Changing field data gives better model results: An example from Papua New Guinea

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Abstract. The recent debate over the exact cause of the 1998 Papua New Guinea tsunami has centered on the agreement between run-up measured in the field and run-up computed by numerical simulations. The practice of all PNG tsunami modelers has been to label their particular combination of bathymetry, topography, and initial condition as "correct" based on the agreement between measurements and predictions. This approach is flawed in that what the models give as output and what was measured in the field do not always refer to the same physical parameter and cannot be used as a basis for validation of a particular hypothesis. A subset of the values recorded in the field and published as "run-up" were derived from inferred flow depths added to the ground level above sea level. The largest of these values ranged from 12 to 15 m and were recorded on a narrow spit of land, which was completely inundated, leaving no corresponding measure of actual run-up. Here, the reported run-up values are reevaluated and differentiated between flow depths and run-up. Modeling results suggest that a variety of landslide-derived initial conditions provide excellent results, as small variations in amplitude, width, and orientation appear of lower order.

1. Introduction

On 17 July 1998 at 08:49 GMT (18:49 local), an earthquake of magnitude 7 occurred near the Pacific coast of western Papua New Guinea. Shortly after the earthquake, a destructive tsunami caused extensive damage along the coast from the town of Aitape west to the region around Sissano Lagoon (Fig. 1). The exact causative mechanism of the tsunami is still the subject of considerable debate. Field surveys conducted after the event observed and reported that the most extensive damage was limited to a relatively short ~20 km stretch of coast. It is customary during a post-tsunami survey to measure the maximum run-up, the vertical excursion of the water surface from normal water level, and the maximum inundation, the horizontal distance that the wave was able to penetrate over land. However, in the case of Papua New Guinea, the worst damage was concentrated in the region around Sissano Lagoon. Sissano Lagoon has the unique feature of a long narrow sand spit, which has no elevation higher than 2–3 m and is as narrow as 150 m in some locations. Because of the low relief of the topography and the extremely large wave heights, the sand spit was completely overtopped and water was able to flow over the spit and into the lagoon. Hundreds of villagers lived along the sand bar, and all of their dwellings, canoes, and other signs of human habitation were uniformly stripped off of the beach.

This fact warrants special care when dealing with measurements taken along the Sissano spit. The data are neither run-up nor inundation distances. Since the spit was overtopped and the flow was allowed to propagate across the waters of the lagoon, no true value of "run-up" is available. Rather,

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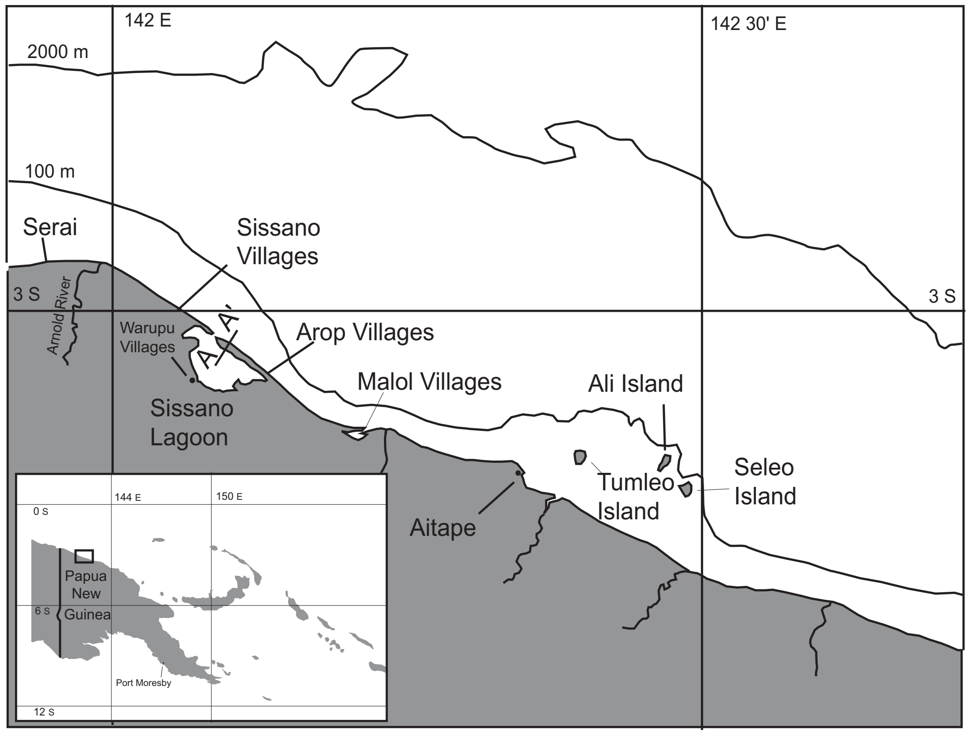

Figure 1: A map of Papua New Guinea and the affected region. A cartoon of section A–A′ is shown in Fig. 2.

what we have for this region are measurements of flow depths, with the value inferred from local clues such as debris on trees or broken branches up to a certain level. Despite the trained eyes of the post event field survey team, there is always the possibility of misidentification of a water mark. In terms of broken branches, the surveyor does not know whether it was the tsunami, a big windstorm the week before, or just a dead branch falling from above. Debris on trees also presents problems, as it could have fallen from a taller tree above, or been blown in by the wind or intentionally put there by a former resident (in the case of rags, or buckets). This paper is not meant to discount the data collected by the field survey team, but rather to highlight the possibility of large errors due to misidentification of a water mark and a wildly varying, highly turbulent flowfield.

2. Modeling the Tsunami

Presently, the published and validated 2+1D tsunami inundation models (Yeh *et al.*, 1996) compute either the largest inundation height over dry land, whether run-up or inundation depth (MOST) or a water surface elevation at the first offshore wet point (TUNAMI-N2) or water elevation at an offshore threshold depth (others). In the case of a low relief topography where overtopping is possible, unless care is taken in the computation, models may output as "run-up" what is really computed flow depth over

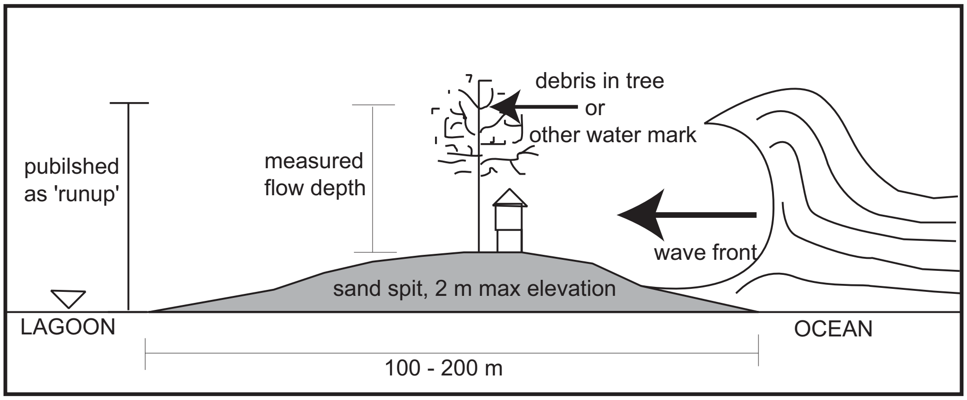

Figure 2: A cartoon showing the difference between measured flow depths and published run-up in the case of the Papua New Guinea tsunami.

the existing topography (see Fig. 2). In order to actually compute run-up in Sissano, the model must compute evolution of the breaking wave over the spit, into and across the lagoon, and finally into mangroves and palm forest. Breaking wave computations are chancy at best with shallow water wave models, and the propagation of a broken wave over extreme shallow water can be unstable.

To test the effect of the sand spit at Sissano Lagoon on the model results, two different models were run. One with the existing topography and bathymetry, and another with a 1:30 slope everywhere along the shore, including the lagoon. A 1:30 slope is used because it is close to the existing slopes. The bathymetry used in these simulations is derived from the bathymetry collected during a post tsunami offshore cruise by the Japanese research vessel *Kairei* (Tappin *et al.*, 1999) and is limited to depths greater than 200 m. For the region between the shoreline and 200 m depths, both linear interpolation and local bathymetric charts were used. An initial grid spacing of approximately 140 m was used. Note that the numerical model used develops a variable spaced grid from the input bathymetry. In these cases, the near shore and overland grid spacing was approximately 80 m.

The tsunami propagation and inundation model used for these simulations is a fully nonlinear, depth averaged, shallow water approximation that solves the equations in characteristic form. The run-up code uses a moving boundary algorithm that extends the computational domain as needed for the flow conditions. The particular version used is known by the acronym MOST (Titov and González, 1998), and is currently used by the University of Southern California and at NOAA's Pacific Marine Environmental Laboratory. The details of this particular implementation of MOST are described in Borrero (2001). It has been validated repeatedly through comparison with laboratory data and comparisons with field measured tsunami run-up data (Titov and Synolakis, 1995, 1998).

The initial wave used in these simulations is the same as was used by Synolakis *et al.* (2001) in their simulations of the Papua New Guinea tsunami. The wave profile is based on the center of mass motion of a 2-dimensional

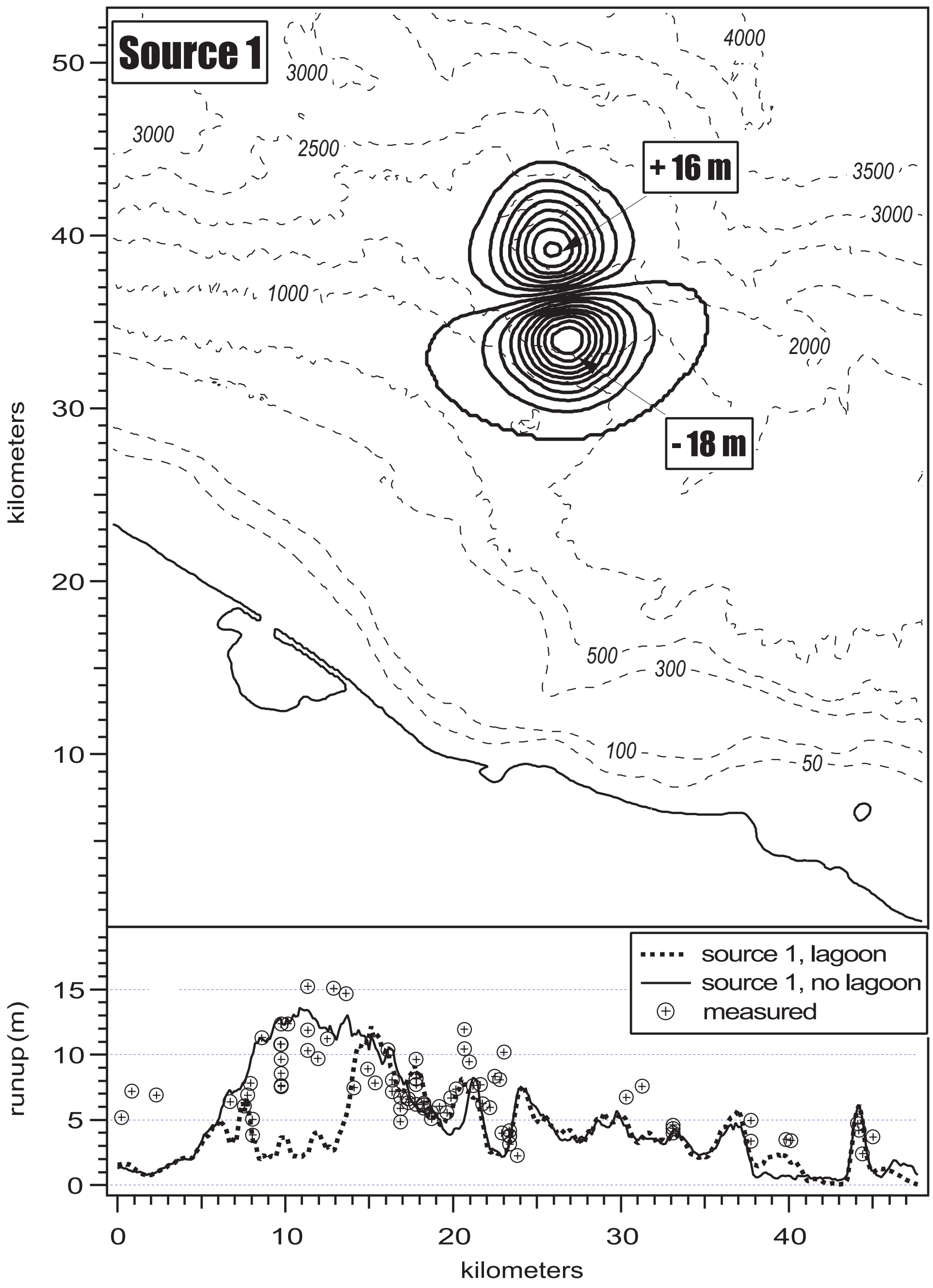

Figure 3: Upper panel—the offshore bathymetry (thin dashed lines) and contours of the initial wave used in the inundation model (thick black contours). Lower panel, computed run-up for cases with the regular onshore topography including the lagoon (thicker dashed line) and with a 1:30 plane beach everywhere along the shore (thin line). Measured run-up data is shown as the circled Xs. The spike on the right side of the figure refers to run-up on Tumleo Island off Aitape. Measured run-up there was 4.5 m.

rotational slump. For the cross profile direction, the tsunami wave shape is described with a hyperbolic secant scaled by the width of the slump as mapped by post-tsunami seismic reflection profiling (Sweet *et al.*, 1999) and bathymetric surveys (Tappin *et al.*, 1999). This particular version of the initial condition will be called source 1. The results from the two cases are shown in Fig. 3. The shoreline shown in the run-up figures is that of the undisturbed real shoreline. In the upper panel, the concentric black contour lines are the contours of the initial surface displacement. In the lower panel, the solid lines show the computed run-up using the existing topography. MOST calculates the largest inundation height over dry land, whether run-up or flow depth. In the case of a uniformly sloping beach, maximum run-up is the highest inundation height. In the case of the model with the Sissano spit the highest inundation height is over the spit. Note how the run-up values drop off in the region of the narrow sand spit. The dashed lines show the computed run-up in the case of a uniform plane beach. The computed run-up values along the sand spit are considerably higher and closer to what was reportedly measured in the field. They are also consistent with laboratory data on solitary waves, which suggest that the maximum run-up is up to twice larger than the flow depth at the initial shoreline.

3. Uncertainty in Field Measurements

As discussed earlier, the field measurements taken along the Sissano sand spit are subject to considerable uncertainty. Are the measured values representative of the flow depths, or are they local maxima? Was the alleged watermark really caused by this event? Is it possible that the flow conditions were so extreme that local extrema could be generated by splash that cannot yet be calculated adequately by the models? Even casual observers of breaking long waves in real beaches would notice that the splash spray exceeds the maximum height of the wave.

To address this question, a series of numerical wave gages was placed along the eastern spit (Fig. 4). Superimposed on Fig. 4 is the maximum computed water elevation (bars) and the field measured flow depths (crosses and circles). To make the measurements compatible with the computational results, the height of the local topography was subtracted from the measured value. If the height of the local topography was not measured, a representative 2-m was subtracted. Adjusting these values and comparing it to a computed flow depth brings the results of the numerical simulation in better agreement with the field-measured data; however, errors of 50% are evident. For comparison, purely tectonic sources do not produce any significant overtopping of the spit.

4. Sensitivity to Initial Conditions

To assess the sensitivity of the simulation to different initial conditions, a parallel set of runs was performed using an alternate source. This initial condition originated during the early days of research into the source mechanism

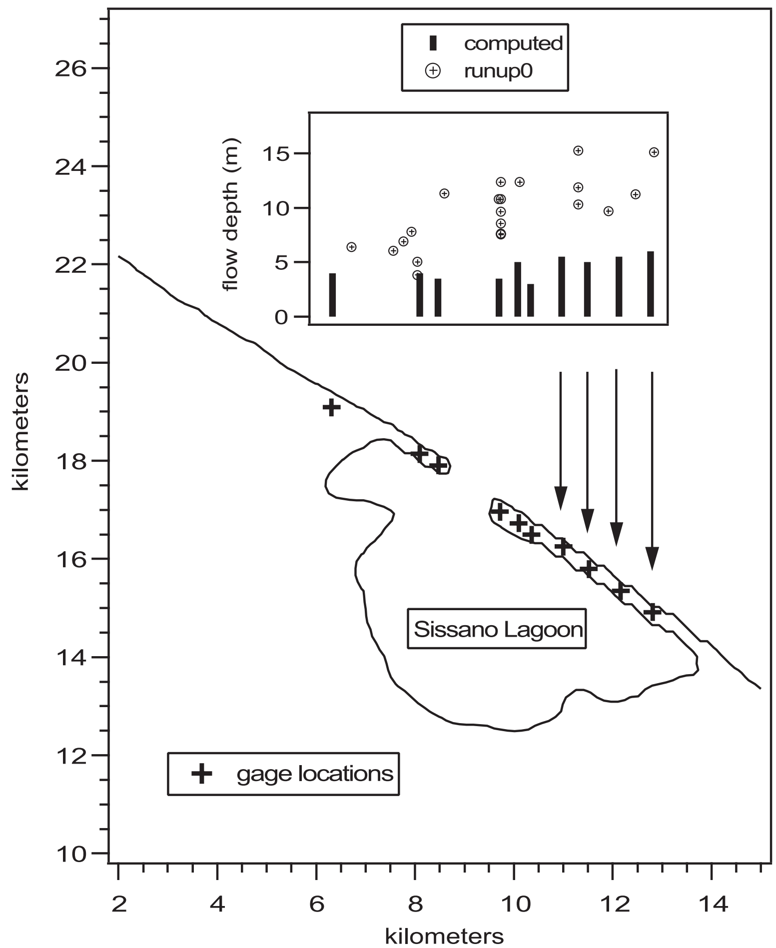

Figure 4: A close-up of the Sissano Lagoon region showing the locations of numerical wave gages (crosses) and the corresponding computed flow depths (black bars). Plotted above the black bars are the measured data converted to a flow depth above the ground surface (circles with cross).

and was derived in a similar manner as source 1. After more information regarding the characteristics of the slump offshore of Sissano lagoon became available, the source was modified and this initial condition was not favored in later work. Figure 5 shows a comparison between computed run-up values for both sources on planar and actual topographies and how the results compare to the published measured data. The slightly elongated, slightly lower amplitude initial wave is contoured over the bathymetry in the upper panel. The lower panels show the relation between cases with the lagoon topography and the planar topography and the published field data.

Interestingly, the results do not vary significantly. Both sources produce nearly the same results for the coastal area immediately east of Sissano lagoon, a region where the field data is unquestionably true run-up. Further east, depending on what part of the coast, the locus of maximum run-up from either source model another intersects with some measured values. In any event, the two sources seem to bracket the measured values.

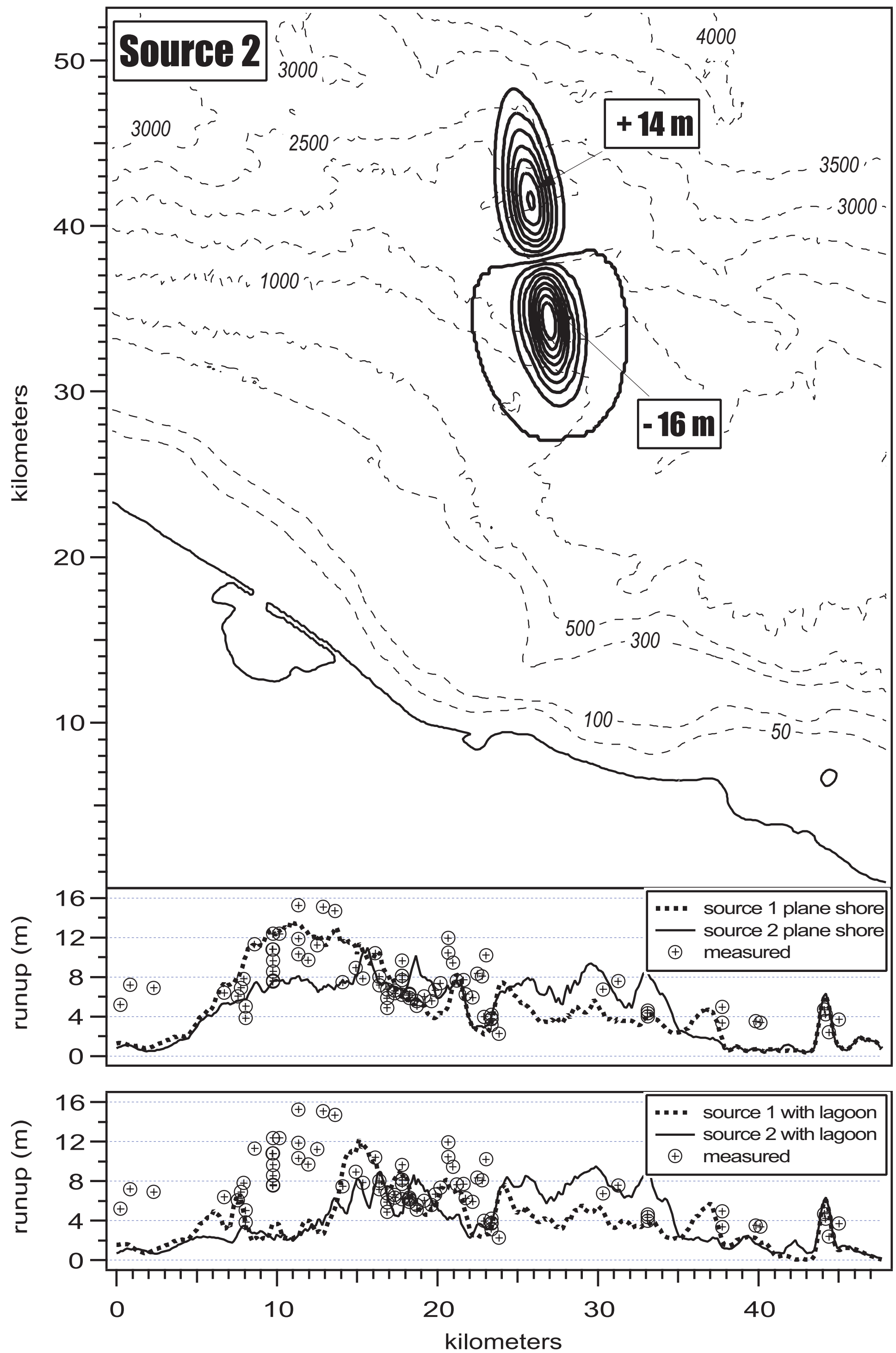

Figure 5: Similar to Fig. 2, except here an alternate version of the initial condition is contoured. The lower panels show a comparison between computed run-up values for each case. The upper run-up plot is for the planar shore and the lower run-up plot is for the existing topography. The spike on the right side of the figure refers to run-up on Tumleo Island off Aitape. Measured run-up there was 4.5 m.

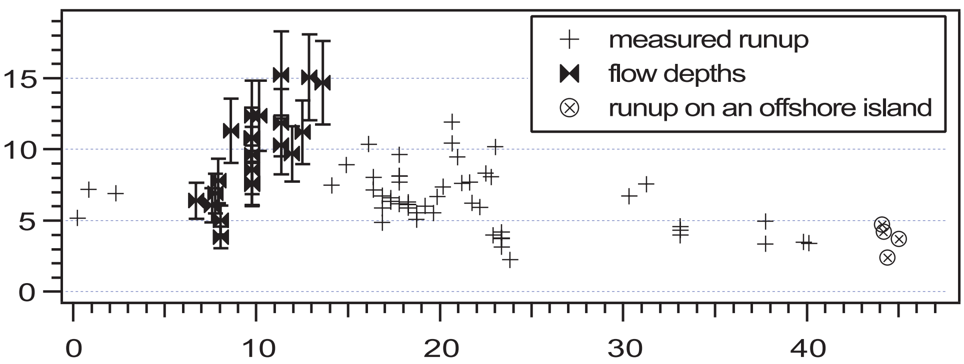

Figure 6: A proposed alternate version of the Papua New Guinea run-up plot, with the values around Sissano Lagoon differentiated as "flow depths" and plotted with 20% error bars.

5. A New Run-up Plot for the Papua New Guinea Tsunami

Due to the problems with the field data recorded after the 1998 tsunami survey, the author proposes that a new run-up plot be considered when discussing the Papua New Guinea tsunami. In this new run-up plot, the points that are true run-up values will be kept the same while points collected along the sand spit or in other areas where a true run-up reading could not be attained will be differentiated and noted as "measured flow depths." An example of this revised run-up plot is shown in Fig. 6.

6. Conclusion

The Papua New Guinea tsunami was a brutal display of the power of nature and a catalyst for a paradigm shift within the tsunami research community. The results of these simulations show that an initial wave based on the motion of a large underwater slump gives a good fit to the observed run-up and flow depth data. Furthermore, it appears that the details of the initial condition are not vitally important. Differences on the order of 10% in the initial wave do not manifest themselves as a 10% difference in computed run-up values. Both initial conditions presented here, to first order, satisfactorily describe the distribution and magnitude of measured run-up. Where the two conditions differ is in the region around the sand spit. With a uniformly sloping beach, source 1 reproduces more closely the upper bound of the measured flow depths presented as run-up, while source 2 more closely reproduces the lower bound. In the case of actual topography, neither case accurately describes the measured flow depths, but the computation is less stable. Source 1 produces better results than source 2, but still under-predicts the measured flow depths up to 50%. Given the behavior of numerical bores, it is recommended that computations with current inundation tools that model evolution over narrow spits are bracketed between two run-up distributions, one over a uniform beach and one over the spit. Finally, since purely tectonic sources do not produce any significant overtopping of the spit, it is concluded that the numerical modeling results are consistent with a slump source.

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