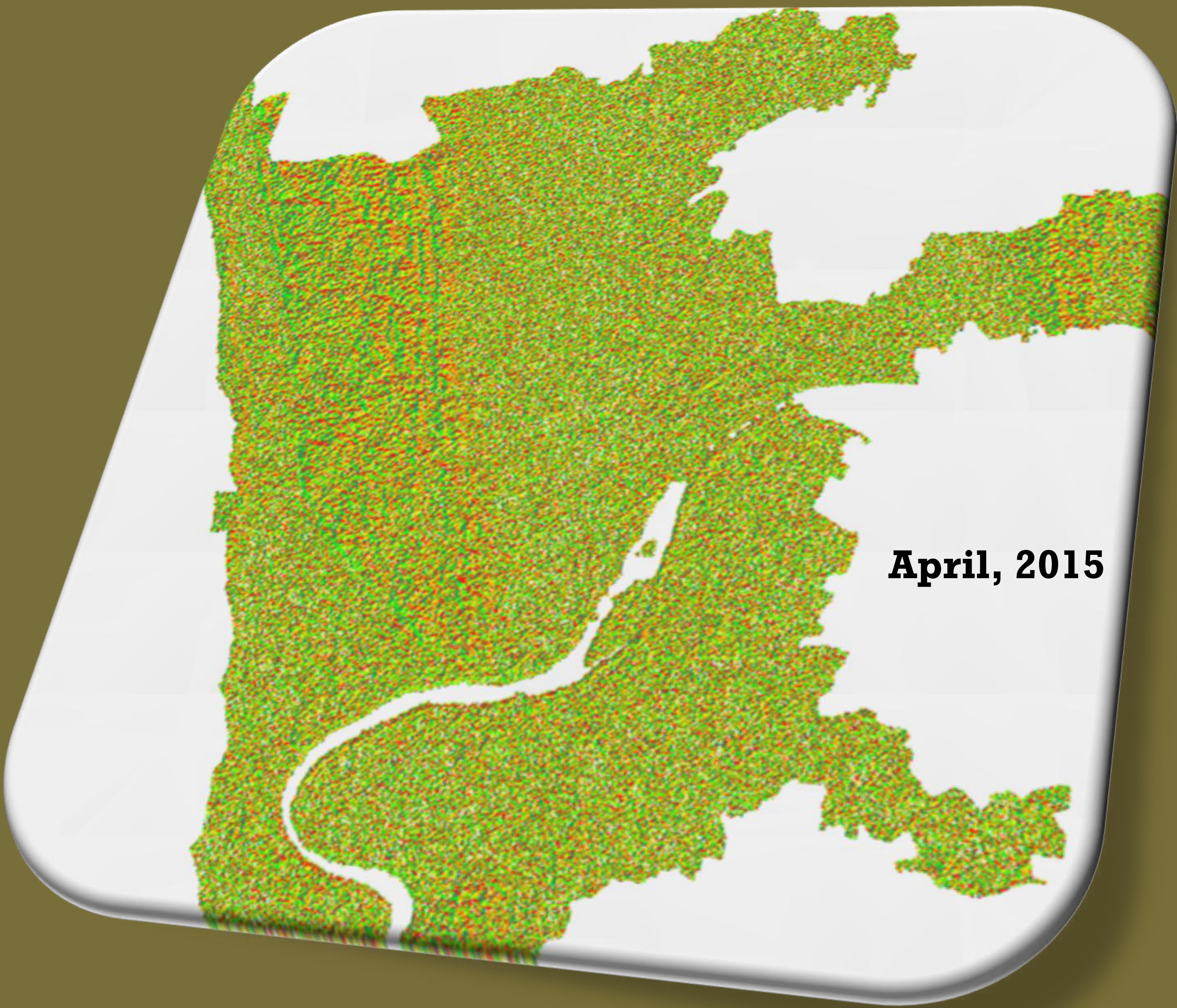
SLOPE STABILITY MAPPING FOR CHITTAGONG METROPOLITAN AREA, BANGLADESH



April, 2015

BUET-Japan Institute of Disaster Prevention and Urban Safety

Bangladesh University of Engineering and Technology (BUET), Dhaka-1000, Bangladesh.

Email: jidpusinfo@jidpus.buet.ac.bd, Phone: +8802-9662975, Fax: +8802-9662975

SLOPE STABILITY MAPPING FOR CHITTAGONG METROPOLITAN AREA (CMA) OF BANGLADESH

1.1 BACKGROUND

Landslide is the hazard significant for most casualties and damages on this earth. The damages in a landslide depend on the type, speed and volume of the soil movement. Hydrology is a major determinant of many natural hazards. Landslide occurs mainly due to slope instability of hilly areas. Slopes may become instable because of ground water fluctuation due to heavy rainfall for some consecutive days, typhoon, hurricanes, earthquake, human activity etc. So, it is very necessary to know about the stability of slope i.e, susceptible areas in a hilly and mountainous region before taking any measure to prevent or manage the devastating disaster and thus reduce the losses.

At inventory stage, we found 57 locations in Chittagong Metropolitan Area (CMA), Bangladesh (field survey, August, 2014) where landslide has already been occurred for several years. But we found no prepared map or information on the stability of slope in any organization related to landslide. It is the scope of this project to prepare a slope stability map of Chittagong Metropolitan Area (CMA) in a scientific way and through it the locations vulnerable to slope failure and landslide can easily be determined.

The climate change is responsible for the slope failure and the ultimate result is slope instability. Surface runoff calculation and ground water movement is important factor in slope instability. Digital Elevation Model (DEM), land cover map, plant cover and plant height; daily rainfall data, evapotranspiration; soil type map with soil properties like hydraulic conductivity of the soil at saturation level, porosity of the soil, internal friction of the soil; field capacity of the soil, wilting point of the soil, angle of internal friction, soil cohesion, specific density regolith, splash detachment erodibility; and soil depth datasets will be used for slope stability mapping.

It is must to know the physical characteristics of soil for making a water balance model. The variation of soil moisture and different processes (infiltration, evapotranspiration, percolation and groundwater flow) in soil layers depend on soil properties. The soil hydraulic properties are determined by two main characteristics of soil named texture and structure. The characteristics of soil are found in soil investigation part of this project.

Land cover change is an important issue in soil failure. Vegetation intercepts rainfall directly in the canopy (overlay) and decrease the amount of rain water reaching to the soil surface. A projected land cover map has prepared earlier during land cover modeling using satellite images (year: 1990, 2000 and 2010) from the United States Geological Survey (USGS).

The average annual rainfall is not same in each year. Excessive rainfall causes lose of soil and landslide in hilly areas. As a result, there is a huge loss of properties and lives in every year. To prepare for the preparedness and mitigation program it is necessary to know the return period of these devastating events calculating the long term rainfall data. From rainfall pattern modeling we have found the pattern of rainfall in the study area.

When groundwater in a slope rises up, the pressure in soil-pore-system is increased and as a result, the slope loses its resistance forces to hold its mass and it fails. The slope may move in different ways like falling, toppling, rotational slipping, sliding, translational slipping, spreading, creeping, or as block slip, avalanche, lahar, mudflow etc. [1] In this study, the driving force (mass of the slope) and resisting forces (for slope failure) will be compared through 'Infinite Slope Model'. The ratio of these two forces is called 'Factor of Safety (FS)'.

$$\mathrm{FS} = \frac{\text{Resisting force}}{\text{Driving force}} = \frac{\text{Share strength of matrial (soil)}}{\text{Share stress required for equilibrium}}$$

Where, FS > 1.0 represents a stable situation and FS < 1.0 denotes failure of soil (soil instability). [2]

To find out the location of unstable slope and time of slope failure, the groundwater movement will be combined with the Infinite Slope Model. A sensitivity analysis will be done to know which combination of parameters will cause the slope instability in a particular area. The output of this portion will be a series map of slope stability factor maps for 365 days of the year. This mapping is expected to be very helpful to identify the endangered area where it is necessary to warn the people through web-GIS based early warning system.

1.2 DATA SOURCE

Table 1.1: Detail of the inputs used for natural hazards modeling/spatial dynamic modeling.

Sl. No.	Input	Description	Source
1.	Digital Elevation Model	ASTER GDEM 30m× 30 m resolution	USGLOVIS
2.	Rainfall station	Point location of rainfall station	
3.	Mask	Definition of Boundary Extent of the study area	Prepared
4.	LDD	Local Drainage Direction	Derived from DEM
5.	Outlet	Outlet of the catchment	Derived from DEM
6.	Soil texture class unit	Derived from geological map	Geological survey of Bangladesh
7.	Rainfall data (mm/day)	Rainfall data of 2008 for Chittagong City	Meteorological Department of Bangladesh
8.	Potential evapotranspiration	Standard Value from literature	Jetten and Shrestha
9.	Soil data	Engineering properties of the soil	Laboratory test and literature
10.	Saturated hydraulic conductivity (mm/h)	Calculated from soil particle ratio	SPAW Model
11.	Soil depth (mm)	Interpolated value from 18 borehole location	Civil Department , Southern University, Chittagong
12.	Stream channel width	Width of stream and river	Derived from LDD
13.	Landcover Map	Classification of Landcover	Classified from Landsat TM image

1.3 METHODOLOGY

1.3.1 Preparation of Input Data

Digital Elevation Model (DEM) is the basic data for any slope modeling. DEM is extracted from ASTER global DEM with 30m spatial resolution (Figure 1.1). Coordinate of rainfall station has been collected from Bangladesh Metrological Department (BMD). Then a raster map rainfall station is prepared with rainfall station location. An area map called mask is prepared for Chittagong Metropolitan Area to define the study area (Figure 1.2). Local Drainage Direction (LDD) map is calculated from DEM (Figure 1.3). The stream network created from a map with surface drainage directions. This is a map with a network connecting all cells according to the steepest slope. A subset of this map is the stream channel network. Therefore, a continuous network is being created that connects every cell to the outlet of the catchment. From this LDD map an outlet map has been prepared to define the outlet point of the catchment. Soil unit map has been prepared based on geological unit map available from Geological Survey of Bangladesh (GSB). Engineering properties of soil units such as hydraulic conductivity of the soil, porosity, internal angle of friction, cohesion has been collected through lab testing and available literature. Soil depth map has been prepared by inverse distance weight (IDW) interpolation of borehole location (Figure 1.4). Depth of top soil class layers has been considered as soil depth of 18 borehole locations.

Figure 1.1: Digital Elevation Model (DEM) of Chittagong Metropolitan Area (CMA).

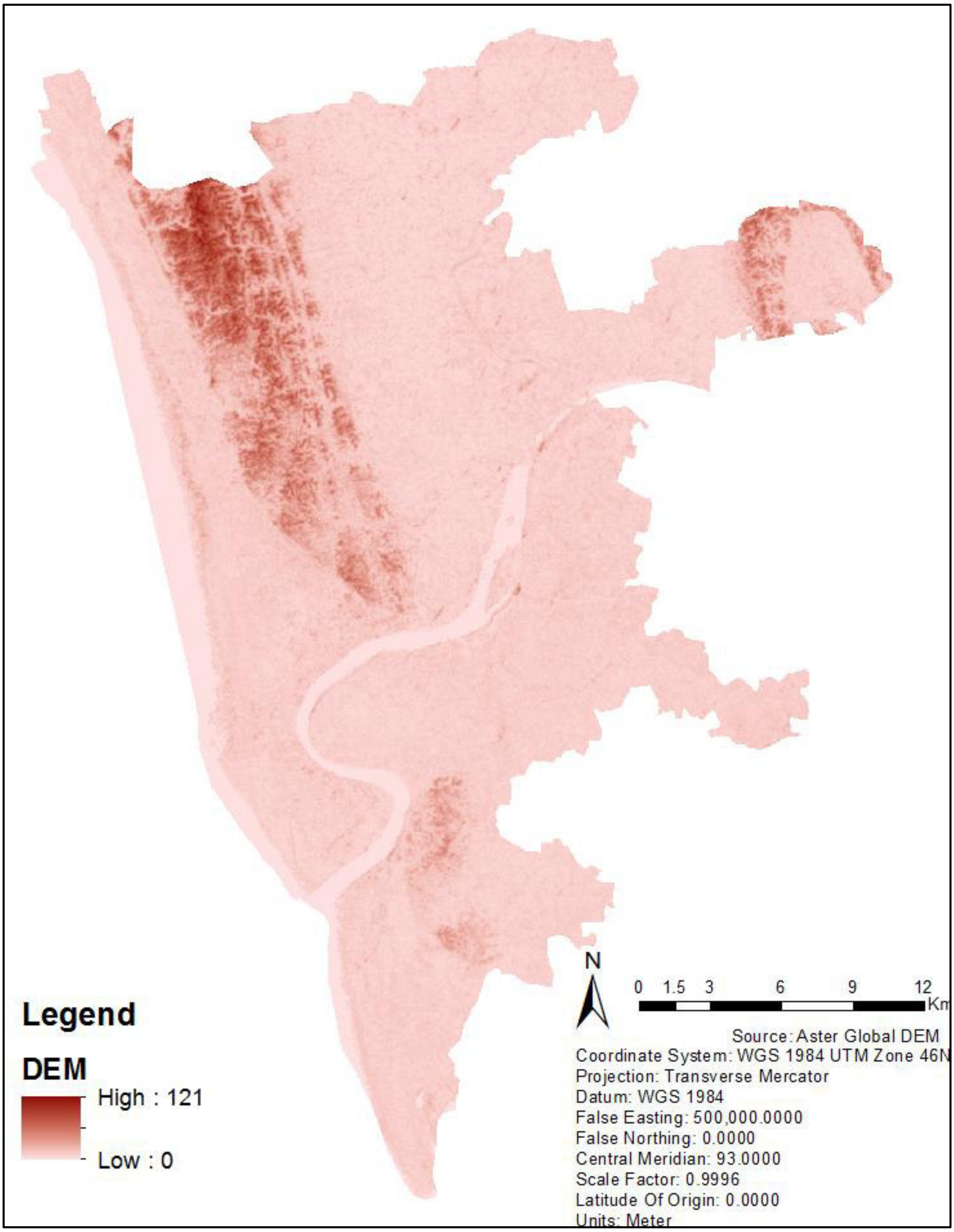


Figure 1.2: Saturated Hydrouclic Conductivity Map of Chittagong Metropolitan Area.

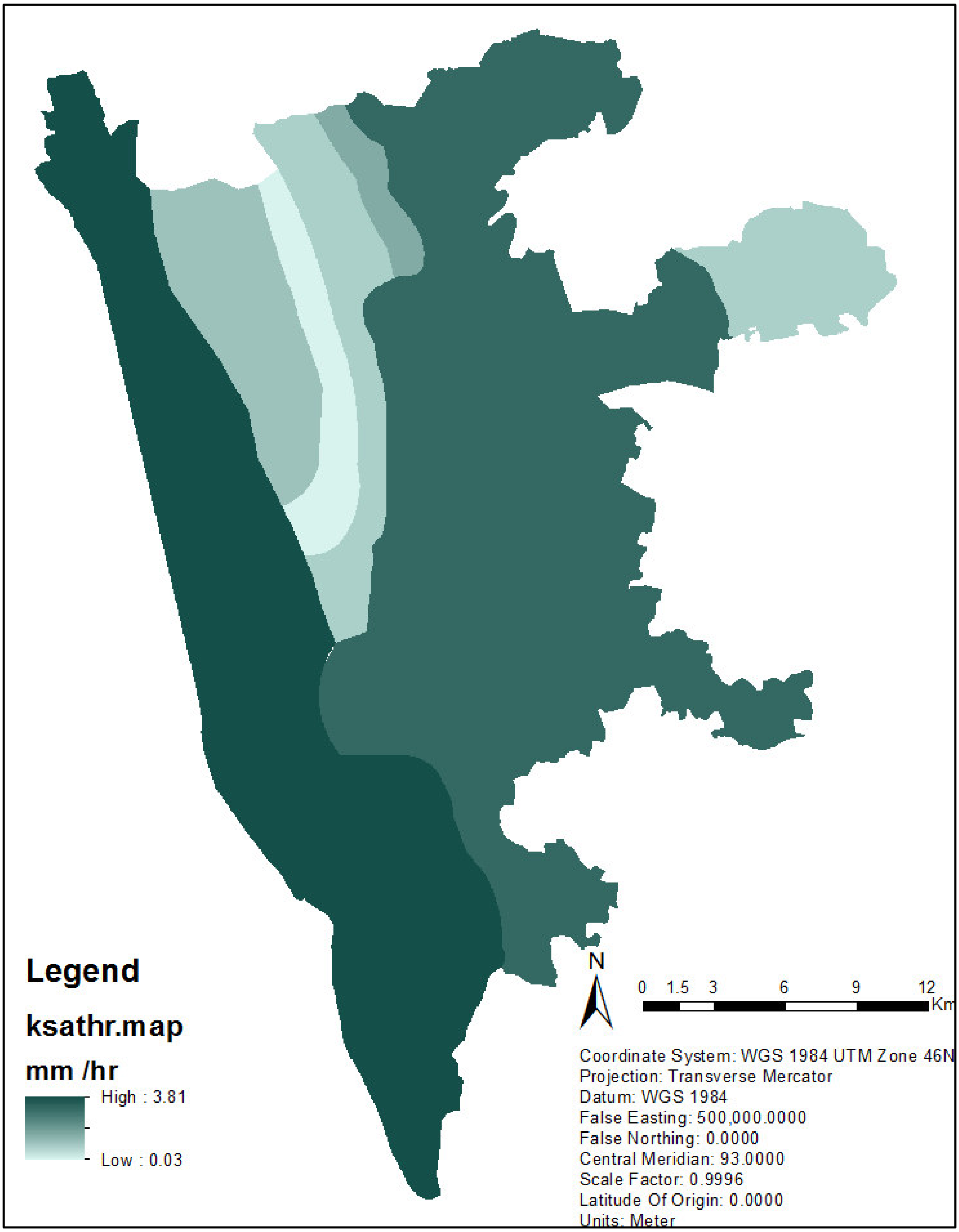


Figure 1.3: Local Drainage Direction (LDD) Map of Chittagong Metropolitan Area.

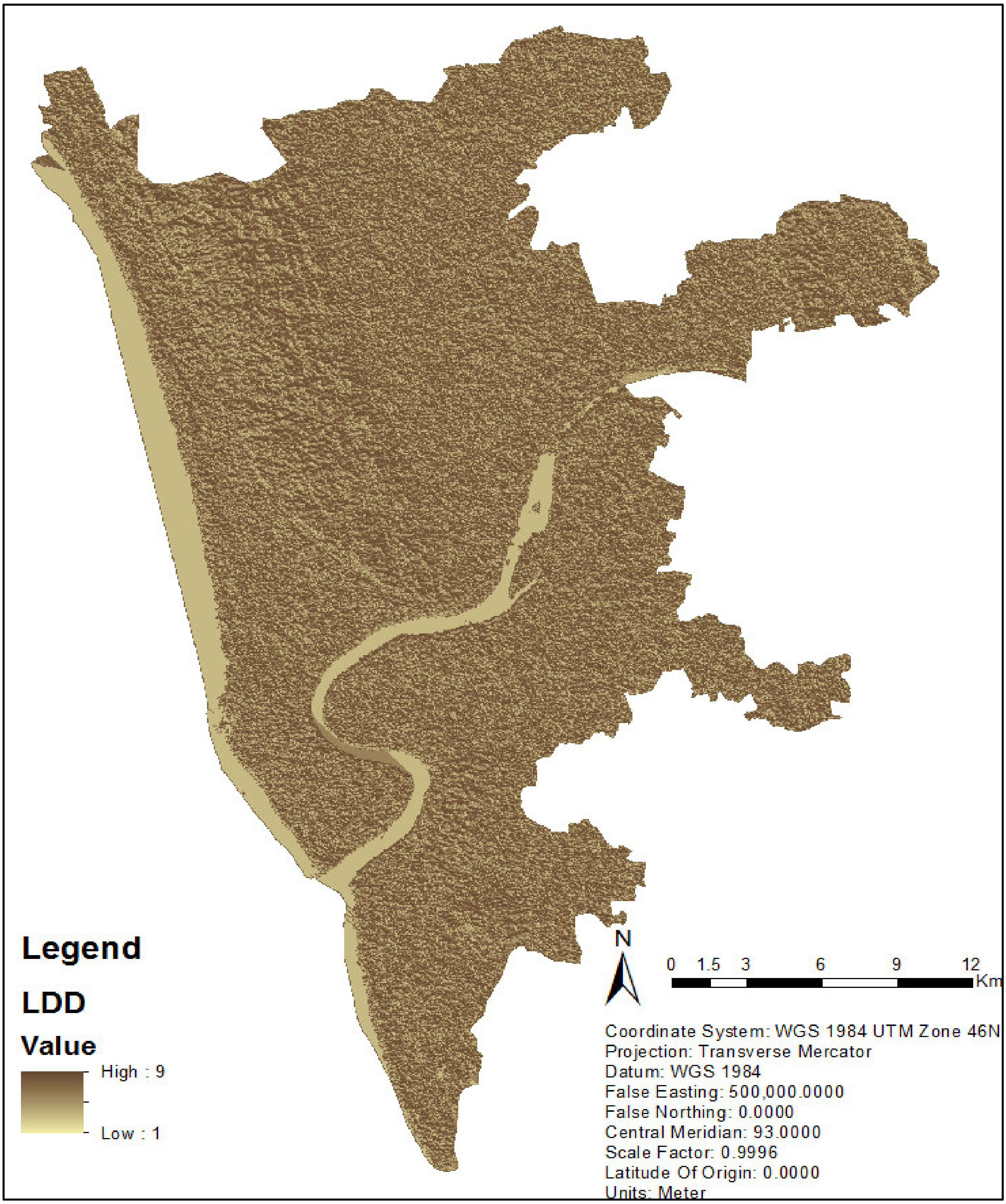
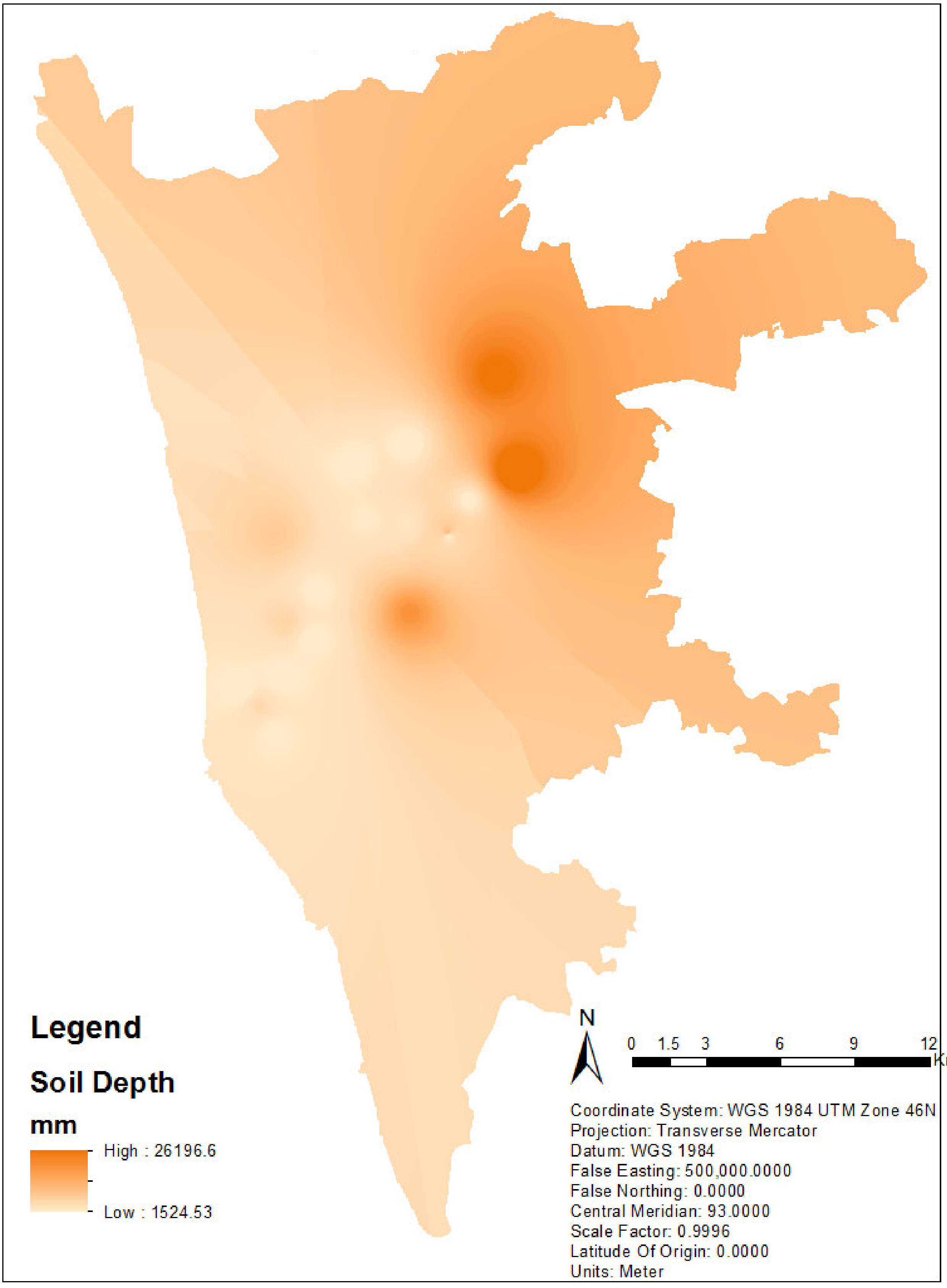


Figure 1.4: Soil Depth Map of Chittagong Metropolitan Area.



1.3.2 Land Cover Mapping

Landsat Thematic Mapper (TM) satellite images were used for the land cover mapping (2010) of Chittagong Hill Tracks (CHT) area. Initially four scenes were collected to cover the whole CHT area. TM sensor collects reflected energy in three visible bands (blue = 1, green = 2, and red = 3) and three infrared bands (two NIR = 4, 5 and one middle infrared = 7). The base year for this land cover mapping is selected as 2010.

Among the four scenes, three were acquired using the Global Visualization Viewer (GLOVIS) of United States Geological Survey (USGS) and the one was from GISTDA (Geo-Informatics and Space Technology Development Agency), Thailand. However, thermal band was not used in this particular study. The details of the scenes used are listed in Table 1.2. All the image-dates are of the dry season in Bangladesh.

The land cover classification methodology for this research is based on 'Object Based Image Analysis (OBIA)'. 'OBIA' is also called 'Geographic Object-Based Image Analysis (GEOBIA)'. 'OBIA' is a sub-discipline of geoinformation science devoted to partitioning remote sensing imagery into meaningful image objects and assessing their characteristics through spatial, spectral and temporal scale. The fundamental step of any object based image analysis is a segmentation of a scene representing an image into image objects. [3, 4]

Table 1.2: Details of the Landsat 4-5 TM scenes of CHT

Satellite	Sensor	Path	Row	Date (DD/MM/YY)	Source Agency
Landsat 4-5	TM	136	044	08/02/2010	USGS
		136	045	06/12/2009	
		135	045	01/02/2010	GISTDA
		135	046	01/02/2010	

At first, the acquired Landsat TM images were inserted in 'eCognition Developer 64 8.7' software for processing. The ''multi-resolution segmentation'' algorithm was used which consecutively merges pixels or existing image objects that essentially identifies single image objects of one pixel in size and merges them with their neighbours, based on relative homogeneity criteria. Multi-resolution segmentations are those groups of similar pixel values which merges the homogeneous areas into larger objects and heterogeneous areas in smaller ones. [4, 5]

During the classification process, information on spectral values of image layers, vegetation indices like the Normalized Difference Vegetation Index (NDVI) and land water mask which were created through band rationing, slope and texture information were used. Image indices are very important during the image classification. Image rationing is a “synthetic image layer” created from the existing bands of a multispectral image. This new layer often provides unique and valuable information not found in any of the other individual bands. Image index is a calculated results or generated product from satellite band/channels. It is helpful to identify different land cover from mathematical definition [4, 5].

NDVI: One of the commonly used indices and it is related to vegetation is that healthy vegetation reflects very well in the near infrared part of the spectrum. NDVI index values can range from -1.0 to 1.0. NDVI was calculated using the following formula:

$$NDVI = (NIR - red) / (NIR + red) \quad [5]$$

Land and water mask: Land and water mask indices values can range from 0 to 255, but water values typically range between 0 and 50. The land and water mask was created using the formula:

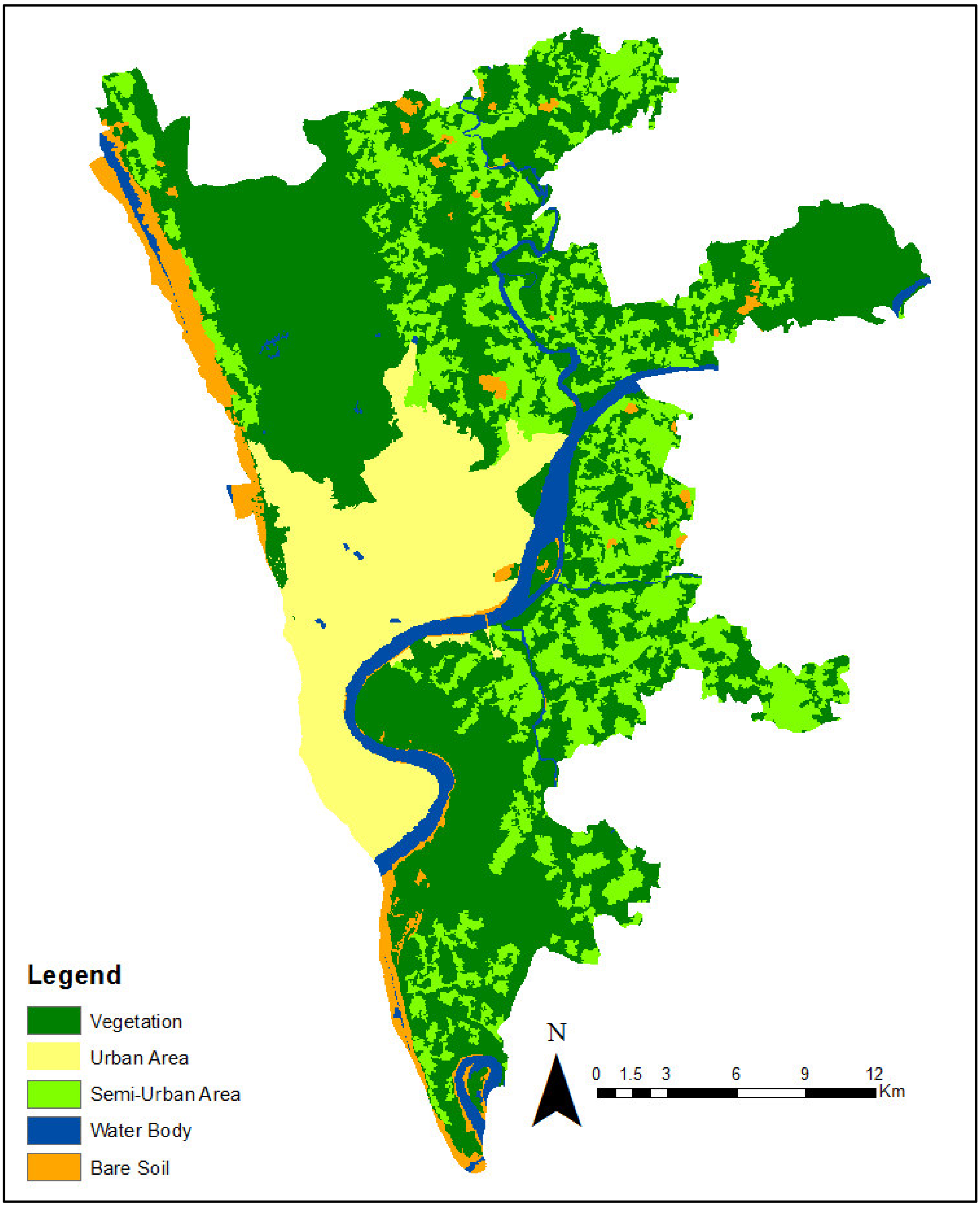
$$\textit{Land and water mask: } IR/Green*100 \quad [4]$$

The next step is to code these image objects according to their attributes, such as NDVI, Land and water mask, layer value and colour and relative position to other objects using user-defined rules. In this process, selected object that represent patterns were recognized with the help from other sources namely already known ground truthing information and high resolution Google earth images. Normally similar features observed similar spectral responses and unique with respect to all other image objects [5].

After that comparison, features using the ‘2D Feature Space Plot’ were used for correlation of two features from the selected image objects. Developing rule sets investigated single image objects and generated land cover map. Image objects have spectral, shape and hierarchical characteristics and these features are used as sources of information to define the inclusion-or-exclusion parameters used to classify image objects. Over each scene rules were generated for each land cover class and evaluated for their separation, tested for their visual assessment over Google earth images [5].

After ascertaining the class separation using segment based approach, classification is performed to get land cover classification map for each scene. Each scene thus prepared again evaluated with available field data and Google earth image over randomly selected points for accuracy assessment. After finalization of classification of each scene, all the scenes were gone through mosaic to obtain land cover map of CMA. For this research purpose, only 5 broad land cover classes (urban area, semi-urban area, water body, vegetation and bare soil) were chosen (Figure 1.5).

Figure 1.5: Landcover Map of Chittagong Metropolitan Area (CMA).



1.3.3 Preparation of Soil Related Map

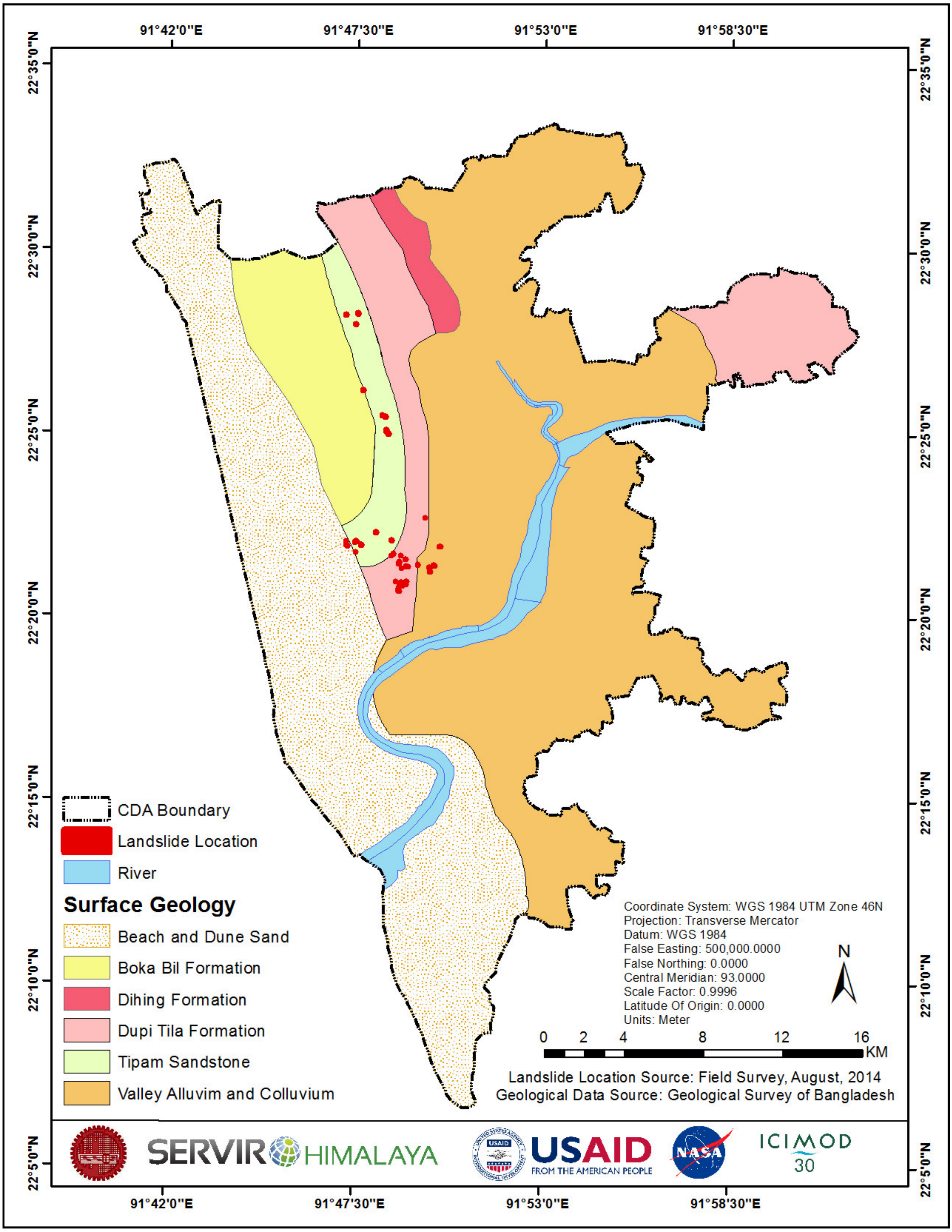
Soil physical characteristics is very much important for this kind of modeling, because soil moisture variations and other processes related to soil layer are strongly related to soil engineering properties. These processes are infiltration, percolation and groundwater flow and slope stability. The soil map of Chittagong Metropolitan Area has six units. Analyzing landslide location with respect to geology it is seen that most of the landslide locations are located in Dulphi tila formation and Tipam sandstone geological class (Figure 1.6). Many soil properties are important in geotechnical discussion. In this study, only the soil properties are considered which is related to hydrology. Only few soil samples were collected from the site and classified them based on the grain size distribution. The texture of the soil depends on the particle size distribution. The soil hydraulic properties are not directly measured. In this case we used Soil Plat Atmosphere and Water (SPAW) model to get some properties such as porosity, saturated hydraulic conductivity, field capacity and wilting point of the soil units. Other properties are collected from laboratory test and available literature (Table 1.3).

Table 1.3: Soil Engineering Properties.

Name of the Unit	Porosity	Field Capacity	Wilting Point	Van Genuchten n-param	Angle of internal friction	soil cohesion (Kpa)	Specific density regolith kN/m3	Erodi-bility (g/J)
csd	0.53	0.41	0.05	0.19	0.47	2.4	16	2.6
Tbb	0.43	0.35	0.08	0.3	0.67	3.6	16	2
Tt	0.49	0.47	0.08	0.1	0.84	4.2	16	1.7
QTdt	0.52	0.45	0.07	0.1	0.6	4	16	2.2
ava	0.42	0.31	0.09	0.22	0.7	2.7	16	2.1
Qtdi	0.44	0.35	0.06	0.2	0.6	3	16	2.3

Raster map of saturated hydraulic conductivity, map of soil porosity, map of wilting point, map of field capacity, map of internal angle of friction, map of soil specific density and map of soil erodibility have been prepared as attribute map based on soil unit and soil engineering properties. All raster layers have been prepared with 30 m resolution. Each soil unit has related property value in raster cell.

Figure 1.6: Landslide locations in different soil classes of Chittagong Metropolitan Area.



1.3.4 Input of Meteorological Data

At this stage, model will get rainfall value (in mm) as input in rainfall station location. Raster IDW interpolation with power 2 is applied to get the rainfall map for the whole study area. Therefore each cell of raster map gets a rainfall value. As this is a very small area and elevation difference is not too high, the orographic effect is ignored. Only one rainfall data from one station has been considered to run this model. Standard potential evapotranspiration value is considered for this model.

1.3.5 Interception

When rain falls from the sky, some part of the rainfall directly fall on the ground, some part is intercepted by the canopy of natural vegetation and crop. The later part of the rainfall is evaporated directly from the canopy and therefore this is not available for the runoff or groundwater recharge. It can be assumed that the storage capacity of the canopy is related to the total surface area of the leaf [2]. For this kind of area especially where grass and shrubs are dominating, De long and Jetten (2007) established an equation to calculate storage capacity which is Smax=0.912 ln (LAI) +0.703 [6]. Leave area index (LAI) can be calculated from the following equation $C=1-e^{-0.4LAI}$ [7]. This interception of rainfall is used as a storage function which is filling by rainfall and emptying by evaporation. The other part of rainfall which goes directly to the ground contributes to runoff and infiltration.

1.3.6 Infiltration

In this flux of the model some initial value has been considered as arbitrary. Initial soil moisture is considered as half of the wilting point of the soil and one-tenth of soil depth is considered as initial ground water depth to run the model. Residual moisture content (ϴr) is considered as 25% of wilting point. Unsaturated soil depth is the soil depth which is not saturated by ground water. Every time step, some part of the rainfall will be infiltrated to the soil which will change the soil moisture and ground water depth. Some part of the rainfall will go to stream as surface runoff. At this stage, soil water storage is calculated from the multiplication of unsaturated depth with the difference of soil porosity (volume of void space) and the initial moisture [2].

1.3.7 Percolation

The remaining water from rainfall after runoff and interception will go downward from surface to groundwater through soil is known as percolation. Percolation is a process to recharge groundwater which is passes through soil layer. The rate of percolation depends upon soil characteristics and soil moisture. Capillary force is responsible to hold water near to pore walls. However, water in the pores can move freely depending on the grain size of the soil. Hydraulic conductivity, the permeability of the soil depends on moisture content and pore size of the soil. Permeability of dry soil is higher than the wet soil. Hydraulic conductivity of fully saturated soil is the maximum value. Following the above concept of flow in the soil, the conductivity of the unsaturated soil is a fraction of the saturated conductivity, but the fraction is a highly non-linear function of the saturated conductivity. This fraction depends on the dimensionless relative degree of saturation (θE) which can be expressed by

$$\theta_E = \frac{\theta - \theta_r}{\theta_s - \theta_r} \sim \frac{\theta}{\theta_E} \qquad [2]$$

Where θ (theta) is the volumetric moisture content, θr the residual moisture content (a very small value that is set equal to 25% of the wilting point), and θs is the saturated moisture content, which equals the porosity.

Normally in the soil, water moves under the influence of gravity and differences in suction (capillary forces). The flux is calculated as the unsaturated conductivity K(θE) (in m/s) multiplied by differences in potential dH (suction + gravity) over a given distance in the soil

dz (in m/m): $Q=K(\theta E)*dH/dz$ [2]

This is a form of Darcy equation for vertical flow in a soil column. For simplicity, Jetten and Shrestha (2014) assumed that there are no suction differences acting on the lower boundary of the soil and that the flux downward, the percolation is driven by gravity only. Since gravity changes linearly with depth the total difference in potential simplifies to unity: dH/dz = 1. Therefore, they also assume that the percolation flux equals K(θE). The following equation for of Van Genuchten (1980), is used for the model.

$$K(\theta_E) = Ksat * f(\theta_E) = \mathrm{Ksat}\sqrt{\theta_E}\left[1 - (1 - \theta_E^{\frac{1}{m}})^{\mathrm{m}}\right]^2 \qquad [2]$$

Where m is the texture depended parameter with guideline value from Van Genuchten curve.

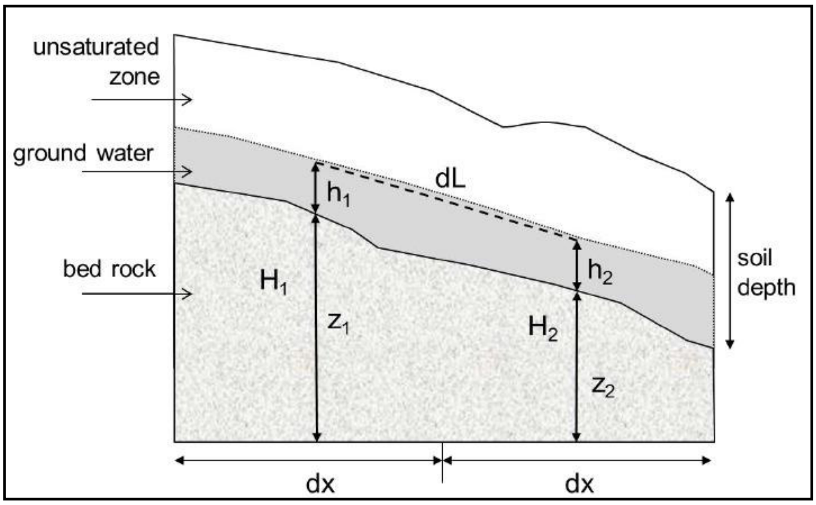
1.3.8 Ground Water Balance

Only top layer property of the soil is considered the property of whole soil. The ground water balance is also a flux where incoming is percolation from the soil layer above and outgoing is flow to neighboring cell. In hydrology, the law of Darcy (1856) is one of the main laws which can be used to calculate water fluxes in the soil. It states that groundwater moves through the soil as a result of differences in hydraulic potential H (in m), caused by gravity. The hydraulic potential H is the sum of the groundwater level h and the absolute elevation at a location z (H=h+z) (Jetten and Shrestha). Below the groundwater table the soil is fully saturated, so the saturated hydraulic conductivity, K(sat) can be used. When there is a difference in hydraulic potential dH between two points (over a distance dL) water will flow from the higher to the lower potential.

$$Q_{GW} = qA = Ksat\left(\frac{dH}{dL}\right) h\, dx = Ksat\left(\frac{dh + dz}{dL}\right) h\, dx \qquad [2]$$

Where QGW is the groundwater flow in m3/s, q is the one dimensional flux in m/s and A is the cross section of flow (m2), which is the product of the cell width dx and the water height h. Ksat is the saturated hydraulic conductivity.

Figure 1.7: Principles of groundwater flow used in our PCRaster model: h1 and h2 are groundwater levels, z1 and z2 absolute elevation above a given datum, dL is the distance between two points along the water surface. [1]

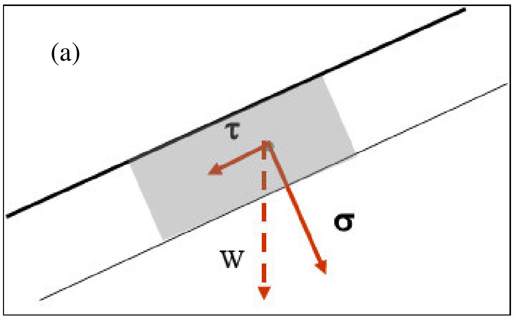


The groundwater flow is based on the difference in hydraulic potential dH (H2-H1) between two points that are spaced dL apart. This is the sum of groundwater layer heights (h2 and h1) and the elevations (z2 and z1) (Figure 1.7).

1.3.9 The Infinite Slope Model

A slope stability map of the Chittagong Metropolitan Area (CMA) can be made based on the "infinite slope" model. There are two forces on a given slope, one is driving force for slope movement and the other is resistance force that holds the slope in position. Here driving force is gravitational force of the slope mass. The driving force is gravity on the mass of the slope. Here, the specific weight of an object is its weight per volume in kN/m3. The value for the specific weight γ is depended on soil type. The weight of a slope element can be decomposed in a vector along the slope, the shear stress τ, and a vector perpendicular to the slope, the normal stress σ. Stress is the term used for force per surface area or F/A (dimension is N/m2). It has the same dimension as pressure. Using the slope angle Θ and material depth h these vectors are defined (Figure 1.8).

Figure 1.8: (a) weight W of a slope segment divided in a normal stress vector σ and shear stress vector τ. (b) Definition of shear stress and normal stress (N/m2) on a slope with a given angle Θ and regolith depth h (m). x = the regolith depth perpendicular to the slope (m) and γ (gamma) is the specific weight (see table 4.1, in kN/m3). [2]



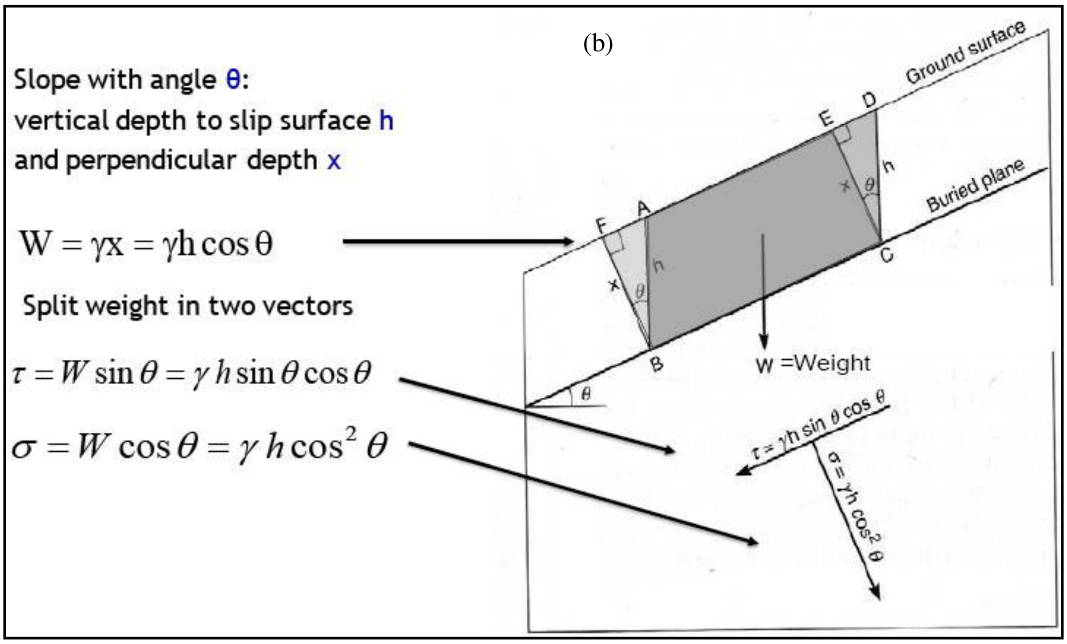


Figure 1.8 shows how the vectors τ and σ are related to the slope angle ϴ: the shear stress vector τ = W sin(ϴ) while the normal stress vector σ = W cos(ϴ). For simplicity, it is assumed here that the potential sliding surface is parallel to the slope surface. Because the soil depth h is measured vertically, while the moving block is perpendicular to a sliding surface the slope with a thickness x, the shear stress is τ = γhsin(ϴ)cos(ϴ), and the normal stress is σ = γhcos2(ϴ).

While shear stress acts on the block to move it downward, it is kept in place by a number of forces that are combined in the shear strength S (the strength of the segment parallel to a potential sliding surface). The shear strength is composed of direct friction caused by weight, which equals the normal stress σ but points in the opposite direction, and other material properties related to strength factors. These are summarized in the law of Mohr-Coulomb, which relates the shear strength S to material properties:

$$S=c+\sigma'\tan(\varphi) \text{.......................i} \quad [2]$$

c=cohesion ()kpa, φ angle of internal friction 'phi' (-), σ'=effective normal stress (kpa).

The effective normal stress $\sigma'$is the normal stress σ decreased by pressure exerted by ground water if that is present in the slope segment.

$$\sigma' = (\gamma - \gamma_w n)hcos^2(\theta) \text{...........ii} \quad [2]$$

Here n= fraction of the segment with thickness h that is saturated with ground water: n=0 means a completely dry segment and n=1 means groundwater reaching the surface.

Combining the equations i and ii we get Factor of Safety (FS)

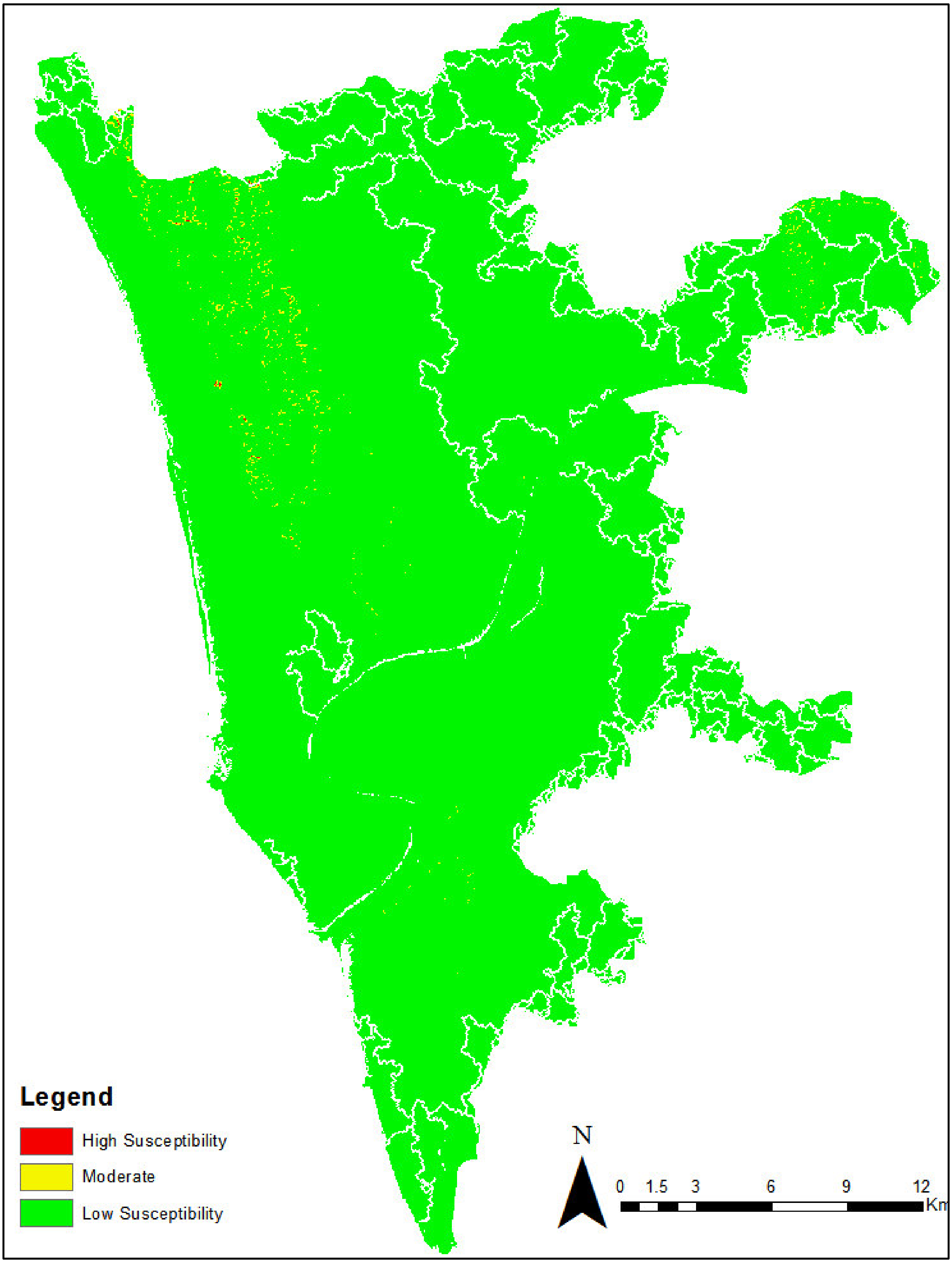
$$\text{FS} = \frac{c+(\gamma-\gamma_w n)hcos^2(\theta)\tan(\varphi)}{\gamma\cos(\Theta)h\sin(\Theta)} \quad [2]$$

Where, FS > 1.0 represents a stable situation and FS < 1.0 denotes failure of soil (soil instability).

1.4 CONCLUSION

Finally through Infinite Slope Model a slope stability map of the study area (CMA) is prepared where the total area is divided into three categories as low, moderate and high susceptible to landslide. From Figure 1.9 we see that highly and moderately susceptible places are in northern-west part in CMA where landslide occurred mostly in previous years (Figure 1.6).

Figure 1.9: Slope Stability Map of Chittagong Metropolitan Area (CMA).



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