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Reactivation of mass movements in Dessie graben, the example of an active landslide area in the Ethiopian Highlands

Abstract Dessie town is located in a tectonic depression along the western rift margin with a young, high energy relief. Study area is known for numerous landslides in the past. These landslides are of different types, from shallow soil creeping to huge deep-seated landslides with appreciable consequences. Landslides endanger the quickly growing regional centre of Dessie and its infrastructure. Four typical recent landslides have been selected and studied in detail using both remote sensing and field observations from 2013. The described reactivation and new landslide events have been caused by a combination of natural influences and anthropogenic activities. Since seasonal rainfall is the main external triggering factor, precipitation data from Dessie weather station were analysed. The degree of negative human impact on slope instability was also discussed. Endangered zones and the actual risk in the studied localities were identified, and adequate measures were proposed.

Keywords Ethiopian highlands · Dessie graben · Landslides · Natural hazards · Human impact

Introduction

The area of Dessie town has been known for almost half a century for its repeated slope instability problems. The basic predisposition of recent slope movement activity is the tectonic pattern, geological setting (fractured, highly weathered volcanic rocks and loose, unconsolidated deposits) and specific topography (steepness of the area together with river erosion). Loss of human life and damage to infrastructure (roads, bridges, houses, communication facilities, etc.) have been caused by landslides and the related geo-hazard (e.g. Woldearegay 2013). Soil creeping, debris flows, landslides or rock falling have been described several times since the 1980s (e.g. Eshete 1982; EIGS 1991, 1995; MoWUD 1995; Hailemariam 1995; Tsehayu and Gezehegn 1995; Ayalew and Vernier 1999; Terefe 2001; Ayenew and Geremew 2002; Ayenew and Barbieri 2005; Fubelli et al. 2008; Abebe et al. 2010 or Beyene et al. 2012). In this study, we have focussed on the most recent landslide activity, which was induced by a combination of specific local conditions and external factors. We selected four landslides: (1) School_Menbere Tshay area, (2) Dessie–Kombolcha road, (3) Kerra area and (4) Doro Mezleya slope (Table 1). These represent different types of landsliding in the area but exhibit identical features—frequent reactivation and potential risk for local inhabitants. We have analysed their geometry in detail, documented their evolution and investigated the main triggering factors (with particular emphasis on the impact of human activities).

Study area

With a population of 151,000 (Central Statistical Agency of Ethiopia 2007), Dessie is an important town in North-central Ethiopia. The study area and its close surroundings are situated in the border zone of the Ethiopian Highlands and the Rift Valley (400 km to the north of Addis Ababa, Regional State of Amhara, Northern Ethiopia) and are characterized by parallel running mountain ranges reaching an altitude of 3025 m a.s.l. (Fig. 1). The Dessie depression is a hanging valley located along the western rift margin with a young, high energy relief. The elevation of its bottom at the outflow of the Borkena River is at an altitude of 2400 m a.s.l. The basin is bound by two major parallel faults running in an N-S direction, represented by the steep slopes of Tossa Ridge to the west and by Azwa Gedel Ridge to the east (Fig. 2). The Dessie graben was produced during the Tertiary-Quaternary extensional phase, which was accompanied by an important regional uplift, raising the Ethiopian plateau by 800–1000 m to attain the present altitude (e.g. Almond 1986; Mohr 1986). In the youngest stages of its development, the Dessie graben was a closed basin, which is documented by swampy-lacustrine sediments (Fubelli et al. 2008). Due to advancing uplift, the graben was deeply incised and then re-opened by the backward erosion of the Borkena River (Fubelli et al. 2008; Abebe et al. 2010).

The outcropping bedrock consists of a sequence of Tertiary Trap Series volcanics (Ashangi basalt formation and Dessie basalt formation—e.g. Gregnanin et al. 1973). Moderately to highly weathered and densely jointed basaltic rock masses correspond to stratified beds of successive lava flows, inter-bedded with weakly degraded volcanic units and several reddish paleosoil horizons. Vesicular basalt is a highly porous and friable rock type, which is dominant in the central part of the town and is locally overlying stratoid basalt outcrops. These highly weathered rocks associated with unconsolidated materials in steep slope areas represent a high landslide and rock fall susceptibility zone (Ayenew and Barbieri 2005). The graben floor is filled by sediments up to several tens of metres thick, which consist mainly of colluvial-alluvial deposits (Ayenew and Barbieri 2005; Fubelli et al. 2008).

The most frequent landslide types include (a) rotational slides, (b) translational slides, (c) rock falls and rock slides (debris avalanches) (Fubelli et al. 2008). The main landslide activity in the Dessie area occurs in silty clay soils and loose deposits of an alluvial and colluvial origin that cover highly weathered basalts (Suyum 2011). Translational slides move along clayey levels of superficial deposits and along the interface between these deposits and the bedrock. Rotational slides mainly occur in alluvial-colluvial and lacustrine deposits. Movement events are commonly restricted to shallow phenomena such as soil slips or mud flows (Abebe et al. 2010). At times, these failures are associated with seasonal earth and soil flows (Ayenew and Barbieri 2005) and very abundant soil-creep movements.

The climate of the study area is sub-humid to humid with a bimodal rainfall regime. The annual rainfall distribution is

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Table 1 Main characteristics of the four selected sites as an example of recent landslide activity with risk potential in the southern part of the Dessie graben

	School_Menbere Tshay area (1)	Dessie–Kombolcha road (2)	Kerra area (3A,B)	Doro Mezleya slope (4)
Type of slope deformation	Rotational slide	Rock falls, debris flows	Translational landslide, rotational landslides, creep	Translational landslide (rock slide), debris flows and rock falls from scarp zone
Geology (landform) unit	Alluvial soil sediment with clay	Stratified basalt (with vesicular basalt layers and paleosoil horizons), colluvial deposits and landfill	Alluvial soil sediment with clay	Fault escarpments build by stratified basalts (with vesicular basalt layers and paleosoil horizons)
Triggering factors (and conditions) of the main slope failure	Human impact—destabilization of slope during building the new road from Kombolcha to Dessie together with rainfall (predisposed by geological setting)	Human impact—building the new road from Kombolcha to Dessie together with rainfall (predisposed by geological setting)	Rainfall (predisposed by geological setting and landform conditions)	Earthquake together with deepward river erosion (predisposed by tectonic crossing of two faults zones and geological setting)
Date of failure	2009	2009	No evidence (landslide activity known before 2001)	Exact dating not possible
Date of reactivation and new events	2010–2013	No special evidence (continuously from 2009 to 2013)	2007, 2010, 2011, 2013	No special evidence, 2013
Nature influences of reactivation	Rainfall	Local conditions around the road, rainfall	Rainfall, river bank erosion and undercutting	Recent landscape morphology, rainfall
Anthropogenic cause of recurring problems and risk	Construction of a road and buildings in the risk area, inadequate technical measures	Artificially built slope exposure and drainage mode along the road	Construction of buildings in the risk area	Encroaching of housing development to the zone of natural hazard, local quarrying activities
Performed technical measures	Retaining walls along both sides of the road, stabilizing walls with piles, infiltration trench and eucalyptus planting on the landslide body	Retaining structures—gabions and retaining walls above the road (still under construction), drainage channels under the road	No technical measures	No technical measures
Current status	Still active (with recent reinitiation and new landslides)	Still active (with recent partial reinitiation by rock falls, debris flows)	Still active (with recent partial reinitiation and new minor landslides)	Still active (with recent partial reinitiation by rock falling, debris flows)
Actual hazard/ risk in the studied area	High/very high	High/moderately low	High/very high	High/moderately low (with the exception of the case of a catastrophic feature)
Endangered zone	Asphalt road, school buildings and surrounding grounds	Asphalt road	Settlement	Settlement and infrastructure above
Proposed measures	Functional drainage and technical treatments (reflecting the depth and real extent of the landslide), no further expansion of school buildings	Completion of retaining walls and gabions, protecting ground cover nets	No further construction of buildings, stabilization of slopes or resettlement of residents away from the risk zone	No further construction of buildings, no major networks or pathways in the risk zone, slope angle reduction and vegetation cover

characterized by pronounced seasonality, with the heaviest rains occurring in July and August (e.g. Ayalew 1999; Fubelli et al. 2008). Intensive rainfall (and occasionally also earthquakes) induces fast moving slope failures, which have affected the Dessie graben several times in the past. The increasing impact of anthropogenic activities (land use changes—especially deforestation and intensive agriculture, quarrying, road construction, urbanization, etc.) has also contributed to slope instability and landslide hazards over the last five decades (e.g. Ayalew 2000; Nyssen et al. 2003; Zvelebil et al. 2010).

Historical evidence contains reports of about 106 landslides (Fubelli et al. 2008). Several catastrophic landslides have occurred

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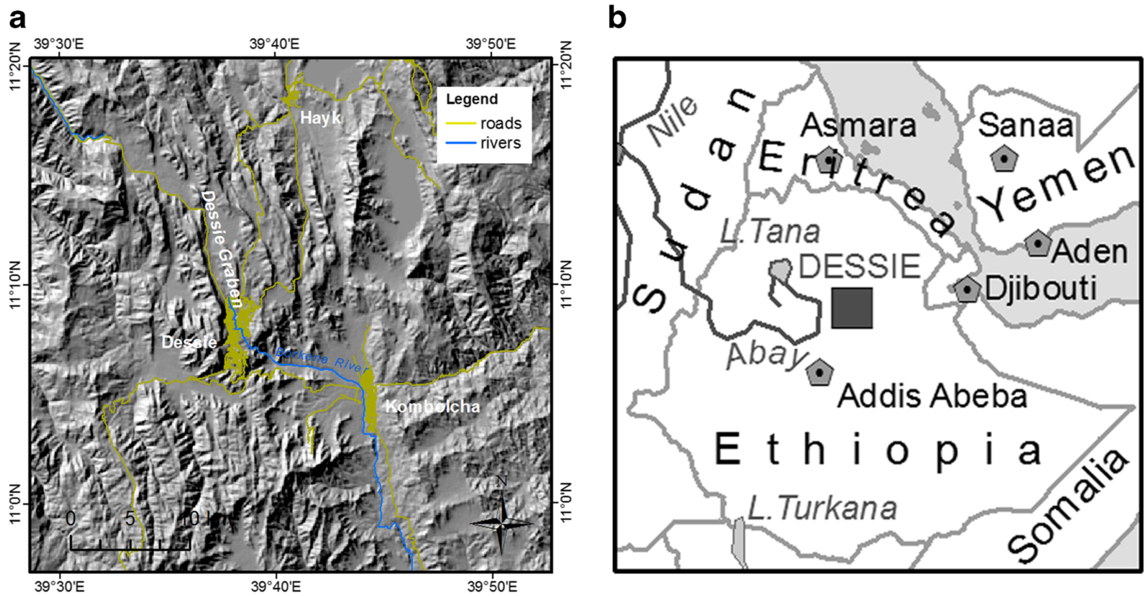

Fig. 1 **a**, **b** The Dessie graben is situated close to the Main Ethiopian Rift, parallel to its western margin

in the past (in 1977, 1979, 1988, and 1994), and there are also numerous records of currently active landslides (Eshete 1982; Ayalew 1999; Terefe 2001; Ayenew and Barbieri 2005; Fubelli et al. 2008). The most recently described example of large mass movement is from July and August 2010, when 37 casualties were registered in the Dessie region (Beyene et al. 2012).

Zonation of landslide risk for the Dessie area has been performed by several authors. Zones of landslide susceptibility for four study localities were defined as being from moderate to very high (Ayenew and Barbieri 2005; Suyum 2011). Old landslide complexes show current signs of reactivation, as revealed not only by the field survey but also by preliminary inclinometer measurements (Ayenew and Geremew 2002) or by applying the DInSAR methodology (Beyene et al. 2012).

Methods

Analysis of remote sensing data and previous studies

A new landslide inventory was carried out using a digital elevation model (DEM) and a high-resolution satellite image in a GIS environment. Pan-sharpened optical satellite images acquired by the Kompsat-2 satellite 21 February 2012 were draped over hillshaded relief and explored using 3D visualization. The DEM was derived from an ALOS/PRISM triplet scene from 4 December 2007 by stereo-processing using the Leica Photogrammetry Suite (LPS) software package. The progresses of landslides and urban development were also checked and identified using GoogleEarth which provides more detail in terms of surface features but less detail in terms of terrain shape. For the identification of landslides, we exploited the following features: the typical concave shape of the head area and convex shape of the frontal lobe in the accumulation zone. We also used typical shades, patterns, and shapes in the multispectral image. Conformity with already published inventories (e.g. Ayenew and Barbieri 2005; Fubelli et al. 2008; Suyum 2011) was also checked. Aerial photographs of the area were provided by the Ethiopian Mapping Agency in Addis Ababa as scanned non-georeferenced files. Images of the Dessie graben were acquired in 1958, 1986 and 1994. These images were ortho-rectified based on ALOS/PRISM DEM using the LPS. We selected four representative landslides in the southern part of the Dessie graben with relatively short-term changes, where the main conditions and triggering factors—especially anthropogenic influences—were discussed.

Fieldwork

Detailed field investigations of the selected landslides were carried out during the field trips in February and October 2013. The distribution and extent of the old deformations were mapped, and recent reactivations were observed and documented. Slope profiles and the height of scarps were measured by a laser rangefinder (NIKON Forestry Pro). This instrument allows the accurate measurement of distance and elevation angle. The coordinates of documentation points were measured using a hand-held GPS device (Garmin, GPSMAP 62 s). Soil samples were collected from two fresh scarps at the Menbere Tshay landslide in the autumn of 2013.

Rainfall data evaluation

Over 50 years (1962–2013) of rainfall and temperature records measured at the weather station in Dessie were provided by the National Meteorology Agency of Ethiopia. The data were used to assess the long-term development of rainfall in the study area. Furthermore, daily and monthly data from the last 11 years were used to calculate the total annual precipitation, which was subsequently compared to the landslide reactivations and to calculate the monthly average precipitation in the rainy season for the period from 2003 to 2013 (July–August–September).

Laboratory analysis

The mineralogical composition of clay fraction samples taken from different parts of the slide was determined on the basis of

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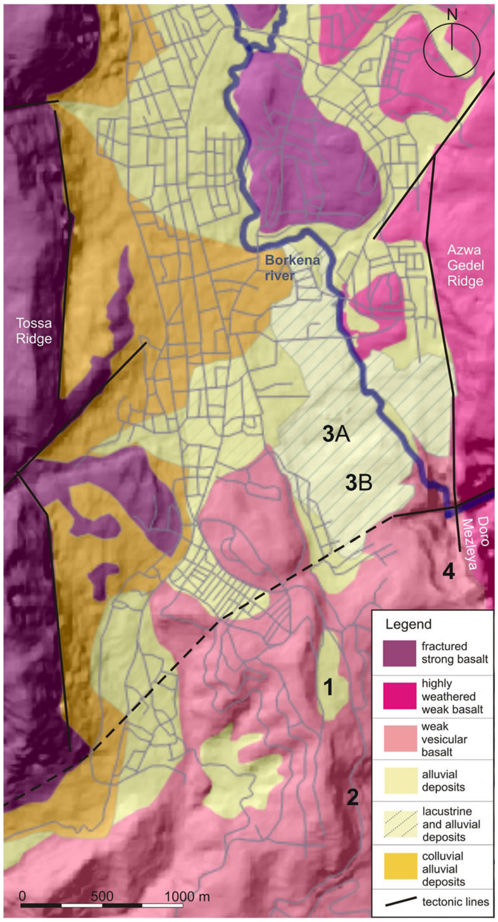

Fig. 2 Geological map of the central and southern part of Dessie town showing the four studied areas with landslide reactivations: 1 School_Menbere Tshay area, 2 Dessie-Kombolcha road, 3AB Kerra area, 4 Doro Mezleya landslide (modified by Ayenew and Barbieri 2005 and by Fubelli et al. 2008)

X-ray analysis of the samples prepared by sedimentation from a water suspension on a glass slide. In order to determine the type of clay minerals, the preparations were analysed in their natural state as well as being saturated with ethylene glycol at 80 °C for 4 h and heated at 550 °C for 4 h. The analyses were performed on a Bruker D8 DISCOVER X-ray diffractometer with the following conditions: CuKα radiation, voltage 40 kV, current 55 mA, goniometer shift of 1°. min^{-1}, analysis range 3–35° 2θ. The X-ray results obtained were evaluated according to Micheejev (1957) and the tables from the Mineral Powder Diffraction File—Data Book (1980). Grain-size analysis of sedimentary rock was performed on a set of commonly used wet networks.

Characteristic of the selected active slope deformations

The landslides included in the study have been primarily influenced by intensive rainfall; in two cases, the rainfall influence is accompanied by anthropogenic factors and one of the most known slope failures was apparently caused by an earthquake (summarized in Table 1). The oral information of local people indicates that the landslides in the study areas have been active for at least the last 6 to 7 years.

The long-term meteorological data from the Dessie station show that the year 2013 had above-average total rainfall. The total rainfall volume during the rainy season in 2013 (July–September) reaches 1041 mm, and the total annual volume reached 1550 mm. This was the third highest annual precipitation value since 1962 after 1998 and 2006 (see Fig. 3). For a detailed analysis of the correlation of the rainfall with the landslide activity, the precise dating of the reactivations is unfortunately missing.

Significant changes in morphology over time caused by a new partial reactivation or new landslides were identified at the described sites. All of these sites represent current or future potential threats to local inhabitants and property.

The landslide near an elementary school (Menbere Tshay area) (1)

This landslide was activated during the construction of an asphalt road in 2009 (Fig. 4) and was formed on a moderate slope of 6.5° covered by alluvial sediments represented by silty clay (clayey silt) soils with an admixture of volcanic pebbles. The original landslide body was more than 110 m wide and 72 m long along the fall line from the main scarp to the road. A new school building was built just above a fresh landslide body in 2009/2010.

The first reactivation after intensive rainfall was described in 2010 (Beyene et al. 2012). Several technical measures were applied within the landslide area in 2010—a retaining wall along the road (see the remedial works/RW3, 4 in Fig. 5a), a stabilizing wall with piles along the main scarp and transverse cracks (RW1 and RW2 in Fig. 5a) and plantation of eucalyptus trees. The pedestrian path along the southern part of the school grounds was partly stabilized by gabion as an erosion control measure (RW5 on Fig. 5a).

Despite this remedial work, slow sliding of soil material was observed by local people every year within the source area of the landslide, especially during the rainy season. Fresh reactivations of slope sediments were also documented after the rainy season in October 2013: (i) a new small landslide body next to the road (55 m wide, 16 m long along the fall line, a scarp with a height of 1.6 m and with partial tears around—see Reactivation 1 on Fig. 5a, b); (ii) another part of the soil material was moved and pushed to the abutment walls along the road (Reactivation 2 on Fig. 5a); (iii) partial landslides after several sliding surfaces along the main scarp zone (Reactivation 3 on Fig. 5a). The analysis of high-resolution satellite images revealed that the main scarp advanced 12 m towards the school buildings and reached the retaining wall (see the close-up photo of RW1 on Fig. 5a). This advancement reached 18 m in the unprotected terrain to the south of the wall. The landslide area limited by the scarp and by the asphalt road is 7800 m^2 which is 17 % larger than in 2009.

Open cracks in the surface parallel with the southern edge of the landslide extend to the slope in a direction towards the school buildings (with a length of 8 m, depth of 0.3 to 1.10 m, becoming deeper and wider in the lower parts of the slope). Open cracks on the school playground parallel to the scarp edge of the landslide are 6 m from the retaining wall and were filled with gravel. Relatively fresh cracks measuring

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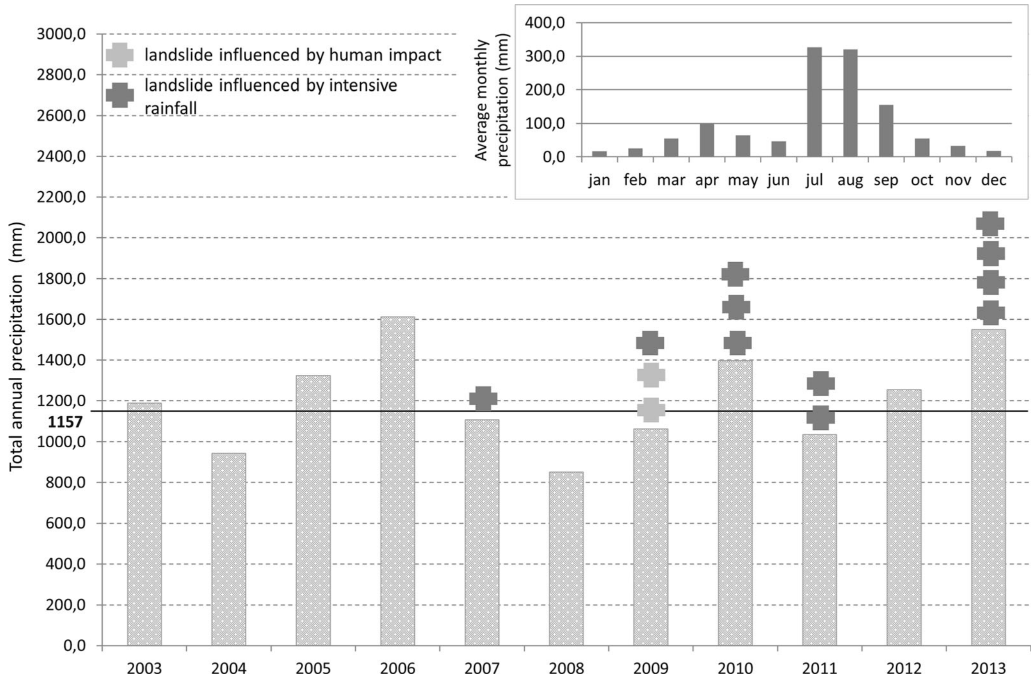

Fig. 3 Rainfall data from the Dessie graben from 2003–2013 compared with landslide events recorded by the testimony of local residents for the last 7 years (information from 2003–2006 is missing). Mean annual precipitation for this period is compared with the long-term average annual precipitation from 1962 to 2013 (which reached 1157 mm—*horizontal black line*). The *small graph* shows periods of high rainfall observed in July, August and September (average monthly precipitation 2003–2013)

Fig. 4 Comparison of the noticeable development of the studied landslide areas (Menbere Tshay area—right, Dessie–Kombolcha road—left) in the years 2005–2009–2012; the first landslide events were caused by the construction of a new asphalt road leading to Dessie town. Numbers in the Menbere Tshay area (2012) indicate the remedial works RW1, 2, 3 and 4

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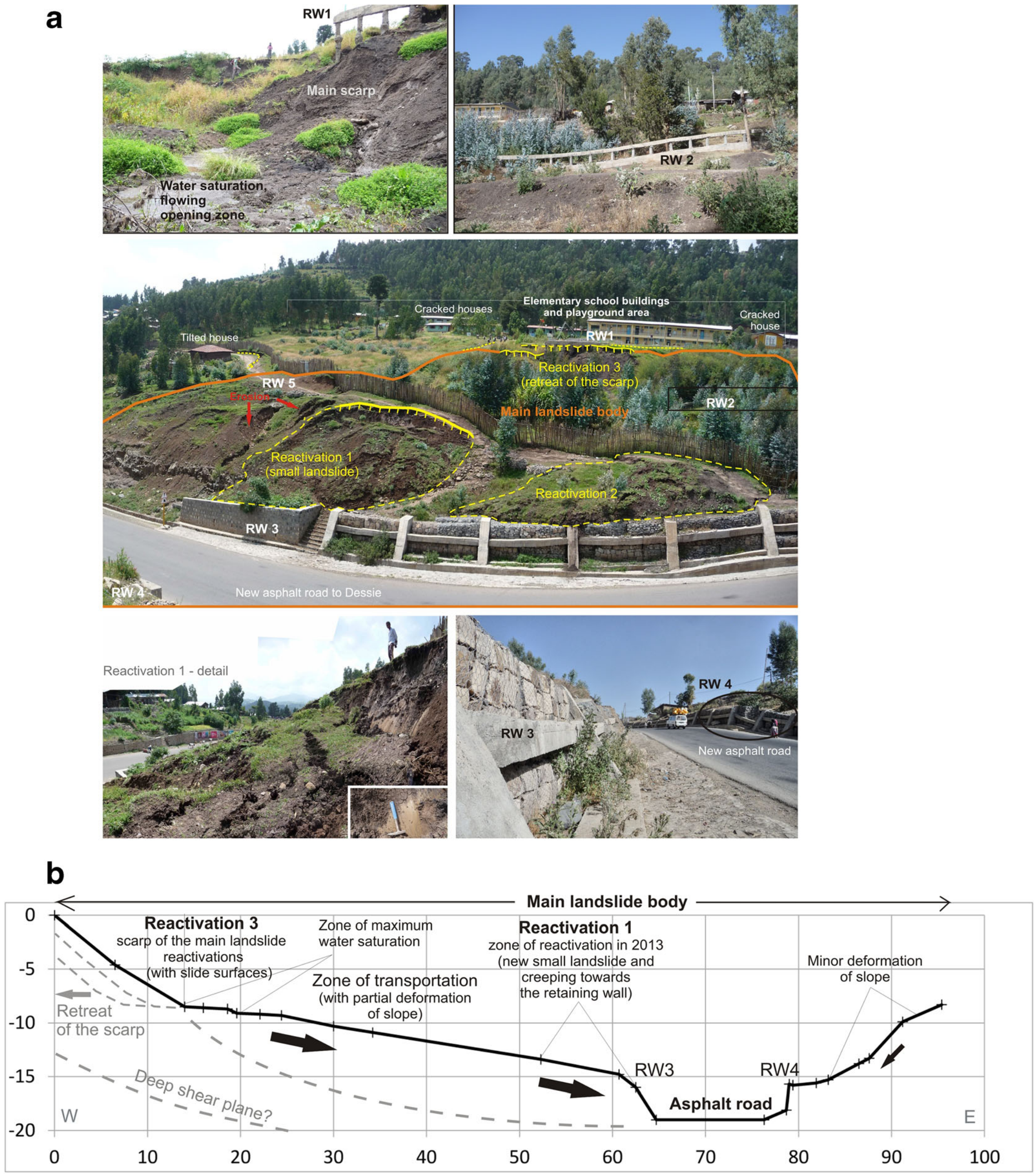

Fig. 5 **a** Overall view of the landslide body near the elementary school in the Menbere Tshay area (photo Z. Vařilová). **b** Longitudinal topographic profile of the landslide

10–15 cm wide were also identified in the southern part of the area close to the tilted house.

Grain-size analyses show the predominance of silt and clay particles in the studied soils. After a detailed study of the individual coarse fraction, it was found that the basalts weathered into spherical pebbles (average size of 0.5 cm), which are surrounded by other phases with varying colour from yellow to brown corresponding to levels of weathering. In the landslide material, the clay content of the soil ranges from 35 to 61 %, the silt content varies from 31 to 45 % and the sand content is very low with percentages below 6 %. The large clay fraction is similar in composition to the Kerra landslide area (see Ayenew and Barbieri 2005) and predisposes the landslide movements there (e.g. Vacondios et al. 2007). X-ray diffraction (XRD) showed that the predominant clay mineral is a mineral from the smectite group—results in Table 2 (Brindley and Brown 1980). Based on the values of the basal reflection, it can be said that it is a Ca-montmorillonite. Other identified clay minerals include illite and kaolinite. Some samples were also found to contain chlorite basal reflections, which coincide with montmorillonite. The other minerals are present with quartz, feldspar, andesine and plagioclase (albite).

There are many indications that this old landslide body is still active and hazardous. Moreover, the irregular tension cracks and sheers in school buildings and a tilted house on the south end of the school grounds (Fig. 5a) show that the unstable area is wider than the original landslide from 2009. The ridge further above the school grounds is built of solid volcanic rock and represents the upper limit of the whole

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Table 2 Clay minerals (%) identified in clay fraction in soil samples within the reactivation in the Menbere Tshay area (numbers of reactivation correspond to Fig. 5a)

Sample	Date	Landslide	Zone of soil sampling	Sm	Ch	I	K	Q	F	and	alb
MT1	10/2013	Reactivation 1	Accumulation	18	0	2	5	30	14	7	24
MT2	10/2013	Reactivation 1	Scarp—slip surface	11	0	4	5	38	16	8	18
MT3a	10/2013	Reactivation 1	Scarp—slip surface	12	0	4	8	48	8	5	15
MT3b	10/2013	Reactivation 1	Scarp zone	20	0	3	13	30	16	7	11
MT4	10/2013	Reactivation 3	Main scarp zone	29	0	14	17	10	10	12	8
MT5a	10/2013	Reactivation 3	Main scarp—slip surface	26	0	7	7	34	10	9	10
MT5b	10/2013	Reactivation 3	Scarp—slip surface	23	6	8	8	21	10	10	14
MT6a	10/2013	Reactivation 3	Main scarp zone	20	0	12	9	16	15	13	15
MT6b,c	10/2013	Reactivation 3	Main scarp zone	11	6	16	7	18	14	12	16
D6A	2/2013	Reactivation 3	Main scarp zone	15	0	9	5	25	14	17	15
D6B	2/2013	Reactivation 3	Main scarp zone	17	0	26	14	14	10	8	11
D6C	2/2013	Reactivation 3	Main scarp zone	16	8	16	9	15	14	7	15

Sm smectite (montmorillonite), *Ch* chlorite, *I* illite, *K* kaolinite, *Q* quartz, *F* feldspar, *and* andesine, *alb* albite

landslide area. The border line between alluvial sediments and volcanic rocks could be a zone of rainfall infiltration which together with surface infiltration and sewage water from the school buildings is the main source of moisture within the landslide body.

The whole area of the school grounds between the new asphalt road and the upper path is threatened by landslide reactivation. In addition, it is clear that progradation of the main scarp edge will continue towards the school building during the next rainy period. The hazard level is high due to the threat to the school building and school facilities above the source zone and the road in the accumulation zone. School staff confirmed that the school administration requested assistance from the government to solve the arising problems.

Landslides along the hillside cut of the Dessie–Kombolcha road (2)

Another destabilization of the slope was registered approx. 0.5 km away from Menbere Tshay locality in connection with the deepening of the slope cut during construction of a new road from Kombolcha to Dessie in 2009.

This hazard area extends more than 1 km along the road and has two main features: (i) highly damaging rock falling from the steep slope (60–80°) and rock walls above the road together with (ii) six well-marked debris flows with their source area below the level of the road (Fig. 6). The material of the debris flows is a combination of natural colluvial deposits, soils and artificial landfill. Newly opened lateral cracks and a down-dip block (1–2 m wide) behind the scarp (currently about 20–30 m from road) were observed. Movement of the unconsolidated material and the creation of the deep erosion gullies partly correlate with the man-made drains under the road.

The geodynamic changes in the study site compared to the original state in 2005 and the situation in 2009 and 2012 are clearly visible on Fig. 4. The biggest problem in this zone is the traffic on the asphalt road, which is threatened by rock falls or rock slides from the steep cliff edges. For this reason, retaining structures (concrete grids and gabions) and retaining walls above the road have been built and other technical measures are still under construction.

The hazard level in this locality is now moderately low compared to the other described sites; thanks to the implementation of remedial measures and the fact that there are no settlements in the area below the slopes. From a long-term perspective, the gradual erosion and cutting processes on the top edge of several debris flows towards the asphalt road may cause problems.

Kerra (3AB)

Landslides at Kerra affect alluvial sediments on a gentle to steep slope around a right tributary of the Borkena River (Fig. 7). The

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Fig. 6 Several debris flows below the cut of the new road from Kombolcha to Dessie; close-up photos **a** scarp in stratified volcanic rocks over the road (along with the construction of the massive retaining walls) and **b** the upper part of the largest debris flow (photo Z. Vařilová)

sediments (with silty clay material) reach a depth of 55 m (Eshetu et al. 2013). The source area borders a densely inhabited zone lined by a trunk road. The main old translational landslide is about 650 m long and 400 m wide. The date of the initiation of the landslide is unknown. This severely affected zone features a long record of reactivations (Terefe 2001; Ayenew and Barbieri 2005 or Eshetu et al. 2013). In Kerra, the risk has led in the past to the evacuation of several households, damage to property and woodland and land degradation.

Various types of recent minor landslides (slump translational planner), longitudinal and transverse cracks were indentified in this area. The slope failures of the unconsolidated material are induced by undercutting by the Borkena River and its tributary. This site can be divided into two parts denoted as A and B in Fig. 7.

Northern landslide, part A: This zone is represented by an old landslide along the bed of the tributary of the Borkena River. It was reactivated 6, 2 and 1 year ago (based on oral information from the local inhabitants). Another reactivation was observed in the southern part within a large old landslide above the Borkena River. This reactivation is approximately 3 years old. Deep erosional gullies and cracks 5–10 cm wide parallel to the scarp at a distance of 0.5–1 m from the existing edge were found in the autumn 2013.

Southern landslide, part B: This landslide is located on a slope with an inclination of 17° at the end of a small E-W orientated valley. The landslide crown is retrogressing up the slope. Nowadays, it is directly bordering a new housing area. Construction of the housing began in 2005 and the built-up area covers a total of 67 ha (Fig. 8). The upper edge of the receding slope represents a threat to the houses. The last large event occurred 3 years ago. New deep cracks at a distance of 5 to 10 m from the houses were observed in 2013. Erosion and recurrent slope movements are induced in connection with intensive rainfall. Every year, a number of new small landslides are registered.

Several measures have been implemented in the past such as the plantation of eucalyptus trees. However, new hazards have occurred in the Kerra area and also in other landslide zones of Dessie town (Eshetu et al. 2013). The hazard level is still high and this area will be at risk in the future. The main factor inducing landsliding is the geological setting together with intensive rainfall. However, another anthropogenic

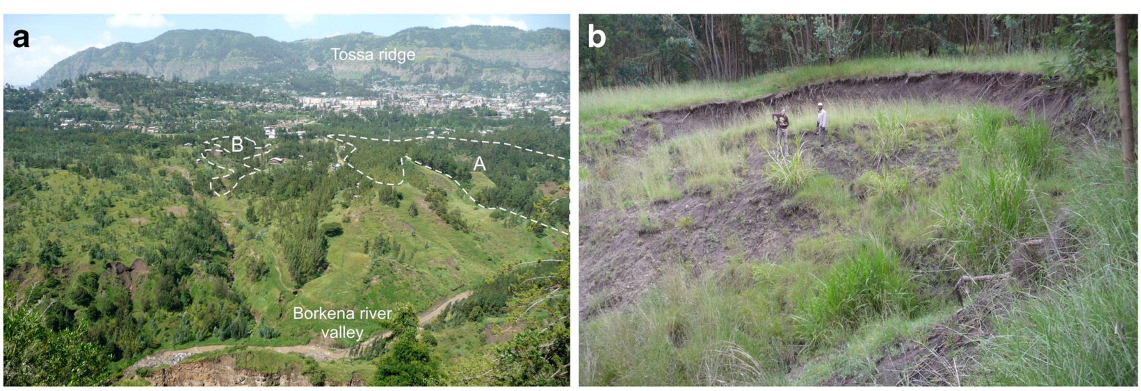

Fig. 7 **a** Two main landslide zones within the Kerra area (*A*, *B*) and **b** one example of a recently developed minor landslide observed there in 2013. Other shallow landslides and abundant creeping are clearly visible between the landslides *A*, *B* and the Borkena river valley (photo Z. Vařilová)

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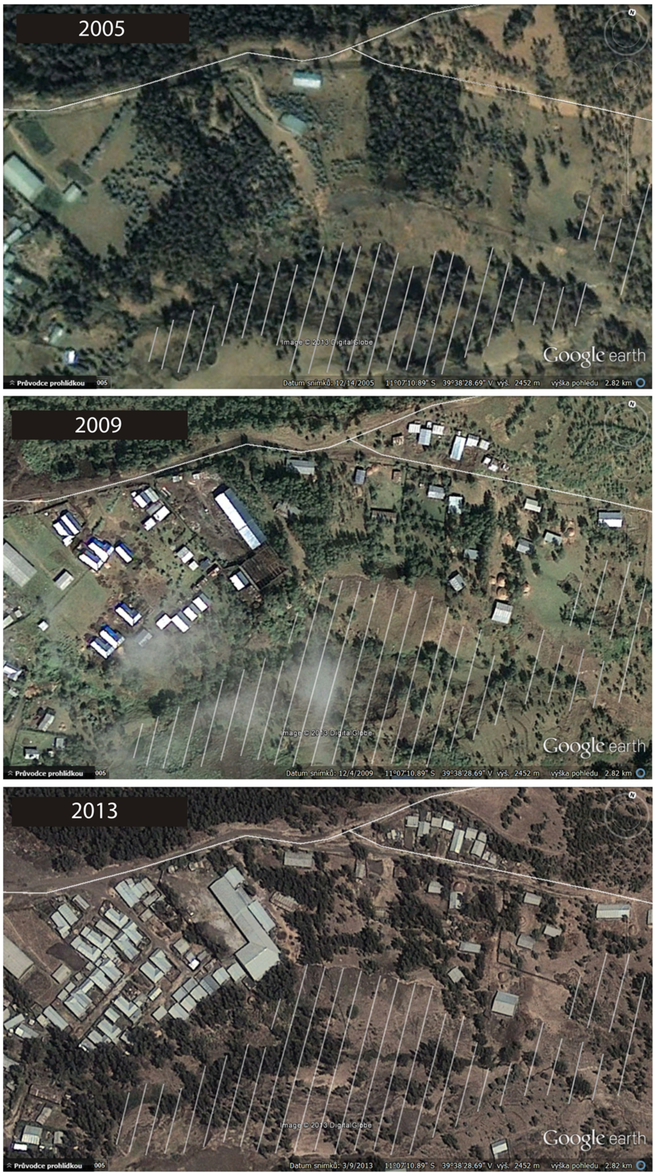

Fig. 8 Satellite images showing the local deforestation and the rapid expansion of settlements in the vicinity of the landslide area (Kerra B—indicated by *hatching*). The built-up area has grown by nearly 6700 square metres in a period of 8 years in this area. This is a typical example of a natural hazard area which will become risky due to changes in land use

phenomenon is observed here, namely the building of new houses near the unstable slope which is directly threatened by landslide activity. There is a clear lack of urban planning that would take into account the potential risks as well as an operational control system that would prevent the building of houses in potentially affected areas. The houses are only a few years old, and eviction from the risk zone is currently under discussion. Interviews with the local inhabitants revealed that they had been relocated to this area from another endangered site.

Doro Mezleya slope (4)

The most remarkable and probably the largest slope failure within the Dessie graben was recorded in the area called Doro Mezleya. The scarp of this huge rock slide/avalanche is directly visible from the city centre (Fig. 9). The tectonic setting (and rock structure) together with the very steep topography and local drainage system predispose the landslide and play a key role in triggering the hazard in this locality. It is located at the outlet of the Borkena River from the basin which forms a narrow 300-m-deep gorge following the fault. The topography of this site is extremely steep due to the backward erosion of the Borkena River, which is marked by a waterfall some 200 m up-stream from the accumulation zone. The Doro Mezleya rock massif is built up of stratified and highly weathered basalt. The site coincides with a crossing of two fault zones (see Fig. 2).

This huge landslide is mentioned several times in the literature (Ayenew and Barbieri 2005; Suyum 2011; Eshetu et al. 2013). Unfortunately, information on the precise timing of the landslide event and its reactivations is missing. Subsets of aerial photos provided by the Ethiopian Mapping Agency show that the sliding occurred in several phases. Erosion and an initial sliding are already visible on the photograph from 1958. This was followed by a mass movement affecting the whole width of the valley. During this significant phase of the landslide activity (rapid slope failure/rock avalanche), a massive part of the slope collapsed damaging an electrical tower, property of local residents, and a church situated on the slope (Eshetu et al. 2013, oral information). The triggering factor of this slope failure was likely an earthquake in the 1970s (oral information from the local people). Earthquakes with their epicentre 33 and 35 km from Dessie were recorded in 1977 and 1979, respectively (Gouin 1979; USGS). However, the largest changes in landslide morphology were newly identified from aerial photographs between 1986 and 1994. These changes could be possibly linked to earthquakes in 1990 or 1993 with their epicentre about 10 km from Dessie (USGS). Based on the observed data and new information, it is clear that the sliding activity occurred in several phases (Fig. 10).

The Borkena River is gradually eroding the base of the sliding mass and adjacent slopes destabilizing blocks in the upper part of the gorge. The main landslide body is currently about 260 m wide and 450 m long. The landslide spans an elevation range of 320 m while the head scarp is 25 m high. The source area has an inclination of 42° while the lower part of the slide is much steeper (50°). The eastern part of the subvertical fault scarp follows a N-S direction towards the Azwa Gedel ridge fault. The western side is characterized by a gently inclined slope with a sharp edge several metres high (see Fig. 9a). This upper edge is formed by columnar jointing of volcanic rocks with an inclination of 48°. The northern part of the block of Doro Mezleya hill is separated by a fissure and shows a subvertical displacement in the order of 6 to 7 m (documented by stratigraphic comparison of adjacent blocks and measured using the laser rangefinder).

Occasional rock falling and small block slides into the gorge are common events. Recent local reactivation (local rock falls and debris flows) could be also influenced by small scale quarrying activities by local people, which take place in the middle part of the rock slide area (Fig. 9c). The upper western part of the scarp is used as a waste disposal site for the town, and the landfill accumulation is gradually increasing in volume and areal extent.

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Fig. 9 Doro Mezleya landslide area: **a** view from the upper southern edge of the scarp towards the Dessie graben with the Borkena river valley, **b** view of the whole landslide area from the Azwa Gedel ridge pathway, **c** small reactivation in the central part of the landslide area partially influenced by quarrying activities, **d** rock fall in the erosion gully adjoining with landslide area to the north (photo Z. Vařilová)

Another morphologically distinctive phenomenon is represented by natural erosion gullies that drain into the Borkena River from the north next to the Doro Mezleya landslide. It can be assumed that deepening of these gullies occurs especially during intense rains by erosion and continuous slope deformation and the related gradual weathering of rocks. A fresh rock fall in the autumn of 2013 (with a volume of more than 10 m3) was observed in one of the erosion gullies (see Fig. 9d). No significant expansion of these gullies towards the town has been found by comparing the satellite images in Google Earth (2005–2009–2013). However, an expansion of settlements in the opposite direction in the same period was documented. This represents an emerging risk as the edge of the new housing area is at present only 50 m from the gully, whereas it was more than 200 m away in 2005.

No prevention action has been taken yet. There are several contour trenches (about 30 cm deep and 7–20 m long) on a gentle slope between the buildings and the upper edge of the landslide scarp to the west of the landfill. The trenches were probably built up in order to reduce surface runoff and related erosion processes, but in this case, they are

Fig. 10 Subsets of aerial photos of the Doro Mezleya locality provided by the Ethiopian Mapping Agency showing that the sliding occurred there in several phases. The major sliding took place between 1986 and 1994

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counterproductive because they bring water to the scarp zone of landslide area and can contribute to future destabilization.

The greatest risk in the future, which would endanger the settlement, electricity lines and infrastructure situated above, could be a repeated large slope failure—e.g. deep-seated gravitational slope deformation initiated by an external impact such as an earthquake. Small scale destabilization of parts of the scar could also be triggered by quarrying activities. From a long-term perspective, there may also be problems with debris flows and erosion of the steep unstable slope. Occasional rock falling and the slow retreat of the upper edge of the scarp towards the housing area may destabilize the extensive landslide area above the Borkena riverbed. Slope angle reduction and planting of more trees could help to minimize the effects of the hazard there. Another problem is the growing waste dump that burdens the upper part of the landslide body and hinders tourist development in this valuable scenic area.

Conclusions

The area of the Dessie graben is prone to slope failure due to the geological setting, high energy relief and rainfall concentrated into short periods. This article presents four typical examples of recent slope movements in the area. The studied landslide areas have been evaluated in terms of their historical development (especially with the use of remote sensing data), the current status (based on field survey results) and also potential risks in the future. New landslides and reactivations were documented in detail from February to October 2013 (after the above-average rainy period) in all of the studied sites.

The most significant morphology changes and recurrent problems were reported for the Menbere Tshay area. The landslide area is much more extensive and affects not only the visible zone of reactivation but the entire school compound. This locality is not only an example of unsuitable foundations and non-functional remedial works but also currently one of the sites with the highest risk.

The problem with slope instability in Dessie town is still also acute in other localities and may increase in the future due to the fast expansion of the town. The influence of anthropogenic activities was identified as one of the main triggering factors of reactivation in the observed cases. Fast urban sprawl leads to construction of houses and infrastructure on the outskirts of the city (including the landslide hazard areas) over the last 8 years. It was documented at the selected sites that construction continues in areas where damage by landslides has already occurred. Moreover, remedial and technical measures implemented in the studied areas were found to be partly inadequate or ineffective, which represents a serious issue causing recurring problems.

A long-term landslide hazard will continue to be a significant problem in the area. At least a part of the problem in the future can be prevented by more appropriate urban planning (functional planning and control of housing development) together with investment in functional drainage systems and also by increasing the awareness of responsive authorities and local residents.

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