ASTEROID IMPACTS:
THE EXTRA HAZARD DUE TO TSUNAMI

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ABSTRACT

This paper provides an introduction to the consequences of an asteroid colliding with the Earth above an ocean. A method of estimating the risk to coastal regions from tsunami generated by such impacts is presented. This risk is compared with the risk of being within the area of direct devastation from an asteroid impact. An advantage of this approach is that uncertainty about the frequency of asteroid impacts does not affect the assessment.

This tentative analysis suggests that the risk from asteroid tsunami has been substantially overstated - particularly in popular books about asteroid impacts with Earth. For typical coastal regions the risk of dying from an asteroid-generated tsunami is probably no greater than that of dying from the indirect effects (for example, global starvation) of a large asteroid striking the Earth. For some coastal regions with unusual vulnerability to tsunami the risk of dying from asteroid-generated tsunami may be several times greater than that of dying from other asteroid-related causes. The tsunami risk from asteroids 200m in diameter or smaller is likely to be very low.

INTRODUCTION

This paper provides an introduction to the topic of tsunami generated by asteroid impacts. It is intended for a general audience and is based on a World Wide Web page created by the author (Paine 1999). A method of estimating the risk to coastal regions from tsunami generated by such impacts is presented. This risk is compared with the risk of being caught within the area of direct devastation from an asteroid impact.

NATURE OF TSUNAMI

The waves created by a sudden disturbance in the ocean are known as tsunami. Typical causes are earthquakes and underwater landslides. Tsunami travel at high speed across the deep ocean - typically 500km/h or more. In deep water the tsunami height might not be great but the height can increase dramatically when they reach the shoreline because the wave slows in shallow water and the energy is concentrated. In addition to the inherent increase in the height of the wave from this shoaling effect, the momentum of the wave might cause it to reach a considerable height as it travels up sloping land. It is typical for multiple waves to result from one tsunami-generating event and these could be several hours apart when they reach a distant shore.

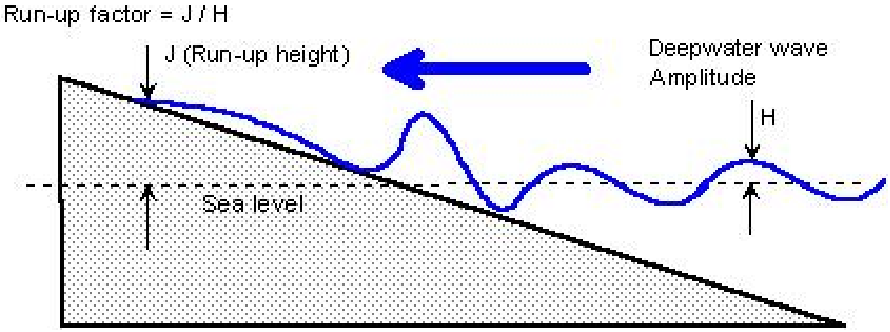

Figure 1: Illustration of Tsunami Terms (Magnified Vertical Scale)

For the purpose of the analysis, several tsunami terms need to be defined: "Run-up height" is the vertical height above sea level of the tsunami at its furthest point inland. "Run-up factor" is the run-up height divided by the deepwater wave amplitude. In effect, "amplitude" is the maximum height of the wave above sea level when in deep water (see Figure 1). This is not the same as the "double amplitude" which is the vertical distance between the crest and the trough and is often used to describe the height of a wave.

The run-up factor can vary considerably, depending on local topography and the direction of travel of the wave. Crawford and Mader (1998) estimate the typical run-up factor for coastal locations is only 2 to 3. Hills and Goda (1998) note that earthquake-generated tsunami in Japan have an average run-up factor of 10 but sometimes reach 25. In Hawaii run-up factors of 40 have been observed for earthquake-generated tsunami.

Recent research suggests that the Australian coastline is vulnerable to tsunami - although not necessarily due to asteroid impacts (Nott & Bryant 1999 and Rynn & Davidson 1999). There is also evidence of substantial variations in run-up factor for tsunami along the Australian coast .

Along a 40km stretch of coastline the run-up height from one ancient tsunami event varied by more than 40 (based on Young et al 1996). The effects are complicated by features such as estuaries, harbours, cliffs and reefs. The topography and features of the continental shelf, the shoreline, an estuary/harbour and the land are all very important is considering the damaging effects of tsunami. Some coastal areas could be vulnerable to relatively small tsunami. Until recently there appears to have very little assessment of this risk except in areas prone to earthquake-generated tsunami such as Japan and Hawaii.

The urgency for increased research on tsunami is reinforced by the devastating tsunami which struck northern New Guinea in July 1998

ASTEROID IMPACTS WITH THE EARTH

Stony asteroids with a diameter less than about 100 metres generally do not reach the Earth's surface. These objects usually explode several kilometres above the surface (an "airburst"). This was probably the case with the "Tunguska" Siberian event in 1908. The kinetic energy involved is substantial - a typical impact by a 50m object is equivalent to about 10 megatons (Mt) of TNT and that of a 100m object is equivalent to about 75 Mt. The actual kinetic energy depends on several factors such as speed and density and can vary by a factor of more than 10. These explosions are equivalent in energy to large thermonuclear explosions and they can cause devastation over thousands of square kilometres. In the case of Tunguska the area of destruction was about 2,000 sq km or a circle of radius 25km.. Fortunately the region was sparsely populated and had little effect on humans (nowadays it might be mistaken for a hostile nuclear explosion).

Estimates of asteroid/comet impact frequency may vary by a factor of ten - "Events like Tunguska occur with uncertain frequency, possibly once every 50 years, if the interpretation of the Spacewatch data is correct, or at most once every 300 to 500 years" (Steel 1995). Subject to this uncertainty, the probability of an impact at a given location, P(L), can be estimated from

$$P(L) = P(D)\, A_D / A_E \qquad (1)$$

where:
P(D) is the probability of an impact by an asteroid of diameter D somewhere on the Earth,
A_D is the area of destruction due to the impact and
A_E is the total area of the Earth's surface (including ocean).

Applying this to the Tunguska event, and assuming an impact frequency of one per century: P(annual)= 0.01, A_D=2000, A_E=5.1×10^8. Therefore the *annual* probability of a given location being within the devastation area is 4×10^{-8} or 1 in 25 million.

Steel (1995) provides the following formula for estimating the area of destruction, based on nuclear weapons tests:

$$A = 400\,(\text{Kinetic Energy})^{0.67} \qquad (2)$$

Using this formula the following table sets out the typical values for stony asteroid up to 200m diameter (assuming velocity=20km/s, density=3 g/cc). Values for asteroids 500m and 1km in diameter are based on Morrison and Chapman (1995). The values are subject to considerable uncertainty and may vary by a factor of ten or more.

Table 1
Risk of Direct Impact for a Given Location

Diameter	Kinetic Energy Mt TNT	Area Devastated sq km	Average. interval between impacts (years)		
			Earth	Point (Town)	Inhabited Region # (Potential fatalities)
50 m	10	1900	100	30 million	900 (1 million)
100 m	75	7200	1000	70 million	8000 (3 million)
200 m	600	29 000	5000	90 million	30 000 (14 million)
500 m	10 000	190 000	40 000	100 million	180 000 (30 million)
1 km	75 000	740 000	100 000	70 million	290 000 (60 million)
2 km	1 million	Global effects	1 million	-	1 million (1.5 billion)
All*			90	12 million	800

*All = $1/ (1/T_{50}+ 1/T_{100} + 1/T_{200} + 1/T_{500} + 1/T_{1000})$ on the basis that probabilities are independent and span the range of asteroid sizes.

Assuming 9% of Earth's surface area is inhabited but taking into account boundary effects from the area of devastation - see Paine 1999.

An impact by a 2km diameter stony asteroid is thought to be at the threshold of a global catastrophe. It has been estimated that one quarter of the world's population could die from starvation and other indirect effects due to such an impact (Morrison and Chapman 1995).

Iron asteroids are more likely to reach the ground intact. They comprise perhaps 5% of the smaller asteroids and are disregarded in the analysis.

TSUNAMI GENERATED BY IMPACTS

Although, for a given location on the Earth's surface, the risk of a "direct" hit from an asteroid is slight, researchers realized that an ocean impact had the potential to be much more destructive due to the additional hazard of tsunami. An airburst explosion is a three dimensional event and energy decreases according to the square of the distance but a radiating ocean wave is a two-dimensional phenomenon and, in theory, energy decreases in proportion to distance. Since the early 1990s some advanced computer simulations have been conducted to estimate the effects of asteroid impacts above deep oceans.

At this stage there are considerable differences in asteroid/tsunami predictions between the researchers. For a review of the methods see Ward & Asphaug (1999).

The main items of contention appears to be:

- the initial size of the wave - based on analysis of the size and shape of the "crater" and the manner in which it collapses, and
- the rate at which a tsunami from an asteroid impact dissipates as it travels.

Crawford & Mader (1998) explain that, for an impact to produce a coherently propagating wave (one that does not dissipate substantial energy when it travels over great distances) the "cavity" must be 3 to 5 times broader than the depth of the ocean. Using a rule-of-thumb (derived from simulations) that the cavity diameter is 20 times the asteroid diameter then, for a typical ocean depth of 4km, the impactor must be at least 1 km in diameter to produce a coherent wave. On this basis, for asteroids smaller than about 1km, the wave will dissipate considerably as it travels over thousands of kilometres of ocean.

Table 2
Estimated Deepwater Wave Height (Above Sea Level) at a Point 1,000km from an Asteroid Impact - Selected Research Results

Asteroid Diameter (m)	Hills & Goda (1998)	Crawford & Mader (1998)
200m	5m	Negligible
500m	11m	<2m
1000m	35m	6m

Ward & Asphaug (1999) predict a similar tsunami height to that of Hills & Goda for a 250m diameter asteroid. There have been no detected asteroid impacts into an ocean on Earth so it is difficult to verify the models. However, the CTH computer code used by Crawford and Mader successfully predicted the consequences of the impact of Comet Shoemaker-Levy 9 with Jupiter. In the (fortunate) absence of experimental evidence on the Earth, the conservative results produced by Crawford & Mader have been used in the following analysis. In other words, it is assumed that asteroid impacts will generally produce non-coherent waves which dissipate quickly.

There may be cases where an asteroid impact produces coherent waves but this would be due to a combination of unusual conditions, such as shallow water, rather than the norm.

In the case of asteroids 200m and larger there is likely to be an impact into the ocean. For objects under this diameter an airburst is likely and there is a corresponding reduction in the size of the predicted deepwater wave due to energy dissipation in the atmosphere. Speed, trajectory, density and strength of the object can affect the nature of the explosion. There does not appear to be an empirical formula available to deal with these smaller objects and it is possible that the smaller asteroids produce no appreciable waves. On the other hand, in the case of serious tsunami generated by earthquakes the energy involved is estimated to be equivalent to about 2 Megatons of TNT (Yabushita 1998). The impact by a 100m asteroid typically involves kinetic energy of about 75Mt so it would only involve the conversion of about 3% of this energy to ocean wave energy in order to produce a serious tsunami. However, the tsunami would probably quickly dissipate, compared with an earthquake-generated tsunami.

On balance, the following conservative values have been used for risk assessment. These are based on extrapolation of Crawford and Mader data (see Appendix). Note that, compared with Table 2, the range has been reduced to 100km to obtain reasonable values for the smaller asteroids.

Table 3
Estimated deepwater wave height (above sea level)
at a point 100km from asteroid impact

Asteroid Diameter (m)	Deepwater Wave Height (m)
50	0.12
100	0.7
200	3
500	22
1000	70

ESTIMATED RISK TO COASTAL LOCATIONS

Taking the New Guinea experience as a reference level, it is assumed that a tsunami with a 10m will be of concern to low-lying coastal areas. The risk is estimated in the following steps:

a) Determine the run-up factor W for the location in question.

b) Determine the critical deepwater wave height that will produce a tsunami with a run-up height of 10m (H = 10 / W).

c) For each size of asteroid, determine the distance over which a deepwater wave will need to travel before it has reduced in size to the critical height determined in step (b). This will be the "danger radius" for this combination of run-up factor and asteroid size.

d) Determine the area of a semi-circular area of ocean with a radius equal to the distance derived in step (c).

e) Calculate the probability of an impact within the area derived in step (d).

In the absence of better data the following estimates of danger radius have been derived by extrapolation of the Crawford and Mader data (see Appendix). This should be regarded as tentative.

Table 4
Danger radius - Estimated radius from impact for a tsunami 10m or higher at the shore (deepwater wave height in metres is 10/run-up factor)

Stony Asteroid Diameter (m)	**Tsunami Run-up Factor**			
	5	**10**	**20**	**40**
	Distance from impact (km)			
50	10	20	40	60
100	40	70	130	230
200	140	250	460	820
500	800	1400	2500	4400
1,000	2800	5000	9000	16 000

It is noted that, irrespective of run-up factor, the radius derived for a 50m asteroid is similar to radius of direct devastation for the Tunguska event.

For most coastal locations the surface area of ocean which poses a tsunami threat is a semicircle with a radius R equivalent to the danger radius. This radius is, however, limited by the size of the ocean. An area corresponding to 30% of the surface area of the Earth has been used for this limit (the approximate size of the Pacific Ocean). Applying equation (1) to the resulting semi-circular areas provides the following estimates of average intervals between events:

Table 5
Estimated Interval Between Major Tsunami Events
(Tsunami Run-up Height 10m or Greater)

Stony Asteroid Diameter (m)	Tsunami Run-up Factor			
	5	10	20	40
	Average interval between tsunami events (years) for a single location on the shore of a deep ocean.			
50	-	81 million	20 million	9 million
100	-	66 million	19 million	6 million
200	83 million	26 million	8 million	2 million
500	20 million	7 million	2 million	670 000
1000	4 million	1.3 million	400 000	330 000
All	3 million	1million	300 000	190 000

In all cases it appears that risk of serious tsunami from asteroids 200m diameter and smaller is much less than for larger objects.

For a given coastal location the predicted average interval between major tsunami events (bottom row from Table 5) can be compared with the average interval between "direct" impacts of 12 million years (from Table 1) to derive the relative risk for that location compared with an inland location (that is, a location which is not vulnerable to a 10m tsunami). This relative risk is independent of the actual rate of impacts.

Table 6 Relative risk of coastal location compared to inland location

Tsunami Run-up Factor	Relative Risk
0 (inland)	1
5	4
10	11
20	46
40	74

This tentative analysis suggests that the risk to a low-lying coastal area from tsunami generated by asteroids is greater than the risk from a "direct" impact by such objects. The average interval between such tsunami events is estimated to range from about 190 000 years for a location with a run-up factor of 40 to about 3 million years for a location with a run-up factor of 5.

DISCUSSION

Comparison with the risk analysis by others

Ward and Asphaug (1999) set out a comprehensive method of determining the impact tsunami risk. The analysis is based on methods they have developed for assessing earthquake risk. Probabilities are derived for a range of tsunami sizes striking a given coastline within a 1000 year period. In that paper tsunami height is measured just before the wave reaches the shore rather than run-up height. They assess the tsunami risk for a generic coastline and for the coastal cities San Francisco, New York, Tokyo, Hilo Harbour (Hawaii), Perth and Sydney.

The risks derived from Table 5 above are considerably less than the risks from an asteroid-generated tsunami derived by Ward and Asphaug. For example, they estimate the risk of a 10m tsunami inundating a generic coastline (with a semi-circular "target area" of ocean having a radius of 6,000km) is 1.1% in 1000 years - equivalent to one event every 91 000 years and about ten times the risk estimated in Table 5. The main differences are likely to arise from assumptions about initial wave size and dissipation.

Comparison with other asteroid impact risks

Table 6 compares the risk of being caught in a region of direct devastation (within the "blast area") with that of being within an area inundated by an asteroid-generated tsunami. In the case of an impact by a large asteroid (diameter 2km or more) is has been estimated that 25% of the human population of the Earth would die. This extreme event is thought to occur with an average interval of 1 million years. The annual risk of dying from such an event is therefore about 1 in 4 million, which is similar to the tsunami risk for a location with a run-up factor of 5 (1 in 3 million).

CONCLUSION

This tentative analysis suggests that the risk from asteroid tsunami has been substantially overstated - particularly in popular books about asteroid impacts with Earth. For typical coastal regions the risk of dying from an asteroid-generated tsunami is probably no greater than that of dying from the global effects of a large asteroid striking the Earth.

For some coastal regions with unusual vulnerability to tsunami the risk of dying from asteroid-generated tsunami may be several times greater that of dying from other asteroid-related causes. For these highly vulnerable areas the typical interval between asteroid tsunami events is likely to be about 200 000 years - assuming that impacts are randomly distributed in time. It appears that there is a very low tsunami risk from asteroids 200m in diameter or less.

There is considerable uncertainty about most of the "input values" used in these estimates. Also it is possible that impacts are not randomly distributed in time (Steel et al, 1995) and the Earth may be subjected to a barrage of small asteroids (or comet fragments) from time to time. Until we better understand the impact threat, there is no cause for complacency over the long intervals derived above. Finally, it is stressed that the run-up factor is not the sole issue in determining the destruction caused by a tsunami.

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APPENDIX

Extrapolation of Crawford & Mader Data

The graph overleaf shows deepwater wave height (metres above sea level) by distance from impact (kilometres) for a range of asteroid diameters. It is a log-log plot of the extrapolations (X) used to derive Table 4, superimposed on the data (C&M) from Crawford & Mader (their Table 1 on page 28). It can be seen that the extrapolations are *speculative* for both smaller asteroid sizes and large distances, since the Crawford and Mader data do not go below an asteroid diameter of 250m and do not go beyond a radius of 1000km (and then only for the 1km asteroid). Strictly the extrapolations for the 50m and 100m asteroids do not take into account airburst effects but since the contribution of these impacts to overall tsunami risk turns out to be very low this will have negligible effect on the risk estimates. As a consequence of the uncertainties the risk estimates derived in this paper should be regarded as ballpark only.

The horizontal lines show the deepwater wave heights that would produce a tsunami with a run-up height of 10m for a range of run-up factors (RUF 5, 10, 20 & 40). An estimate of "danger radius" can be derived from the intercept of these lines with the asteroid lines. For example, the horizontal dot-dash line shows a deepwater wave height of 0.5m. This would produce a 10m tsunami at a location with a run-up factor of 20. This line intercepts the extrapolated line for a 500m asteroid at a "distance from impact" of about 2400km. It is therefore predicted that an impact by a 500m diameter asteroid anywhere within a radius of 2400km would produce a tsunami 10m or higher at a location with a run-up factor of 20 (this is an unusually high factor).

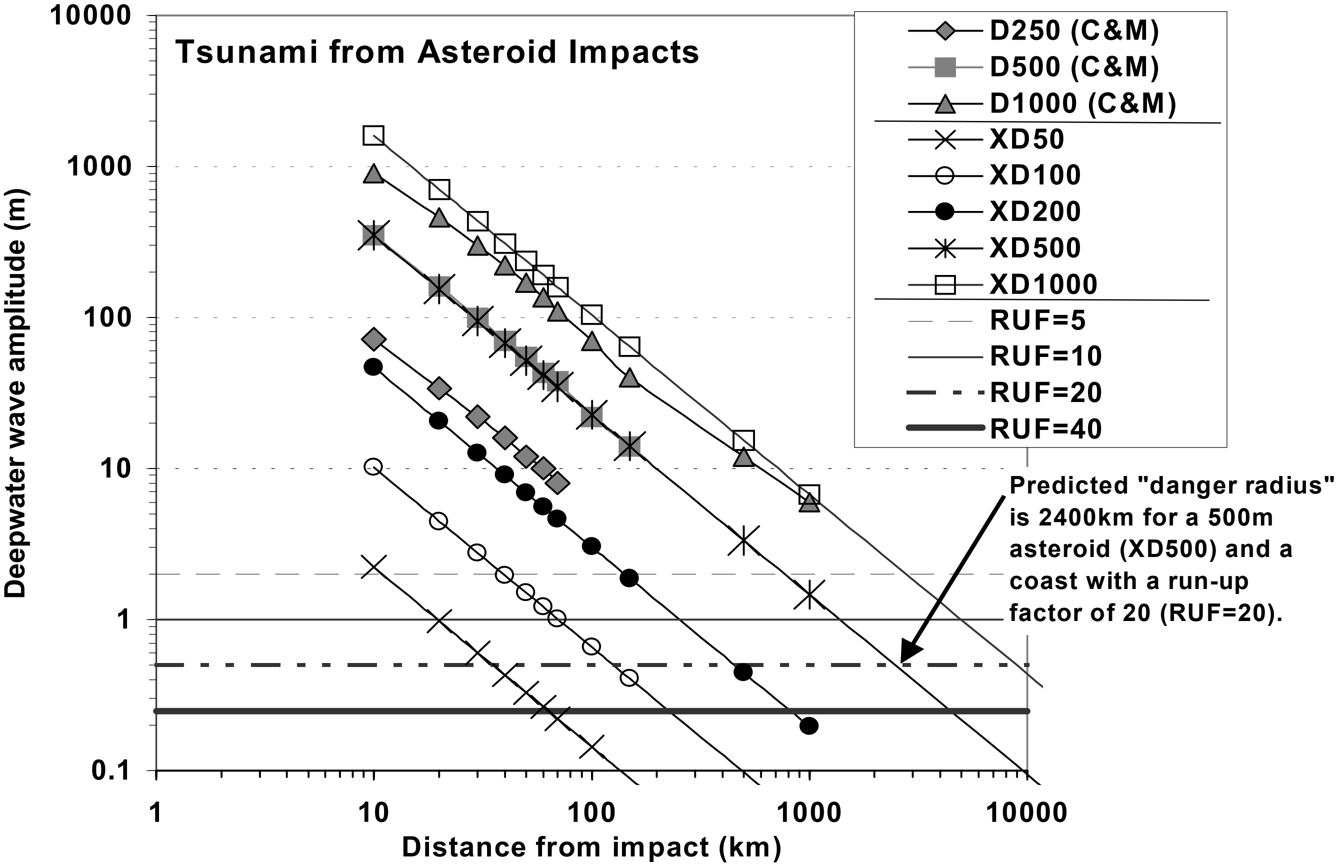

Figure 2: Prediction of the range of impact tsunami by extrapolation of the data ("C&M") provided by Crawford and Mader (1998). A tsunami run-up height of 10m is assumed for the run-up factor (RUF) intercepts.