Reply to anonymous reviewers #1 and #2

We appreciate your valuable comments to improve this study. We hereby revised our manuscript as described below. Newly added description in the manuscript are colored in red.

Reply to Reviewer #2

The paper describes well the management and processing of remote sensing data, but it is still poor from the geomorphological point of view. In particular, I suggest to describe better the event occurred starting from the abstract and then in the text.

For the abstract I suggest to describe better that (if I understood correctly) the work described the effect of the catastrophic avalanche deposit area. The paper analyzed the effects of different deposition processes that are the related to the catastrophic avalanche made by rock, ice and snow.

We massively updated the manuscript including detail interpretation of deposition sequence from the sediment layers identified with WV-3 high-resolution image. The abstract is revised as follows.

> *… In the WV-3 image, surface features were classified into 10 groups. Our analysis suggests that the avalanche event contains a sequence of (1) fast splashing body with air blast, (2) muddy huge mass flowing, (3) less mass flowing from another source, (4) smaller amount of splashing and flowing mass, and (5) splashing mass without flowing at the east and west sides. By means of satellite-derived pre- and post-event digital surface models, differences in the surface altitudes of the collapse events estimated the total volume of the sediments as $5.51 \pm 0.09 \times 10^6$ m^3, most mass of which are distributed along the river floor and a tributary water stream. These findings contributes for detail numerical simulation of the avalanche sequences as well as source identification, and furthermore, altitude measurements after ice/snow melting would reveal a contained volume of melting ice and snow.*

A good geomorphological description of the avalanche deposition area is missing in chapter 2 and a partial description of results from previous study, that considered also field surveys, are presented only at the end of the manuscript (chapter 4.2). I think that readers need these details at the beginning of the text, to understand better what is occurred and what has been already published on this catastrophic event. At the end of the paper, in the discussion, authors can consider again bibliography to compare obtained results.

Previously known facts are summarized in the method chapter as follows.

> ***2.2 Avalanche event***
>
> *In this catastrophic event, co-seismic snow-and-ice avalanches and rockfalls with concurrent air blasts (Cadwalladr 2015). This contains multiple phenomena as described as "disaster-within-a-disaster" (Kargel, 2015). The sediment deposition is consists mostly of*

accumulated snow and less dominantly of glacier ice (Fujita et al. 2016). Satellite-based thermal infrared observation on 5 days after the quake denoted the deposition has 10-20 K lower surface temperature than surrounding terrains (Kargel et al. 2016). Water stream of the Langtang river was blocked once by the deposition but quickly recovered as the ice-and-snow deposition was melted (Kargel et al. 2016). The materials near the river bed had less boulder and sand-rich deposition, suggesting that they are originated from snow avalanche (Fujita et al. 2016). From the sediment volume and catchment area on the mountain hill, original snow depth before the avalanche occurrence was estimated at 1.82 m in the catchment hillslopes (Fujita et al. 2016). A meteorological observation at a neighbouring glacier suggested four major snowfall events since Oct 2014 and an anomalous large amount of snow was charged before the quake. An interview reported that many hanging glaciers were cracked and huge pieces of ice falling occurred forming a cloud gathering snow and rocks with air blast (Cadwalladr 2015). However an in-situ survey suggested that detached glacier ice was less dominant than involved snow, represented by observed clear ice balls in the deposition (Fujita et al. 2016). After an following mas movement between 8 and 10 May, ice-and-snow melting decrease the sediment volume by 40% until Oct, 2015 (Fujita et al. 2016).

Multiple landslides was also reported (Cadwalladr 2015). Ice cliffs, exposure of ice-rich thick layer under a bolder-rich debris layer, are identified near the Langtang river, suggesting different timing of avalanche and subsequent rockfalls (Fujita et al. 2016). In the opposite-side north-facing steep slopes, debris materials were found at 200-m higher places above the deposition bottom, which suggested that they travelled at 63 m s^{-1} *(Kargel et al. 2016). On the other hand, avalanche entraining sand and silt was reported as "black avalanches" (Fujita et al. 2016). Post-event photographs and satellite images suggested debris materials originated from rockfall and landslide were not dominant in the deposition (Fujita et al. 2016; Kargel et al. 2016).*

The related articles all reported trees fallen down to uniformed directions at the opposite-side north-facing slope (Cadwalladr 2015; Fujita et al. 2016; ICIMOD 2015; Kargel et al. 2016). This was caused by catastrophic air blast reaching 332 km h^{-1} *travelled up to neighbouring villages of Singdum and Mundu (Kargel et al. 2016). Location change of a boulder over the event suggest that it received a blast exceeding 50 m* s^{-1} *(Fujita et al. 2016).*

In terms of collapse trigger, three separated main sources were suggested around the mountain peaks at 7000 m a.s.l. by snow cover thinning (~20 m) between April 2014 and May 2015 (Lacroix 2016). Hanging glacier detachment was considered by another study (Fujita et al. 2016). As described above, furthermore, anomalous winter snow seemed to amplify the sediment mass (Fujita et al. 2016). Topographic comparisons over the event revealed that the total mass of the sediment deposition was $6.81 \pm 1.54 \times 10^6$ m^3 *before the second mass movement caused in 8-10 May (Fujita et al. 2016) and* 6.95×10^6 m^3 *including* *the second mass deposition (Lacroix 2016)*

Another important element is figure 5a; this picture represents the area covered by avalanche deposits. This area has been divided in different sectors and (in my opinion) lectors should have the possibility to understand which choices did authors for dividing this area in sectors (morphological, sedimentological, thickness of deposits?). Again, the description from the geomorphological point of view is too poor to have a complete description of the event. This paper present a remote sensing application, but if authors want to work with natural disaster, they should provide a (complete) description of the case study also using elements and data already published.

We totally changed the delineation method more quantitatively and repetitively using un-supervised classification. The new method is described as follows.

2.4 Post-event optical imagery and DSM

Post-event optical satellite imagery and DSM were used to recognize the damaged situation in detail. A DigitalGlobe's satellite, WorldView-3 (WV-3) observed the Langtang valley on May 8, 2015, with a panchromatic sensor of 0.31 m spatial resolution and a multispectral sensor of 1.24 m spatial resolution to generate a set of pan-sharpened stereo pair imagery (Fig. 3). First, Area of Interest (AOI) is defined as that includes all sediment depositions. The complicated sediment outlines are delineated from the WV-3 near-infrared band, which appears the best clear contrast between the sediment depositions and the surface terrain, by means of a segmentation function of Iterative Self Organizing (ISO) cluster classifier in ArcGIS (e.g. Ball and Hall, 1965; Richards and Richards) (Fig. 4a). Other multispectral band images (Red, Green, and Blue) and the panchromatic image are synthesized into a pan-sharpened image (i.e. color imagery with 0.3-m spatial resolution). Using this image, the sediment depositions are divided into several groups based on visible characteristics of colors (dark or light) and deposition features (splashing, muddy, and flowing) (Figs. 4b-4f). After all the steps these images and delineated polygon layers are orthorectified with 174 tie points onto the ALOS pan-sharpened image taken on October 12, 2008.
Using the set of…

Then we describe how we have classified the layers in the result chapter with closed-up images as follows.

3.3 Collapse mapping with a post-event optical imagery

Visual identification and mapping of the sediment depositions from the very-high-resolution WV-3 image resulted in 0.88 km^2 covering which was classified into 10 groups (A-J) (Fig. 3; Table 1). The group (A) (area: 0.16 km^2) is characterized by dark muddy bottom to splashing uphill parts (Fig. 4b) where numerous trees fallen to the splashing direction are identified as previous studies reported (Fig. 4c) (e.g. Kargel et al. 2015). The group (B) (area: 0.25 km^2) begins from the headwall just under a glacier with relatively lighter colour than (A) (Figs. 4b; 4d). It flows to the river floor with curved streaks (Figs. 3; 4d; 4e). In the river flow, it shows more mud-like feature with visible wrinkles as group (C) (area: 0.13 km^2), accumulating to the downstream and slightly to the upstream, maintaining the same colour (Fig. 4b). The group (D) (area: 0.14 km^2) basically has clearly darker surface than (B) and (C) with less streaks and several splashed patches (Fig. 4e). Simultaneously gradual colour transition is seen from (D) to (B) (Fig. 4e). The group (E) (area: 0.02 km^2) is located at the lower side of (D) with the same colour and rather muddy feature quite like (C) (Fig. 4e). Gradual colour transition is also seen from (D) to (B). On the east side, very dark-colour patches of (F) (area: 0.02 km^2) and detached parts (G) (area: 0.01 km^2) are found (Figs. 3). They seem splashing, but have relatively muddy feature and not so homogeneous directivity compared to (A). Dark aperture deposition of (H) (area: 0.07 km^2) begins from another headwalls which is wider than and is independent from that for (B) (Fig. 4f). The splashing parts are blocked by (B) and (C), whereas the western part starts flowing along a narrow path to the river floor grouped as (I) (area: 0.02 km^2) (Fig. 3). This flow is finally connected to and covers (C) (Fig. 4c). The group (J) (area: 0.05 km^2) is a parallel and more aperture/splashing deposition compared to (H) (Fig. 4f). The surface colour varies from lighter to darker than (J), not related to the flow path.

Page 7 line 7: In this paragraph, authors described the volume change analysis. In particular, they assumed that negative changes are mistakes and they correct them to zero. In my experience, the transition zone of large landslides (and in particular of rock avalanches) is often characterized by negative changes that are caused by the erosional effect of the huge mass and its velocity. Of course I hadn't the possibility to analyze "uncorrected" data, but I suggest that authors consider the possibility that this complex process can cause also negative changes during its runout.
The interpretation of DEM comparison results is often a very complex task. The recognition of real negative changes from artefacts can be usually based on the shape and distribution of negative areas. A morphological validation can be usually considered a good solution.

As advised, we considered negative altitude changes using DoD tool recommended by another reviewer. Especially, the north-facing steep slope corresponding to the sediment group (A) seems to have lower reliability on DSM generation as entire negative trend. Destruction of forest and buildings as well as surface erosion are also considered in the revised manuscript as follows.

DoD3.0: http://gcd.joewheaton.org/downloads/older-versions/dod-3-0

3.4 Surface elevation changes

…Altitude decreasing was denoted in the groups (A), (F), and (G), where dominance of surface erosion and DSM error are considered. Mean altitude changes in the groups (D), (H), and (J) are smaller than the defined uncertainty level, 1.5 m.

Calculating the altitude change and surface area, a total deposition volume of 5.51± 0.09×10^6 m^3 was estimated, which is included within the estimated volume range by Fujita et al. (2016) (6.81±1.54×10^6 m^3) and not larger than the volume including the second mass movement (6.95×10^6 m^3) (Lacroix 2016). In addition, total eroded volume of 1.64±0.06×10^6 m^3 was estimated, most of which belongs to the group (A). In addition to the effect of the fallen trees, fundamental bias error induced by WV-3 DSM generation is considered for this extremely steep slope, because splashed patches and muddy deposition both denotes negative values. As well, groups (F) and (G) have negative net volume difference, possibly because of building collapse and slightly negative DSM bias larger than the deposition volume of the dark-colour materials.

Considering language, I suggest to revise in particular the following paragraphs because they are not very clear:

Page 1, line 12 – 17: please consider to rewrite this paragraph because it is not very clear

We revised that to follows.

The main shock of the 2015 Gorkha Earthquake in Nepal induced numerous avalanches, rockfalls, and landslides in Himalayan mountain regions. A major village in the Langtang valley was destroyed with numerous victims by a catastrophic avalanche event, which consists of snow, ice, rock, and blast wind. The hazard process is understood mainly depending on limited witness, interview, and an in-situ survey after a monsoon season. To record immediate situation and to understand deposition process, we performed an assessment by means of satellite-based observations carried out in no later than two weeks after the event. The avalanche-induced sediment deposition was delineated with calculation of decreasing coherence and visual interpretation of amplitude images acquired from the Phased Array-type L-band Synthetic Aperture Radar-2 (PALSAR-2). These outlines area highly consistent with that delineated from a high-resolution optical image of WorldView-3 (WV-3). The delineated sediment areas were estimated as 0.63 km2 (PALSAR-2 coherence calculation), 0.73 km2 (PALSAR-2 visual interpretation), and 0.88 km2 (WV-3), respectively. In the…

Page 6, lines 14 and 15: sectors 1 to 4 are considered “dark” but also sectors 12 to 15 are considered dark too, is it correct?

The chapter 3.3 was completely rewritten as described above. The sediment deposition has several dark parts in separated locations. We distinguish them with differences of surface features (flowing or splashing, for example).

Page 7, line 7 to 15: please consider to rewrite this paragraph because it is not very clear

We changed the method and results, adding consideration of negative altitude changes. The description on this line was therefore rewritten as follows.

> *Calculating the altitude change and surface area, a total deposition volume of* $5.51 \pm 0.09 \times 10^6$ m^3 *was estimated, which is included within the estimated volume range by Fujita et al. (2016)* ($6.81 \pm 1.54 \times 10^6$ m^3) *and not larger than the volume including the second mass movement* (6.95×10^6 m^3) *(Lacroix 2016). In addition, total eroded volume of* $1.64 \pm 0.06 \times 10^6$ m^3 *was estimated, most of which belongs to the group (A). In addition to the effect of the fallen trees, fundamental bias error induced by WV-3 DSM generation is considered for this extremely steep slope, because splashed patches and muddy deposition both denotes negative values. As well, groups (F) and (G) have negative net volume difference, possibly because of building collapse and slightly negative DSM bias larger than the deposition volume of the dark-colour materials.*

Reply to Reviewer #1

(1) You can use DEM of difference (DoD) algorithm to estimate the Surface elevation changes.

As advised, we considered negative altitude changes using DoD tool recommended here. Summary is described in Table 1. Especially, the north-facing steep slope corresponding to the sediment group (A) seems to have lower reliability on DSM generation as entire negative trend. Destruction of forest and buildings as well as surface erosion are also considered in the revised manuscript as follows.

DoD3.0: http://gcd.joewheaton.org/downloads/older-versions/dod-3-0

(2)You should refine the "discussion", not only present the result (you already write in the part of "result", you should discuss the "advantages, disadvantages, future work et al.,")

One core part of discussion was replaced as follows. we demonstrated temporal sequence of sediment deposition layers from identified layer orders. Connection to future studies is also describes at the end.

4.3 Temporal sequence of the avalanche event

Identification of sediment deposition layers from the interpretation of a high-resolution WV-3 image suggests that different sources provided various types of deposition continuously in a short period (Fig. 3). Splashing feature of the group (A) denotes a uniformed scattering direction along lines (x) to (y), suggesting an origin around the cross point of the lines (Fig. 4a). The group (B) and (C) has a lighter similar color than that of (A) and range wider coverage along the line (z) without splashing (Fig. 4a). Thus a border between (A) and (C) is visually identifiable (p1 in Fig. 4b). Huge mass of (B) and (C) denoted in Fig. 6a implies slower continuous flowing, whereas negative altitude change on (A) implies fast scattering with air blast which mowed trees down with less mass deposited on the steep slope. These conclude that the group (B) was provided after deposition of (A) with slower speed and larger volume from a different source, which was terminated filling the riverbed in (C) at the end.

Closing up, the west side of the group (D) has a similar surface feature and gradual color similarity to (B) (p2 in Fig. 4e). In addition, the group (E) has a similar surface feature to that of (C) with some wrinkles with a different surface color. These suggests that the layers of (D) and (E) are much thinner layer than those of (B) and (C), and they rode the formerly deposited (B) and (C).

The group (F) is connecting to (D) and similar darker color to the detached group of (G) (Fig. 3). They seem to have smaller amount of mass deposition than (D) at the same or later time from different sources. There are distributed with many ununiformed apertures, implying vertical dropping from the source (possibly after hitting some headwall surfaces), rather *than the fast second scattering after once hitting the ground terrain as seen on (A).*

The group (H) is distinguished from (B) by its darker color (Fig. 4d) and the beginning headwall foot at the west side (Figs. 3; 4f). The group (I) have a narrow flow with a certain thickness (~10 m) (Table 1) originated from the westernmost part of (H). It is terminated at the river floor, where it pushes and displaces the snout of (C) (p3 in Fig. 4c). They suggest that (H) and (I) are accumulated later than (B) and (C) from another source.

The group (J) has many apertures with slight flowing (fig. 4f). Its lighter and darker colors than (H) is not related to the flow direction, that implies heterogeneous mixture of materials were supplied, possibly hitting and involving several origins along the headwall.

Consequently, these considerations give a perspective of temporal sequence that avalanche event provided multiple types of depositions in order of,

(A) with extremely fast speed with air blast,

(B) with less flowing speed which covers the entire surface from the hoot of the headwall to the river floor,

(C) as a stacking part of (B) with the least flowing speed along the river flow to the downstream and partially upstream, depositing huge mass,

(D) which covers the eastern part of (B) after its deposition with some splashing,

(E) as a terminal part of (D) which covers the eastern part of (C) with thin layer,

(F) and (G) with a relation to (D), with which splashing in a larger area implies dropping from relatively higher position,

(G) with which splashing feature implies experience of hitting the headwall before deposition,

(H) as the terminal part of (H), riding the terminus of (C) with muddy flowing.

The group (J) is an independent deposition from neighboring (H), however the deposition timing in the above sequence is unknown. In addition, the group (H) has a possibility of earlier deposition than (D) to (G), because the groups of (D) and (H) has no direct relationships in evidence.

The suggested sequence is applied on the vertical profiles of Figs. 6b and 6c, schematically illustrated in Figs. 6d and 6e. Multiple types of avalanche-induced sediments are deposited in layers. The initial sediment, (A) will exist under the following sediment of (B) to (C) along A-A', and additionally (D) to (E) along B-B'. An in-situ survey with boring core and/or ground penetration radar might give some supporting findings. Realistic numerical simulation of *avalanche collapse and analysis of heat balance related to the melting process would need the consideration of multiple layers precisely mapped by our study. The muddy features interpreted in some layers imply high ice and snow content which are confirmed in an in-situ survey after the monsoon season (Fig. 9). Coupling further altitude measurements with temporal intervals would clarify the surface lowering by ice/snow melting, for which the water content estimation is invaluable as one of the input data for avalanche simulation and source consideration.*