaSz)	Area of the fan below the maximum width with the advance propagation of the fan area	SRTM DEM
	Actual area of the Total fan surface (AaTfs)=(AaNsz+AaSz)		SRTM DEM
	Ideal area of Triangular surface (IaTs)	Ideal fan shape above maximum width with mature stage	Amron, 2019
	Ideal area of Half circular surface (IaHcs)	Ideal fan shape below maximum width with mature stage	Amron, 2019
	Ideal area of the Total geometric surface (IaTgs)=(IaTs+IsHcs)		Amron, 2019
Total Fan Area Coefficients	Ideal area of Conical fan (IaCf)		Amron, 2019
	Conicality Index (CI)= (AaTfs/ IaCf)	<1= Alluvial fan; >1= Not an Alluvial fan	Mukharji, 1976
	Triangular Co-efficient (TCo)=(AaTfs/IaTs)x100	100 % = Ideal geometric shape. The mature stage of the fan surface. A stable tectonic environment is observed. <100% = Immature stage. Moving towards an ideal geometric shape. A stable tectonic environment may be observed. >100% = Immature stage. Moving from its ideal geometric shape. An unstable tectonic environment is observed.	Sasmal, 2024
	Semi-circular coefficient (ScCo) =(AaTfs/IaHcs)×100		Sasmal, 2024
	Typical coefficient (TyCo) =(AaTfs/IaTgs)×100		Sasmal, 2024
Old and Younger Fan Surface Coefficients	No-serve coefficient (NsCo) =(AaNsz/IaTs)×100		Sasmal, 2024
	Serve coefficient (SCo) =(AaSz/IaHcs)×100		Sasmal, 2024
	Fan shape coefficient (FsCo) =(AaNsz/AaSz)×100	<100% = Younger stage of fan. Fast fan propagation is observed in the serve area due to active depositional lobes. 100% = Middle stage of fan. Mostly equal depositional lobes in the serve and no-serve zone. >100% = Mature stage of fan shows very low or absence of depositional lobes.	Sasmal, 2024

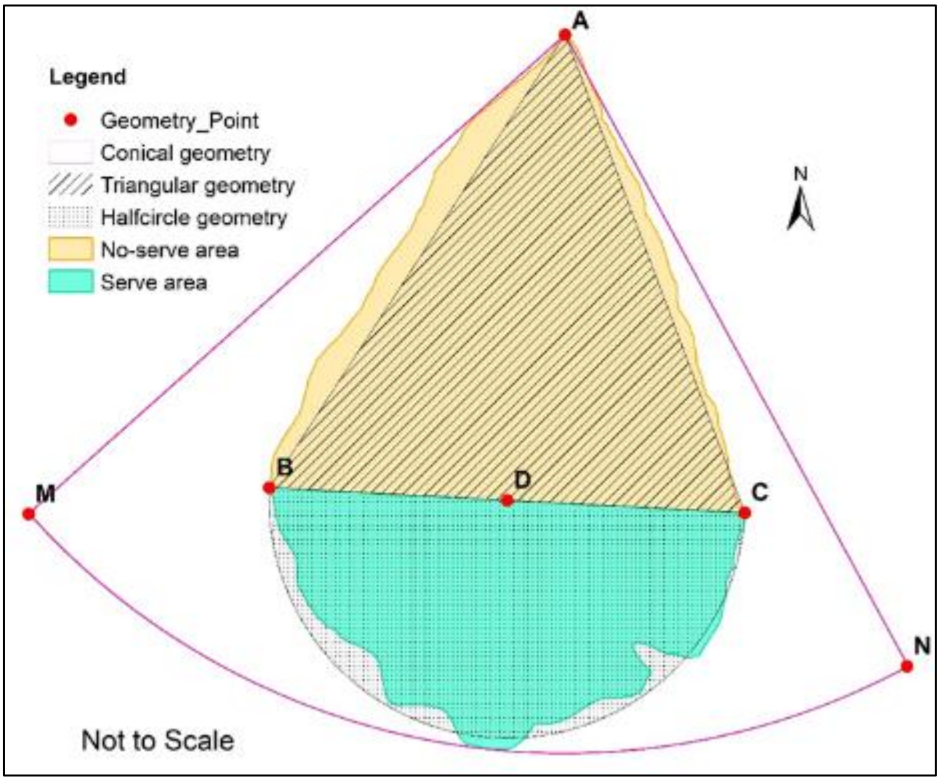

Figure 3 Index map of the geometric index

Table 2 Data source

Data Type	Source					Data Analysis
Fan area, Hydrology,	SRTM DEM	Sensor	Date	Extension	Resolution: 30 m	ArcGIS; QGIS; ERDAS IMAGINE; Microsoft Excel
		SIR-C/X-SAR	11/02/2000	87°E to 88°E and 26°N to 27°N		
			11/02/2000	88°E to 89°E and 26°N to 27°N		
Land use & Land cover	LANDSAT 9	OLI-2; TIRS-2	05/01/2025	Path: 139; Row: 041		
			13/01/2025	Path: 139; Row: 042		
			04/01/2025	Path: 140; Row: 041		
Tectonics	Dasgupta et al. 2021					
Geology	Amatya et al., 1994					
Geometric surface	Amron, 2019					
Coefficient analysis	Sasmal, 2024					

3. Observation

3.1. Geology and Geotectonic

The eastern Nepal Himalayas are a tectonically highly sensitive zone (Fig 4a). The surface erosion of this Himalayan part is the source of alluvium of the studied fan area. Geology and geotectonic are the factors of this surface erosion. The mountain area shows five major groups of geological formations (Table 3). The crystalline groups are less erosive than the Siwalik and meta-sedimentary groups (Amatya et al, 1994) in this area. The presence of transverse faults makes the Crystalline Group of rocks erosion-prone and the tectonic thrusts-faults like the Main Central Thrust (MCT), Main

Boundary Thrust (MBT) and Main Frontal Thrust (MFT) cause regional instability (Fig 4b). The northeastern part of the mountain area records a higher earthquake epicenter than the other part (Fig 4b).

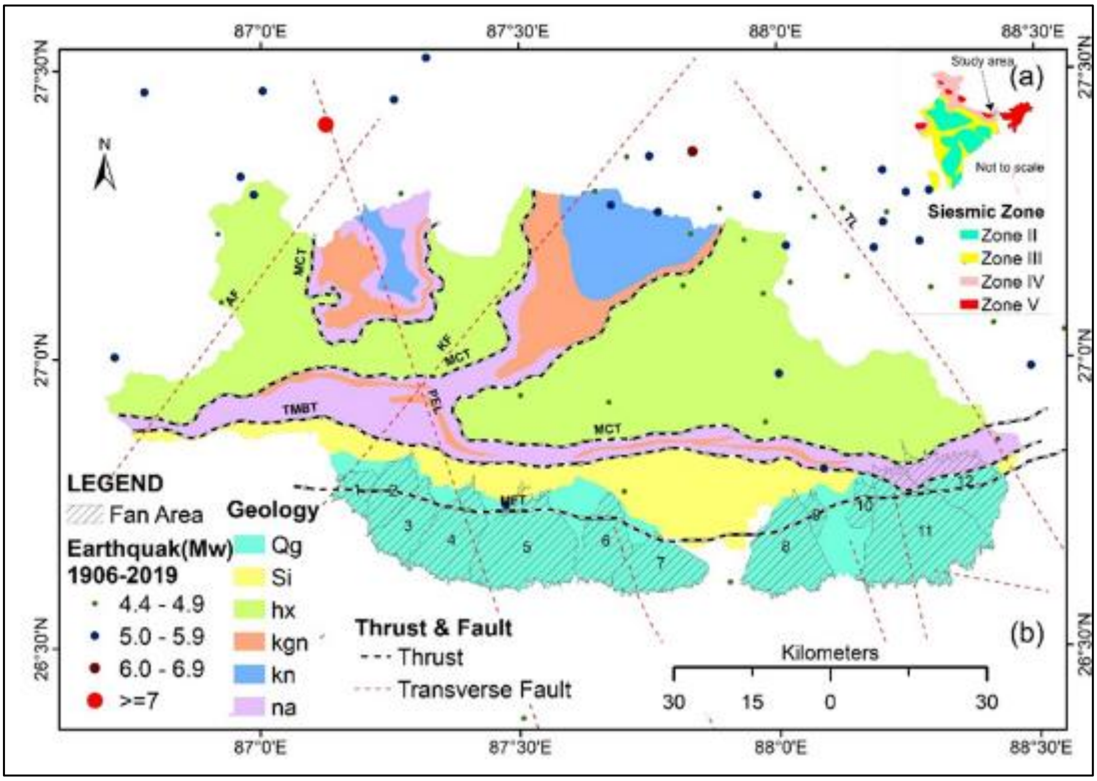

Figure 4 a) Seismic zone of India and Nepal. b) Geology of the study area and surroundings

Table 3 Geology of the study area

Index	Description	Formation	Group
Qg	Quaternary alluvial deposits		
Si	Fluvial/ Flavio-glacial gravels, conglomerates and lacustrine clay deposit	Plio-Pleistocene to Quaternary.	Siwalik Group
hx	High-grade metamorphic rocks: quartzite and marbles, Migmatite, granite gneisses.	Precambrian	Higher Himalayan Crystalline
kgn	Augen gneisses and two mica granites are mainly in the Kuncha Group, some in the Nawakot Group.	Precambrian and probably Paleozoic.	Lesser Himalayan Crystalline
kn	Flyschoid sequence (bedded schists, phyllaite and meta sandstones), locally shallow water quartzite beds and basic sill and dykes present.	Precambrian.	Lesser Himalayan Meta Sediments
na	Shallow marine sediments; dominant with phyllaite, sandstones, quartzite, calcareous sandstones, Stromatolitic limestones and black slates.	Pre-Cambrian to Lower Paleozoic formation	Lesser Himalayan Meta Sediments

3.2. Drainage

Drainage is another factor that transports sediments from the mountain area to the fan surfaces. Higher stream order causes higher stream competency. Maximum 2nd order small river basins between the MBT and MFT supply the sediments to the studied fans, but a single fan receives sediments from more than one basin (Fig 5).

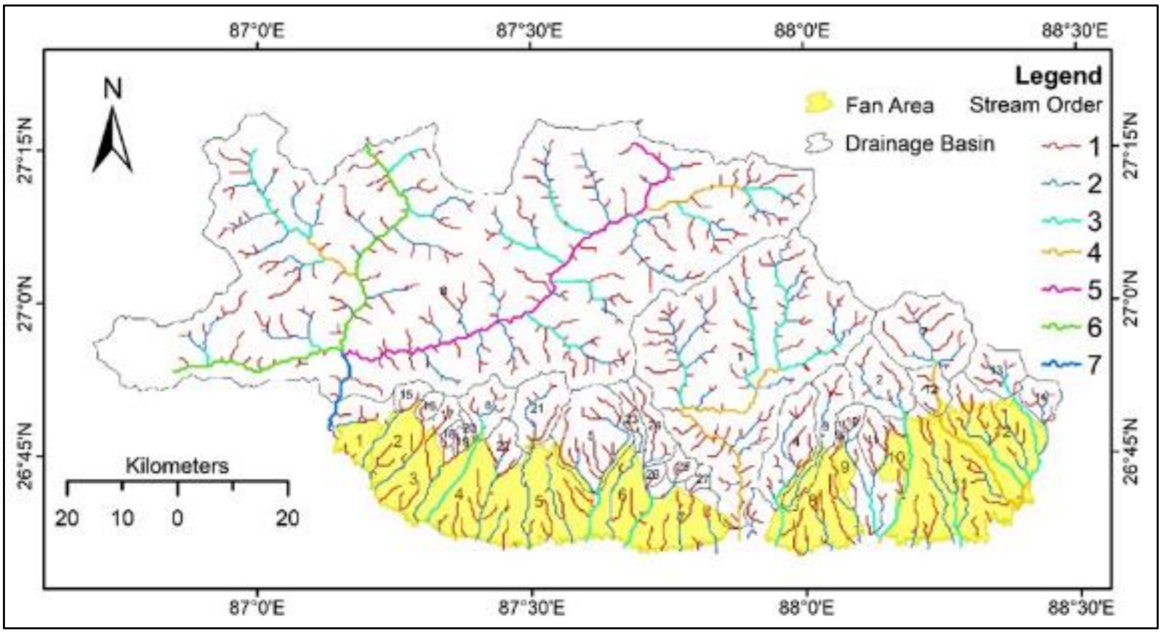

Figure 5 Drainage basin of the study area

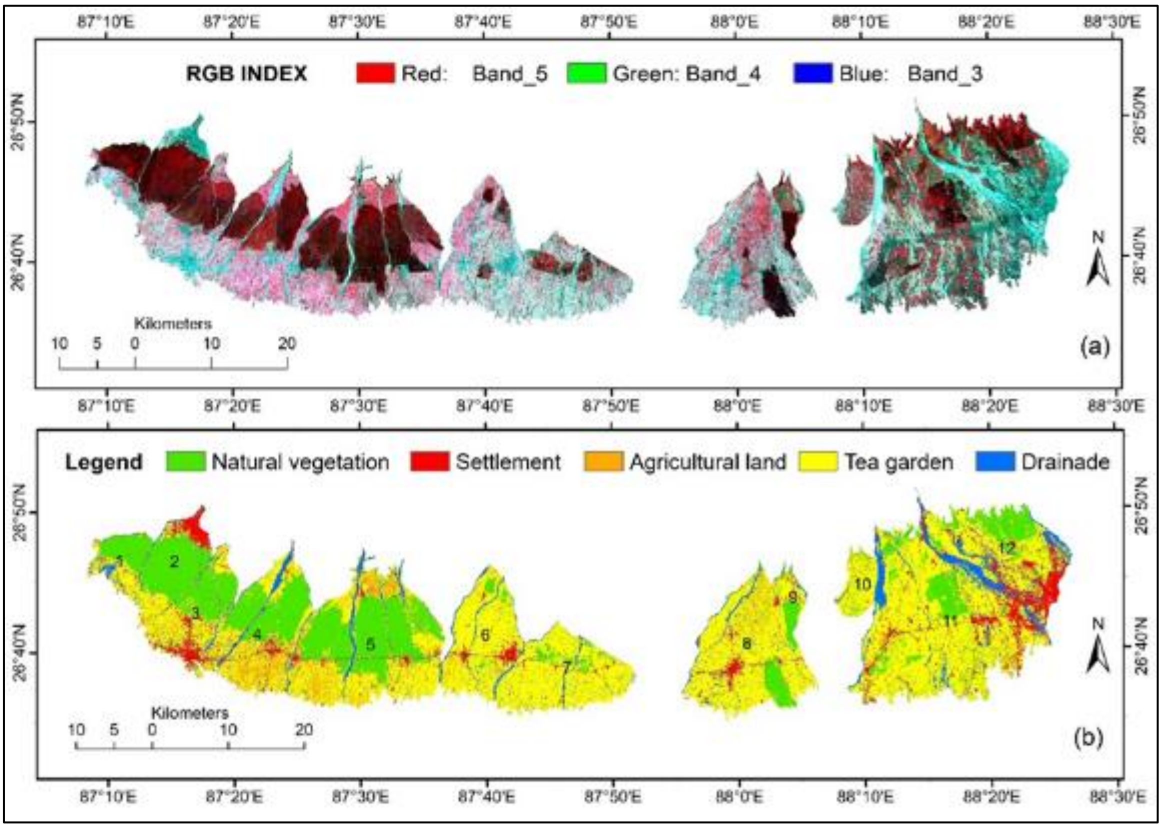

Figure 6 a) Landsat 9 image b) Land cover and land use of the study area

3.3. Land use and Land cover

The alluvial fans at the eastern Himalayan foothills are ideal for tea plantations due to their fertile, moisture-rich soil. The studied fan surfaces show five major types of land use and land cover, i.e. - i. Water bodies, ii. Natural vegetation, iii. Tea plantations, iv. Agricultural land and v. Settlements (Fig 6). The streams that separate alluvial fans represent the water bodies. Natural vegetation covers about 50% of the surface area of the fans having IDs from 1 to 5. All other fans show a little patch of natural vegetation in their fan head area. The alluvial fans having IDs from 6 to 12 are dominated by tea plantations that cover about 80% of the fan surfaces. The other fans show moderate coverage of tea plantations. The agricultural land is higher in the western fan areas (IDs 1 to 5) than the eastern fan surfaces (IDs 6 to 12). The settlements form patches in the lower fan area. Only the 2nd fan in the west shows a high density of settlement in its fan head area.

3.4. Coefficient analysis

Coefficient analysis of the fan surface geometry reveals the variation of fan dynamics in the studied geomorphic surfaces (Table 4). Difference from an ideal value of 100% indicates the instability of the fan surface. Greater the difference refers to higher instability. CI measurement reveals all the studied geomorphic surfaces at the foothills are alluvial fans. The analysis of TCo and ScCo shows that all the immature alluvial fans of the study area are moving away from the ideal triangular or semi-circular shape. The ideal triangular and semi-circular shape combination form the ideal-typical fan shape. TyCo refers to the fans 2, 3, 5, 6 and 9 moving away from the ideal-typical fan shape and the fans 1, 4, 7, 8, 10, 11 and 12 moving towards the ideal-typical fan shape. NsCo shows most of the no-serve area of the alluvial fans are moving away from its ideal triangular shape. ScCo shows an immature stage of the serve zones that vary in their dynamics. The fans 1, 2, 3, 4, 7, 8, 10, 11 and 12 are moving towards their ideal semi-circular shape, and the fans 5, 6 and 9 are moving away from their ideal semi-circular shape. FsCo signifies the stage of fan development (Sasmal, 24). Fans 1, 3, 7, 8 and 11 show a mature stage and fans 2, 4, 5, 6, 9, 10 and 12 show an immature stage of fan development processes.

Table 4 Fan surface measurement and Co-efficient analysis

FAN IDs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
AaNsz (Km²)	33.12	14.98	85.36	139.13	106.56	59.01	88.24	163.62	5.76	10.72	283.89	74.72
AaSz (Km²)	12.95	69.18	11.87	20.64	167.43	62.79	48.44	37.42	14.60	23.63	80.67	91.28
AaTfs (Km²)	46.07	84.16	97.23	159.77	273.99	121.80	136.68	201.05	20.36	34.34	364.56	166.00
IaTs (Km²)	29.77	17.71	64.83	108.35	83.67	48.30	79.57	149.52	3.41	10.53	272.33	44.05
IaHcs (Km²)	35.68	22.65	31.99	61.81	145.13	38.72	138.24	125.59	9.14	25.72	292.47	150.17
IaTgs (Km²)	65.46	40.35	96.82	170.15	228.80	87.02	217.82	275.11	12.55	36.24	564.79	194.21
IcFa (Km²)	115.58	232.57	184.66	261.66	413.32	284.65	196.87	295.94	74.53	94.08	526.72	460.29
CI	0.40	0.36	0.53	0.61	0.66	0.43	0.69	0.68	0.27	0.37	0.69	0.36
TCo	154.73	475.26	149.97	147.47	327.46	252.17	171.77	134.46	597.30	326.29	133.87	376.88
ScCo	129.10	371.64	303.95	258.50	188.78	314.57	98.87	160.09	222.87	133.56	124.65	110.54
TyCo	70.38	208.56	100.42	93.90	119.75	139.97	62.75	73.08	162.31	94.77	64.55	85.47
NsCo	111.24	84.58	131.66	128.41	127.36	122.17	110.89	109.43	169.02	101.81	104.25	169.64
ScCo	36.28	305.50	37.09	33.40	115.36	162.17	35.04	29.80	159.80	91.88	27.58	60.79
FsCo	255.84	21.65	719.43	674.00	63.65	93.98	182.16	437.22	39.47	45.35	351.92	81.85

4. Analysis

To identify the foothill instability, different coefficients of the alluvial surfaces are measured, and to understand the cause of variation in the instability among the alluvial surfaces and their different parts, controlling factors like geology, geotectonic, drainage and land use are studied. The study reveals that the foothills of the studied surfaces (Fig 7a) are a colony of alluvial fans (analysis of CI). The fans receive sediments from numerous very small river basins (maximum 2nd order). Small basins are unable to form an alluvial colony. However, the location of these small river basins between the MBT and MFT indicates the presence of volatile neotectonic movement in the study area. The geology of river basins (Table 3) is highly erosive. Tectonic instability and erodibility of geological formations provide huge sediments that are transported by the perennial streams at the foothills and form the colony of alluvial fans.

Coefficient analysis (TCo and ScCo) reveals the immaturity which signifies the high instability of the fan surfaces at the foothills of the eastern Nepal Himalayas. Instability provides various typical shapes of the fan surfaces. Neotectonic environments and structural controls are responsible for this difference in fan shape typicality. The movement of 2, 3, 5, 6 and 9 alluvial fans from the ideal-typical shape (TyCo analysis) signifies the rejuvenating nature of the fans after their maturity (Table 1). The presence of the earthquake epicentre (Fig 4b) is responsible for such rejuvenation. The immaturity and movement of 1, 4, 7, 8, 10, 11 and 12 fans towards ideal-typical (TyCo analysis) shape advocate for a relatively stable tectonic environment in those areas.

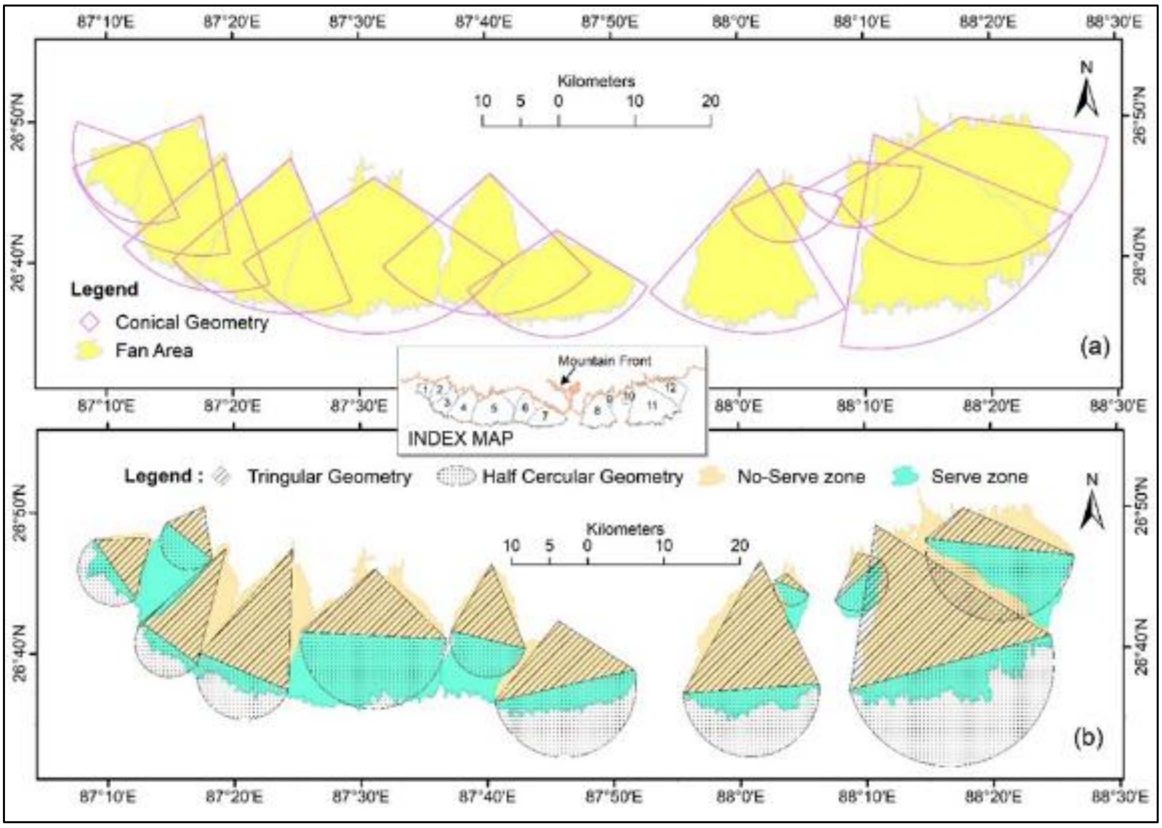

Figure 7 Geometric shape of the studied fan surfaces

The no-serve zones (Fig 7b) are moving away from maturity and most of the serve zones (Fig 7b) are moving towards maturity (NsCo and ScCo analysis). This opposite of movement signifies the upslope rejuvenation of the alluvial fans under neotectonic controls. The location of tectonic thrust (Fig 4b), number and size of the river basins (Fig 5) and land use patterns (Fig 6b) are responsible for the mature stage (FsCo analysis) of the fans 1, 3, 7, 8 and 11. The low amount of sediment supply from one or few small basins (fans 1, 3 and 7), the resistance of thick forest to soil erosion (fans 1 and 3) and the relatively low tectonic effect due to location of MFT to the outer part of the fan area (near head of the fan 7, 8 and 11) causes the mature stage of the alluvial fans. The reverse situation for all other alluvial fans (fans 2, 4, 5, 6, 9, 10 and 12) causes their immature stage of development.

5. Conclusion

Overall observation shows that the no-serve zone of the alluvial fans is more dynamic than the serve zone in the study area. The variation in surface dynamics among and within the fans signifies the variation in controlling factors. The control of natural vegetation over fan dynamics is higher than the settlement and agricultural activities. Neotectonics dominates over all controlling factors.

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