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# Role of various geomorphic parameters in landslide susceptibility of the Balason river basin of Darjeeling Himalaya, India

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**ABSTRACT**

Occurrences of landslides are affected by geomorphic, tectonic and hydrologic parameters. Balason basin of Darjeeling Himalaya, exhibits these parameters which are analyzed in the context of landslides occurrences. In the present work, we carried out an overlay analysis of various data layers such as elevation, slope, geology, geomorphology, soil, rainfall, drainage density and drainage frequency with the landslide distribution data layer to assess the probability of class of the landslide causative factors. Frequency ratio (FR) value estimate, for both landslide affected pixels and total pixels of a class, help in establishing the relationship between the probability of landslide and each class of the landslide causative factor. The result showed that, those areas which are characterized by elevation of 2130 – 2603 m, slope of 47.00 – 71.00°, rainfall of 2559 – 2617 mm, drainage density 10.60 – 15.10 km/sq. km, 70.35 – 104.30 no. of stream/sq.km drainage frequency are registered with high frequency ratio and high landslide susceptibility. In addition, the probability of landslide occurrences is also found high in Darjeeling gneiss, lower hill and fine loamy to coarse loamy soil textural area.

**Key words:** Frequency ratio (FR), Susceptibility, RS and GIS, Balason river basin**.**

## INTRODUCTION

Landslides can be defined as the movement of mass of rock, debris or earth materials down the slope under the influence of gravitational force. Many researchers in India (Nautiiyal, 1966, Sengupta, 2000, Mandal and Maiti, 2014) carried out demand based studies in mountainous and hilly areas and tried to find out the causative factors and consequences of landslide occurrences and recommended some mitigation practices to reduce its hazardous impact. In Darjeeling, the spatial extents of landslides are increasing day by day, causing severe damage to lives and properties. The Balason river basin is not an exception to these phenomena, which is characterized by distinct geographical environment. The evolution of landforms is largely dependent on its geological structure, lithology, relief configuration, climatic characteristics and bio-physical processes. Researchers like Tamang (2013) and Lepcha (2012) carried out studies on geophysical set up of Balason River basin. This basin has been experiencing active denudational processes since its origin because of high relief diversity, tectonic influences, human interferences, stream activities, monsoonal rainfall and so on. Free face and rectilinear facets of slope of the landforms situated in higher altitude, especially cliffs, spurs and tea garden areas are more instable in nature of this basin. However, in this study an attempt has been made to understand the role of various geomorphic attributes i.e. elevation, slope, geology, geomorphology, soil, rainfall, drainage density and drainage frequency, to visualize the nature and extent of variations in landforms characteristics and landslide susceptibility.

## STUDY AREA

The Balason river basin, situated in the western part of the Darjeeling district, that suffered several large and small landslides and affected many properties and lives, was chosen as the study area (Figure 1). The major right bank tributary of the Mahananda river and the Balason river, originates from Lepchajagat (2361 m) which is located on the Ghum-Simana ridge. Balason river basin covers parts of Darjeeling district in West Bengal having an area of 378.45 sq. km. The main Balason river flows north to south-east, having length of about 51.92 km and joins Mahananda River at around 26°41´28´´ N and 88°24´15´´ E . The highest elevations are 2613 m (SE corner) and lowest 105 m, in Southern part of the basin. The area above 30° slope consists of comparatively harder gneissic rocks and the area in between 0°-5° have the permeable subsurface materials. The average rainfall of the basin is 2300 mm (range 2000-5000 mm), which is dependent on southwest monsoon and occurs mostly in the months of June to September. The mean annual temperature is about 20.94° C. The northern uplands and southern lowlands have a mean annual temperature of 12° C and 24.70° C respectively (Lama, 2003). The area is predominately represented by very shallow to deep soils. The major portion of the basin (about 74%) consists of Darjeeling gneisses, Daling series rocks and the Damuda series.

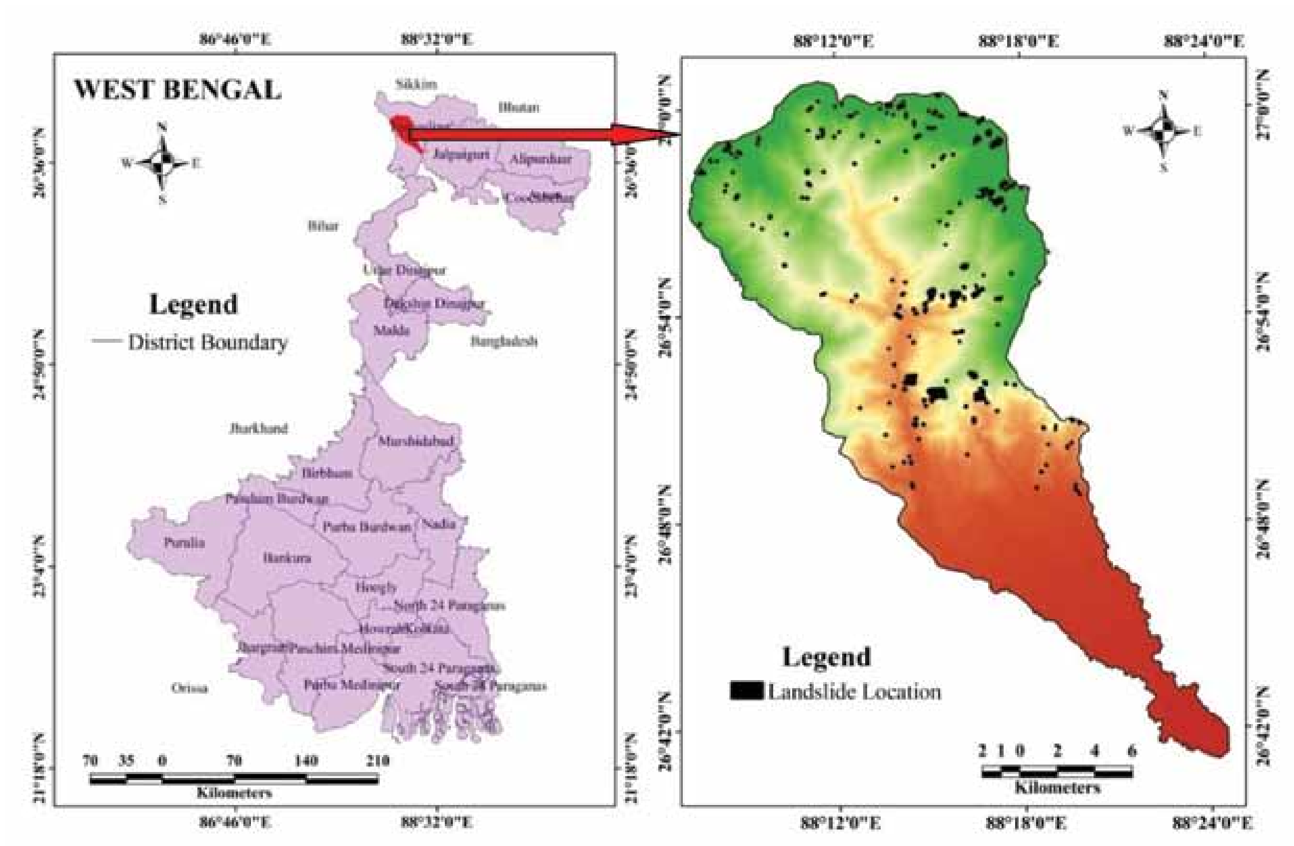


**Figure 1.** Location map of the study area.

## METHODOLOGY

In the present work, eight parameters i.e. elevation, slope, geology, geomorphology, soil, rainfall, drainage density and drainage frequency have been used to assess the role in landslide susceptibility. Basically, landslide susceptibility refers to the possibility or chance or likelihood of potential landslides in a given area of interest based on the local terrain conditions (Grozavu et al., 2013). Elevation and slope data layers were directly derived from SRTM DEM (30m spatial resolution) in Arc GIS 10.1 environment which was downloaded using https://earthexplorer.usgs.gov link. The soil and geological maps were collected from NBSS (National Bureau of Soil Science and Land Use Planning, Kolkata) and GSI (Geological Survey of India, Kolkata) respectively and digitized in Arc GIS 10.1 platform. Geomorphological map was digitized from Unpublished Ph.D. Thesis of Lama (2003) using Arc GIS environment. Rainfall data was downloaded from http://www.worldclim.org link in Continuous raster data format and imported in Arc GIS environment. Drainage network was digitized from Survey of India (SOI), Kolkata. Map nos. 78a/4, 78a/8, 78b/1, 78b/5 and 78b/6 and was checked with and google earth image (2015). Inverse distance weighted (IDW) method was incorporated to prepare drainage density and drainage frequency map in Arc GIS 10.1 software. The database of landslide distribution map was generated from Google earth historical imageries (2000-2016), Landsat 7 ETM+ imageries (2000-2005), Landsat 4-5 TM imageries (2006-2007, 2009-2011), LISS III imageries (2008, 2012-2013), Landsat 8 OLI (2014-2015), High resolution Sentinel-2 imagery (2016), Arc Map high resolution world imagery and intensive field survey data (2015-2016). Total 295 landslide polygons were mapped in an area of 378.45 sq.km (Table 1). The average area of the landslides was 3762.90 $m^2$.

To establish the relation between each factor and landslide occurrences, the frequency ratio (FR) value was used (Karim et al., 2011).

$$Fr_i = \frac{\{N\ pix\ (Si)/N\ pix\ (Ni)\}*100}{\{\sum N\ pix\ (Si)/\sum N\ pix\ (Ni)\}*100} \qquad \text{............. (1)}$$

Where, N pix (Si) is the number of pixels containing landslide in each class (i), N pix (Ni) is the total number of pixels having class (i) in the whole basin, or simply the percentage of landslide pixels to total pixels in a class, ∑N pix (Si) total number of pixels in each class and ∑N pix (Ni) total number of pixels in the whole basin or simply percentage of pixels to total pixels in class. To calculate the number of landslide pixels of each class of the respective

**Table 1.** Area and location of the landslides in Balason river basin from 2000-2016.

| S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area | S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area |
|---|---|---|---|---|---|---|---|
| 1 | 707.199 | 88.2957 | 26.866 | 149 | 1062.05 | 88.2308 | 26.8763 |
| 2 | 1241.36 | 88.3238 | 26.8357 | 150 | 9596.98 | 88.2323 | 26.9005 |
| 3 | 31.7915 | 88.328 | 26.8172 | 151 | 50.3166 | 88.1552 | 26.9443 |
| 4 | 39.2974 | 88.3282 | 26.8173 | 152 | 1064.16 | 88.2108 | 26.9096 |
| 5 | 74.7919 | 88.3277 | 26.8153 | 153 | 1842.76 | 88.1723 | 26.9248 |
| 6 | 202.192 | 88.3303 | 26.8127 | 154 | 382.255 | 88.1405 | 26.9607 |
| 7 | 443.925 | 88.329 | 26.8144 | 155 | 395.708 | 88.1413 | 26.9636 |
| 8 | 182.456 | 88.1269 | 26.9448 | 156 | 244.159 | 88.1268 | 26.9694 |
| 9 | 76.8791 | 88.2955 | 26.9618 | 157 | 656.173 | 88.1278 | 26.9708 |
| 10 | 135.181 | 88.2954 | 26.9617 | 158 | 2051.94 | 88.129 | 26.9697 |
| 11 | 18.0313 | 88.2936 | 26.9614 | 159 | 826.188 | 88.1328 | 26.9755 |
| 12 | 4.79447 | 88.2935 | 26.9614 | 160 | 1431.73 | 88.1648 | 26.9482 |
| 13 | 115.793 | 88.3003 | 26.9606 | 161 | 2284.52 | 88.1736 | 26.9398 |
| 14 | 17.4485 | 88.2958 | 26.9627 | 162 | 244.237 | 88.1939 | 26.911 |
| 15 | 6.26611 | 88.2958 | 26.9624 | 163 | 473.227 | 88.2084 | 26.9073 |
| 16 | 61.9584 | 88.2918 | 26.9602 | 164 | 1118.3 | 88.1849 | 26.9571 |
| 17 | 21.4497 | 88.2922 | 26.9603 | 165 | 1343.13 | 88.1822 | 26.9573 |
| 18 | 20.2991 | 88.2894 | 26.9611 | 166 | 58.4183 | 88.1584 | 26.9833 |
| 19 | 28.2176 | 88.2895 | 26.9629 | 167 | 75.5655 | 88.159 | 26.9858 |
| 20 | 71.8128 | 88.2903 | 26.9623 | 168 | 114.422 | 88.1588 | 26.9855 |
| 21 | 23.3692 | 88.2905 | 26.9627 | 169 | 1045.16 | 88.1908 | 26.9865 |
| 22 | 15.4175 | 88.2908 | 26.963 | 170 | 72.5905 | 88.1933 | 26.9869 |
| 23 | 35.9775 | 88.291 | 26.9631 | 171 | 162.601 | 88.1935 | 26.9898 |
| 24 | 21.1504 | 88.2911 | 26.9633 | 172 | 1738.58 | 88.1929 | 26.99 |
| 25 | 92.1921 | 88.2908 | 26.9639 | 173 | 167.346 | 88.1937 | 26.988 |
| 26 | 32.9415 | 88.2913 | 26.9636 | 174 | 467.586 | 88.1856 | 26.9898 |
| 27 | 53.7706 | 88.2914 | 26.9641 | 175 | 530.686 | 88.1938 | 26.9698 |
| 28 | 17.3334 | 88.2918 | 26.9632 | 176 | 151.251 | 88.1858 | 26.9994 |
| 29 | 38.7774 | 88.2922 | 26.9635 | 177 | 108.052 | 88.187 | 27.0002 |
| 30 | 51.2226 | 88.2929 | 26.9635 | 178 | 158.193 | 88.1876 | 27.0007 |
| 31 | 68.9653 | 88.2852 | 26.9596 | 179 | 694.12 | 88.209 | 26.9963 |
| 32 | 379.161 | 88.2814 | 26.9609 | 180 | 509.409 | 88.2095 | 26.9967 |
| 33 | 1699.4 | 88.2809 | 26.9601 | 181 | 79.7281 | 88.2076 | 26.9966 |
| 34 | 2346.11 | 88.28 | 26.9597 | 182 | 51.9661 | 88.2119 | 26.9981 |
| 35 | 358.216 | 88.2803 | 26.9581 | 183 | 154.707 | 88.2041 | 27.0023 |
| 36 | 282.583 | 88.2857 | 26.9548 | 184 | 180.331 | 88.2003 | 27.0012 |
| 37 | 39.415 | 88.2862 | 26.9543 | 185 | 237.411 | 88.1997 | 26.9865 |
| 38 | 39.1453 | 88.2856 | 26.9538 | 186 | 192.888 | 88.2024 | 26.9888 |
| 39 | 22.5493 | 88.286 | 26.9536 | 187 | 1740.5 | 88.2106 | 26.9734 |
| 40 | 37.5993 | 88.2872 | 26.9537 | 188 | 337.62 | 88.243 | 26.9935 |
| 41 | 35.2606 | 88.288 | 26.954 | 189 | 383.982 | 88.2563 | 27.0058 |
| 42 | 48.6892 | 88.288 | 26.9544 | 190 | 31.9148 | 88.2553 | 27.006 |
| 43 | 166.631 | 88.2877 | 26.9547 | 191 | 233.374 | 88.2374 | 27.0011 |
| 44 | 42.7794 | 88.2871 | 26.9549 | 192 | 248.928 | 88.2373 | 27.0009 |
| 45 | 27.9714 | 88.2867 | 26.9549 | 193 | 65.6938 | 88.2373 | 27.0031 |
| 46 | 22.5377 | 88.2868 | 26.955 | 194 | 1664.16 | 88.2354 | 27.0014 |
| 47 | 41.6531 | 88.287 | 26.9551 | 195 | 64.8215 | 88.2367 | 27.0014 |
| 48 | 77.0869 | 88.2876 | 26.9552 | 196 | 2662.13 | 88.2354 | 27.0007 |

| S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area | S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area |
|---|---|---|---|---|---|---|---|
| 49 | 7.44129 | 88.2882 | 26.9551 | 197 | 256.755 | 88.2352 | 27.0002 |
| 50 | 48.5958 | 88.2885 | 26.9552 | 198 | 910.659 | 88.2346 | 27.0004 |
| 51 | 76.4866 | 88.2883 | 26.9555 | 199 | 94.6291 | 88.2305 | 27.0015 |
| 52 | 23.7807 | 88.2881 | 26.9558 | 200 | 166.369 | 88.2298 | 27.001 |
| 53 | 179.457 | 88.2893 | 26.956 | 201 | 28.7871 | 88.2286 | 27.0013 |
| 54 | 41.638 | 88.2896 | 26.956 | 202 | 13.5587 | 88.2304 | 27.0019 |
| 55 | 42.7744 | 88.2895 | 26.9563 | 203 | 360.114 | 88.2283 | 27.0012 |
| 56 | 25.8678 | 88.2889 | 26.9542 | 204 | 73.1794 | 88.2286 | 27.001 |
| 57 | 80.355 | 88.2899 | 26.9543 | 205 | 176.405 | 88.2246 | 26.9997 |
| 58 | 11.6655 | 88.2898 | 26.9544 | 206 | 57.8003 | 88.2282 | 26.9979 |
| 59 | 13.3572 | 88.29 | 26.9543 | 207 | 29.0432 | 88.2317 | 26.9969 |
| 60 | 52.2182 | 88.2881 | 26.9541 | 208 | 645.099 | 88.2233 | 26.9841 |
| 61 | 17.4687 | 88.2869 | 26.9531 | 209 | 1045.4 | 88.2148 | 26.9871 |
| 62 | 75.9915 | 88.2793 | 26.9568 | 210 | 106.941 | 88.254 | 26.9982 |
| 63 | 201.801 | 88.2791 | 26.9567 | 211 | 217.025 | 88.258 | 26.9959 |
| 64 | 434.811 | 88.2768 | 26.957 | 212 | 299.998 | 88.2566 | 26.996 |
| 65 | 5056.89 | 88.2778 | 26.9845 | 213 | 32.9966 | 88.2548 | 26.9982 |
| 66 | 653.957 | 88.2758 | 26.9844 | 214 | 9.42264 | 88.2545 | 26.9977 |
| 67 | 133.234 | 88.2764 | 26.9853 | 215 | 45.1092 | 88.2539 | 26.9973 |
| 68 | 78.322 | 88.2765 | 26.9855 | 216 | 6.65395 | 88.2533 | 26.997 |
| 69 | 71.0966 | 88.2772 | 26.986 | 217 | 207.835 | 88.2505 | 26.9906 |
| 70 | 92284.2 | 88.2872 | 26.9825 | 218 | 67.6416 | 88.2512 | 26.9901 |
| 71 | 7635.69 | 88.2885 | 26.9846 | 219 | 61.1047 | 88.253 | 26.9904 |
| 72 | 23530.9 | 88.283 | 26.9878 | 220 | 300.908 | 88.2541 | 26.9903 |
| 73 | 1342.71 | 88.2775 | 26.9928 | 221 | 30.4599 | 88.243 | 26.9917 |
| 74 | 2953.5 | 88.2798 | 26.9944 | 222 | 133.583 | 88.2508 | 26.9986 |
| 75 | 20926.3 | 88.2692 | 26.9967 | 223 | 465.7 | 88.2459 | 26.9867 |
| 76 | 649.424 | 88.2385 | 26.9974 | 224 | 36.006 | 88.2444 | 26.9866 |
| 77 | 68.4146 | 88.2384 | 26.9956 | 225 | 11.4642 | 88.2444 | 26.9865 |
| 78 | 982.645 | 88.2692 | 26.8557 | 226 | 37.306 | 88.2438 | 26.9857 |
| 79 | 315.397 | 88.287 | 26.8951 | 227 | 319.488 | 88.2328 | 26.9563 |
| 80 | 7041.19 | 88.2786 | 26.9122 | 228 | 602.203 | 88.253 | 26.9719 |
| 81 | 10350.4 | 88.2876 | 26.9076 | 229 | 209.096 | 88.2575 | 26.9754 |
| 82 | 241.655 | 88.1912 | 27.0038 | 230 | 174.979 | 88.2584 | 26.9764 |
| 83 | 1791.87 | 88.1862 | 26.9635 | 231 | 675.168 | 88.2589 | 26.9768 |
| 84 | 1133.26 | 88.1853 | 26.9642 | 232 | 253.721 | 88.2636 | 26.9773 |
| 85 | 7687.55 | 88.1851 | 26.9697 | 233 | 172.194 | 88.2756 | 26.9829 |
| 86 | 35391.3 | 88.2693 | 26.9233 | 234 | 41.7062 | 88.2757 | 26.9832 |
| 87 | 8668.89 | 88.1469 | 26.9579 | 235 | 377.121 | 88.2381 | 26.9792 |
| 88 | 96.2151 | 88.2784 | 26.9603 | 236 | 13.6503 | 88.2592 | 26.934 |
| 89 | 153.184 | 88.2796 | 26.959 | 237 | 103.161 | 88.26 | 26.9435 |
| 90 | 327760 | 88.254 | 26.862 | 238 | 83.3302 | 88.256 | 26.9453 |
| 91 | 86276.3 | 88.2515 | 26.9106 | 239 | 39.2229 | 88.2623 | 26.9495 |
| 92 | 178297 | 88.2394 | 26.869 | 240 | 11.7083 | 88.2612 | 26.9495 |
| 93 | 51441.1 | 88.2733 | 26.8709 | 241 | 292.799 | 88.267 | 26.9538 |
| 94 | 34320.9 | 88.2753 | 26.9101 | 242 | 75.0716 | 88.2831 | 26.9577 |
| 95 | 26807.8 | 88.2629 | 26.9093 | 243 | 92.8112 | 88.284 | 26.9581 |
| 96 | 50497.7 | 88.265 | 26.9098 | 244 | 141.598 | 88.2848 | 26.9585 |
| 97 | 1356.49 | 88.1428 | 26.9831 | 245 | 44.7715 | 88.2842 | 26.9587 |
| 98 | 302.838 | 88.2356 | 26.8291 | 246 | 65.5269 | 88.2836 | 26.9595 |

| S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area | S.No. | Area of the slides (Sq. m) | X coordinate of centroid of the slides area | Y coordinate of centroid of the slides area |
|---|---|---|---|---|---|---|---|
| 99 | 4286.21 | 88.2783 | 26.8624 | 247 | 30.6295 | 88.2834 | 26.9586 |
| 100 | 67.006 | 88.2906 | 26.9501 | 248 | 19.372 | 88.2831 | 26.9592 |
| 101 | 207.329 | 88.2915 | 26.9515 | 249 | 153.508 | 88.2832 | 26.9595 |
| 102 | 3608.52 | 88.2776 | 26.8639 | 250 | 47.3037 | 88.2833 | 26.9596 |
| 103 | 594.788 | 88.2946 | 26.9197 | 251 | 23.1429 | 88.2912 | 26.963 |
| 104 | 8094.87 | 88.28 | 26.8669 | 252 | 59.9813 | 88.2839 | 26.9556 |
| 105 | 293.191 | 88.2766 | 26.8611 | 253 | 156.932 | 88.2373 | 26.916 |
| 106 | 167.62 | 88.1591 | 26.9864 | 254 | 2103.85 | 88.243 | 26.9009 |
| 107 | 205.681 | 88.2295 | 26.827 | 255 | 1549.07 | 88.2619 | 26.9045 |
| 108 | 31.4893 | 88.1604 | 26.9424 | 256 | 63.8999 | 88.2639 | 26.9048 |
| 109 | 529.442 | 88.226 | 26.8423 | 257 | 251.299 | 88.2633 | 26.9045 |
| 110 | 6607.22 | 88.1428 | 26.9818 | 258 | 64.6839 | 88.2636 | 26.9064 |
| 111 | 187.824 | 88.142 | 26.9805 | 259 | 2342.79 | 88.2632 | 26.9066 |
| 112 | 209.821 | 88.1405 | 26.9805 | 260 | 1326.81 | 88.2689 | 26.908 |
| 113 | 81.1721 | 88.1412 | 26.9814 | 261 | 212.756 | 88.269 | 26.9133 |
| 114 | 101.34 | 88.145 | 26.9699 | 262 | 314.619 | 88.2756 | 26.9138 |
| 115 | 48.6915 | 88.1362 | 26.9754 | 263 | 43.8935 | 88.2797 | 26.919 |
| 116 | 25.7825 | 88.1465 | 26.9772 | 264 | 2120.05 | 88.2505 | 26.9079 |
| 117 | 165.093 | 88.1442 | 26.9789 | 265 | 242.618 | 88.2634 | 26.8916 |
| 118 | 93.9419 | 88.2303 | 26.917 | 266 | 252.802 | 88.2644 | 26.8913 |
| 119 | 717.515 | 88.1491 | 26.9788 | 267 | 262.503 | 88.2667 | 26.8917 |
| 120 | 458.494 | 88.1486 | 26.979 | 268 | 1719.26 | 88.2677 | 26.892 |
| 121 | 70.2184 | 88.2336 | 26.9036 | 269 | 43.2021 | 88.2662 | 26.887 |
| 122 | 548.314 | 88.1479 | 26.9797 | 270 | 27.6787 | 88.259 | 26.8683 |
| 123 | 1859.56 | 88.2423 | 26.85 | 271 | 6.49692 | 88.2282 | 26.8839 |
| 124 | 29211 | 88.2751 | 26.8605 | 272 | 407.037 | 88.2477 | 26.8563 |
| 125 | 854.153 | 88.2477 | 26.9021 | 273 | 279.718 | 88.2122 | 26.8555 |
| 126 | 11015 | 88.2418 | 26.8472 | 274 | 28.7389 | 88.2281 | 26.8577 |
| 127 | 328.532 | 88.1923 | 26.9103 | 275 | 5350.87 | 88.2772 | 26.8624 |
| 128 | 252.397 | 88.2343 | 26.9044 | 276 | 30543.9 | 88.2777 | 26.8597 |
| 129 | 3010.4 | 88.2363 | 26.8644 | 277 | 243.052 | 88.2809 | 26.8573 |
| 130 | 1247.26 | 88.2468 | 26.8589 | 278 | 260.571 | 88.2803 | 26.8575 |
| 131 | 789.487 | 88.2464 | 26.8472 | 279 | 212.472 | 88.2862 | 26.8534 |
| 132 | 14854.8 | 88.2509 | 26.8593 | 280 | 14374.7 | 88.2736 | 26.8491 |
| 133 | 1947.98 | 88.2402 | 26.8172 | 281 | 289.395 | 88.2698 | 26.8325 |
| 134 | 416.474 | 88.2414 | 26.8869 | 282 | 402.556 | 88.2435 | 26.8402 |
| 135 | 63.2228 | 88.2392 | 26.8897 | 283 | 196.266 | 88.3069 | 26.8162 |
| 136 | 842.363 | 88.2418 | 26.9028 | 284 | 1235.7 | 88.3111 | 26.8451 |
| 137 | 179.9 | 88.2487 | 26.906 | 285 | 603.006 | 88.291 | 26.8667 |
| 138 | 245.819 | 88.2485 | 26.903 | 286 | 571.366 | 88.3095 | 26.8239 |
| 139 | 1051.9 | 88.2476 | 26.9052 | 287 | 220.043 | 88.3099 | 26.8238 |
| 140 | 424.025 | 88.2481 | 26.9056 | 288 | 500.193 | 88.3123 | 26.8269 |
| 141 | 3158.76 | 88.236 | 26.9102 | 289 | 497.139 | 88.3259 | 26.8376 |
| 142 | 1685.25 | 88.2513 | 26.908 | 290 | 193.821 | 88.3303 | 26.8471 |
| 143 | 4283.61 | 88.2573 | 26.909 | 291 | 25.5029 | 88.3269 | 26.8482 |
| 144 | 826.283 | 88.2398 | 26.8187 | 292 | 16.4798 | 88.3262 | 26.8485 |
| 145 | 2661.94 | 88.2394 | 26.8289 | 293 | 142.254 | 88.3176 | 26.8458 |
| 146 | 440.653 | 88.2386 | 26.8318 | 294 | 54.7755 | 88.3173 | 26.8442 |
| 147 | 8140.19 | 88.2341 | 26.8994 | 295 | 52.0469 | 88.3134 | 26.8371 |
| 148 | 803.776 | 88.2306 | 26.8658 | | | | |

**Table 2.** Elevation character of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Elevation (meter) | 106-298 | 368681 | 21.92 | 4 | 0.08 | 0.00 |
| | 298-539 | 139536 | 8.30 | 270 | 4.93 | 0.59 |
| | 539-792 | 135130 | 8.03 | 876 | 15.96 | 1.99 |
| | 792-1030 | 172562 | 10.26 | 1240 | 22.60 | 2.20 |
| | 1030-1240 | 181438 | 10.79 | 1457 | 26.55 | 2.46 |
| | 1240-1440 | 189984 | 11.30 | 573 | 10.44 | 0.92 |
| | 1440-1650 | 169253 | 10.06 | 273 | 4.97 | 0.49 |
| | 1650-1880 | 144806 | 8.61 | 75 | 1.37 | 0.16 |
| | 1880-2130 | 118740 | 7.06 | 180 | 3.29 | 0.47 |
| | 2130-2603 | 61869 | 3.68 | 539 | 9.82 | 2.67 |

factor, zonal statistics as a table under spatial analyst tool in Arc GIS 10.1 environment was used. In can be mentioned that, higher the frequency ratio value stronger the relationship between landslide occurrence and the given conditioning factor. As indicated by many researchers, natural break method was applied to determine different subclasses of continuous geomorphic parameters (Poli and Sterlacchini, 2007; Althuwaynee et al., 2014; Mahalingam et al., 2016). Finally, the composite index map of landslide susceptibility was obtained using following equation in Arc Map 10.1 GIS environment.

$CLS = Fr_1 + Fr_2 + Fr_3 + \ldots\ldots\ldots\ldots + Fr_n$ .............(2)

Where, CLS is the composite landslide susceptibility index and $Fr_1 + \ldots\ldots FR_n$ is the frequency ratio of each factor.

## RESULTS

### Elevation character and landslide susceptibility

The elevation of the Balason river basin was classified into 10 categories where elevation ranges from 106 meter to 2603 meter (Figure 2a). Extreme north-western part and north-eastern part of the basin was dominated by higher elevation whereas, southernmost section was characterized by low elevation. However, no direct relationship can be made between elevation and landslide occurrences. Several researchers showed that landslides have the more tendencies to occur at the higher El areas, so the high El areas have the greater landslide susceptibility (Devkota et al., 2013; Umar et al., 2014). Moderate elevation zones were found in the central portion of the basin. Maximum area of 21.92% was covered by 106-298 meter elevation zone while a small area of 3.68% was dominated by 2130-2603 meter elevation zone. The highest and lowest frequency ratio value was found in the elevation class of 2130-2603 meter (2.67) and 106-298 meter (0.00) respectively, which indicated greater and lower chance of slope failures respectively (Table 2).

### Slope angle character and landslide susceptibility

The slope map of the Balason river basin was made from the SRTM DEM and it was classified into 10 different slope zones (Figure 2b). Basically, the river basin is attributed with maximum slope angle where slope angle ranges from $0^0$ to more than $71.10^0$. The basin is dissected by well developed drainage network which made the slope steepened by continuous branching of the drainage and its headword erosion. The slope plays an important role for the growth and development of drainage network, surface run-off and soil erosion, as well as drainage concentration over the space. Not only that the stream power index (SPI) and topographic wetness index (TWI) are influenced by slope steepness, but the study also revealed that there is a positive relationship between slope and landslide frequency ratio. The slope having greater than $26.60^0$ is attributed with the frequency ratio value ranges from 1.13 to 13.57, which showed high probability of landslide phenomena (Table 3).

### Geology and landslide susceptibility

The geology of Balason river basin was divided into five major categories viz., Darjeeling Gneisses, Daling Series, Damuda Series /Lower Gondwanas, Nahan Group and Alluvium (older and recent) (Figure 3a) (Lama, 2003). The Darjeeling gneisses covered a large part of the basin (68.33%) where it varied from a foliated granitoid rock composed to quartz, felsper and biotite to more or less pure mica schist. The Daling series consists of phyllite, slate and quartzite which are being found in the Middle East and Middle West portion of the basin. Damuda Series /Lower Gondwana series consisted of quartzitic sandstones, shales and slates, semi-anthracitic (graphitic) coal, lamprophyre silts and minor bands of limestone. The Nahan Group or Lower Siwalik deposits are mainly composed of soft greyish sandstone, mudstone, shales and conglomerates.

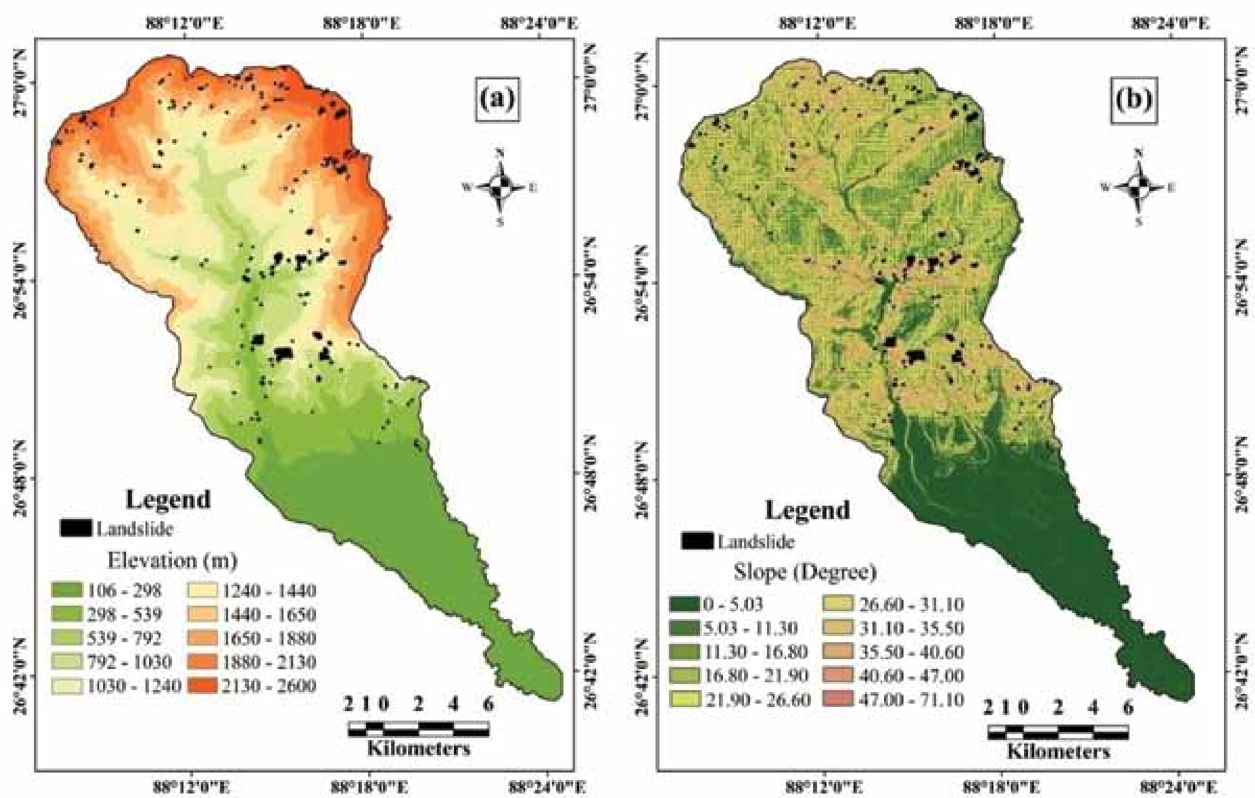


**Figure 2.** Maps showing data layers of (a) elevation and (b) slope.

**Table 3.** Slope character of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Slope (Degree) | 0-5.03 | 400086 | 23.79 | 47 | 0.86 | 0.04 |
| | 5.03-11.30 | 167825 | 9.98 | 202 | 3.68 | 0.37 |
| | 11.30-16.80 | 219531 | 13.05 | 522 | 9.52 | 0.73 |
| | 16.80-21.90 | 231356 | 13.75 | 736 | 13.41 | 0.98 |
| | 21.90-26.60 | 207903 | 12.36 | 601 | 10.95 | 0.89 |
| | 26.60-31.10 | 169058 | 10.05 | 625 | 11.38 | 1.13 |
| | 31.10-35.50 | 126742 | 7.54 | 611 | 11.14 | 1.48 |
| | 35.50-40.60 | 91415 | 5.43 | 663 | 12.09 | 2.22 |
| | 40.60-47.00 | 51416 | 3.06 | 742 | 13.52 | 4.42 |
| | 47.00-71.10 | 16667 | 0.99 | 738 | 13.44 | 13.57 |

Alluviums (older and recent) are composed of boulder beds and other sands and gravels. Similarly, Drift Formation and younger flood plain deposits comprise sand and gravel, pebbles, etc. It can be seen that, Darjeeling Gneiss had the greater potentiality of landslide occurrences (1.44) while, Damuda Series /Lower Gondwana and Nahan Group, Lower Siwalik deposits were registered with lowest FR value (0.00), which indicated no chance of slope failures phenomena (Table 4).

## Geomorphology and landslide susceptibility

Lama (2003) divided the Balason river basin into 7 distinct geomorphological groups i.e. upper hill (>2000m), middle hill (1000-2000m), lower hill (<1000m), foothill (piedmont), upper alluvial fan, lower alluvial fan and river flood plain (Figure 3b). Middle hill (1000-2000m) covered larger area of the basin (46.22%), while river flood plain had the smallest area of the basin (4.07%). The greater

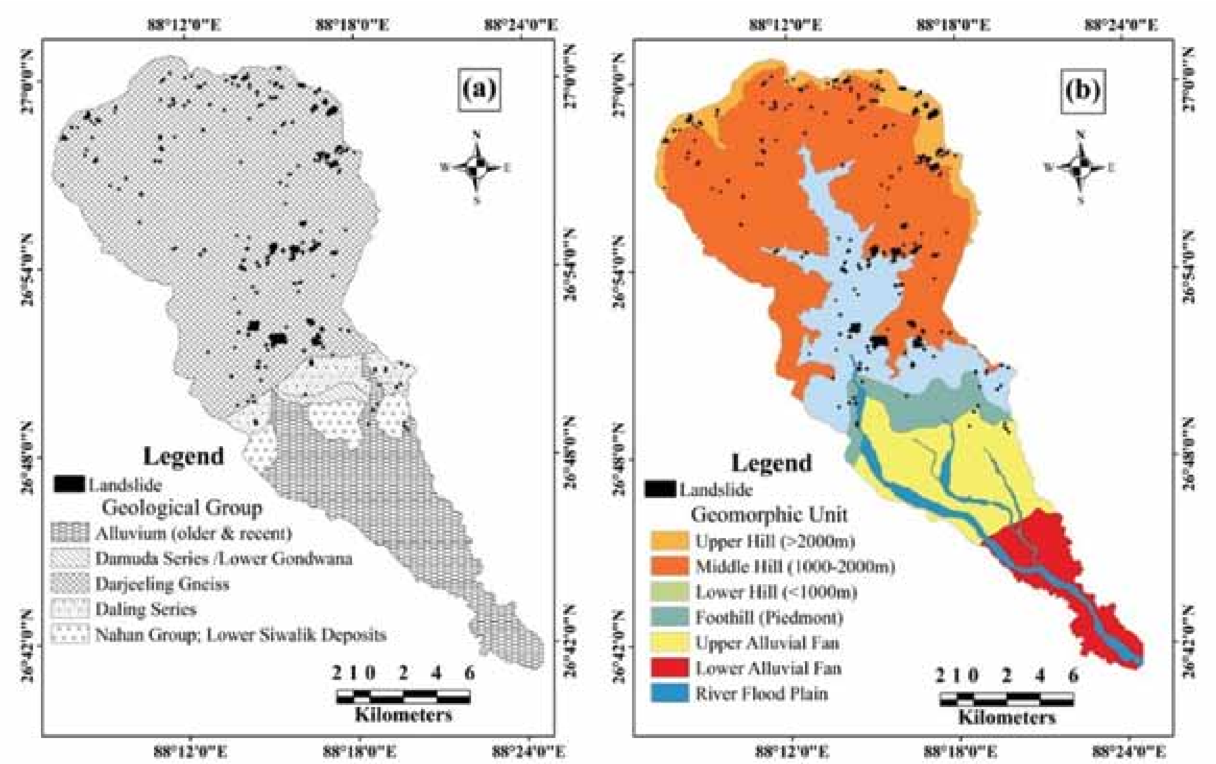


**Figure 3.** Data layers of (a) geological map and (b) geomorphological map (after Lama, 2003).

**Table 4.** Geology of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Geology | Darjeeling Gneiss (Dg) | 287309 | 68.33 | 1345 | 98.32 | 1.44 |
| | Daling Series (Ds) | 18518 | 4.40 | 21 | 1.54 | 0.35 |
| | Damuda Series /Lower Gondwana (DAs) | 4784 | 1.14 | 0 | 0.00 | 0.00 |
| | Nahan Group, Lower Siwalik Deposits (Ng) | 16839 | 4.00 | 0 | 0.00 | 0.00 |
| | Alluvium (older & recent) (Al) | 93050 | 22.13 | 2 | 0.15 | 0.01 |

potentiality of landslide occurrences was found in lower hill (<2000m) (1.90). The chance of slope failures was lowest in the class of lower alluvial fan and river flood plain, both were registered with 0.00 FR value (Table 5).

## Soil character and landslide susceptibility

Five types of soil were identified in the basin i.e. W002, W003, W004, W006 and W009 (Figure 4a). The soil of the Balason river basin is favorable for tea plantation. The original soil of the area is drastically changed either by the process of new soil formation on the truncated top or by removal of soil by erosion (Sarkar, 1990). The parent soil of this region has changed due to its nature and it has formed more than one time (Lama, 2003). In the sandy area, soils are generally siliceous and aluminous. The lower Balason basin is formed by fine grained clay loam. In some cases, the top soils are finer in nature than the subsurface soils. The detailed characteristics of each type of soil of the Balason river basin were presented in Table 7. In this basin, W003 soil type was registered with highest frequency ratio is 1.88. On the other hand, W006 and W009 soil types covering almost 17% area of the basin, have the lowest chance of landslide events (Table 8).

## Spatial distribution of Rainfall and landslide susceptibility

Landslides are closely associated with duration, amount and intensity of rainfall. The intensity and amount of

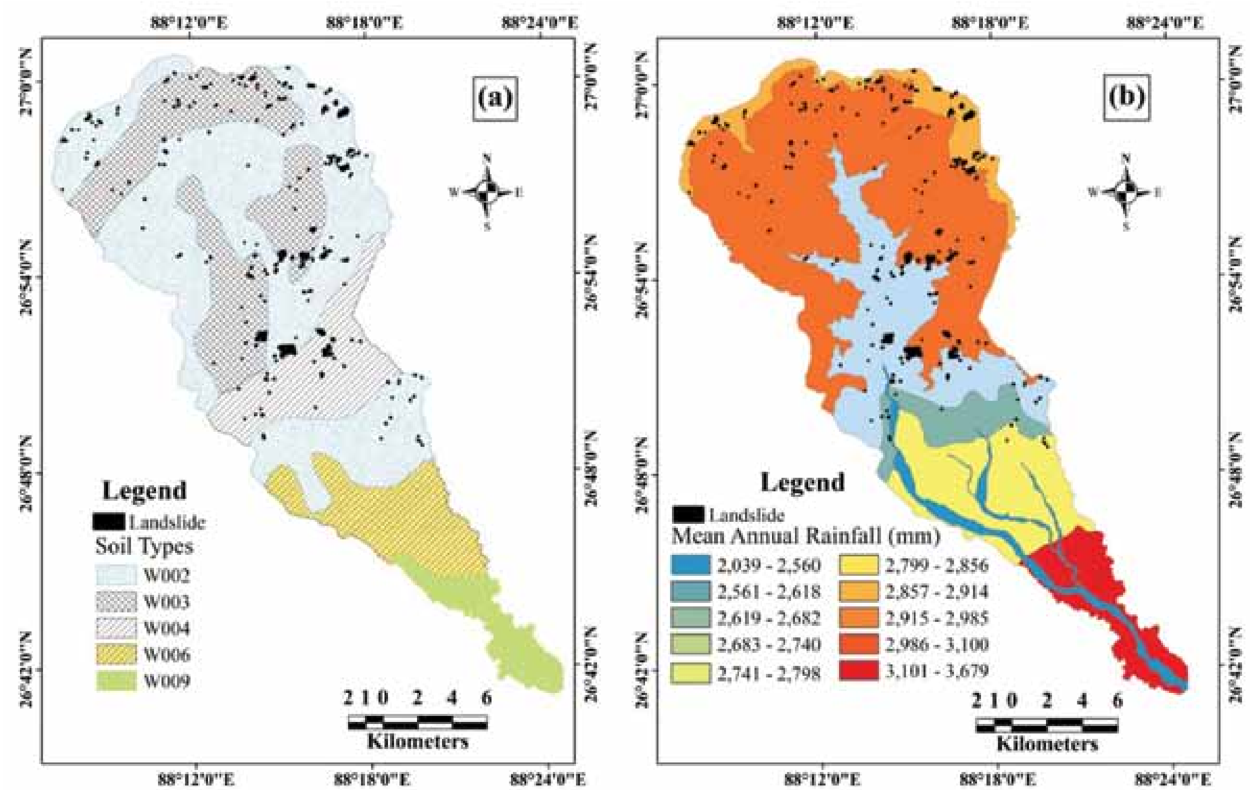


**Figure 4.** Data layers of (a) soil and (b) rainfall maps**.**

**Table 5.** Geomorphology of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Geomorpholoy | Upper Hill (>2000m) | 29309 | 6.97 | 150 | 10.96 | 1.57 |
| | Middle Hill (1000-2000m) | 194339 | 46.22 | 732 | 53.51 | 1.16 |
| | Lower Hill (<2000m) | 77058 | 18.33 | 477 | 34.87 | 1.90 |
| | Foothill (Piedmont) | 21111 | 5.02 | 7 | 0.51 | 0.10 |
| | Upper Alluvial Fan | 53984 | 12.84 | 2 | 0.15 | 0.01 |
| | Lower Alluvial Fan | 27588 | 6.56 | 0 | 0.00 | 0.00 |
| | River Flood Plain | 17111 | 4.07 | 0 | 0.00 | 0.00 |

rainfall varies from one place to another in the basin due to topographic configuration. The mean annual rainfall ranges from 2041 mm 3673 mm. Based on the rainfall distribution Balason river basin was classified into ten zones (Figure 4b). Around 35% landslide affected area and 50% area of basin are characterized by mean annual rainfall of more than 2790 mm. More than 1 frequency ratio was found in the class ranges from 2559 to 2847mm and 3090-3673 rainfall which was characterized by high landslide occurrences events. Rest of the class having less than 1 frequency ratio value which indicating minimum chance of landslide occurrences. Some high annual rainfall classes i.e. 2847-2905 mm, 2905-2975 mm and 2975-3090 mm, have low FR value because of the unfavorable geo-environmental conditions for landslide occurrences in the concerned area (Table 9).

## Drainage density and landslide susceptibility

The drainage network development on both sides of the slope segments make the interfluves area more steep resulting mountain slope instability. The drainage network development, slope steepening, and slope failure are regular processes which promotes equilibrium in the geomorphic system. The concentration of drainage network and their engagement in the process of erosion and transportation make the slope more vulnerable to landslip phenomena. The drainage density varies from one place to another based

**Table 7.** Soil characteristics of Balason river basin

| Symbol | Soil characteristics | Taxonomic name |
|---|---|---|
| W002 | Moderately shallow, excessively drained, coarse loamy soils occurring on steep side slopes with gravelly loamy surface, severe erosion and strong rockiness, associated with moderately shallow, well drained, gravelly loamy soils with loamy surface and moderate erosion. | Coarse loamy, typic Udorthents; Loamy skeletal, typic Dystrochrepts |
| W003 | Deep, well drained, fine loamy soils occurring on steep side slopes with gravelly loamy surface, moderate erosion and moderate rockiness, associated with moderately shallow, excessively drained, coarse loamy soils with loamy surface, severe erosion and moderate rockiness. | Fine loamy, Umbric Dystrochrepts; Coarse loamy, Typic Udorthents |
| W004 | Moderately shallow, well drained, gravelly loamy soils occurring on steep side slopes with gravelly loamy surface, moderate erosion and moderate rockiness, associated with moderately shallow, somewhat excessively drained, gravelly loamy soil with loamy surface, moderate erosion and moderate rockiness | Loamy skeletal, Typic Haplumbrepts; Loamy skeletal, typic Udorthents |
| W006 | Very deep, imperfectly drained, coarse loamy soils occurring on very gently sloping upper piedmont plains with loamy surface and moderate erosion, associated with very deep, imperfectly drained fine loamy soils. | Coarse loamy, Umbric Dystrochrepts; Fine loamy, Fluventic Dystrochrepts |
| W009 | Very deep, imperfectly drained, coarse loamy soils occurring on nearly level lower piedmont plain with loamy surface, associated with very deep imperfectly drained, fine loamy soils. | Coarse loamy, Aquic Udifluvents; Fine loamy, Fluventic Eutrochrepts |

**Table 8.** Soil of the Balason river basin and landslide susceptibility.

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Soil | W002 | 198569 | 47.22 | 524 | 38.30 | 0.81 |
| | W003 | 102249 | 24.32 | 626 | 45.76 | 1.88 |
| | W004 | 49222 | 11.71 | 218 | 15.94 | 1.36 |
| | W006 | 46327 | 11.02 | 0 | 0.00 | 0.00 |
| | W009 | 24133 | 5.74 | 0 | 0.00 | 0.00 |

**Table 9.** Rainfall of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Rainfall (mm) | 2041-2559 | 40635 | 9.66 | 130 | 9.48 | 0.98 |
| | 2559-2617 | 42137 | 10.02 | 209 | 15.25 | 1.52 |
| | 2617-2681 | 44545 | 10.59 | 186 | 13.58 | 1.28 |
| | 2681-2732 | 38867 | 9.24 | 161 | 11.80 | 1.28 |
| | 2732-2790 | 45248 | 10.76 | 186 | 13.58 | 1.26 |
| | 2790-2847 | 41930 | 9.97 | 147 | 10.72 | 1.08 |
| | 2847-2905 | 41695 | 9.92 | 87 | 6.36 | 0.64 |
| | 2905-2975 | 42379 | 10.08 | 40 | 2.91 | 0.29 |
| | 2975-3090 | 42956 | 10.22 | 62 | 4.53 | 0.44 |
| | 3090-3673 | 40108 | 9.54 | 161 | 11.80 | 1.24 |

on the developed drainage network in the basin. Higher the drainage density more is the drainage concentration and slope saturation over the space. The drainage density map was divided into 10 classes (Figure 5a). It was observed that moderate level of drainage density have high frequency ratio and greater probability of slope instability. High drainage density of more than 5.39 covere about 21% area of the basin. 10.60-15.10 class have maximum chance of landslide occurrences (2.94), whereas 0-1.31drainage density class have least chance of slope failures (0.00) (Table 10).

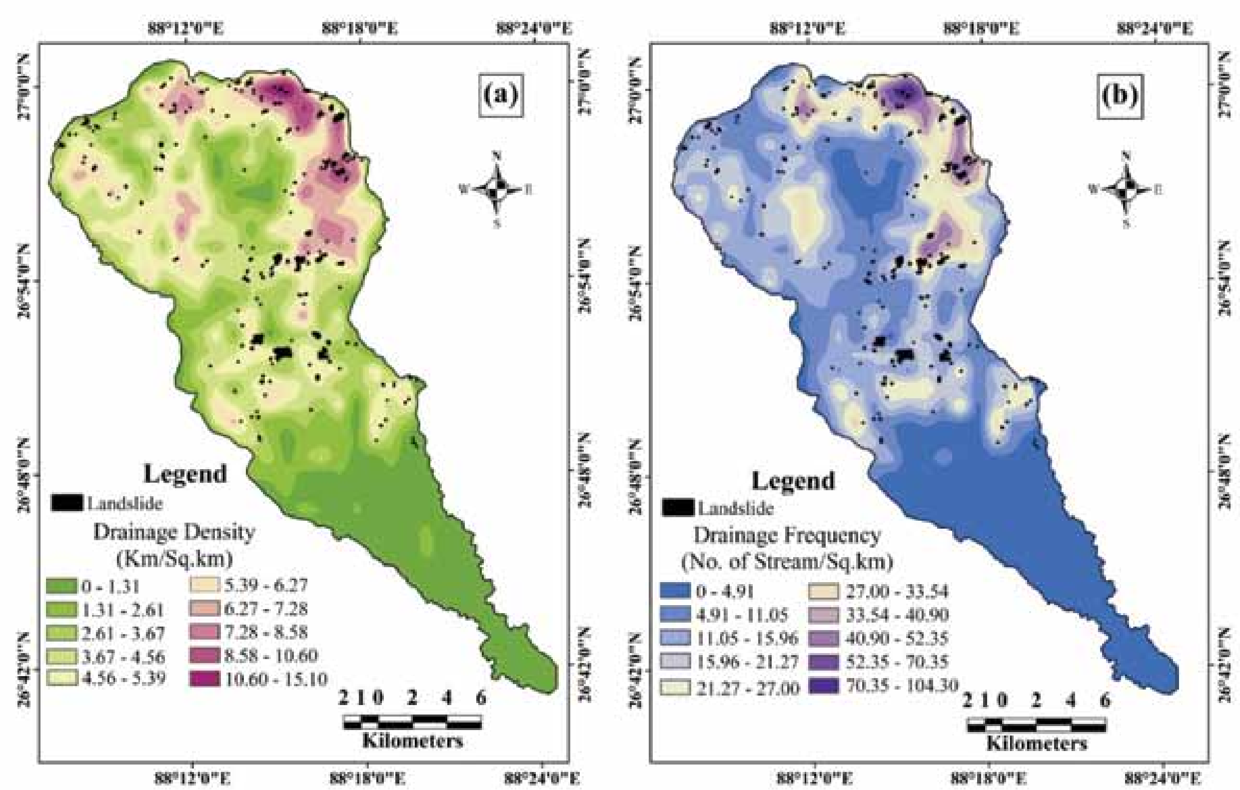


**Figure 5.** Data layers of (a) drainage density map and (b) drainage frequency map.

**Table 10.** Drainage density of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Drainage density (Km/Sq. Km) | 0-1.31 | 338135 | 20.10 | 4 | 0.07 | 0.00 |
| | 1.31-2.61 | 197209 | 11.72 | 8 | 0.14 | 0.01 |
| | 2.61-3.67 | 239068 | 14.21 | 783 | 14.27 | 1.00 |
| | 3.67-4.56 | 284654 | 16.92 | 1830 | 33.35 | 1.97 |
| | 4.56-5.39 | 246882 | 14.68 | 1108 | 20.19 | 1.38 |
| | 5.39-6.27 | 177847 | 10.57 | 746 | 13.59 | 1.29 |
| | 6.27-7.28 | 103596 | 6.16 | 494 | 9.00 | 1.46 |
| | 7.28-8.58 | 60735 | 3.61 | 366 | 6.67 | 1.85 |
| | 8.58-10.60 | 25924 | 1.54 | 73 | 1.33 | 0.87 |
| | 10.60-15.10 | 7951 | 0.47 | 76 | 1.39 | 2.94 |

## Drainage frequency and landslide susceptibility

Similar to the drainage density map, drainage frequency of the basin was also divided into 10 classes (Figure 5b). About 67% area of the basin registered drainage frequency value of 0 to 15.96. 70.35-104.30 class has the greater potentiality in landslide occurrences (4.59) and 0-4.91 class have the minimum probability of slope failure events (0.00) (Table 11). In addition, the classes having drainage frequency value of 33.54-40.90 (4.37), 52.35-70.35 (2.76), 11.05-15.96 (2.17) and 27.00-33.54 (1.87) were also characterized by high landslide susceptibility.

## DISCUSSION

The trend line of FR values reveals that elevation, slope, drainage density and drainage frequency were positively correlated with slope failure which means that slope instability increasing with increasing the value (Figure 6a, b, d and e). On the other hand, there was negative relation

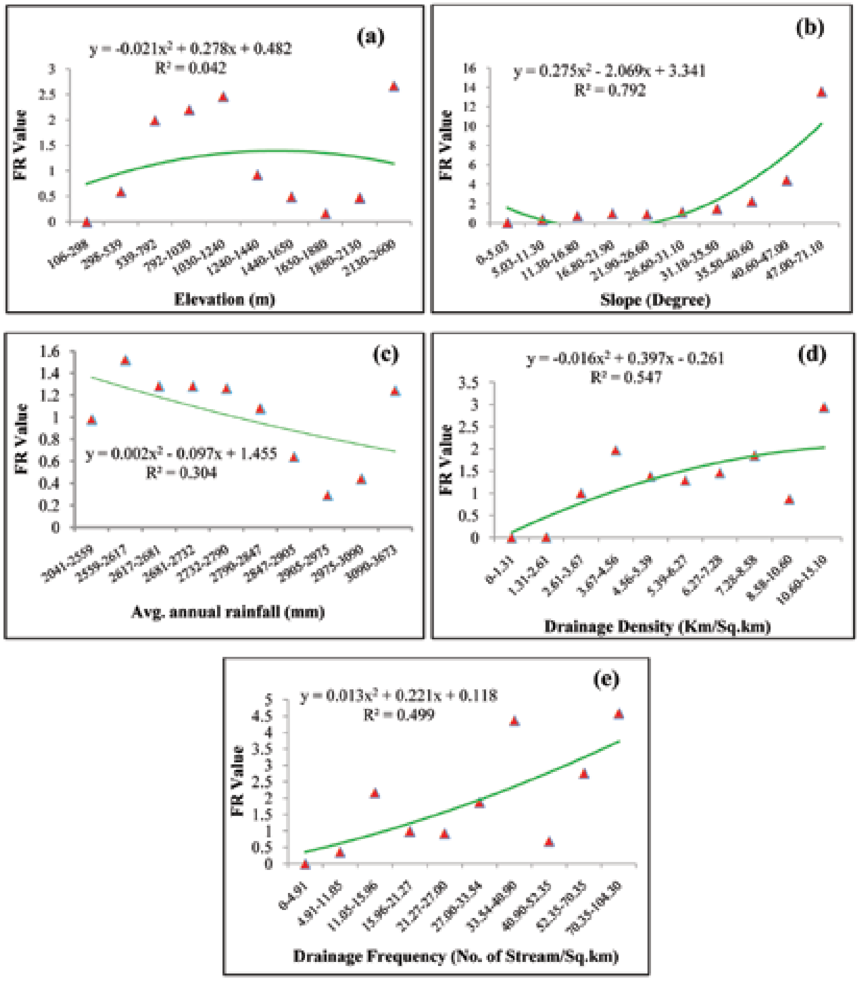


**Figure 6.** Relation between data layers and FR value (a) elevation (b) slope (c) rainfall (d) drainage density and (e) drainage frequency.

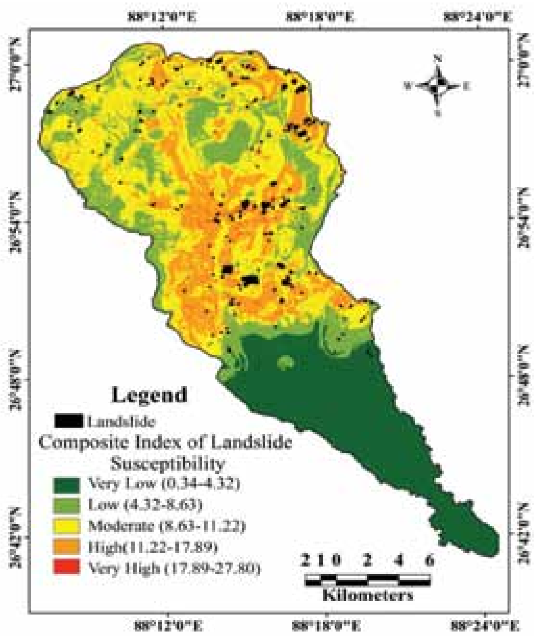


**Figure 7.** Composite index map of landslide susceptibility using FR value.

**Table 11.** Drainage frequency of the Balason river basin and landslide susceptibility

| Factors | Subclasses | Total pixels | | Landslide occurrence pixels | | FR value |
|---|---|---|---|---|---|---|
| | | Absolute | Percentage | Absolute | Percentage | |
| Drainage frequency (No. of stream/Sq.km) | 0-4.91 | 446653 | 26.55 | 4 | 0.07 | 0.00 |
| | 4.91-11.05 | 315499 | 18.76 | 370 | 6.74 | 0.36 |
| | 11.05-15.96 | 374903 | 22.29 | 2657 | 48.42 | 2.17 |
| | 15.96-21.27 | 260262 | 15.47 | 842 | 15.35 | 0.99 |
| | 21.27-27.00 | 131533 | 7.82 | 394 | 7.19 | 0.92 |
| | 27.00-33.54 | 73153 | 4.35 | 446 | 8.13 | 1.87 |
| | 33.54-40.90 | 42087 | 2.50 | 600 | 10.94 | 4.37 |
| | 40.90-52.35 | 27831 | 1.65 | 62 | 1.14 | 0.69 |
| | 52.35-70.35 | 6621 | 0.39 | 60 | 1.09 | 2.76 |
| | 70.35-104.30 | 3458 | 0.21 | 52 | 0.94 | 4.59 |

**Table 12.** Spatial correlation between the landslide susceptibility index values and the various geomorphic parameters

| Model/ geomorphic parameters | Elevation | Slope | Geology | Geomorph ology | Soil | Rainfall | Drainage density | Drainage frequency |
|---|---|---|---|---|---|---|---|---|
| Landslide susceptibility index values | 0.67 | 0.62 | 0.79 | 0.83 | 0.68 | 0.36 | 0.72 | 0.61 |

between rainfall and landslide occurrences (Figure 6c). In case of geology, soil and geomorphology, trend line of FR value was not shown in a diagram due to its categorical nature. In addition, geomorphology was most intimately associated with the determination of landslide susceptibility with correlation value of 0.83. Next highest relationship with landslide susceptibility was observed in case of geology (0.79) followed by drainage density (0.72), elevation (0.67), slope (0.62), drainage frequency (0.61) respectively. Lastly, rainfall exerted lowest influence on landslide susceptibility as indicated by correlation value of 0.36 (Table 12). Finally, composite FR index of landslide susceptibility was made by considering the eight factors, and divided it into five landslides susceptibility zones using natural breaks classification method i.e. very low (0.34-4.32), low (4.32-8.63), moderate (8.63-11.22), high (11.22-17.89) and very high (17.89-27.80) (Figure 7).

## CONCLUSIONS

All the geomorphic parameters play a significant role in assessing landslide susceptibility in the Balason basin. Not only the factors but also the individual category of all the landslide occurrence factors showed a distinct level of landslide probability. Generally elevation, slope, drainage density and drainage frequency were positively correlated with landslide susceptibility, whereas rainfall was negatively associated with landslide occurrences. It is assumed that the prepared landslide susceptibility analysis will help the policy makers, developers and engineers for choosing suitable locations to implement slope management plans, land use plans and other development action plans, although this method can be less useful on the site-specific scale.

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## Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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