Review of “Quantifying sediment mass redistribution from joint time-lapse gravimetry and photogrammetry surveys, by Mouyen et al.

This paper describes a field effort to quantify sediment mass redistribution over three years at a study area in Taiwan. The study integrates, for the first time that I am aware, repeat microgravity and photogrammetry measurements. The paper is well written and needs minimal editing. The study has some limitations, most of which are noted.

The figures are well prepared and appropriate to the manuscript. There are a large number of them, perhaps some could be combined. For example, the gravity time series is shown in 3 different figures and a plan-view map is in 4 figures.

Major comments:

1) The paper would be improved by considering the problem in a more general sense, in particular, the relation between mass change and the region of sensitivity of the gravimeter. For example, its not clear to me how mass redistribution on the hill slope affects the gravity change; mass moving down the slope, towards the gravity transect, would seem to cause a net decrease in gravity (i.e., the force of the mass is greater, because its closer to the gravimeter, but it’s a negative change in gravity because mass is above the transect). Presumably this is handled implicitly in the least-squares solution but a more general discussion is warranted. Nowhere in the paper is the difference between mass change above and below the meter discussed.
2) I disagree with the reliance on improved, future gravimeters to justify the work. For one, they are far from a successful field demonstration, much less buried underneath a stream channel. Constraining instrument drift in that environment would seem impossible. Second, the FG-5 absolute-gravity meter (and even the A-10) provides accuracy quite sufficient for this type of study, given the uncertainty in the other parameters. I think it would be more effective to investigate further what could be learn using a dense network of gravity stations, and/or using a network of combined relative/absolute measurements to reduce uncertainty (gravity-change uncertainty of 3-4 uGal should be possible).
3) The introduction provides a broad overview of erosion and surface processes, but nothing on why measurements of sediment mass are important, rather than just sediment volume. Is sediment mass (or mass flux) an important parameter in landslide or sediment transport models? Given that sediment density is readily measured from soil samples, volume is accurately measured from photogrammetry, and the density estimate from gravity is relatively uncertain, what is the big advantage of gravity measurements? (for one, they can be used where site access is prohibited or dangerous, e.g. volcanos)
4) Relying only on global hydrology models is a major shortcoming. The river level varied by over 1 m between surveys, indicating groundwater-level changes were also large. The gravity effect of this local change is likely as large or larger than the global changes, but is ignored completely. There is likely large storage changes in the unsaturated zone, and possibly a variable rain-shadow effect at each station (i.e., the gravitational effect of soil-moisture change is different at each station, even if the soil moisture change is the same).
5) Data are available by contacting the author. I believe this is against the spirit, if not the letter, of the journal: “Copernicus Publications requests depositing data…in reliable (public) data repositories…” I would strongly prefer the data were made available online. Certain aspects of

the manuscript, such as measurement uncertainty, were difficult to evaluate without access to the data. If some data are published by others (e.g., stage and sediment data provided by the Taiwan Water Resources Agency) you should provide as precise a reference/URL as possible. I looked on the WRA website but found no data for the Laonong River.

Minor comments:

The review copy lacked spacing or indentation between paragraphs, making reading difficult.

51: This line ("The surveys were done…") seems out of place. Perhaps split off the description of the study area/data from the paragraph about surface processes.

Intro: Suggest discussing the 1-d simplification often used in hydrology and why it can't be used for 3-d surface processes.

68: Are you using the point mass approximation for all of the forward gravity modeling? Are you sure that's appropriate for the nearby prisms (please state that, if so). Consider using the Leiriao (2009) approach that uses the prism/McMillan/point mass formulas, depending on distance.

70-75: Suggest discussing the importance of the horizontal angle, and the relative effect of mass change above and below the gravimeter.

74-76: These lines seem out of place. Move to the conclusion?

84: The *exact* location…

84: How long were the GPS occupations, and what is their estimated precision? RTK indicates they may have been as short as a few seconds. In that case I would expect the vertical precision to be on the same order as the indicated vertical movement. I.e., you may be adding noise to the data rather than correcting for elevation change. 4 cm of motion over a year is a lot in this environment – is there an indication why there is so much movement?

87: "are not plain" is unclear. Do you mean they are not present? Change "will be" to "was".

88: If measurements began in 2006, are there several more data points that could be shown on fig. 3?

Along with major comment 1, consider revising the methods section to present more prominently the "big picture": a least-squares inversion to determine sediment density. As written, you jump directly into the details of the gravity surveys. It might just require a short introductory paragraph in Methods. Also, you could move the Study Area information after Methods – what's important is the development and demonstration of the method, not the details of a particular study area.

122: Was the drift correction first-order linear? I would be interested in the statistics of the adjustment. Measurement uncertainty (i.e., a posteriori standard deviation from the network adjustment, which accounts for the measurement uncertainty at each station) doesn't appear to be included in Table 1? Typically earth tide and ocean load, possible atmospheric pressure, corrections would be applied to the relative gravity measurements prior to the network adjustment, and therefore their uncertainty would be included in the a posteriori standard deviation. Other corrections (ground motion, hydrology) would be applied after the network adjustment.

175: What's the estimated vertical accuracy of the photogrammetry? Fig. 8 suggests it might be pretty low; there are a lot of orange and blue pixels (+/- 5 m) outside of the landslide area in areas that presumably had little elevation change. Does uncertainty in the photogrammetry influence the density determination?

225: Given that you go into a lot of detail on least squares, it may be nice to mention in the A matrix that each row represents an observation and each column a density to solve for. The A and X matrices seem incomplete: the two elements in the bottom right of A should be in a 4th column, and ρ_l in X should have two parts, ρ^{1615} and ρ^{1716} (?)

233: The text and figures indicate the gravity station is AG06 and the GPS station is PAOL. Suggest using "AG06" in the equations. Or better, rename it BA10 – the method of measurement isn't important to the interpretation.

254: Delete 's from 2017's

254: Care to comment on the effort required to take density samples vs. gravity surveys? Do they provide the same information? How does their uncertainty compare?

257: Since "the density sample illustrate the variety of materials carried by the river and the landslide," implying you took samples in both areas, why don't you present the results for each area, instead of just the average?

261: A wrong site location? How could that happen? Surely there are other explanations beyond just bad data: heterogeneous sediment density, underwater topographic change near these stations…

263: Suggest deleting: "…showing the interest…of the redistributed materials" – doesn't say much.

269: delete "three"

The large amount of overlap on the error bars on the densities shown in figure 2 would suggest the method can't really differentiate between river and landslide density. Also, 1.6 is very very low density and doesn't seem justified given the data in fig. 9.

285: Is there any literature that discusses how landslide deposits change density as the landslide evolves? Is it reasonable to expect density increases in the downslope direction?

6.2: This analysis, to account for the effect of water in the river, seems like it should have been part of the data processing, as its removing a part of the gravity signal that you're not interested in. I don't understand why you would just assume the meter is 1-m deep at every location. Since you know the river stage during each survey (fig. 13), and its lowest in 2015, shouldn't you use the actual change in stage between each survey (a little over 1 m from 2015 to 2016, and 0.3 m from 2016 to 2017)? If cells were dry in 2015 and wet in 2016 you could estimate the elevation of the cell bottom (i.e., the land surface) from the photogrammetry.

Assuming for the minute this analysis is correct, the corrected sediment density is 1.7 – this doesn't agree too well with your sediment samples?

318: Delete "Eventually"

328/332: use either density inversion or density-location inversion.

342: You acknowledge that you would have better data with a more extensive gravity network, which is good, but you would still need some constraint on geometry to identify mass redistribution. Gravity change alone is insufficient.

346: I don't think there's any advantage to a permanent quantum gravimeter vs. a permanent FG-5. Much remains to be seen regarding the quantum and MEMS instruments. I would be much more interested in a discussion of what's possible with present-day instrumentation (combined absolute/relative measurements to improve accuracy, SG meters for continuous observation, maybe even borehole instruments)

6.4 I was a little confused by this section, you claim that you could quantify sediment discharge if bedload is at least 12.5 cm thick, as that is the amount required to provide a sufficiently large signal. But, in that case are you not just measuring the bedload, not total sediment discharge? A stream carrying 12.5 cm of bedload is likely carrying a significant amount of suspended sediment as well, but that would cause only a small gravity signal. Therefore, you *might* be able to measure bedload using gravity but not total sediment discharge.

Furthermore, since you are only measuring the change in bedload, you would need much more frequent surveys, or continuous data, to identify anything.

360: Change "measuring" to "estimating"

375: Change "should" to "would need to"

376: Change "strong" to "concentrated"

387: You imply 10 µGal is the expected accuracy of a gravity-change measurement with today's gravimeters, but that's misleading. Sub-5 µGal accuracy is typical for surveys using combined absolute/relative measurements, especially if multiple absolute-gravity stations are measured. Most of the uncertainty in this study is from uncertainty in the hydrology correction

399: Can you justify this work based on the value of sediment mass data, vs volume? If the goal is estimates of "sediment redistribution" it seems that the photogrammetry would be sufficient for that.

References:

There are a lot of references, many of them minimally relevant. The list could be shortened quite a bit.

Titles should be lowercase, e.g., Carbone et al.

IES-AS: Include the URL.

600: Delete *

Appendix B: If you think this is useful information, it would be worth elaborating. Its an interesting approach, one I hadn't seen before. I suggest either explaining it completely or just including it as a single sentence in the main text.

30-40 cm depth is a rather large hole, often density samples are taken from a 5cm x 5cm pit.

Did you calculate wet bulk density? I assume so, as oven-drying is not mentioned. Typically density is reported for dry material.

Step 3 is unclear, you mean that you should weigh the sediment (subtracting the weight of the bucket) and divide the sediment mass by the sediment volume.