Chapter 8

Landslide Susceptibility of Chittagong City, Bangladesh, and Development of Landslides Early Warning System

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Additional information is available at the end of the chapter

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Abstract

Chittagong, the second largest city of Bangladesh, is mostly developed in the hilly areas. Hills are mostly covered with loose and weathered tertiary sedimentary rocks susceptible to landslides. Generally, during heavy rainfall within a short time, water infiltrates into the loose rocks and soils, which increase the pore water pressure, and finally exceeds the shear strength of the materials to initiate landslides. Landslides history, slope characteristics, geology and geotechnical properties have been considered to divide Chittagong City and surrounding areas into four landslide hazard zones. Zone I in the east of Chittagong City persists as the most susceptible area for landslides, and the city becomes gradually less susceptible further westward up to zone IV. Prevention of landslides in most cases requires costly engineering solutions. Therefore, mitigation through timely evacuation of people from hazardous areas might be a good solution to combat landslides. Two automated rain gauges are installed at high risk landslide zones with built-in rainfall threshold values. Threshold values for early warning of landslides are set after statistical analysis of past landslides in relation to total amount of rainfall and local geology. The threshold values of rainfall are set to 100 mm in 3 h, 200 mm in 24 h and 350 mm in 72 h.

Keywords: landslides, tertiary sedimentary rocks, hazard zoning, rainfall threshold values, landslides early warning

1. Introduction

In the southeast of the country, Chittagong City has developed partly in the hilly area and the rest in the coastal plain. The area is bounded by longitudes 91° 46′–91° 50′ E and latitudes 22° 22′–22° 29′ N (**Figure 1**) that cover the Survey of Bangladesh topographic sheet no. 79 N/15, scale 1:50,000. Hills are composed mostly of weathered and loose sedimentary rocks of Tertiary (65–1.8 Ma) age which are prone to landslides. More than 200 people were killed in and around Chittagong City due to landslides between the years 2006 and 2013. Rainfall-induced landslides are common in this part of country like in other tropical mountainous regions of Southeast Asia [1–3].

The scope of investigation is to realize the actual causes of landslides in order to recommend prevention and controlling measures against the catastrophe, zoning for landslides hazard and to establish an early-warning system for landslides to save lives and properties. A landslide-zoning map of Chittagong City has been prepared, and the investigation also includes establishment of a network of automatic rain gauges for landslides early warning. Moreover, the purpose of the study is to help the engineers, town planners, policy makers and geologists to build a reasonably safer hilly city.

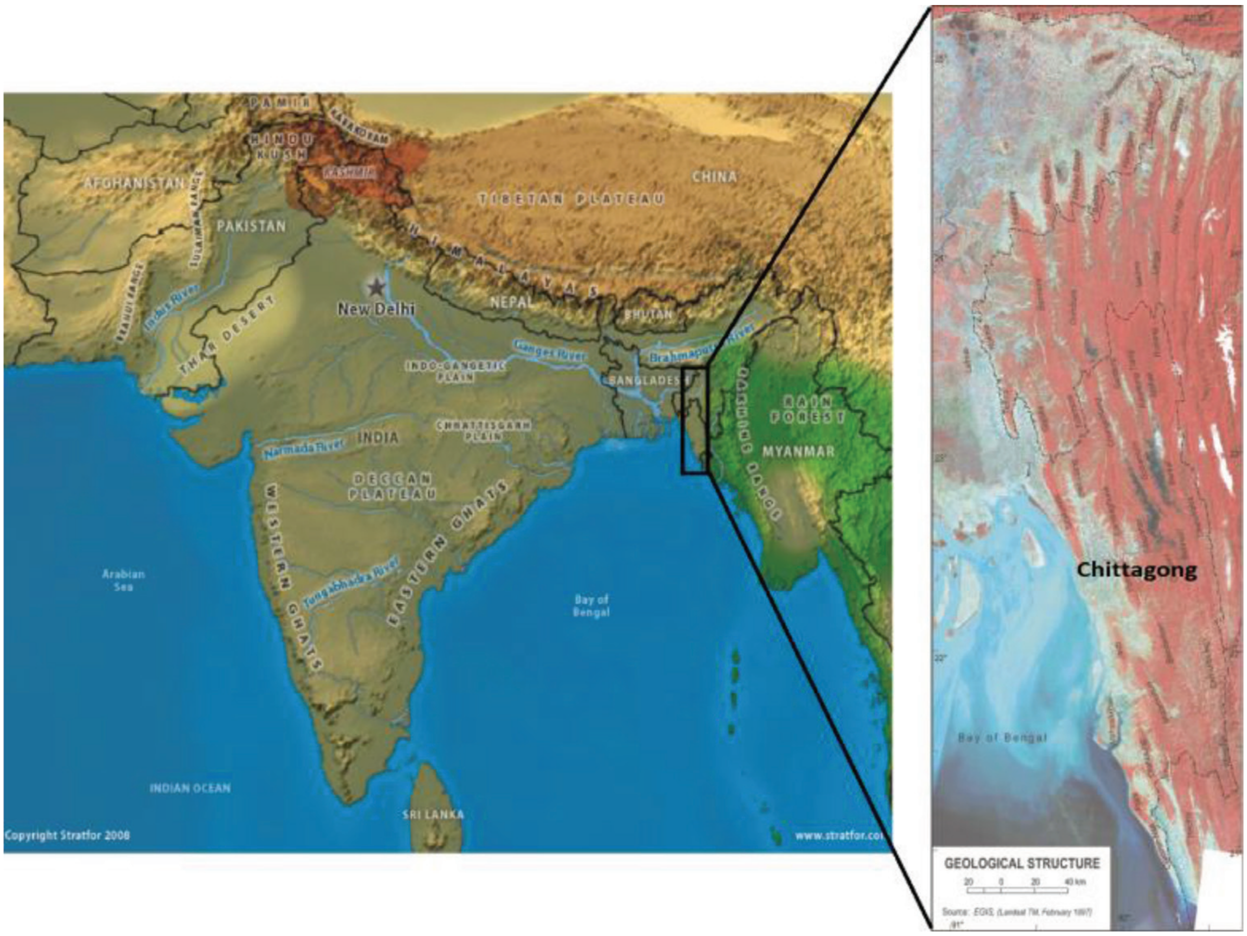

Figure 1. Location map of Chittagong area.

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The investigated area falls under tropical monsoon climate. The mean monthly maximum and minimum temperature ranges between 78.76–90.44°F and 55.88–77.38°F. The monthly average minimum and maximum rainfall is 0.66 mm in the month of January and 74.70 mm in the month of July, respectively. The yearly average rainfall is about 2794 mm [4]. The northwester and monsoon clouds are primarily responsible for the rainfall in the area. Almost 90% of the total yearly precipitation takes place between the months of June and October.

A topographic sheet on scale 1:50,000 has been used for landslide investigation. Locations of the landslide areas have been taken by global positioning system (GPS) and correspondingly marked on a topographic sheet. The geological and geotechnical properties of the landslide materials and the nature of failures have been studied in detail. Landslide spots have been mapped on the geological map of the area and correlated with the geological structure and regional geology of the area. For preparation of landslide hazard-zoning map of the area, rock types, geological structures, nature of weathering and groundwater condition have also been studied. The dimensions of each landslide (lengths, width, depth, etc.) have been measured in the field. Geotechnical properties of the rocks, specially unconfined compressive strength, have also been measured in the field. Samples from each landslide site have been collected to determine the geotechnical properties in the GSB's laboratory, Dhaka.

In the study area, most of the landslides are triggered by rainfall. Event-based rainfall data of the area have been collected and statistically analysed to resolve the threshold values of rainfall which trigger landslides. Accordingly, an automated rain gauge network has been installed in the area to anticipate potential landslide hazard. This system notifies about an impending landslide occurrence to local administration and the first responding organizations via mobile text messages to take necessary steps to save lives and properties.

2. Geomorphology and geology of the area

Chittagong area lies along the western margin of tectonically active Chittagong-Tripura-folded belt [5, 6] (**Figure 2**). The folds are mostly tight, plunging and faulted in nature with NNW-SSE alignment. On the basis of landforms, its genesis, evolution and morphodynamics, Chittagong City can be divided into three broad distinct geomorphological divisions: (1) hilly area, (2) fluvio-tidal plain and (3) tidal plain (**Figure 3**). The hilly part of the city is characterized by different types of erosional processes, and therefore landforms have distinctive erosional features, whereas Fluvio-tidal and tidal landforms are depositional landforms that has distinctive accretion features. Each type of landform is again divided into the number of geomorphic units.

Each geomorphic unit on the map has been identified from the oldest available (years 1953–1954) aerial photograph interpretation and field checking of those units. Every small feature on the photograph was considered, and interpretation was made with the help of

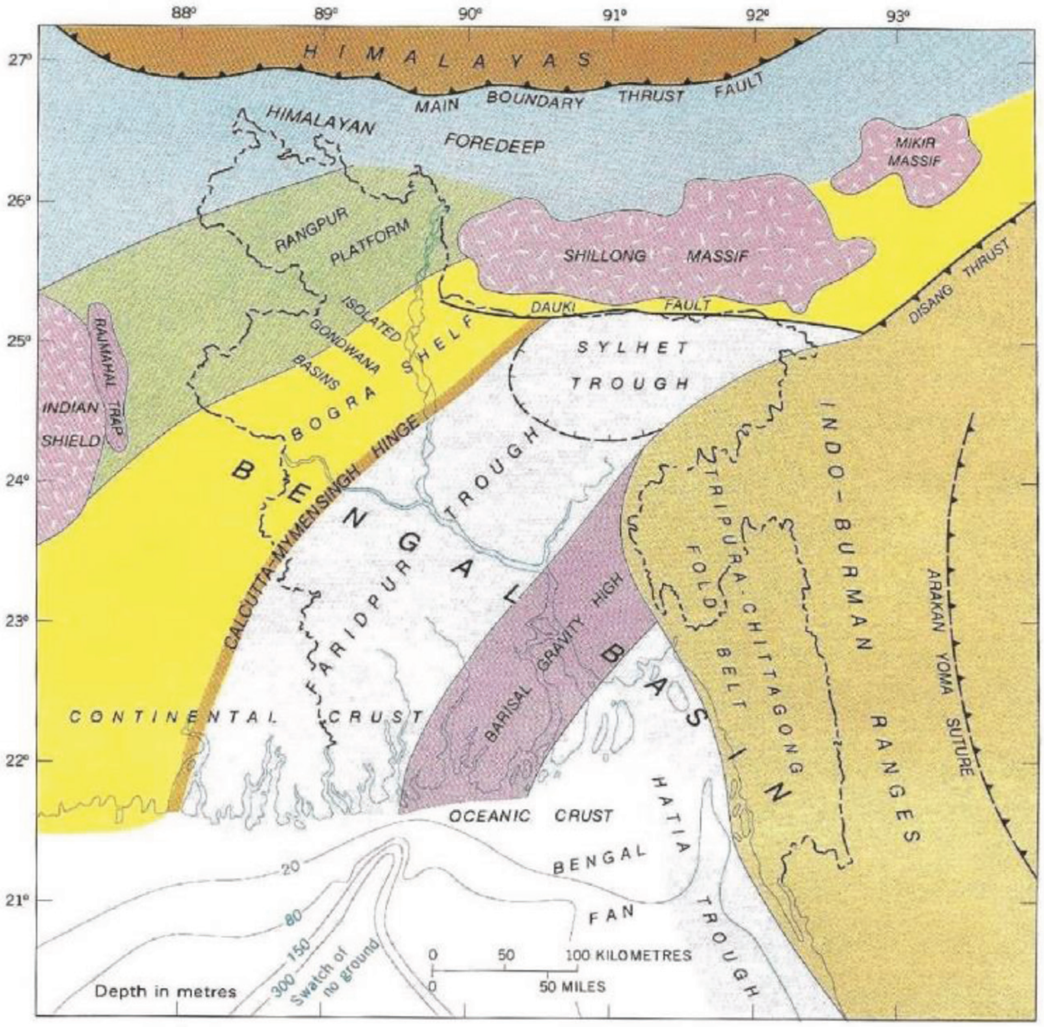

Figure 2. Generalized tectonic map of Bangladesh and adjoining areas.

their specific characteristics. Then, a field survey was done accordingly to confirm each geomorphic unit on the map.

Only hilly areas have been taken into account for landslides investigation. Chittagong City lies in the southern plunging part of the Sitakund Anticline. The anticline is asymmetrical and is characterized by a steeper western (faulted) flank and a gently sloping eastern flank. In the plunge area around the city, the folded sediments are highly twisted and distorted [7, 8].

The investigated area forms a part of the Chittagong hills constituted of rocks of the Boka Bil to Dihing Formation. Around Chittagong City, from east to west, exposed geological formations are Dihing Formation, Dupi Tila Formation, Tipam Sandstone and Boka Bil Formation [6]. Under varying environments, these formations (**Figure 4**) were deposited during Mio-Pliocene time (25–2 Ma). As a consequence, their rock types as well as their geotechnical properties are non-identical.

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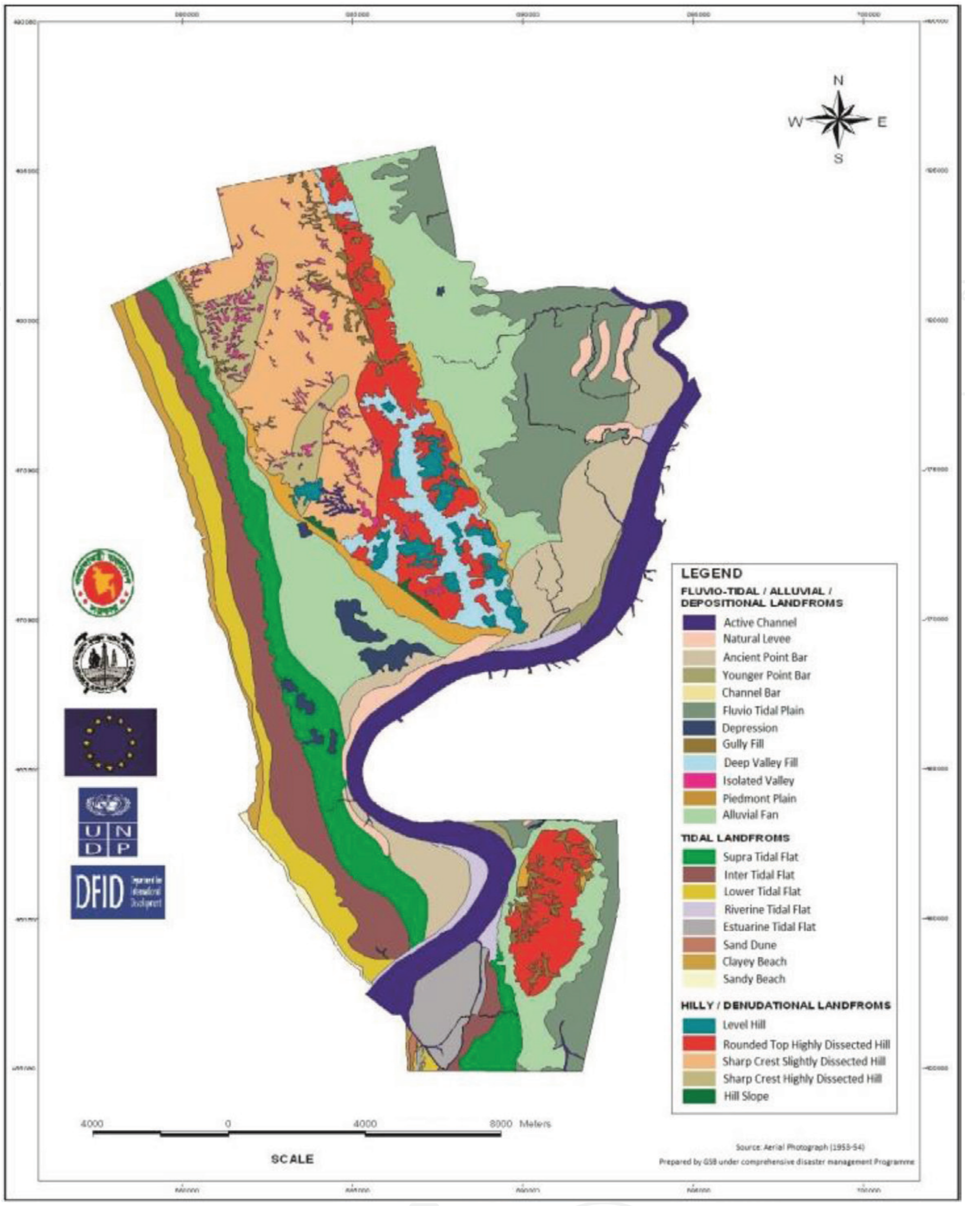

Figure 3. Geomorphological map of Chittagong City and its environs.

Moreover, since its deposition, the rocks have undergone different climatic conditions as well as tectonic activities which eventually influenced the geotechnical properties of the rocks. The presence of ripple marks and the frequent alternation of sand and silt of the Boka Bil Formation reveal that the sedimentation took place in strong current at times [9]. The change of facies from argillaceous to arenaceous points out that the environmental condition gradually changed. The presence of clay galls and lignite suggests that the rocks of Tipam Formation display arenaceous in the northern part and argillaceous in the south [9]. This change of lithofacies in the formation reveals that the gradual regression of sea started in the northern part earlier than the south. The environmental condition was later reduced to estuarine [9]. The sediments of Dupitila Formation were deposited in this

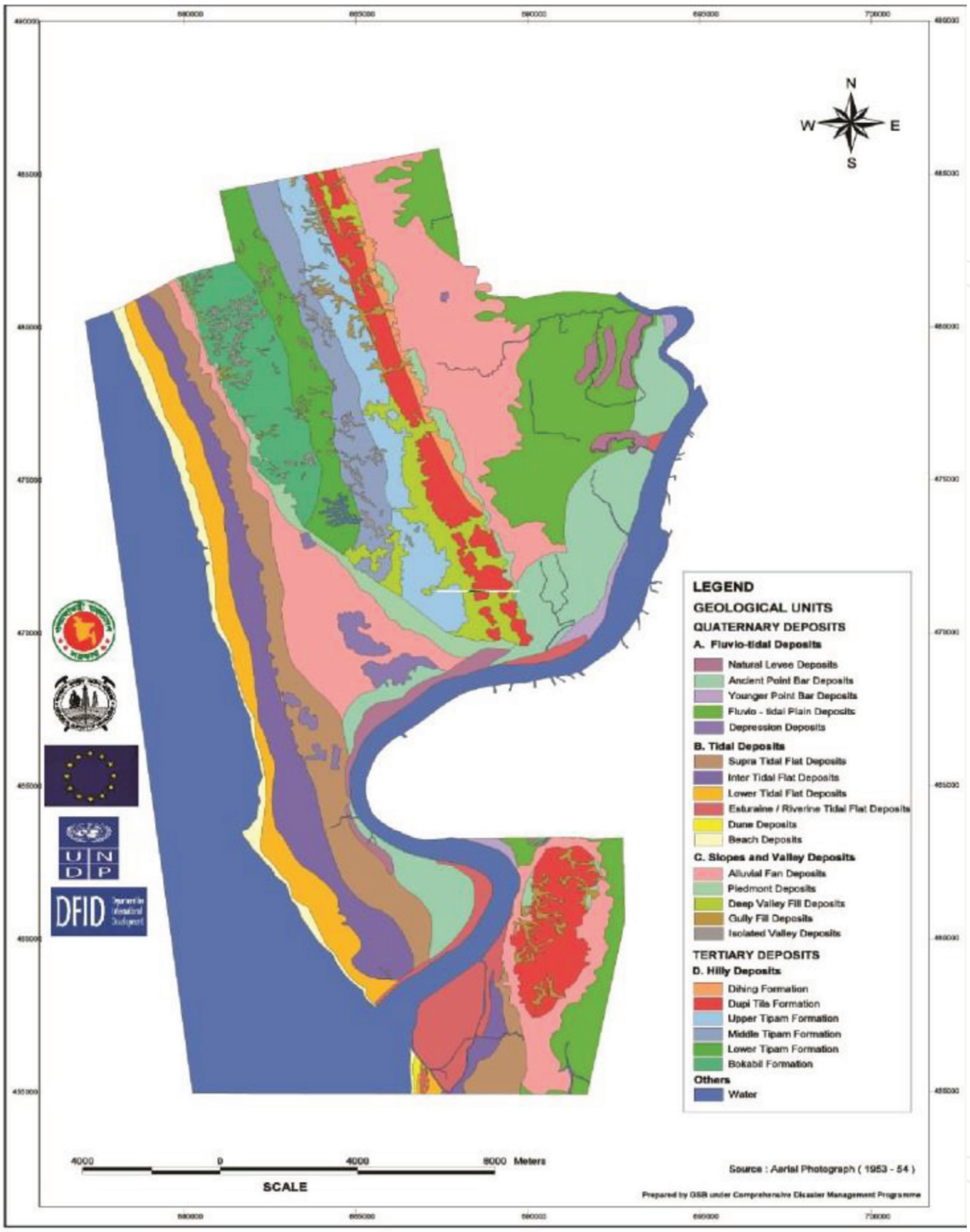

Figure 4. Geological map of Chittagong City and its environs.

environment and continued to occur towards the close of Pliocene. The occurrence of shale and sandstone pebbles, iron incrustations and silicified wood establishes the fact that the sediments of Dihing Formation were derived mostly from older Formations in a fluviatile environment [9].

The generalized stratigraphic succession and geotechnical properties of each formation of the city area are given in **Table 1**.

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Name of the formation/age		Rock type	Geotechnical characters
Dihing Formation/Pliocene (13–1 Ma)		Reddish brown to brick red, massive, highly ferruginous, weathered sandy to clayey silt, clay and pebbly sandstone at places, oxidized iron incrustation. On top weathered residual soils.	Very soft (30–10 kg/cm^2) to soft (100–30 kg/cm^2) in hardness, low-to-medium relative strength, uniaxial compressive strength of 1–2 kg/cm^2.
Dupi Tila Formation/Mio-Pliocene (15–5 Ma)		Sandstone and alternation of silty sand and silty shale. Sandstone massive and medium to fine grained, silty sand beds are grayish to yellowish brown, thickly laminated to bedded. Silty shale is light gray to gray, very thinly laminated, fissile. Presence of iron incrustation.	Longitudinal joints are present dipping almost parallel to the bedding, spacing varies from closed to 1.5 cm, filled with ferruginous band with coarse sand. Soft (100–30 kg/cm^2) in hardness. Low-to-medium relative strength.
Tipam Sandstone Formation/Mid Miocene (25–13 Ma)	Upper Tipam	Sandstone, siltstone and occasional shale, Sandstone cross-bedded and local unconformity at the base	Soft in hardness (100–30 kg/cm^2), moderately weathered, faulted, conjugate (planar) joints are present with vertical and dipping orientation, spacing <1 cm, medium relative strength, uniaxial compressive strength >550 kg/cm^2
	Middle Tipam	Silty shale and shale, bedded, shale relatively hard, at places calcareous.	Moderate (250–100 kg/cm^2) to hard (700–250 kg/cm^2) in hardness, faulted, laminated, medium to high relative strength, uniaxial compressive strength varies from 550 to 1100 kg/cm^2.
	Lower Tipam	Massive sandstone, yellowish brown to brown, medium to coarse grained, loose to dense, cross-bedded.	Moderate (250–100 kg/cm^2), at places hard (700–250 kg/cm^2) in hardness, slightly to highly weathered, faulted, planar and conjugate joints are seen with vertical and dipping orientation, spacing <1 cm, ferruginous and argillaceous filling, medium to low relative strength, uniaxial compressive strength varies from 275 to 750 kg/cm^2.
Boka Bil Formation/Early Miocene (34–25 Ma)		Silty shale, siltstone, sandstone and alternation of sand and siltstone. Cross bedding, cross lamination, ripple marks and load casts are present.	Moderate (250–100 kg/cm^2) to hard (700–250 kg/cm^2) in hardness, fresh, faulted, planar diagonal to conjugate joints present, closed spacing, filled with mainly parent material, medium to high relative strength, uniaxial compressive strength varies from 250 to 700 kg/cm^2.

Table 1. Stratigraphic succession of Chittagong City and its surrounding areas [10].

3. Description of landslides

Locations of landslides in Chittagong City indicate that most of them occurred in sandstone of Dupi Tila and Upper Tipam Formations. The hills of Dupi Tila and Upper Tipam Formations exhibit rugged topography with numerous valleys and ridges. With an average elevation of about 30 m from the ground, the hills are dome-shaped with a flat top. The lengths of the flanks range from 15 to 50 m, and most of their gradient varies from 10° to 40°. The profile of the slopes is primarily convex to concave and finally fairly regular at the end. Two types of valleys are prominent here. They are V-shaped and U-shaped valleys. V-shaped valleys mainly occur along the strike and have a higher gradient in the eastern side than that in the western. U-shaped valleys are formed across the strike and they are shallow, open and smooth. The hills are rolling type with sub-dendritic medium-dense drainage system [10].

Most of the landslides are found small in size but there are a number of slides at each location. A high death toll at some locations can be attributed to repeated landslides one after another in the same area. In some cases, when a landslide took place, local people start rescue operation but subsequent landslide buried even the rescuers.

Most of the landslides initiated as a slide type but eventually terminated as dry flow, with exceptions in some rock fall areas. Due to modification of hills around the city, slopes are observed with a gradient of almost 90° in many places. Each landslide shows well-developed main scarp and surface of rupture. The slope materials are characterized by loose sandstone with little or no silty shale or shale. High permeability of sandstone allows rainwater to infiltrate easily. Except small bushes and grass cover sparsely, most of the hill slopes are barren. The main scarps have heights of about 1 m or less. In some places, lunar cracks were developed above the main scarps, in the crown of the landslides. Rainwater penetrates more easily through the lunar cracks, and it was sufficient to initiate the surface rapture. The main bodies of the landslides are generally free from debris and minor scarp. Under the influence of gravity, sediments slide and started to flow rapidly over the gentle part of the slopes.

4. Causes of landslides

A change in hillside equilibrium is mostly attributed to the landslide occurrences. The three factors that influence stability of hill slopes are [11] as follows:

4.1. Internal properties of earth materials

Landslides have mostly occurred along North–South orientation in the eastern part of the city. Around Chittagong City, Dupi Tila, Tipam and Boka Bil Formations are exposed. However, landslides occurred mostly in the sandstone of Dupi Tila and Upper Tipam Formations. The sandstone of these formations consists of 52–74% medium to coarse sand, 28–45% fine sand and only 2–4% silt. Field investigation and laboratory tests show that landslides happened in sandstone which consists of very little or no silt and clay particles. Sands are primarily medium to coarse grained, poorly sorted, moderately weathered, loose with no cementing materials,

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highly porous and permeable and easily powdered between the fingers, indicating little bond strength between individual particles. It is massive, joints and fractures are not common but occasionally with inter-bedded iron bands. Unconfined compressive strength, cohesion and angle of internal friction of sandstones range from 1.2 to 1.8 kgf/cm^2, 0.0459 to 0.0801 kg/cm^2 and 32.3° to 34.3°, respectively. Hezen's uniformity coefficient is less than 2. The specific gravity ranges from 2.39 to 2.57 and the permeability ranges from 0.2116 to 0.5184 cm/s.

4.2. Geomorphic setting and environment

The area is characterized by dome-like low hills with a flat top. The flanks of the hills are very short in length (15–50 m). The natural slope angle of landslide areas varies from 34 to 84° but most of the slopes are more than 40° which is greater than the average values of the angle of internal friction of slope materials (26–34°). Hence, slopes are unstable under natural condition. The profile of the slopes is convex at the top, at the middle it is concave and it is fairly regular at the bottom. The valleys and gullies, which follow the east-west direction, are open, shallow, U-shaped and smooth. The valleys trending north-south are V-shaped, relatively deeper, elongated and parallel to the strike of the bedding. The hill slopes lack large trees and covered mostly with grass- and shrub-type vegetation.

4.3. Independent external factors

External factors are triggering factors that cause landslides. Excessive precipitation, human activities and earthquakes are the three most common triggering mechanisms of landslides. On or close to the day of landslides, there is no record of earthquakes. Human activities such as deforestation and hill-slope modification through cutting are common phenomena. Chittagong City is characterized by excessive precipitation within a short period of time, the important triggering factor for landslides.

The magnitude, intensity and duration of rainstorm play vital roles in determining whether a hill slope will fail or not. Rainfall lubricates and increases the weight of slope materials. Excessive rainfall weakens earth materials by displacing air and increasing the pore water pressure along shear surfaces. The probability of ultimate failure enhances when surface materials are porous and permeable and are underlain by sediments of low permeability. Inadequate drainage facility of rainwater also causes more infiltration into the ground.

5. Mechanism of landslides

The slopes are almost barren and hence rainwater easily infiltrated into the slope materials that eventually increases the pore water pressure. As a result, crown cracks developed on top of hills. Those cracks allow much more water to penetrate the materials. During heavy rainfall, pore water pressure surpasses the shear resistance of the slope materials. Landslides initiate when this shear resistance threshold is exceeded.

The pore water pressure generally develops in the convex part of the slope. As the pore water pressure exceeds the resistance of the materials to shear, the slope materials start to move.

Initially, the materials with a huge volume of water in the convex part of the slope begin to slide and roll over the concave part and finally on a fairly regular part (settlement areas). The extraordinary rapid movement of sediment and water destroys and buries people and houses, and finally due to the non-cohesive nature of slope materials, the slide terminates as dry flow. The steps involving the development of landslides (**Figure 5**) can be summarized as follows:

- Due to torrential rain, rainwater starts to infiltrate into the slope materials increasing pore water pressure.
- On top of hills, crown cracks developed and those cracks allow more and more water to infiltrate into the materials.
- The resulting pore water pressure exceeds the shear resistance of the slope materials.
- Landslides initiate when threshold for shear resistance is exceeded by pore water pressure.

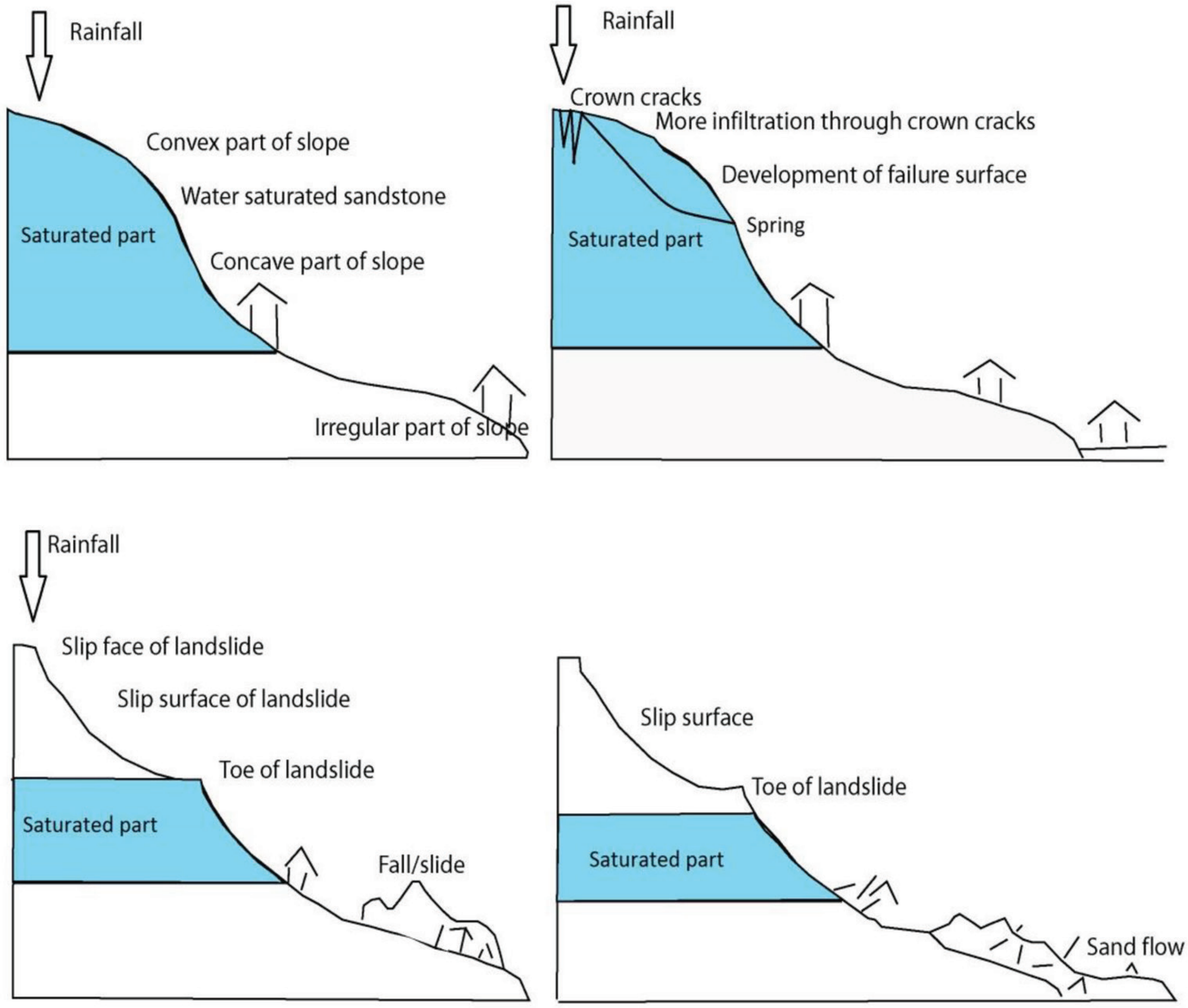

Figure 5. Stages of development of landslides.

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6. Landslides prevention and control

The choice of landslides prevention and control measures depend upon the geological condition, physiography, available technology and above all the socioeconomic condition of the people. Important landslides prevention and control methods are [11] as follows:

Avoid method: If slope is extremely hazardous and landslides control measures are expensive, complete avoidance of the area is the only sustainable solution.

Water control method: Usually, rainwater infiltrates into the slope materials and makes them exposed to landslides. Proper management of rainwater through drainage from the slope instead of infiltration into the soil can significantly reduce landslide vulnerability. This can be realized by afforestation and building suitable drainage structures on slopes.

Excavation method: A slope turns out to be vulnerable when the natural angle of the slope becomes higher than the angle of internal friction of slope materials. The main objective of excavation method is to stabilize the slope by modification of the slope angle so that the internal friction angle of slope materials is higher than the slope angle.

Retaining structure: Structures that can be used for slope stability are buttresses, retaining walls, shear keys, guide walls, and so on.

The best prevention method for Chittagong area might be complete avoidance of hazardous slopes. A second option might be excavation method which suggests reforming the slope so that the slope angle becomes less than the angle of friction of slope materials. Thirdly, retaining structures like retaining wall, guide walls or buttresses can be constructed to protect the slopes from further landslides. However, if we could harness the modern communication and information technology to provide an in-advance warning prior to an incidence by developing real-time landslides early-warning system, then that should be one of the best options at least to save lives.

7. Landslides susceptibility zoning and early warning

The hilly part of Chittagong City and its surrounding areas have been classified into four zones on the basis of locations of past landslides, rock types and their geotechnical properties (**Figure 6**). These potential zones are very closely correlated with the geology of the area. Based on these parameters, Zone-I is most dangerous and Zone-IV is relatively less dangerous for landslides hazard. In Zone-I, the rock type is mostly loose, highly weathered sandstone and Zone-IV constitutes mostly of compacted shale. Considering the age of the rock types, Zone-I is younger than Zone-IV. Zone-I in the map represents Dupi Tila and Upper Tipam Formations, zone-II corresponds to Middle Tipam, zone-III falls into Lower Tipam and finally zone-IV to Boka Bil Formation.

Rainfall-induced landslides are common phenomenon in Chittagong and in adjoining areas where scores of people are being killed each year due to landslides. Under present situation, it

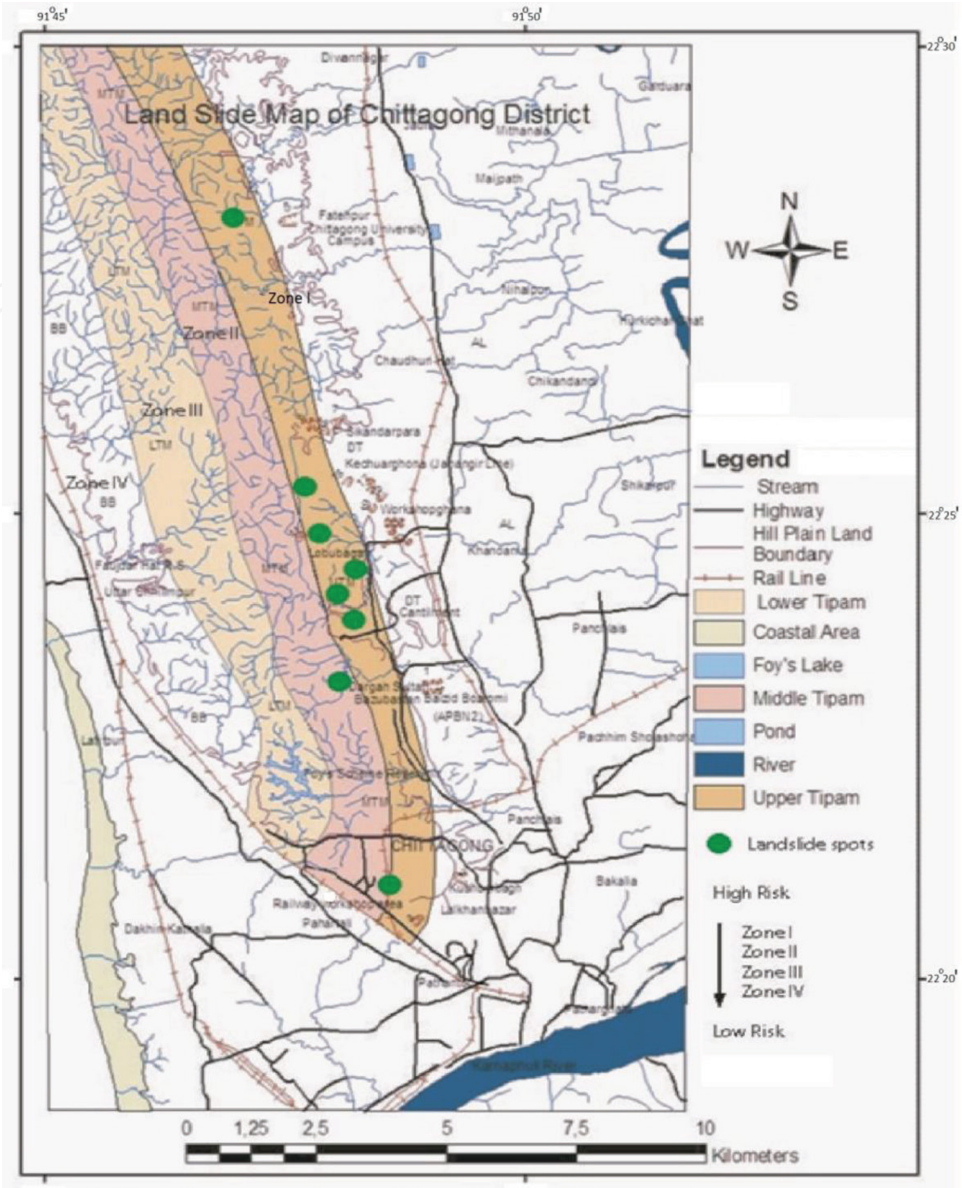

Figure 6. Landslide hazard-zoning map of Chittagong City and its surroundings.

is most important to save lives and properties from the potential hazard of landslides. To serve this purpose, the Geological Survey of Bangladesh (GSB) and the Norwegian Geotechnical Institute (NGI) are working together to lessen the landslides hazard level in Chittagong City. The co-operating partners have developed an early-warning system to forecast rainfall-induced landslides in Chittagong so that people can be aware of the impending landslides beforehand.

GSB has carried out a study to rectify empirical data from years 2003 to 2010 and still studying various landslides to rectify the rainfall threshold value. Event-based rainfall data are statistically analysed (**Figures 7** and **8**) to determine the rainfall threshold values for landslides in Chittagong City (**Table 2**). For analysis on experimental basis, the total rainfall duration was split into three separate durations such as 1 day, 3 days and 7 days. For all these periods, respective landslide events were correlated with the total amount of rainfall. During analysis, it was found that rainfall within a very short period of time (such as 3 h) is also associated

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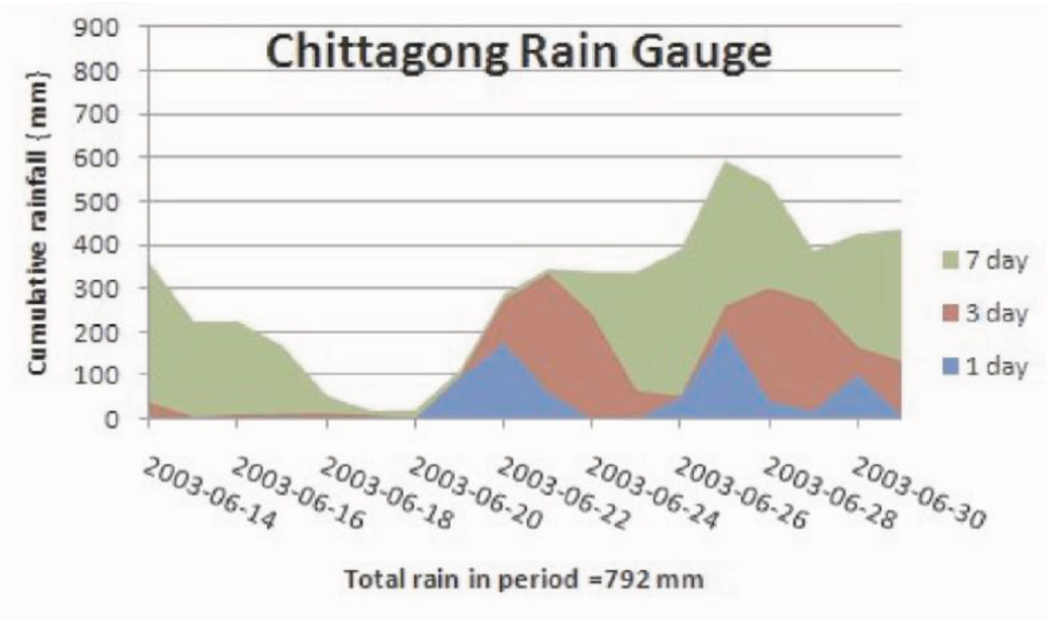

Figure 7. Statistical analyses of rainfall data.

with landslide events. Hence, rainfall threshold values for landslides were set for even shorter periods such as 3 h, 1 day and 3 days.

After rainfall data analysis, the threshold values for Chittagong City are set to.

3 h to 100 mm.

24 h (1 day) to 200 mm.

72 h (3 Days) to 350 mm.

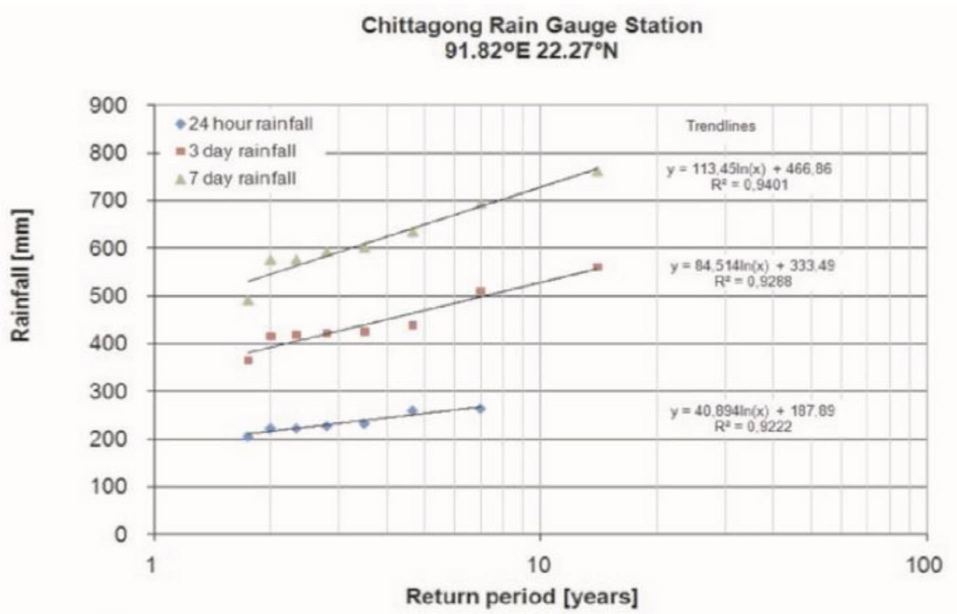

Figure 8. Return periods analysis of extreme rainfall events.

Chittagong rainfall (mm)				
	Return period (years)			
Period	1	2	3	4
7 days	467	545	591	624
3 days	333	392	426	451
1 day	188	216	233	245

Table 2. Results of statistical analysis of rainfall data.

Automatic rain gauges for landslides early warning have been installed in Chittagong City Corporation and Chittagong University Campus which record rainfall data every 15 min and send it to a server through an online system. Historical rainfall data are stored in the server for further analysis. In addition, when the rainfall threshold values, which have been set in the system, are exceeded, the rain gauges are programmed to send SMS messages to registered mobile phones of 10 different organizations/personnel (**Figure 9**).

These rain gauges send real-time early warning to the registered mobile phones so that the first responding organizations can take action straight away before landslides happen. This is intended to facilitate the timely evacuation of the people residing close to landslides-prone areas. The automatic rain gauges installed are receiving power from a solar panel to

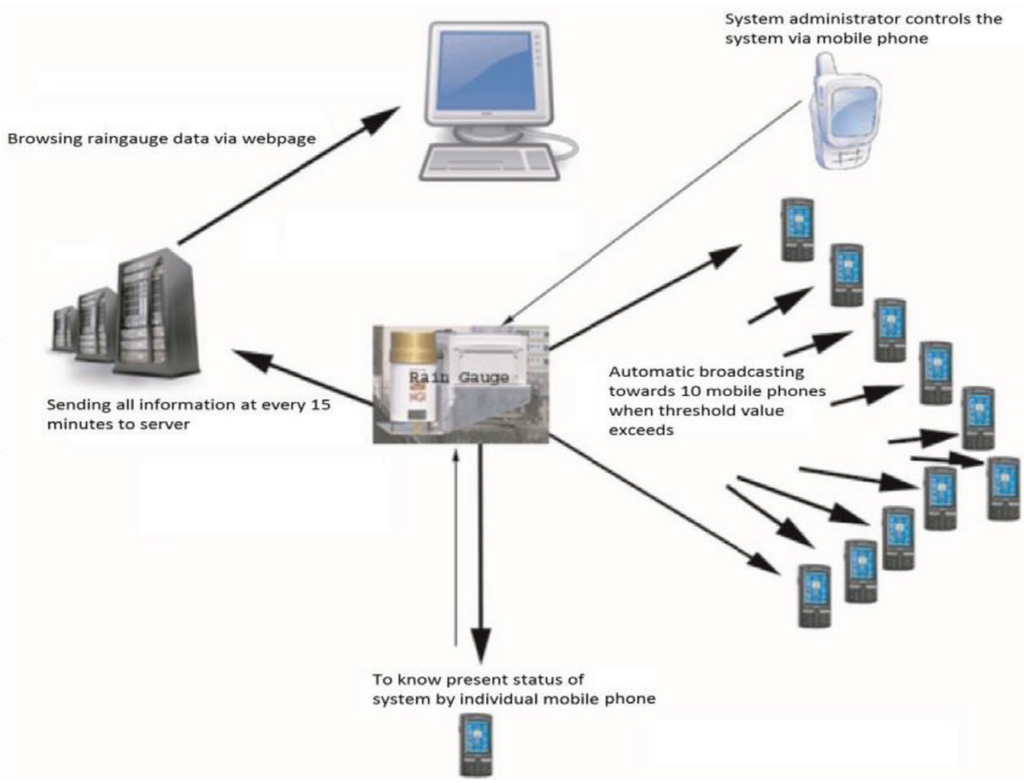

Figure 9. Schematic diagram for landslide early-warning system.

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charge the batteries and require only mobile telephone coverage at the installed location. The stations work with standard mobile telephone SIM cards and do not require any special infrastructure from the local mobile telephone operator. Installation is simple as the station is a compact unit that can be placed on the ground or on a roof, or mounted on a mast.

8. Conclusions

The main cause of landslides in and around Chittagong City is heavy rainfall in a short span of time. At the same time, geotechnical properties of the slope materials (loose, well-graded sand, high permeability and porosity, low internal friction angle and weathering characteristics) are also responsible. In several cases, hill cutting accelerates the process of landslides but was not the main cause of landslides.

Depending on the locations of landslides, geology and geotechnical properties of rocks, Chittagong City and its surrounding areas have been classified into four landslide hazard zones. Of these, Zone-I is very much susceptible to landslides and Zones-II, -III and -IV are progressively rather less vulnerable.

Rainfall becomes the primary triggering factor of landslides, and it is statistically calculated that 100 mm of rainfall in 3 h, 200 mm in 24 h (1 day) and 350 mm in 72 h (3 days) can be the threshold values of rainfall to initiate landslide occurrence. Event-based statistical analysis of rainfall data is still taking place to rectify these threshold values for the city.

Accordingly, two automated rain gauges have been installed in and around Chittagong City. If threshold values exceed, the system automatically sends landslide early warning to 10 selected mobiles of local administration and the first responding organizations so that they can alert people in advance before landslides. GSB is also working to increase the number of such systems especially in other landslide-prone areas of the city. The ultimate goal is to save the people from landslide disaster and build a landslide resilience community.

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