GEOLOGICAL CONTROLS IN THE FORMATIONS AND EXPANSIONS OF GULLIES OVER HILLSLOPE HYDROLOGICAL PROCESSES IN THE HIGHLANDS OF ETHIOPIA, NORTHERN BLUE NILE REGION

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ABSTRACT
The Northern Blue Nile River source region shallow depth highly weathered and fractured flood basalt with several local structures and intrusive dykes. Volcanic morphological features and erosion has formed smaller watersheds that exist within the Blue Nile basin. The control of the flow behavior of both surface and subsurface water form a central pool for the sediment transported to the Sudanese plain. The objective of this study is to define the geologic controls of hydrological processes aiding in the formation and expansion of gullies along hill slopes in a micro watershed in the Blue Nile River source region.

Twenty-four piezometers were installed, and soil hydrological behavior was studied in 17 ha of land in the Debremawi watershed. Geologic features of the watershed include shallow depth, highly weathered and fractured basalt, an impermeable layer and a local dyke. Layers of clay soil deposits are defined in the middle down slope area of the watershed. The basalt is exposed in the upper slope area and underlies most of the watershed, forming a fractured media aquifer. The impermeable layer consists of weathered silt sand clay pyroclastic fall that has formed a compacted layer at the surface on the up hill.

The local intrusive basaltic dyke, located at the middle of the watershed and perpendicular to the flow direction, has significant effect on the local ground water table distribution. Clay soil covering the middle area of the watershed and overlying on the basalt layer confines the water in the fractured media aquifer. Different sites with saturation excess runoff and infiltration excess runoff are identified to be controlled by the combined effect of the local geological material and land use type.
Water head upstream of the dyke is near or above surface, but it is at a considerable depth below the surface when downstream of the dyke.

Local saturation zones are subject to pore water pressure development and landslides. Saturated area soils have little strength and result in soil slumps. High piezometric head and small scale earth movement are identified in relation to the confining effect of the clay layer. Topographically controlled saturation zones are also vulnerable to landslides and extensional soil cracking failures. The ultimate impact of the local geology control is subsurface erosion features (soil pipes and tunnels) that develop into gullies. Hence, land management practices should consider detailed studies of the local geologic materials and structures. Incorporation of subsurface drainage mechanisms with the usual soil and water conservation practices are of paramount importance for a better achievement in resolving the existing erosion and sedimentation problems.
BIBLIOGRAPHIC SKETCH

Antenhe Zewdie Abiy is born in the 27, July-1980 to his lovely mother Tiruwork Eyasu and father Zewdie Abiy. He completed his first degree at Mekelle University in Applied geology during July 2003. Anteneh has worked on developmental activities in rural Amhara, Ethiopia, specifically in projects for planning and implementing intergrated water resource development. He is particularly interested in understanding the integrated system dynamics of environment and water resource development. He would like to combine science, politics and application within developmental policy planning and implementation for sustainable development in developing countries.
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1.0 CHAPTER ONE

1.1 INTRODUCTION

Soil and water erosion is a chronic problem in Ethiopia; the country loses more than 3% of the annual GDP from agricultural (WDR, 2008). Erosion is manifested through any scale of mass wasting processes (Ayalew et al., 1999), development and expansion of gullies (Daba et al., 2003; Tamene and Vlek, 2007) and top soil removal through sheet and rill erosion (Taddese, 2001). Although exact reasons are not yet well defined (Haile et al. 2006), accelerated erosion has resulted from the development and expansion of gullies and is threatening the land and life in the country (Daba et al., 2003; Tamene and Vlek, 2007, Billi and Dramis, 2003), especially in the highlands of the country. The controlling factors of erosion and the relevance of the complicated geologic setup in the country are neither known nor fully studied in the country.

Geological conditions such as topography, type of parent material, presence of regional and local geological structures, and degree and depth of weathering are important in defining the overall hillslope hydrological process and soil water erosion. Geologic conditions control the presence and distribution of soil water in space and time. Hence, sites’ susceptibility to local saturation (Nilsen et. al., 2003), as well as the soil’s strength to overcome the developed local soil pore water pressure, are predetermined by the geologic conditions (Márquez et. al., 2005; Avanzi et. al., 2004) and by local structural barrier and type of soil parent materials.

Various kinds of social and environmental crises, such as loss of agricultural land, depletion of the water resources, drying of annual and ephemeral springs and streams, sedimentation of reservoirs, and reduction of vegetation cover are enhanced by the formation and expansion of gullies. Land destruction along animal and human trails
and around houses have been observed in the field and mentioned by the local farmers as critical problems manifested due to gully expansion in the study area. Sites around gully formations are known to experience reduction in spring yield and reduction or total drying up of streams and hand dug wells. Furthermore, gully formations with deeper excavations of geologic materials aggravate the situation of reservoir sedimentation by supplying more silt and sand. Sites that used to be the source area for animal feed, grass and other types of forage are shrinking in area or have been completely demolished by gully formation. This increases the complexity of crop land and animal feed shortages in the country (Amssalu et. al., 2006).

With limited understanding of the formation and expansion of gullies by local dwellers, it is considered as punishment from God. Hence, only limited effort has been made to control the situation, and the management is often beyond the local technical skill and technological level. The available scientific evidence and associated information on the formation and expansion of gullies are also lacking full support to effectively facilitate the activities to control and manage soil erosion (Haile et al. 2006).

Therefore, this study has defined the geologic conditions and related specific hillslope hydrological elements to the dynamics of gully formation and expansions in the Debre Mawi sub-watershed in the northern region of the Blue Nile River Basin in the central western plateau of the Ethiopian highlands. This site is representative of most geological features of the Northern Blue Nile Region. Significant gully development extending from hill bottoms to hill tops and pockets of saturation zones are major and fast growing geo-environmental hazards in the area. The dominant natural processes influencing the formation of gullies in this area involve formation and expansion of
smaller potholes and/or collapses of local curvatures, soil pipes and tunnels. Head cuts and bank failure as small to medium scale landslides are mechanisms of gully expansion in the area.

This study contributes relevant information to the increasing importance of hillslope hydrology in the highlands of Ethiopia and associates the geological conditions with the dynamics of gully formation and expansion, surface runoff characteristics and ground water recharge/discharge relations. Such information is needed for proper planning and implementation of gully controlling activities in the area.

1.2 OBJECTIVE

General Objective:
The objective of the study is to elucidate specific hillslope hydrological elements and associated gully formations in relation to existing local geology in the Debre Mawi micro watershed situated in the Blue Nile River source region on the Ethiopian highlands.

Specific objectives:

- To define the nature of soil water erosion through gully formations and expansion in the Debre Mawi Watershed.
- To identify local and regional geologic setup parameters for specific hillslope hydrological elements and related formations and expansion of gullies.
- To define the geological parameters needed for the advancement of knowledge required in sustainable land management practices.
- To identify soil properties as influenced by geologic parameters and the ultimate impact on hydrology and the resulting erosion process.
- To put forward opportunities of sustainable soil water conservation practices.
2.0 CHAPTER TWO

2.1 METHODOLOGY

Observational physical geology studies, lithology identifications, and geological structure studies were conducted through continuous field surveys in the study area. Geological test pits sunk at different locations of the watershed were studied in defining the geologic units, soil types and stratifications. Sites for different studies of soil properties and hydrologic processes were selected with respect to the local spot geology, observable soil type, slope angle and micro topography.

The most striking characteristics of soil considered within this study included the soils’ hydraulic and physical parameters such as infiltration capacity, texture, moisture holding behavior, atterberg limits, color, reaction with HCL and other observable soil structures.

Specific measurements in the study encompass soil water infiltration capacity using double ring infiltrometers, saturated soil water level fluctuation records from twenty four piezometers, soil moisture behavior and soil atterberg limit test.

The 24 piezometers were installed with a hand auger to the depth of the impermeable layer in depth ranges of 1.5m to 4m. Effort was made to align the transects of the piezometers perpendicular to the ground water flow direction from hill top to the saturation zone of the watershed. Specific sites such as gully heads, gully junctions, saturation sites, as well as gully beds were considered in piezometer installations. Readings of the saturated soil water table were taken from zero to four times a day. The piezometer readings were conducted using a 250m long deeper meter.
The rainfall in the watershed was measured with a weir constructed by local materials at the center of the watershed. Runoff in the watershed is measured manually at a concrete weir constructed at the watershed outlet.

Five Soil water infiltration capacity studies were conducted at five locations in the watershed with a double-ring infiltrometer. An infiltration test lasting from 1 to 10 hours was conducted at each of the five locations. The infiltration rate versus total cumulative infiltration time was plotted in Microsoft® Office Excel-2003. The average of the last three to five readings, where the infiltration curve became nearly horizontal, was considered as the saturated infiltration capacity of the soils.

Thirty soil samples were collected from all the geological test pits and along gully banks to define the physical and mechanical behavior of soils in the watershed. Pressure plates in the soil laboratory at Amahra Bureau of Water Resource Development were used to determine the soil moisture contents at different pressure bars: 0 bar, 0.33 bar, 5 bar, 10 bar, 12.5 bar and 15 bar, and to determine volumetric water content at wilting point (WP), field capacity (FC) and saturation. Soil bulk density and soil in situ moisture contents were determined with standard core cutters and oven drying at 105°C for 24 hours. Samples were collected from all geological test pits for the purpose of determining bulk density and assessing moisture behavior of the soils. The soil texture of these samples was determined by hydrometric and wet sieve grain size determination methods. After defining the percent of sand, silt and clay, the soil texture was plotted in a ternary diagram by using Triplot version 4.1.1 (Todd Thompson Software, Indiana).
The topography was mapped using geographic longitude and latitude data base consisting of 1034 points collected by differential GPS positioning (GPS 1200 Leica Geo Systems). After georeferencing the data projection from the ethio-gis database, spatial analyses were conducted by ArcGIS 9.1.

Every piezometer location was georeferenced using a GPS unit, and the mean water level was mapped against the topography. Time series water levels are plotted in Excel-2003.

Discussion with selected farmers, local development agents and land owners was made separately and in groups to understand the plowing and land use patterns across the watershed. Observation, discussion with the farmers, field and laboratory tests and measurements reveal the important watershed parameters of hill slope hydrological processes and the characteristic erosion types. Accordingly, the boundary conditions of surface water flows were defined along with the flood routes and the topographical situation. A large ditch has been formed at the upper slope area of the watershed due to animal compaction and defines the upper slope boundary of the surface hydrology. The saturated soil water flow boundary condition was defined based on the recharge behavior of various geological units at the depth of investigation.
3.0 CHAPTER THREE

3.1 STUDY AREA DESCRIPTION

3.1.1 LOCATION AND ACCESSIBILITY

The Debremawi watershed, bounded in 37°25′00″, 11°21′17″ to 37°25′42″, 11°20′55″, is located in the western plateau of the Ethiopian highlands at the northern source region of the Blue Nile River (Figure 1). The watershed faces to the west and drains into the Blue Nile River. The Debremawi watershed is located approximately 31 km from Bahir Dar along the main road to Mota, an alternate route from Bahir Dar to Addis Ababa. The settlements in the watershed are sparse with small huts.

3.1.2 PHYSIOGRAPY AND RELIEF

Debremawi watershed forms a narrow land form, 160 m width and elongated 1.05 km, with a total area of 16 ha. It is wider at the upper slope 240 m and narrows towards the saturation zone, 78 m, at the outlet. It ranges in elevation from 2184 to 2300 m a.s.l.

Being part of the regional geology, the Debremawi watershed is defined by chains of volcanic formed hills and gently sloped mountains. Hill formations cover about 15% of the watershed primarily at the top, ranging from 13° to 30°. 65% of the watershed lies in the middle slope class (5° to 13°), and approximately 17% in the saturation zone with less than 5° slope (bottom map in Figure 1). Specific slope anomalies from 30° to 54° and less than 3° have been observed along gully banks and river beds, respectively.
Figure 1: Location Map of the Debremawi Watershed
(Source, the Ethio GIS database for the top, and hill shed of the kriging interpolated GPS data collected in the field, bottom)
Two major gullies aligned east and west run down slope from the beginning of the middle slope class (Figure 1) to the bottom of the middle slope class joining and passing through the saturation zone of the watershed. The left gully (LG) looking upslope from the saturation zone to the upper slope class was formed in the top soil formation at a relatively shallow depth of 55cm and average width of 20cm and less than \(23^0\) of bank slope. Contrarily, the right gully (RG) is deeper at 260 cm deep and 240cm wide with a relatively steeper in slope of more than \(35^0\). The left gully and right gully join at the end of the mid-slope area forming one larger, wider and deeper stream. Below the junction of the two gullies, the depth of the larger gully decreases and the width expands, forming a local deltaic depositional zone. Finally it reaches the saturation zone of the watershed (Figure 1, and Figure 2).

Figure 2: The right gully (RG) and left gully (LG) of the watershed, (As it is seen from the saturation zone to the upper slope of the watershed).
The stream side exposure along gully banks revealed soil sequences of black clay at the top, light brow clay below, and then succeeded by deeply weathered saprolith. The gully heads form fan-shaped (concave land form, named as ‘land curvatures’ in the Figure 2 above).

Although the hill at the top forms a natural watershed divide for the upper slope class, a topographic sag forming an artificial ditch aligned from the right hill top to the left middle slope, passing out of the watershed, directs the run-in from the top part of the watershed outwards (Figure 3 below). This is further enhanced by the use of the ditch as an animal pathway. Furthermore, it is located along geological weak zones marked by the intermingled contact of the basalt and pyroclastic units. Hence, the ditch acts as an artificial watershed boundary at the upper slope area of the watershed.

Man-made rock bunds separate the upper slope area from the middle of the hill slope. Although the rock bund does not have significant effect on the flow of surface water within the watershed, it does reduce the flow velocity and favors surface impoundment, which may have hydrological significance. At the foot of these stone bunds, seepage zones were observed. Where the two gullies transect, the middle slope of the watershed forms a half convex-convex-half convex cross sectional landform (See cross section BB’ in Figure 3).
Figure 3: Topographic map of the Debremawi watershed

The center of the two half convex sections along the margins of the longitude of the two sides of the watershed forms a natural watershed divide at the middle slope. These two divides progress down slope converging into a flat zone below the gully junction. This flat zone encompasses the deltaic depositional zone and extends down to the zone of saturation near the watershed outlet.
The saturation zone is a pocket of flat, elongated land connected to the major watershed. It maintains high moisture conditions during dry seasons and becomes a swampy area during the annual rains.

3.1.3 LAND USE LAND COVER

The upper slope class that covers about 13% of the watershed is sparsely covered by small bushes and shrubs. The gentle slope area in the upper slope class is crop land commonly cultivated with maize and teff.

The construction of rock bunds as farmland boundaries is a common practice in Ethiopia. A man made rock bund was constructed at the boundary between the upper slope class and the middle slope class, perpendicular to the surface flow direction, and forms an artificial conservation structure allowing soil deposition. Hence, the relatively gentle slope upslope of the bund where eroded soil has been deposited has become farm land. The area downstream of the rock bund forms a topographic drop characterized by high seepage.

The middle slope class, >60% area of the watershed, encompasses crop fields. Only very few plots were uncultivated at the beginning of the main rainy season but were reserved for cultivation at the beginning of September. Most crop fields in the middle slope class are cropped twice in a rainy season with continuous plowing up to 15 to 18 cm depth. After harvest, crop land is left free with the crop residue for livestock grazing.
The saturation zone is a grassy wetland where the grasses are cut and supplement animal feed during the dry period, and hence, only very little animal interference has been observed in the area.

3.2 GEOLGY

3.2.1 REGIONAL GEOLGY

The Ethiopian highlands, the source region of the Blue Nile River in the northwest Ethiopian plateau are covered by a thick sequence of volcanic province. It contains a Trap Series of flood basalt superimposed by thick flow of lava forming shield volcanic mountains (Geological Map of Ethiopia, 1996; Pik et. al., 1998). The Trap Series encompasses intercalations of Felsic lava and Pyroclastic rocks that characterizes different groups of volcanic deposits classified as follows:

Asanghi Formation (Eocene): This contains deeply weathered alkaline and transitional basalt flows with intercalations of Pyroclastics, Ignimbrite, and Rhyolite covered by Tuffaceous materials and rare Lacustrine deposits. It is often tilted and contains dolerite sills, acidic dykes and undifferentiated intrusions.

Tarmaber Formations (Oligocene-Miocene): These form characteristic shield volcanoes. The Tarmaber Formation contains Alkaline to Transitional Basalt, with minor Trachyte and Phonolite. North–south aligned shield volcanoes, volcanic edifices and fields of small basaltic vents are the characteristic features of the Tarmaber Formation. The Tarmaber Formation form deeply weathered surface layers in various localities of the central western plateau, and it is the parent material for the top soil cover on the major part of the source region of the Blue Nile River. It also forms a
natural barrio on the flow of the Blue Nile Rive, dictating the flow into the Sudanese plain (Pik et al., 2003; Geological Map of Ethiopia, 1996).

Shield volcanoes forming the Choke and Guna Mountains (sources of major tributary rivers of Lake Tana) and numerous volcanic edifices and vents in the Central North Western Plateau form the Blue Nile River watershed. Extended from the source spring at ‘Gishe Abay’, the river flows through the Lake Tana basin named “Ghion/Abay” until it reaches the outlet to the Sudanese plain. The entire length of the river course is bounded by the spectacular natural morphology of the Tarmaber Formation. This morphology also controls the rainfall distribution of the area (Pik et al., 2003) by affecting wind patterns and the uplifting of the air.

The overall geomorphology, following the tectonic characteristics of the area, has been reshaped by erosion. Accordingly, the area contains numerous sub-watersheds and micro watersheds of variable hydrological behavior. Several topographic pockets of saturation zones, emanations of structure and gravity control springs are common in the area.

The overall interplay among lithology, fracturing, degree and depth of weathering and stratigraphy contribute significantly to the land reformation processes (Pik et. al., 2003). Generation of high surface runoff and the related soil erosion, as well as seepage, are the dominant geo-environmental processes observed in the Blue Nile river basin in Ethiopia (Ayalew et al., 1999). Hence, the Tarmaber Formation not only controls the surface and subsurface water flow, but also forms a central of pool of sediment to be transported by the tributaries to the Blue Nile River and Blue Nile River to the Sudan (Pik et al., 2003).
In addition to the geologic parameters, formation and expansion of gullies can also be the result of intensive agricultural activities, climatic conditions and the modification of vegetation cover.

### 3.2.2 LOCAL GEOLOGY

As part of the regional geology, the local geology contains volcanic flows and Pyroclastic fall of Cenozoic deposits. Indicated in the test pits and at quarry side exposure, the Pyroclastic fall is sandwiched in between sequences of lava flows. It is exposed at the left side of the upper slope class.

Exposures of lava flow are located at the hilltop (Figure 4) in the right side of upper slope class, and at the beginning of the middle slope class. The lava flow is highly fractured and highly weathered at a shallow depth. The fractures are highly interconnected with limited clay infillings. With limited persistency of the fractures, they form rock fragments, and the size of the rock fragments increase with depth, forming rock blocks. The fracture aperture is increasing and the degree of weathering and amount of infilling material is decreasing with depth at the depth of investigation.

This shallow, highly weathered and fractured basalt covers the entire part of the subsurface geological formation, and it is covered by soil sequences. The depth and degree of weathering increase progressively downslope. Remarkable weathering products containing clay soil layers and saprolithic material with reserved rock structures (Illustration 1) lay on top of the lava flow exposed at the beginning of the middle slope classes.
Figure 4: Geological map of the study area
Illustration 1: Seepage along reserved rock structures (joint), at the right gully bed, below the P18.

In sites where the lava flow is not exposed, a succession of soil layers is superimposed. Hence, this fractured and weathered basalt and the underling block rock are the major water circulation media in the area, whereas the top clay layer forms a confining layer.

The Pyroclastic material is a volcano clastic unit that contains 20 - 36cm diameter of dark and light colored clastic materials within a fine grained (sillicic silt and sand), reddish groundmass. It is highly scoriacious and is very porous and has conduct water well. The overall unit of the Pyroclastic material is moderately to deeply weathered.
The top of the Pyroclastic material is covered by a thin layer 12 to 16 cm of hard pan formation. The hard pan is a highly compacted sandy-silt-clay. From the information elicited from land owners, this area has been cultivated for the last 20 years or more. It is now abandoned due to limited productivity.

An intrusive basaltic dyke is found at the bottom of the upper slope area of the watershed in the right gully side exposure (See Illustration 2). This basaltic dyke has a general north-south/west $22^\circ$ trend, nearly perpendicular to the flow direction of the watershed. This forms the dyke trending against the watershed flow direction, from west to east; and favors the formation of local over/saturations for the soil layers above it.

Illustration 2: The baked soil (red bracket at the bottom), dyke (red brace) and water flow direction (blue arrows at the top) of the study area

Additionally, this trend of the dyke prohibits the flow of water downstream, in the right side of watershed. Upstream of the dyke is an active land slide area on both sides of the right gully bank. This active slump is attributed to local pore water pressure development in the soils as indicated by the near surface and above surface water level.
readings. The piezometer water level readings upstream of the dyke remain near the surface for longer periods, although the downstream points exhibit deeper water level.

3.2.3 **SOIL COVER**

Only very thin layers of soil have been observed in the lower end of the upper slope class (Figure 4). The left side of the lower end of the upper slope class exhibits a 12 to 15 cm layer of silt-sand soil with a high degree of compaction. This impervious soil layer has formed a characteristic hard pan.

The right upper slope class contains a layer up to a meter thick of dark brown clay soil (Figures 5 and 6). This is transported deposition on the upslope part of the rock bund. It is relatively loose with organic matter inputs from the remnants of crop residue since the land is a crop field. At the top of the dark brown clay, rock boulders and cobble rock fragments are deposited. With a relative decrease of this clay soil to the upper part of the right side of the upper slope class, it exhibits infilling materials on top of the highly fractured shallow highly weathered basalt. Hence, the right side of the upper slope class is mapped as highly fractured, shallow and highly weathered basalt.

Remarkable soil thickness begins at the middle slope area of the watershed (Figure 4). Along a vertical column of the geological test pits (Figure 5), the top most part of the middle slope class contains black clay, light brown clay, red saprolith, and the highly fractured, shallow and highly weathered basalt.

All the middle slope class areas have black clay cover on the upper most part. This black colored soil has high soil water holding capacity but limited soil water
infiltration capacity. It has a maximum thickness of 1.2m at the central watershed, at the axis of the central convex land form. It formed from a consistent crack with a considerable aperture. Vitreous luster and slickenside are commonly observed in the micro relief of this layer. It has a heavy clay soil texture area highly visible in the field. Only at the beginning of the middle slope class is the black clay soil observed covering the red saprolitic material. In the dominant part of the middle slope class it overlays the light brown clay soil forming accumulations in the brown clay.

The second layer is the light brown clay. It is exposed at the gully bank and was observed within the geological test pits. Some surface exposures of the light brown clay are not uncommon at the middle slope class nearer to the right gully. It is also exposed at the left margin of the gully bank at the saturation zone with maximum thickness of 3.5m. High moisture content, high tendency of crack formation on exposures along the gully bank, vitreous luster and formations of slickensides are characteristically observed within this soil layer. The deposition of the light brown clay starts at the middle part of the middle slope class, extending down to the saturation zone. This layer lies on top of the red saprolith in the middle part of the middle slope class and the saturation zone. It pinches out to the upper part of the middle slope class, however. The third layer is red saprolithic material with reserved rock structures, or joints. It is exposed along the right gully bank of the middle slope class. This exposure along the deeper gully bank extended down to the end of the middle slope class and beyond the junction of the two gullies. It covers the entire subsurface of the middle slope and saturation zone of the watershed.
Figure 5: Vertical soil profile of the geological test pits
In the upper part of the middle slope class, where the light brown clay is not deposited, it forms sharp contact with the top most dark clay layer.

This saprolith is an in situ deposit as a result of the high degree of weathering of the basalt. This layer has also been observed overlaying the basaltic layer in the upper part of the middle slope class.

The soil in the central saturation zone forms a top organic soil cover underlined by the light brown clay soil observed in the middle part of the middle slope class of the watershed. The top organic soil cover is grasses with a root depth of approximately 25 cm. The formation of 5m and longer pipes with diameters up to 50 mm were observed in the gully side exposure of this area. Pipes aligned along the flow direction were observed in the vertical gully exposures of the moved land mass in the left saturation zone. However, the left gully side exposure of the saturation zone does not have the
organic soil layer and exhibited similar soil layer sequence of the middle part of the middle slope class.

<table>
<thead>
<tr>
<th>Thickness, cm.</th>
<th>Layer Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>not to scale</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Organic rich soil at the central saturation zone</td>
</tr>
<tr>
<td>210</td>
<td>Black clay, usually wet and sticky, high tendency of moisture absorption and cracking</td>
</tr>
<tr>
<td>260+</td>
<td>Light Brown clay, usually wet and sticky, high tendency of moisture absorption and cracking</td>
</tr>
<tr>
<td>90</td>
<td>Dark Brown, loose clay</td>
</tr>
<tr>
<td>13</td>
<td>Dark Brown, highly compacted clay, and accumulated in to the fractures of the weathered rock fragments</td>
</tr>
<tr>
<td>105+</td>
<td>Deeply weathered red saprolith, preserved rock structure, with water striking through distinct voids and preserved joints</td>
</tr>
<tr>
<td>70</td>
<td>Highly weathered Basaltic rock with accumulations of clay in to the fractures</td>
</tr>
<tr>
<td>155+</td>
<td>Blocky Basalt, heterogeneously fractured</td>
</tr>
<tr>
<td>12</td>
<td>Hard pan, highly compacted, lower moisture content, non plastic and inconsistent sandy silt clay</td>
</tr>
<tr>
<td>34</td>
<td>Deeply weathered Pyroclastic material(fall), granular with reddish fine groundmass</td>
</tr>
<tr>
<td>154+</td>
<td>Slightly weathered Pyroclastic material(fall)</td>
</tr>
</tbody>
</table>

Figure 7: Over all vertical section of the geological test pits/ formation sequences
3.0 CHAPTER THREE

3.1 RESULTS AND DISCUSSIONS

3.1.1 SOIL PROPERTIES

3.1.1.1 TEXTURE

The soil in the study area consists predominately of clay as clearly demonstrated in the ternary diagram (Figure 8.) and indicated in Table 1.

![Ternary diagram of the percent clay, silt and sand contents of the soils](image)

**Figure 8**: Ternary diagram of the percent clay, silt and sand contents of the soils

**Table 1**: Statistical report table, of the clay, silt and sand proportions of all the soils samples

<table>
<thead>
<tr>
<th>Number of Sampling Points</th>
<th>Statistical Parameter</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Range:</td>
<td>6 - 3</td>
<td>17 – 47</td>
<td>31 – 69</td>
</tr>
<tr>
<td></td>
<td>Mean:</td>
<td>17.6</td>
<td>25.6</td>
<td>56.3</td>
</tr>
<tr>
<td></td>
<td>Standard deviation:</td>
<td>5.1</td>
<td>7.07</td>
<td>8.41</td>
</tr>
<tr>
<td></td>
<td>Standard error:</td>
<td>0.93</td>
<td>1.29</td>
<td>1.54</td>
</tr>
</tbody>
</table>

As explained in the geology and soil sections, the upper slope class of the watershed contains two types of depositions. The hard pan formation samples P8: 0-12, P8: 12-
52 and P8: 52-200 represent clay contents as shown in Table 2 below. The light brown clay layer on the right side of the upper slope class is a clay loam. The soil layers in the middle slope and saturation zone of the watershed contain relatively higher proportions of silt and sand than in the upper slope. Along the vertical profile of the soil layers in the upper slope class, where the basaltic formation is exposed, the texture changes from clay to rock fragments and block rock, providing an overall coarsening sequence with increasing depth.

The top cover black clay and the succeeding light brown layer in the middle slope class and saturation zone represent a heavy clay to clay origin. The texture of the top black clay soil samples (Table 2: P12: 0-115, LGB_P16: 0-100, RGB_P13: 0-50) is predominately clay (> 50%). The succeeding light brown soil had a heavy clay texture, ranging from 57 – 65% (Table 2: P12: 115 +, LGB_P16: 100+, RGB_P13: 50-140).

The black clay and light brown clay soil layers in the saturation zone represent similar soil texture to the middle slope class.
Table 2: Soil layers / rock fragment texture along vertical column in geological test pits, as land marked by the nearby piezometers

<table>
<thead>
<tr>
<th>Piezometer number: Depth of Sampling</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Soil Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>P8: 0-12</td>
<td>20</td>
<td>39</td>
<td>41</td>
<td>Clay</td>
</tr>
<tr>
<td>P8: 12-52</td>
<td>22</td>
<td>35</td>
<td>43</td>
<td>Clay</td>
</tr>
<tr>
<td>P8: 52-200</td>
<td></td>
<td></td>
<td></td>
<td>Rock Fragment/Volcano Clastic Origin</td>
</tr>
<tr>
<td>P4: 0-13</td>
<td>22</td>
<td>47</td>
<td>31</td>
<td>Clay loam</td>
</tr>
<tr>
<td>P4: 13-35</td>
<td>16</td>
<td>34</td>
<td>47</td>
<td>Clay</td>
</tr>
<tr>
<td>P4: 35-65</td>
<td></td>
<td></td>
<td></td>
<td>Rock Fragment</td>
</tr>
<tr>
<td>P4: 65-200</td>
<td></td>
<td></td>
<td></td>
<td>Blocky rock</td>
</tr>
<tr>
<td>P1: 0-12</td>
<td></td>
<td></td>
<td></td>
<td>Rock Fragment</td>
</tr>
<tr>
<td>P1: 12-190</td>
<td></td>
<td></td>
<td></td>
<td>Blocky rock</td>
</tr>
<tr>
<td>P7: 0-43</td>
<td>12</td>
<td>35</td>
<td>53</td>
<td>Clay</td>
</tr>
<tr>
<td>P7: 43-145</td>
<td></td>
<td></td>
<td></td>
<td>Rock Fragment</td>
</tr>
<tr>
<td>P7: 145-165</td>
<td></td>
<td></td>
<td></td>
<td>Blocky rock</td>
</tr>
<tr>
<td>P12: 0-115</td>
<td>20</td>
<td>17</td>
<td>63</td>
<td>Heavy clay</td>
</tr>
<tr>
<td>P12: 115+</td>
<td>18</td>
<td>17</td>
<td>65</td>
<td>Heavy clay</td>
</tr>
<tr>
<td>LGB_P16: 0-100</td>
<td>30</td>
<td>19</td>
<td>51</td>
<td>Clay</td>
</tr>
<tr>
<td>LGB_P16: 100+</td>
<td>14</td>
<td>23</td>
<td>63</td>
<td>Heavy clay</td>
</tr>
<tr>
<td>RGB_P13: 0-50</td>
<td>22</td>
<td>25</td>
<td>53</td>
<td>Clay</td>
</tr>
<tr>
<td>RGB_P13: 50-140</td>
<td>14</td>
<td>29</td>
<td>57</td>
<td>Clay</td>
</tr>
<tr>
<td>RGB_P13: 140+</td>
<td></td>
<td></td>
<td></td>
<td>Reserved Rock structures</td>
</tr>
<tr>
<td>Sat_RGB: 0-100</td>
<td>22</td>
<td>19</td>
<td>59</td>
<td>Clay</td>
</tr>
<tr>
<td>Sat_RGB: 100+</td>
<td>12</td>
<td>27</td>
<td>61</td>
<td>Heavy clay</td>
</tr>
<tr>
<td>Sat_LGB: 0-210</td>
<td>24</td>
<td>19</td>
<td>57</td>
<td>Clay</td>
</tr>
<tr>
<td>Sat_LGB: 210+</td>
<td>14</td>
<td>21</td>
<td>65</td>
<td>Heavy clay</td>
</tr>
</tbody>
</table>

3.1.1.2 INSTANTANEOUS FIELD MOISTURE CONTENTS

The moisture content observations reveal 15% gravimetric water content from the right upper slope class to 21% in the saturation zone. Remarkable moisture anomalies (Table 3) were observed in the left side of the upper slope class, where the weathered and fractured basalt is exposed. The soil samples from piezometer locations P2, P4 and P1 indicate about 20% gravimetric water content. However at the right side of the
upper slope class, where the hard pan formation is exposed at piezometer P8, the soil percent water content is relatively lower, 18%.

Table 3: Instantaneous percent water content at location piezometers at the right and left side of the watershed

<table>
<thead>
<tr>
<th>Location at Piezometer</th>
<th>%water content</th>
<th>Location at Piezometer</th>
<th>%water content</th>
<th>Location at Piezometer</th>
<th>%water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>P8</td>
<td>18.3</td>
<td>P2</td>
<td>20.3</td>
<td>P26</td>
<td>19.8</td>
</tr>
<tr>
<td>P6</td>
<td>17.1</td>
<td>P4</td>
<td>19.2</td>
<td>P25</td>
<td>18.5</td>
</tr>
<tr>
<td>P9</td>
<td>15.4</td>
<td>P1</td>
<td>20.3</td>
<td>P23</td>
<td>19.7</td>
</tr>
<tr>
<td>P7</td>
<td>20.4</td>
<td>P13</td>
<td>17.8</td>
<td>P24</td>
<td>21.5</td>
</tr>
<tr>
<td>P10</td>
<td>17.2</td>
<td>P14</td>
<td>19.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P11</td>
<td>16.6</td>
<td>P18</td>
<td>16.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P12</td>
<td>17.4</td>
<td>P19</td>
<td>18.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P15</td>
<td>17.6</td>
<td>P20</td>
<td>16.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P16</td>
<td>17.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P21</td>
<td>17.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both sides of the surface confining clay layers at the middle slope class, at the piezometers P10 to P19, exhibit lower percent water contents by mass than the right side of the upper slope class and the saturation zone. The P7 piezometer, located below the rock bund, also exhibits relatively higher percent water content by mass than the down slope clay cover. The saturation zone, where the piezometer P26, P25 and P23 are located, has the water table near or above surface and had the greatest water content.

As indicated by the percent water contents by mass of the soil samples from piezometers P21 and P19, the surface soils immediately adjacent to the gully bank had the lowest soil water contents (Table 3).
Besides the measurements, the right side of the upper slope class is wet throughout the entire rainy season, and despite its topographic location, it exists as a wet zone (Figure 9 and Figure 10: section BB’). However, the water contents recorded seem to be underestimated. Despite the low moisture content, water is seeping into the gully near piezometers P4 and P7.

In contradiction to the near surface piezometric water level, the moisture of the surface soil immediately upstream from the dike at P13 (Figure 10, traverse BB’) is similar to that of the surrounding area.

The middle slope class surface soils at piezometers P12, P15 and P16 have relatively lower moisture contents (Figure 10-Section AA’). The low moisture content of these sites is not expected because of the high water table at these locations. The saturation zone exhibits an increase in water content (Figure 10-section Saturation Zone).
Figure 9: Kriging interpolation of the soils instantaneous percent water content
(Point data is collected from the piezometer locations)

%moisture content of the surface soil
Value
High : 21.532000
Low : 15.411000

Saturation zone

Shallow highly Weathered and fractured Basalt

Slope gradient

Figure 9: Kriging interpolation of the soils instantaneous percent water content
(Point data is collected from the piezometer locations)
Figure 10: Percent gravimetric water content along section AA’, BB’ and Saturation zone
3.1.1.3 BULK DENSITY

The soils’ bulk density varies from 1.1 g/cm$^3$ to 1.3 g/cm$^3$, with a variance of 0.006. The maximum bulk density is recorded in the compacted hard pan in the left upper slope class of the watershed, and the minimum in the light brown clay surface layer in the right side of the upper slope class. The clay layers in the middle slope class and saturation zone have a bulk density of 1.2 g/cm$^3$. In vertical succession the upper slope hardpan formation area shows decreasing soil bulk density with increasing depth (Figure 11). The soil sample at P4, the shallow highly weathered and fractured basalt area, exhibits an increase of soil bulk density with increasing depth. Additionally, at P4 the second soil layer just below the depth of plowing is compacted clay.

![Figure 11: The bulk density of the top two soil layers in selected geological test pits](image)

Although not significant, the clay soils in the middle slope class and the saturation zone show increasing soil bulk density with increasing depth. The black clay of the top
soil had an average bulk density of 1.22 g/cm$^3$, and the light brown clay sublayer had an average bulk density of 1.35 g/cm$^3$.

### 3.1.1.4 SOIL MECHANICAL BEHAVIOUR: the Atterberg Limits

Clay soils in the middle slope class and saturation zone were examined to determine the amount of water retained immediately prior to cracking, i.e. the plastic limit, and the amount of water held in the soil to lose inherent cohesion, i.e., the soils liquid limit. Accordingly, the fresh soil samples from the middle slope class soils at piezometers P16 and those in the saturation zone represent the highest level of soil-swelling behavior with maximum water contents up to 50% by mass. The gully side exposed clay soils at the gully banks of the middle slope class showed relatively lower water holding capacity prior to slumping. See in Table 4 below.

Table 4: Percent water contents by mass of the soils at the liquid limit, plastic limit and saturation

<table>
<thead>
<tr>
<th>Sample: depth range of sampling, cm</th>
<th>LL</th>
<th>PL</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P16: 0 to 100</td>
<td>46.3</td>
<td>23.00</td>
<td>25.8</td>
</tr>
<tr>
<td>P16:100+</td>
<td>44.6</td>
<td>24.24</td>
<td>25.7</td>
</tr>
<tr>
<td>RGB: 0 to 100</td>
<td>30.7</td>
<td>22.95</td>
<td>25.5</td>
</tr>
<tr>
<td>RGB: 100+</td>
<td>31.2</td>
<td>15.00</td>
<td>26.7</td>
</tr>
<tr>
<td>SAT_LGB: 0-210</td>
<td>38.3</td>
<td>23.23</td>
<td>24.5</td>
</tr>
<tr>
<td>SAT_LGB: 210+</td>
<td>41.6</td>
<td>22.33</td>
<td>25.3</td>
</tr>
<tr>
<td>Sat_RGB: 0-100</td>
<td>39.0</td>
<td>22.06</td>
<td>28.2</td>
</tr>
<tr>
<td>Sat_RGB: 100+</td>
<td>52.8</td>
<td>22.00</td>
<td>25.5</td>
</tr>
</tbody>
</table>

The plastic limit tests also indicated that a considerable amount of water remains in the soil as cracks begin to form (Table 4). The chance of soil crack formation is highly sensitive to minute water losses below saturation (Figure 12). The light brown soils in
the middle slope and saturation zone showed the highest sensitivity to crack formation at limited water losses (<5%) below saturation.

Figure 12: Saturated water contents and Atterberg limits of selected soil samples

The soils retained a considerable volume of water before they lost their cohesion causing the soils to slump. As indicated in Figure 12, the middle slope class and saturation zone soils have the highest volume of water (above saturation) retention capacity before they lose strength.

3.1.2 RAINFALL AND RUNOFF RELATIONS

With high tendencies of runoff generation, two models of runoff generation processes are demonstrated in the area. The saturation excess and infiltration excess processes, or direct runoff processes, were defined in the basaltic exposure and hard pan
formations, respectively, in the upper slope class. The study area rainfall runoff relations indicated that about 30% of the rainfall becomes runoff.

The double ring infiltration test over the dominant part of the watershed reveals that the rainfall intensity is greater than the saturated soil water infiltration capacity (Table 5 below).

Table 5: Saturated soil water infiltration capacity at various locations and land uses

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Fc, cm/day</th>
<th>Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>P4, US left</td>
<td>14.1</td>
<td>Dark brown compacted clay layer below the depth of tillage</td>
</tr>
<tr>
<td>P8, US, right</td>
<td>8.3</td>
<td>Hardpan</td>
</tr>
<tr>
<td>P1, US, right</td>
<td>595.5</td>
<td>Weathered and fractured basalt</td>
</tr>
<tr>
<td>P7, MS top</td>
<td>54.8</td>
<td>Weathers basalt with clay infillings</td>
</tr>
<tr>
<td>P17, MS, gully junction</td>
<td>3.6</td>
<td>Black clay, not tilled</td>
</tr>
<tr>
<td>P17, MS, Middle</td>
<td>144.0</td>
<td>Black clay, tilled</td>
</tr>
</tbody>
</table>

The minimum amount of rain, recorded above the detection limit, has been observed to alter the color of the water in the gully without any significant change in the quantity of flow. A full description of the results and discussions of the rainfall and runoff measurements can be found in the Appendix.

The highest of all saturated soil water infiltration capacities was recorded at piezometer location P1 where there was exposed weathered and fractured basalt and no soil coverage. Likewise, the right side of the upper slope class, at piezometer P4, and the upper middle slope area, at P7, had the highest soil water infiltration capacities. Despite having the highest soil water infiltration capacities, these sites were found to be concentrated seepage zones during the wet season. As observed in the instantaneous soil moisture distribution, these areas were defined as permanent wet
zones during the rainy season. Hence, the runoff generated at this site is saturation excess.

Contrarily, at the left side of the upper slope area, where the hard pan formation is indicated at piezometer P8, the soil water infiltration capacity is negligible, approximately 8.28 cm/day. This indicates the combined effect of the geologic formation and the impact of the prolonged agricultural activity that has caused compaction and reduction in infiltration capacity. This was defined as a direct runoff generation area in the upper slope class of the watershed.

The very high soil water infiltration capacities, high saturation water contents, topographic locations within the upper slope class, and the higher wetness levels at piezometer locations P1 and P7 are indicative of saturation excess runoff and provide evidence of the presence of local subsurface barriers that can hinder the down slope flow of water. Contradicting the general understandings of the hillslope continuum (Lyon et al., 2004; Beven and Kirby, 1979), these findings denote the control that the local geology exerts on upslope saturation and saturation excess runoff generation processes.

The impacts of land use activity, tillage and the formation of a compacted clay layer below the plowing depth are demonstrated by the infiltration studies at P17 and P4. Accordingly, soil layers below the depth of plowing have limited soil water infiltration capacities than the inherent soil material. However, the top newly tilled soil layer (Table 8: P17, MS, and Middle) shows more significant infiltration capacities than the stabilized crop field (Table 8: P17, MS, gully junction). Newly tilled soil layers
exhibited a relatively higher infiltration capacity (144 cm/day) than the stabilized and fallow lands (3.6cm/day).

Hence, the middle slope area of the watershed that is covered by crop land is susceptible to runoff generation. Therefore, the watershed’s runoff generation trend is higher. This further has a tendency to control the overall type and extent of soil water erosion through sheet and rill erosion or by the formation of shallow pipes in the crop fields. The formation of small size pipes and potholes were observed in the area. As well, the prominent land curvatures at the gully heads and margins are associated with such erosion processes that can remove the surface and subsurface soil layers.

### 3.1.3 SOIL WATER RECHARGE AND WATER LEVEL FLUCTUATION

In line with the local geology, soil water infiltration capacities and soil moisture contents, the dominant source of soil water recharge is generated from the surface protrusion of the weathered and fractured basalt in the right side of the upper slope class. The piezometer readings and the surface soil water contents of the site indicate high water bearing and transmitting capacity. Hence, this layer forms the shallow layers’ water bearing stratum in the watershed. However, at the middle slope class this formation is covered by the black clay layer; thus, it is a confined aquifer. Due to the adverse effect of the dyke to the down slope movement of water along the right side of the watershed, the water table in the right middle slope class, at piezometers P18 and P19, was further below the surface than the water table confined on the left side at P16 (Figure 13).

Table 6 and Figure 10 represent the piezometric readings in the left side following the topographic gradient. However, due to the confining effect of the clay layer at the
end of the middle slope class at P16, the piezometric head is above the surface and represents the artesian pressure of the confined aquifer formed by the shallow depth of the highly weathered and fractured basalt.

Table 6: Mean water level of the piezometers

<table>
<thead>
<tr>
<th>Piezometers</th>
<th>Slope Class</th>
<th>Exposure Type</th>
<th>Mean water levels from the surface, cm</th>
<th>Elevation, m.a.s.l</th>
</tr>
</thead>
<tbody>
<tr>
<td>P8</td>
<td>Upper Slope</td>
<td>Hard Pane</td>
<td>nil</td>
<td>2270.6</td>
</tr>
<tr>
<td>P6</td>
<td>Upper Slope</td>
<td>Light brown clay</td>
<td>46</td>
<td>2262.7</td>
</tr>
<tr>
<td>P9</td>
<td>Upper Slope</td>
<td>Weathered Basalt</td>
<td>-4</td>
<td>2264</td>
</tr>
<tr>
<td>P7</td>
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1 Negative numbers indicate water table is above the land surface
On the right side of the watershed, the topography and piezometric comparison graph (Figure 14) illustrates the local damming effect of the dyke. The piezometric head is above the surface at the upper slope of the watershed, but the water table remained deeper below the surface at the middle slope class.

While the kriging interpolation in Figure 15 represents the high and low piezometric head readings, the local geologic material and stratigraphy sequence understandings of Figure 5 (section 2.2.3) and water levels and topographic elevation relations in Figures 13 and 14 define the aquifer types in the upper slope class and middle slope class and the potential characteristics of erosion. Accordingly, the upper slope class on the right side watershed is an unconfined fractured media aquifer and on the left side of the
middle slope class is a confined fractured media aquifer. Piezometer P8 was dry throughout the entire wet season of the research period. This indicates that the rain water infiltrated rapidly and flowed down hill.

Figure 15: Kriging interpolated spatial distribution of the mean water level from the land surface

**USR:** Upper Slope class Right is the unconfined perched aquifer formed due to the surface exposure of the shallow depth highly weathered and fractured basal and the damming effect of the dyke below it. This is the recharge zone to the middle slope class. It forms the saturation excess runoff and it is characterized by over saturation of the soil, irrespective of the topographic location.

**MSL:** Middle Slope class Left is the confined aquifer formed due to the confining effect of the clay soil layers that overlay on the shallow depth highly weathered and fractured basal. It is characterized by confined water table that rises above the surface and drier surface soil moisture content

**SZ:** Saturation Zone is the watershed wetland area. It is characterized by high water table. The water from upslope collects here.
Figure 16: the interpolated water level and topographic elevation m’s a.s.l. along the CA line, in the left side of the watershed

Figure 17: the interpolated water level and topographic elevation, m.a.s.l. on the BA line on the right side of the watershed
The mean water levels of the piezometers exhibit an erratic relation with the topographic elevation as indicated in Figure 18. Both the deeper water level, 308 cm, and the highest water level, -44 cm (or 44 cm above the level of the ground), are located in the middle slope class of the watershed at a mean elevation of 2,225 m a.s.l. The piezometers reading in the highest elevation zone and lowest elevation zone fall in an apparently similar water level range, 0 to 50 cm from the surface. In the middle section the deepest groundwater levels are recorded. This can be explained by the fact that the gully is deep and drained the water, but the dyke prevents water flowing from uphill.

In Figure 19, 20, 21 and 22 the water levels are shown over the project period. A set of the piezometers rises during the rainfall and then drops gradually after the rainfall event (P1, P2, P4 and P7, in Figures 19 and 20). These are located on the hillside and water flows down hill. Another set of piezometers stay more or less constant over the period of measurement indicating that they have a downstream control in which the water level stay constant, (P13, P16, P14, P18, P19 in Figures 20) This could be gully close by or water table reached the surface of the soil. In some of this piezometer the water table is above the soil surface indication artesian condition (P13 and P16, in Figure 19 and 20). Finally there is set of piezometers that show a sudden drop of 25 or more cm. These sudden drops are associated with bank failures and a sudden release of the water pressure resulting in a drop in water table (P 23 and P24, in Figure 21). The water level in piezometer P13 dropped suddenly around day 95 from 40 to 165 cm. This coincided with a large soil slump.
Figure 18: Mean water levels of the piezometers as influenced by the topography, geology and soil cover
Figure 19: Time series piezometer head of the left side of the watershed (Top) and the Standard deviation of the water levels (Bottom).
The water level readings in the saturation zone (Figure 21) of the watershed indicate relatively lesser sensitivity to rainfall events. P23, located at the gully head, indicated a remarkable decline in water level after every sliding event. Contrary to P23, the P24
was more or less constant and was located from the gully and not affecting by bank failures.

Figure 21: Comparison of the water levels of the piezometers at the Saturation Zone.
Figure 22: The water levels fluctuation (Top), and STDV (Bottom) of the piezometers at the saturation zone.
3.1.4 EROSION CHARACTERIZATIONS

Subsurface erosion, manifested through the formation of soil pipes and pot holes and through complete bank failures due to overpressurized water, in addition to various kinds of land slides, soil falls and/or shallow slumps are the characteristic erosion activities in the expansion of the gullies on both sides of the watershed. Other kinds of soil water erosion were not the focus of this study.

As indication of the damming effect of the dyke in the upper slope class, active landslides have been observed on both sides of the gully bank. This impounded water, due to the geologically intrusive dyke (Figure 4), exerts excess saturation of the soils; thus, the soil lost its natural strength and caused mass slumping (Illustration 3, Left). With rapid lateral expansions, the slide land mass exhibited indicators of soils remolding, vertical striations (tiny parallel grooves in the soil indicating high shear areas) along failure plains, and curved failure plains. Hence the entire cause for the landslide in this area was attributed to the impounding of the subsurface water.

Illustration 3: Land slid at the top part of the RG, left; and Soil falls and slumps, right in the right middle slope class.
Following any orientation, soil falls and slumps (Illustration 3, right) also occurred on the gully banks. In line with the soils’ mechanical properties and field observations of the soils’ nature to form silken slides, vitreous luster and inter fingering soil layers, the soil falls are attributed to the high tendency of crack formation and intrusion of water via the cracks.

Such near surface erosion features as potholes and soil pipes (Illustration 4) were formed from the near surface flow of water recharged in the middle slope class. The soils exhibit only limited soil water infiltration capacity, and hence the water recharged into the soil at the middle slope class formed local saturation wash outs of the soil, such as pothole Illustration 4 A and/or concentrated flows Illustration 4 B, so that soil pipes were formed.

Illustration 4: Potholes and smaller pipe A, and concentrated water outflow zones, B.
Areas having the confining effect of the clay layer were the major sufferers in the formation of the local land curvatures. As observed at the left side of the gully, the relatively flat area with concentrated seepage widened during the study period. The piezometer reading at P16 indicated that the water head at this area was relatively high with a total pressure head of 45cm above the surface.

Two destructive slides were observed from the two slides of the saturation zone gully banks (Illustration 6). The first was a vertical slide in the wettest, vegetated part of the central, plain saturation zone, i.e. to the right of the gully. A larger landslide, with characteristic head toe and/or base failures, showed prominent extensional failure plains in the sloping left side of the saturation zone of the watershed. This left gully bank landslide had a well defined failure plain, as well as head base failures. The overall landslide in the saturation zone was an active process and the dominant sediment (clay and silt) source.

Illustration 5: Slides in the saturation zone of the watershed, vertical slide in the left and head toe/extensional base failure in the right photo.
4.0 CHAPTER FOUR

4.1 CONCLUSIONS AND RECOMMENDATIONS

4.1.1 CONCLUSIONS

Local geological studies are not only important to understand specific hillslope hydrological processes but also to help in defining the type and extent of interventions required in soil and water conservation projects. The study defined the various soil properties and the relative importance of specific hillslope hydrological elements in the Debremawi watershed. This includes the contribution and controlling effect of local geologic materials and geologic structures on the type and extent of soil water erosion attributed to specific hillslope hydrological processes. Geological and soil maps were produced to better assess the distribution of soils and the relative analogy with the geology of the study area.

The specific hydrological process that are generated as a fact of the local geological conditions, soil behavior and common land use practices are tabulated below in Table 7. The location and type of runoff is defined as a factor of geologic materials and land use types.

The gully formation in the Debremawi watershed is more importantly caused by subsurface erosion generated from soil pore water pressure. Concentrated flow of water in the near surface soil layers in the middle slope class form potholes that potentially lead to land curvature formation and ultimately develop into stream channels. All the pore water pressure development and concentrated flow conditions are dictated by the nature and composition of the local geology in the area.
Limited soil thickness with exposure of shallow depth, highly weathered and fractured basaltic rock in the upper slope class of the watershed favors higher rates of ground water recharge. However, the damming effect of local geologic structures influences the subsurface flow patterns and behavior. Accordingly, local saturation zone formations are defined irrespective of the topographic location. This favors the saturation excess runoff generation processes. However, prolonged agricultural activity in silt soils forms soil compaction that favors direct runoff.

Local saturation caused by geological barriers and/or topographic setup in any slope class triggered land slides and soil slumping. This is the main cause of the expansion of gullies in the study area.

The covering of the shallow, highly weathered and fractured basalt by clay materials formed confined aquifers. This enhances subsurface soil erosion, which leads to the formation of curvature land forms and the ultimate development of gullies.

The middle slope class clay soils tend to have the highest tendency towards cracking and water percolation through these cracks. Hence, recharge to the soil water is from the saturation excess runoff zone.

The intrusive dyke, as a subsurface barrier, controls the subsurface water flow processes, contradicting the general understandings of flow processes along topographic gradients. This not only dictates the subsurface water flow behavior but also the development of local pore water pressure and the formation and expansion of gullies. Hence, the local geology in the study area controls both the runoff processes.
and the formation and expansion of gullies irrespective of the topographic location and topographic gradient.

The interplay among the upper slope class recharge in the exposure of weathered and fractured basalt and the confining nature of the clay layers in the middle slope and saturation zone has formed a high piezometric surface above the confining top clay layer. These tend to have a high subsurface pore water pressure and high subsurface water flow rates. The over all erosion characterization in the area is found to be several and combined effects of the nature of the aquifer type, slope location and land use as summarized in the Table 7, below.

4.1.2 RECOMMENDATIONS

Land management processes that effectively drain subsurface water and reduce the potential pore-water pressure in shallow soils are necessary in the DebreMawi watershed. This will reduce, and even prevent, subsurface erosion processes which ultimately lead to gully formation.

In cases where gullies are formed in thick clay soil, as in the saturation zone of the Debremawi watershed, plans to implement any soil conservation structures should consider the recharge-discharge behavior of the watershed and the soil-water properties. Although it is important to manage rill and sheet erosion in the upper slope class through terracing and tree plantations, enhancing recharge in the upper slope class raises the pore water pressure in the middle and saturation zone leading to erosion. This adversely affects gully formation and expansion. All in all, subsurface drainage structures in conjunction with bio- physical soil and water conservation
structures will be of paramount importance for better achievement of sustainable land management.

Table 7: Summary of the study conclusions

<table>
<thead>
<tr>
<th>Slope Class</th>
<th>Hydrologic processes and influence of local and regional geology</th>
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</table>
| Upper Slope Class >13 to 30 degrees | • Soil water recharge through exposures of shallow depth high degree of weathered and fractured basalt exposure  
  • Compaction of silt lay soil  
  • Runoff generation and associated erosion:  
    o Saturation excess in the right side and  
    o Infiltration excess runoffs in the left hard pan formation of the watershed. |
| Middle Slope (MS) 5 to 13 degrees | • Clay deposit that can act as confining layer to the subsurface water in the basaltic horizon.  
  • High pressure development and exertion in the top clay soil, subsurface erosion and formation of collapse zones as land curvatures.  
  • Cracking and fall of the Soil along the shallow gully banks  
  • Potential soil water transportation at near surface and manifestations through formations of potholes/soil pipe formation,  
  • Development of smaller rills from smaller pipes  
  • Transportation runoff water from US to DS,  
  • Perched aquifers saturation at clay lens layers,  
  • Discharge at depressions through preserved rock structures and/or as ephemeral depression springs from of the saprolith,  
  • Runoff generation and transport to DS.  
  • Local small rate infiltration in to the clay layer to incases the saturation of the top/crest layer,  
  • Erosion due to the runoff at US and DS |
| Down Slope (DS) <5 degrees | • Discharge as swamp, springs or over saturation of the soils  
  • Loss of soil cohesion due to over saturation, that leads to bank slope failure. Cohesive clays grading to silt and sandy clay which generates hillslope slumping and/or larger land slides  
  • Extensional crack formation |
REFERENCES


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The geological map of Ethiopia, Second edition, 1996 GSE.

APPENDIX

Rainfall and runoff measurements

The runoff record in the study site indicates that the flow rises rapidly and falls gradually. Although the rising limb in the Figure A1 indicates a rapid increase in discharge, the falling limb is decreasing at a slower rate.

Figure A1: Event storm and runoff record

The runoff in the rising limb likely results from a relatively small area of the middle slope and saturation zone of the watershed through drainage ditches from farmlands.

As part of the interest of this study, observations made during storm periods may be of interest.

- The low flow (base flow) of the watershed was turbid although rainfall occurred as much as three days ago.
• The sources of the low flow water is observed as consecrated seepage from the middle slope class of confining clay layer in the left gully, the area above the dyke in the upper slope class, at the exposures of the reserved rock structures in the right (deeper) gully and below the gullies junction.

• The seepage from the confining clay layer in the middle slope class dried up three days after the rainfall. However, the water originating rock structures in the deeper gully side and the gully junctions flowed over an extended time. This is was confirmed by the local dwellers who indicated that the discharge lasted till after the wet season.

• The interflow and base flow (occuring after the peak flow) originated from the middle slope class, where thick clay depositions were found. (The source of this water may be the water draining out of potholes, soil fractures, and impounded water in the farmlands due to the rugged surface of the plowed farmlands). This extended runoff water exhibits lighter color than the peak runoff, but darker than the low flow.

• Although discharge in the creek barely increased, the smallest amount of rainfall caused a remarkable darkening in the color at the weir site.

• Recorded at the rain gage located to the north at around 1 km distance from the study site, the area has received the highest rainfall 34 mm at the beginning of August and average monthly rainfall is 6.3 mm (Figure A2) Event storm records in the watershed has been observed to last in a durations less than half an hour.
Figure A2: Daily Rainfall recorded. (Data source, the Adet Research center)