

Causes and consequences of Rishiganga flash flood, Nanda Devi Biosphere Reserve, central Himalaya, India

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On 7 February 2021 at 10:30 am, a huge amount of slurry material flooded the Rishiganga catchment, resulting in excessive flow along the valley. The main cause of this flood was the dislocation of a huge rock mass approximately 540 m wide and 720 m long from the main rock body, which slipped down towards the Raunthi Gadera valley floor, causing massive devastation in the areas such as Raini, Tapovan, and Vishnuprayag. This event was not expected and was the first event in history when a flash flood occurred in winter. In this study, we tried to answer two major questions which are not been explained so far that are related to this disaster. These questions are (i) why did this event occur in winters? (ii) where did so much debris and water come from?. This study clearly answers these questions based on field observations.

Keywords: Flash flood, Himalaya, Nanda Devi, Raunthi Gadera, Rishiganga.

THE mountain ranges like the Himalaya have suffered from natural hazards from time to time, which have caused the deterioration and imbalance in the Himalayan environment¹. It is well known that the Himalaya has a young and fragile ecosystem due to the ongoing tectonic or neotectonic activities². Moreover, climatic factors like global warming as indicated by the recession of the glaciers, are also responsible for the worsening of the environment³. Besides, anthropogenic activities, unplanned developmental works and the rapidly increasing population have also affected the Himalayan environment⁴. In the morning of 7 February 2021, there was a huge flash flood/debris flow originating from the Raunthi glacier (4250 m amsl), Rishiganga catchment, central Himalaya, Uttarakhand, India. It traversed (~32 km) from the Raunthi Gadera to Raini (2000 m amsl) and Vishnupryag (1400 m amsl) areas, and destroyed the Rishiganga hydroelectric dam site (13 MW) near Raini village and Tapovan Vishnugad project (530 MW) near Tapovan. The local bridges, roads and footpaths between Raini village and Vishnuprayag were also washed away by this event. Further, the loss of a large number of human lives and damage to property and livestock have been reported

from the region. Around 205 people were reported missing, 77 bodies and 35 human body parts were recovered from different places⁵.

The Raunthi is a compound valley-type glacier formed by two tributary glaciers, extending between 4250 and 6500 m amsl and laying on 12° surface slope (Figure 1). A huge rock mass approximately 540 m wide and 720 m long appended with glacier ice and snow triggered at an altitude of 5600 m amsl due to slope failure in the Raunthi Gadera valley floor (Figure 2 a–c). This created an admixture of snow, glacier ice, rock fragments, water-saturated sediments and moraine debris, in the valley floor, defined as slurry. It is assumed that this slope failure formed small ponds/lakes at the valley bottom at an altitude of about 3800 m amsl (Figure 2 g and h). Subsequently, the large section of rock mass and hanging glacier fell down and breached these ponds/lakes, which washed away both the banks of the Raunthi Gadera, Rishiganga and Dhauliganga valleys causing massive devastation to areas like Raini, Tapovan and Vishnuprayag. This event was not expected and was the first of its kind in the

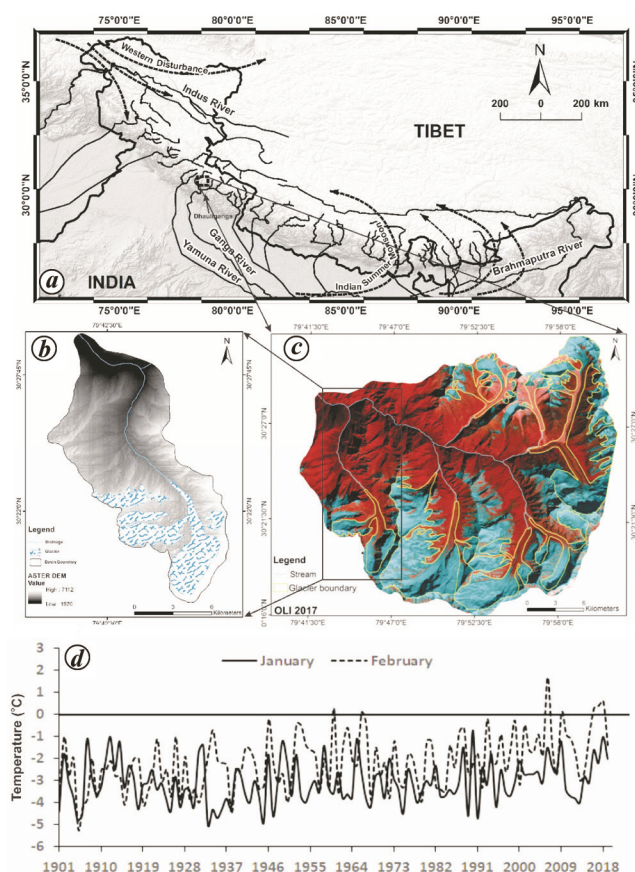


Figure 1. a, SRTM DEM of India showing the location (black dashed line) of the Nanda Devi Biosphere Reserve and major river systems of the Indian Himalaya. b, c, Satellite images of ASTER DEM (2011) and Landsat OLI (2017) respectively, showing the location of the Raunthi glacier and its catchment from where the disaster originated on 7 February 2021. d, Temperature variability during January and February from 1901 to 2018 in the study area derived from CRU TS 4 data.

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history when a flash flood occurred in winter. This catastrophic event changed the landscape in the Rishiganga and Dhauliganga valleys, making the entire region more fragile and vulnerable to landslides and debris flow. The disaster of such a magnitude was perhaps not witnessed in the region at least for the last 100 years, and thus can be categorized as an ‘extreme event’ of this century in Uttarakhand.

Nanda Devi Biosphere Reserve falls within the upper Rishiganga catchment (a tributary of Dhauliganga), central Himalaya (30°16′–30°32′N and 79°40′–80°02′E) covering an area of ~690 km² (up to Raini village), of which 26% is covered by glaciers⁶. The catchment area has glaciers-modified U-shaped valleys; the altitude ranges from 2000 to 7817 m amsl (Figure 1). Some of the prominent glacier peaks in the area are Nanda Devi (7817 m asl, 7434 m East), Trishul (7120 m), Devasthan (I – 6490 m, II – 6465 m), Mrigthuni (6855 m) and Nanda Ghungti (6369 m). The Raunthi, Trishul, Dakshni Rishi Bank (DRB), Dakshni Nanda Devi (DND) and Ramni glaciers have a crescentic course. The Rishiganga river

originates from the Dakshni Rishi glacier (4570 m) near the base of the Nanda Devi Peak (Figure 1) and joins the Raunthi Gadera (originating from Raunthi glacier) at 2346 m amsl (Figure 1), passing through Raini village. The Rishiganga is the main tributary of the Dhauliganga river and joins the latter near Raini village (1940 m). The Dhauliganga joins the Alaknanda river at Vishnuprayag (1440 m). Geologically, the area is composed of rocks belonging to the Vaikrita Group like garnetiferous mica schist and garnet mica schist which are well exposed along the Rishiganga catchment⁷. The catchment is dominated by Higher Himalayan rugged topography with high-elevation ridges adjacent to deep glacial valleys. The concave side of the glacier valleys face west and their crescentic course extends from cirques to the point where the glaciers melt and emanate streams that join the Rishiganga (Figure 1).

On 7 February 2021 at 10:30 am, a huge amount of slurry material flooded the Rishiganga catchment, resulting in excessive flow along the valley. The main cause of this flood was the dislocation of a huge rock mass approximately 540 m wide and 720 m long from the main body, which slipped down towards the Raunthi Gadera valley floor (Figure 2 a–c). The approximate area and volume of this rock mass were about 0.17×10^6 m² and 20 MCM respectively. The National Polar Ice Glaciology, Glaciology Group, Norwegian Polar Institute estimated the maximum and minimum depths by differencing Pléiades stereo imagery of the dislocated area to be ~150 and ~75 m respectively⁸. We have used an average depth of ~112.5 m ($(150 + 75)/2$) of the dislocated area for volume calculation. In this study, we address two important questions (mentioned below) regarding the disaster in Raunthi Gadera, Rishiganga catchment, Uttarakhand.

To understand the causes of the flash flood in winter, first we need to understand the climatic conditions of the region. In the absence of any instrumental meteorological data for the catchment, we have used the Climate Research Unit Time Series (CRU-TS 4.03) data to understand the climatic conditions of the study area⁹. Interpolated gridded data (30.25N and 79.75E) derived from CRU-TS 4.03 for 118 years (1901–2019) show that the temperature in January and February is below 0 degrees (Figure 1 d). The CRU data clarify that heavy snowfall was not the only factor which was responsible for the triggering of this event, because most of the glacier part is frozen during winter. The long-term cumulative effect of multiple factors (weathering, percolation of melt water into the joints, crevasses, freezing and thawing, snowfall and overloading) is responsible for the same.

During field surveys (from 8 to 12 February and again from 19 to 27 February 2021), we could identify the scar of a huge rock/ice mass that fell down due to slope failure, into the Raunthi Gadera valley and created havoc in the downstream region (Figure 2 a–c). It was observed that a hanging glacier was lying over the big chunk of

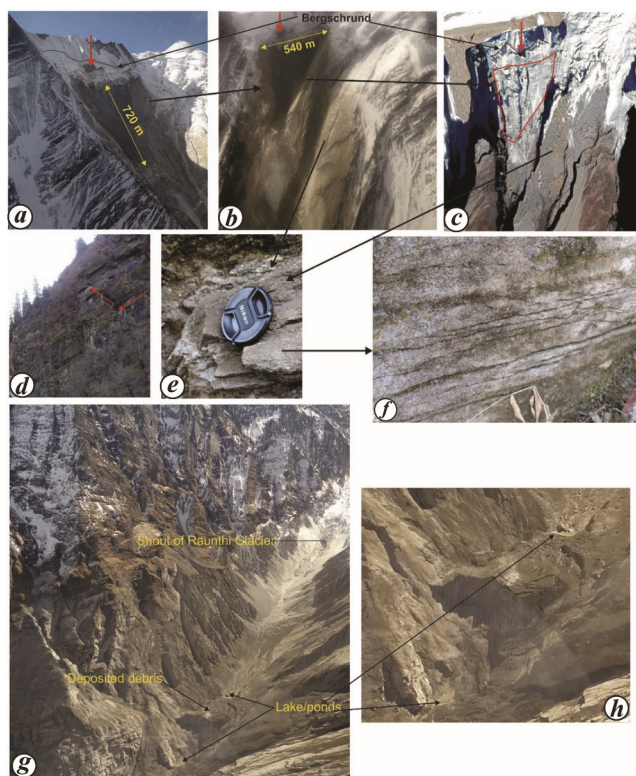


Figure 2. Field photographs showing the (a, b) post-event and (c) Google Earth Image pre-event scenario of the Raunthi Gadera valley, from where the disaster originated. The rock and glacier fall zone are shown in (a–c), red arrows indicate the reference points (a–c). The rock mass overlying the hanging glacier detached ~100 m below from this point (red arrows). (d–f) Lithology in and around Raunthi catchment. Red arrows in (d) indicate the joints pattern (two sets of joints) in the rocks. (g, h) Post-event field photographs showing the area from where debris deposited and formed small ponds/lakes, some have still remained after the disaster (shown by black arrows).

rock mass and the slope of the scar ranged between 35 and 45 degrees (slope gradient was 613 m/km). The rocks of the area (Raunthi Gadera catchment) consist dominantly of garnet mica schist, micaceous quartzite and quartz mica schist^{7,10} (D. Sati, unpublished). The rock mass on which the hanging glacier was seated was highly weathered garnet mica schist. During the field survey we observed that the rocks of the surrounding area were highly jointed (two sets of joints) (Figure 2 *d* and *e*), dipping 40° and strike of 140°. Due to the thawing and freezing processes, joints of the weathered rock mass were exposed and shattered, which made this rock vulnerable and fragile in due course of time (Figure 2 *e*). Simultaneously, on the hanging glacier huge transverse crevasses had developed (~100 m) below the bergschrund (Figure 2 *a–c*). Due to this, the hanging glacier was detached from the main body (accumulation zone of the glacier) and formed a weak zone on the shattered rock surface along the joints. In addition, the valley received heavy snowfall on 4 and 5 February 2021 (India Meteorological Department). Therefore, due to the cumulative effect of all these factors (weathering, percolation of melt water in the joints, crevasses, freezing and thawing, snowfall and overloading), the weathered rock mass could not bear the load of the hanging glacier/snow. As a result, the hanging glacier along with the rock mass slipped down across the dipping direction (wedge failure). This can be assigned as ‘structural discontinuities like the interface between weathered rock and the underlying bedrock’.

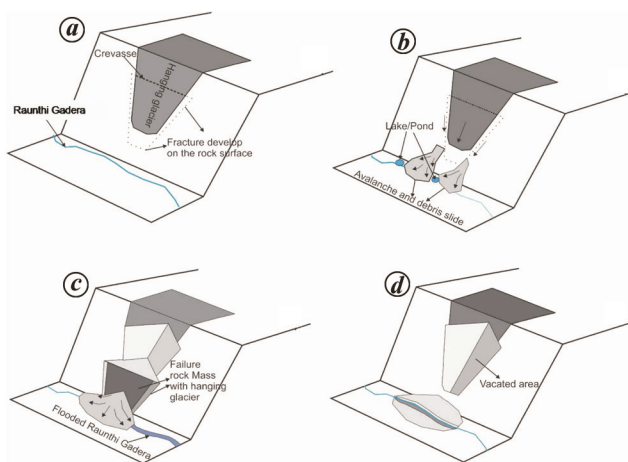


Figure 3. Schematic diagram describing how the flash flood occurred in the Raunthi catchment. *a*, Triangular-shaped fracture (black thin dotted line) developed on the surface of the rock where the hanging glacier was connected with the rock mass. Along this fracture, a huge transverse crevasse (black thick dotted line) developed over the surface of the glacier. *b*, The slide started along this fracture and pieces of ice mixed with debris fell down in the form of an avalanche, that blocked the Raunthi Gadera and formed small lakes/ponds. *c*, After some time a huge block of rock mass with hanging glacier fell down and started flowing downwards with water. The flooded material was constituted by debris, water and a block of ice which made it slurry. *d*, The rock mass was highly weathered and brittle due to chemical and mechanical weathering. Hence it broke and shattered after its fall; therefore no rock pieces are visible as remnants.

It has been confirmed that the disaster in the Rishiganga (Raunthi Gadera valley) occurred due to the failure of the large rock mass and attached hanging glacier. It has been observed that this event was episodic. First, an avalanche may have brought with it debris, and then gradually the slide would have started from a few days or a few hours before the disaster. The material coming from this slide blocked the stream coming from the Raunthi glacier (4250 m) and formed temporary ponds/lakes at an altitude of ~3800 m amsl. The evidence of ponds/lakes (craters) due to the blocking of the Raunthi stream is still present in the Raunthi catchment (Figure 2 *g* and *h*). Subsequently, a large section of rock mass and hanging glacier fell down and breached the temporarily formed ponds/lakes. Figure 3 is a sketch explaining the whole process. The weathered rock (mica schist) was brittle due to chemical and physical weathering; hence it broke and shattered after it fell down and increased the volume of debris at the valley bottom (Figure 2 *d* and *e*). A Google Earth image of 2016 showed that the huge avalanche or dead ice (approx. 2 km long) with debris was deposited in the valley between 3200 and 3600 m amsl, covering an area of about 0.2 km² (Figure 4 *a*). This deposited material clearly shows the kettle holes (sink holes) which are formed at different altitudes. This deposited material and kettle holes suggest that it has been formed due to the avalanches or dead ice released by the glaciers (Figure 4 *a*). As a result, a large volume of debris and water struck the valley bottom, which simultaneously collected huge amounts of loose sediments enroute^{11,12} (Figure 4 *b*). The impounded water studded with debris from the surrounding regions and glacial loose sediments (moraines) moved downstream, washing off the upper part of the valley (Rishiganga and Tapovan hydropower projects, bridges, forests, roads, etc.), leading to the biggest ever devastation in the region during winter.

Historical studies show that the highest risk of instability processes in the Uttarakhand Himalaya is related to high-intensity hydro-meteorological events¹³. During the last millennium, the region has experienced more than 40 mega floods¹⁴. As a result, the state has suffered serious losses to lives and property. The magnitude of the 7 February 2021 Rishiganga disaster was probably the largest in the history during winter. The damage caused by this disaster is similar to the Kedarnath disaster of 2013 (refs 1, 3).

The huge amount of debris, ice block and water released from the Raunthi Gadera led to heavy devastation in the downstream areas, and its effect was clearly seen till Vishnuprayag (~32 km) (Figure 5 *a* and *b*). During the disaster, the high flood level (HFL) of the Raunthi Gadera rose to 80–100 m above the normal flow stage causing intense bank erosion (Figure 5 *a* and *c*). This flood completely washed away the forest located on both sides of the Raunthi Gadera, and dislodged huge debris, boulders and tree trunks from the catchment area. Due to higher

gradient (150 m/km), Raunthi Gadera brought massive debris that completely blocked the flow of the Rishiganga. Thereafter, due to the blocking of water of the Rishiganga, a freshwater lake (30°28'04.06"N, 79°44'09.8"E) was formed at an altitude of ~2390 m amsl, which is about 500 m long and 100 m wide near the front. This lake can prove dangerous in the future (Figure 5 *d*). Moreover, the material moved down and demolished the Rishiganga hydro project; which reduced its gradient (50 m/km) significantly at this point (Figure 5 *e*). Further, the water destroyed a cemented bridge, barrage site, suspension bridge, settlements and deposited large amounts of debris along the river. Due to higher gradient (150 m/km), the Rishiganga (Raunthi Gadera) brought massive debris that blocked the flow of the Dhauliganga river for an unknown duration and formed a lake about 1.5 km long. Further downstream, the river gradient suddenly decreased to 45 m/km and the Rishiganga water met with the Dhauliganga and increased its erosion intensity. Thereafter, huge debris mixed with water, tree trunk and ice blocks

eroded both banks of the Dhauliganga and hit the barrage site of the Tapovan Vishnugad, completely filling the hydroelectric dam site (22 m height) and then flowed above from the dam axis (Figure 5 *f*). The magnitude of this event was very high, as more than 205 human lives were lost or were untraceable, two hydropower dams were completely demolished, and four suspension bridges and one motorable bridge were washed away^{15,16}. An initial survey by an agency of the World Bank, NTPC and the media estimated the financial loss incurred due to the event to be more than Rs 1500 crores.

The intensity and frequency of the disasters have increased in the Himalaya during summers¹. However, disasters like flash floods generally do not occur in the area during winter. This event can also be related to the effect of global warming, as the breaking of the hanging glacier or detachment from the main body indicates melting. Even before the hanging glacier was laid over the bed-rock, due to climate change the former melted out and the latter was exposed. Thereafter, due to physical and chemical weathering weak zones had developed along the

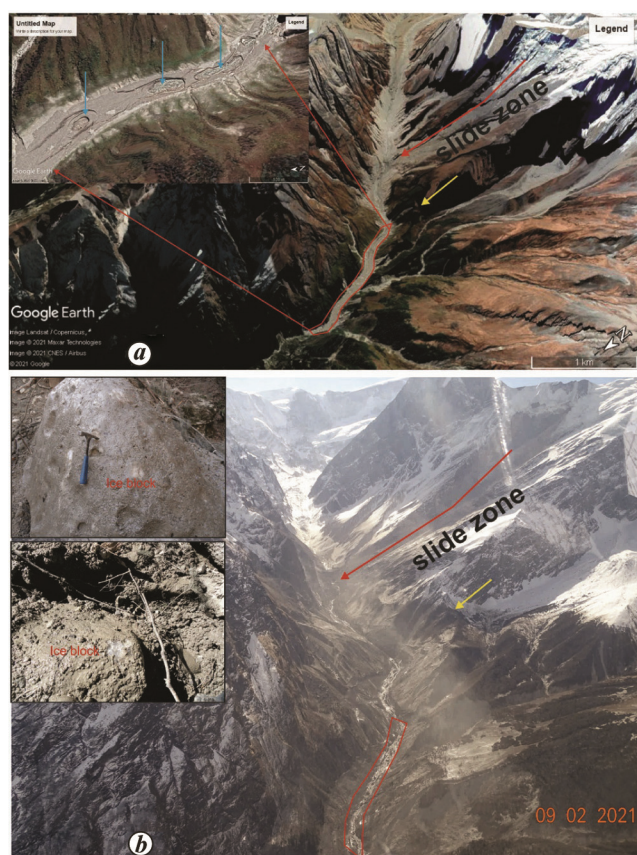


Figure 4. *a*, Pre-disaster scenario of the Raunthi catchment (Google Earth Image); red polygon in the valley bottom shows the deposition of slurry material (also shown in the Inset). (Inset) Blue arrows show the kettle/sink holes formed due to the melting or collapse of the subsurface ice. *b*, Post-disaster photograph of the Raunthi catchment showing the destruction caused by the flash flood. The bank of river valley and slurry material (red polygon in *b*) have been completely washed out. (Inset) Large blocks of ice which have been transported and deposited downstream over long distances till the Tapovan dam site.

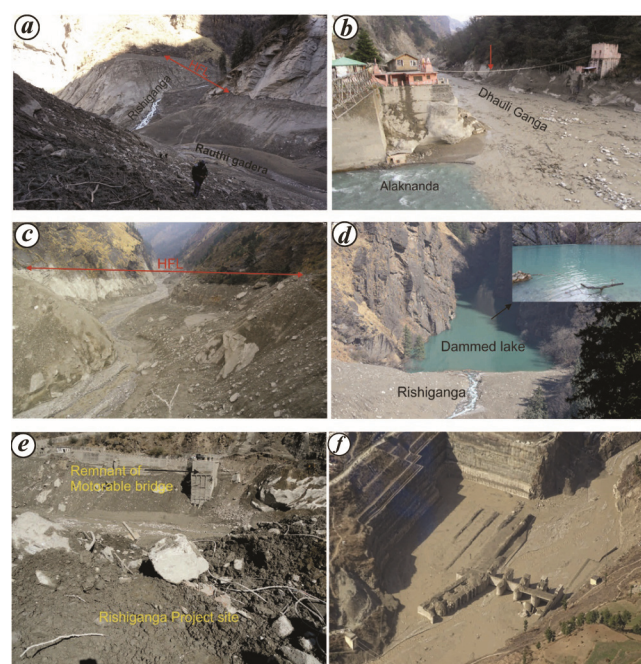


Figure 5. Post-disaster field photograph showing the consequences of the flash flood between Raunthi glacier catchment and Vishnuprayag. *a*, Confluence of the Rishiganga and Raunthi Gadera, and a freshwater lake that was formed ~300 m above the confluence point. During the flash flood, the high flood level (HFL) (red arrows) was about 80–100 m. *b*, A suspension bridge (shown by red arrow) near Vishnuprayag was washed away due to the flash flood. *c*, Downstream view of the Rishiganga catchment showing debris deposited along both banks of the river; HFL was about >80 m. *d*, Rishiganga dammed freshwater lake which was formed due to the blocking of the channel of Rishiganga by the debris transported through the Raunthi Gadera. *e*, Rishiganga project site and remnants of a motorable bridge connecting to Raini and Malari that was completely demolished. *f*, Barrage site of the Tapovan Vishnugad project near Tapovan, which has been completely filled with debris.

joints in the rock. This was also the main cause of slope failure in the Raunthi catchment.

The disasters have increased in the area as a result of increasing anthropogenic activities. This trend is likely to continue in future as development activities are a threat to the environment. The natural flow paths of rivers have been obstructed due to the construction of man-made structures, resulting in the deviation of natural flow. Apprehending the tendency of increasing urbanization due to increase in developmental activities in the area, selection of safe land-use locations would be a formidable task to accomplish. However, the Government has to consider these issues in future while rebuilding the devastated area.

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Economic analysis of pesticide expenditure for managing the invasive fall armyworm, *Spodoptera frugiperda* (J.E. Smith) by maize farmers in Karnataka, India

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The fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) invaded India for the first time in May 2018 in Karnataka and since then has threatened maize production in the country. In this study conducted during 2017–2020, a total of 150 smallholder maize farms were randomly selected and surveyed from three major maize-growing districts in Karnataka for the pesticide usage patterns, pesticide cost and yield. During 2020, FAW infestation level was recorded at 2.15 larvae per 100 plants with an overall Davis damage score of 3.80. Maize farmers used on an average 2.12 pesticide sprays per season for FAW management in the surveyed districts in 2020. Maize yield was 4.46, 3.76, 4.06 and 4.18 tonnes per hectare in 2017, 2018, 2019 and 2020 respectively, and the average cost on

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