Decision Model for Potential Asteroid Impacts

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EXECUTIVE SUMMARY

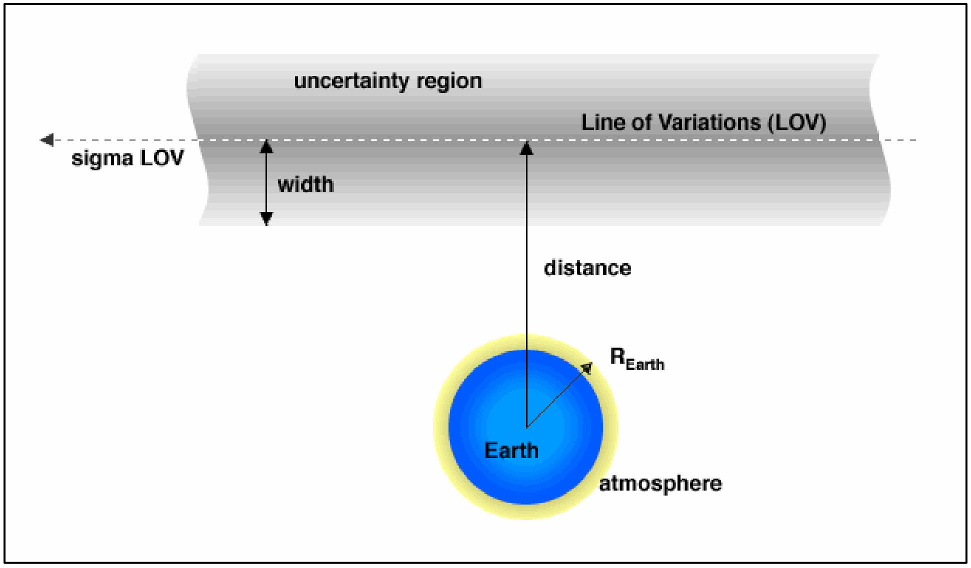
Research in asteroid detection and orbital characterization has identified a new class of possible natural disaster. Asteroids are the only known type of natural disaster that could potentially destroy civilization. The societal importance of asteroid detection is assumed to be high, given the destructive capacity of Potentially Hazardous Asteroids (PHAs). This paper offers a decision analysis framework to aid in decision making regarding *what to do* when confronted by a particular PHA of a given size with a given probability of impact. Three decisions are modeled: (1) Study the PHA with a large telescope to further refine orbital estimates; (2) Send a small reconnaissance spacecraft to survey the PHA; and/or (3) Send a large spacecraft mission to disrupt the orbit of the PHA using nuclear explosives.

INTRODUCTION: THE ASTEROID IMPACT HAZARD

Asteroid impact is considered a significant hazard, with a history of small and large-scale planetary destruction (it is generally held to be responsible for the end of the dinosaurs). Potentially Hazardous Asteroids (PHA's) are defined as any near-Earth asteroid that has an orbital intersection distance of less than 0.05 astronomical units (AU) from the path of Earth. In other words, an asteroid that is expected to pass within 7.5 Million kilometers from Earth at a certain point in the future (roughly 20 times the distance from the Earth to the Moon) is defined as a PHA.

In order to understand the statistical significance of the probability of impact Figure 1 is offered below (JPL, 2003a), showing a hypothetical asteroid trajectory as it passes Earth. Note that the nominal trajectory or 'line of variations' (LOV) clearly does not impact. However, the uncertainty region or width of the LOV does intersect with Earth at a given value of sigma (standard deviation). The probability of impact is therefore the likelihood that the estimated line of variations actually does intersect with Earth. In other words, it is the probability that the LOV is wrong.

Figure 1. Diagram of statistical uncertainty for the path of a hypothetical PHA (JPL, 2003a).



In order to improve the estimate of the LOV, more observations of the asteroid along its trajectory are required. This is usually done with an optical telescope, although sometimes it is also done using a radar signal originating from a radar telescope such as Aricebo in Puerto Rico. While estimates are available regarding likelihood of impact for a particular PHA that has been discovered, it should be noted that less that 20% of the expected number of PHAs have currently been identified. Another important data set that is used to predict asteroid impact rates is the crater record on Earth and on the Moon. For the purposes of this paper, modeling will be limited to PHAs that have been already identified.

ECONOMIC MODEL OF POTENTIAL IMPACT DAMAGE

Impact damage models to date have been limited to predictions of the amount of physical damage that would ensue from a collision of given magnitude. No models yet exist regarding the economic damage resulting from an asteroid impact (Chapman, 2001). For that reason, a preliminary model of economic damage has been constructed to fit a range of asteroid sizes.

The starting point for the damage model is the chart in Appendix 1 (source – Atkinson, 2000) that shows expected physical damage related to asteroid size and impact frequency. Note there is a rough correlation between crater size and asteroid size that suggests a multiplier of around 20:1.

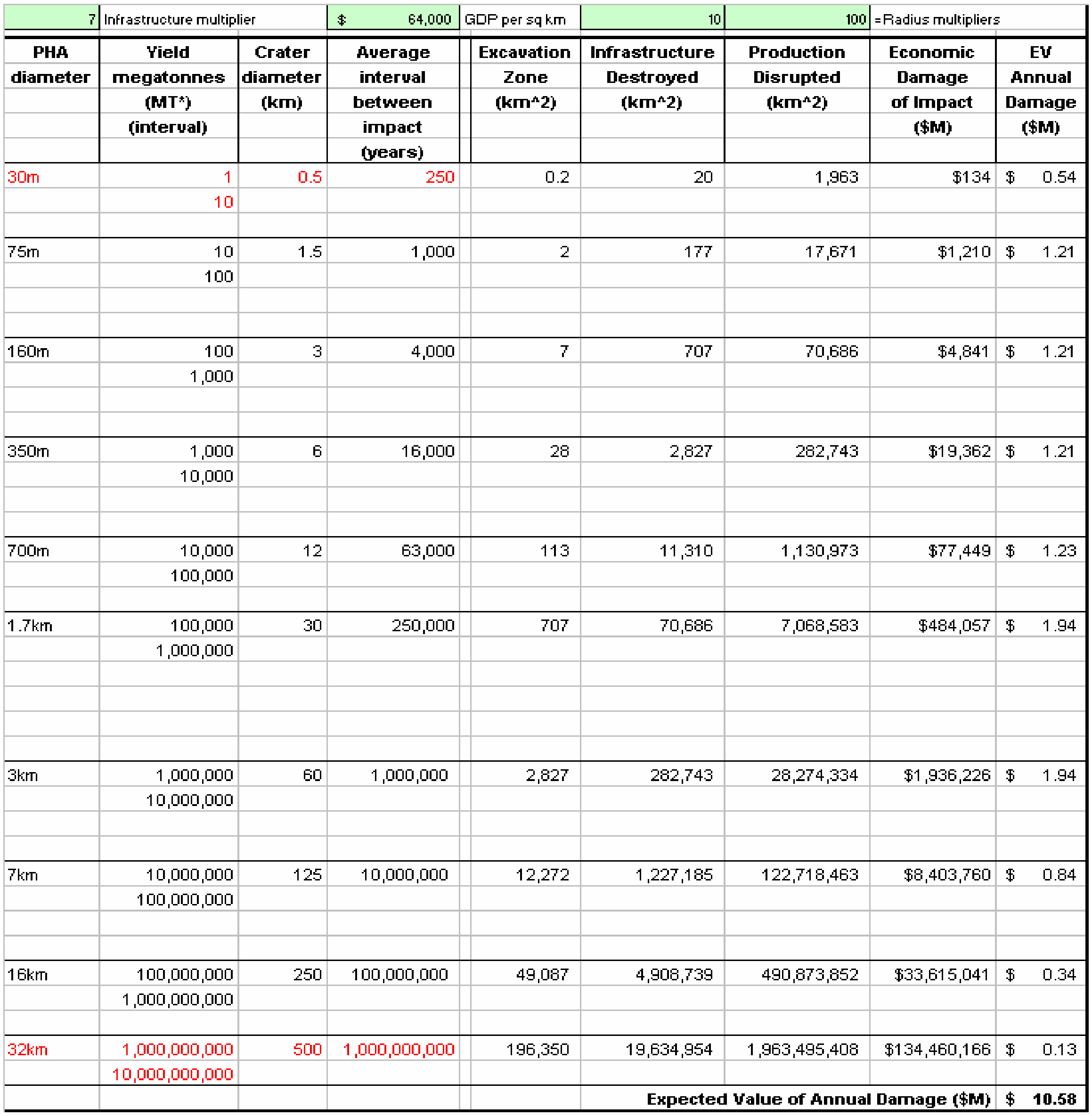
In order to translate the physical damage into expected economic damage, a number of assumptions were made. The first assumption is that due to the random nature of the impact phenomenon (i.e., the probability is equally likely for an impact to occur anywhere in the world), an averaged value of global domestic product per square kilometer would capture the potential economic disruption of a truly random impact. This metric has the advantage of quantitative scaling with the expected area of damage, with the units are in square kilometers. For the purposes of this analysis, the GDP_{world} value for the year 2001 of $32 Trillion dollars was used. Next, the number of square kilometers in the entire world (including oceans) is estimated to be 500 Million. This yields an average value for GDP per square kilometer of $64,000. Note that by including the area of the ocean this estimate of potential damage factors in the likelihood of an ocean impact. In other words, an impact on land would cost on average four times that value ($256,000), while an ocean impact is assumed to generate zero cost (note that the ocean covers roughly 75% of the surface of the Earth). So indeed, a random impact in 2001 would generate roughly $64,000 of damage *on average* to the productivity of each square kilometer of Earth that was affected.

The second assumption considers the difference between disruption of productivity and damage to infrastructure. It is not difficult to see that the value that one square kilometer of productive land can *produce in one year* is different than the value of that land and the factors of production that lie on it. For the purposes of the proposed economic damage model, the land value is ignored and the value of factors of production become the focus. It is assumed that a typical amortization period of 7 years reflects the average multiplier in value for infrastructure that generates the annual productive output (for example, a plant that produces $64,000 per year of value that must be replaced after 7 years would exactly pay for itself in that period). Thus, it is assumed that the multiplier of 7 times the annual productivity of the land can be used to estimate the damage to infrastructure, provided that infrastructure was completely wiped out by the impact.

The third assumption concerns the amount of disruption in square kilometers that an impact of a given size would generate. It is assumed that for a given crater size, the area within the crater is vaporized (the planetary scientists prefer the term excavated). It is further assumed that an area within 10-crater-diameters experiences destruction of its infrastructure. Finally, it assumed that an area within 100-crater-diameters experiences disruption of one year's worth of annual productive output. Note that when a crater is excavated, most of the material is deposited near the crater. However, a shock wave propagates outward from the center of the impact, and the heat associated with the impact can ignite structures that are nearby. These estimates are considered reasonable, perhaps conservative (however, an expert in the physical damage associated with potential impacts should check them for validity).

The chart in Appendix 1 was extrapolated to produce Table 1 below (the extrapolated data is shown in red), with the economic assumptions in the above paragraphs integrated into the columns on the right side. The 'expected value' column multiplies the *total economic damage* with the *annual likelihood of impact*. Note that the combined figure of annual expected economic damage is $10.58 Million dollars. This estimate is surprisingly similar to the annual budget allocated to asteroid detection worldwide.

Table 1. Model of economic damage associated with a given set of PHAs (after .



7	Infrastructure multiplier	$ 64,000	GDP per sq km	10	100	=Radius multipliers

PHA diameter	Yield megatonnes (MT*) (interval)	Crater diameter (km)	Average interval between impact (years)	Excavation Zone (km^2)	Infrastructure Destroyed (km^2)	Production Disrupted (km^2)	Economic Damage of Impact ($M)	EV Annual Damage ($M)
30m	1 10	0.5	250	0.2	20	1,963	$134	$ 0.54
75m	10 100	1.5	1,000	2	177	17,671	$1,210	$ 1.21
160m	100 1,000	3	4,000	7	707	70,686	$4,841	$ 1.21
350m	1,000 10,000	6	16,000	28	2,827	282,743	$19,362	$ 1.21
700m	10,000 100,000	12	63,000	113	11,310	1,130,973	$77,449	$ 1.23
1.7km	100,000 1,000,000	30	250,000	707	70,686	7,068,583	$484,057	$ 1.94
3km	1,000,000 10,000,000	60	1,000,000	2,827	282,743	28,274,334	$1,936,226	$ 1.94
7km	10,000,000 100,000,000	125	10,000,000	12,272	1,227,185	122,718,463	$8,403,760	$ 0.84
16km	100,000,000 1,000,000,000	250	100,000,000	49,087	4,908,739	490,873,852	$33,615,041	$ 0.34
32km	1,000,000,000 10,000,000,000	500	1,000,000,000	196,350	19,634,954	1,963,495,408	$134,460,166	$ 0.13
							Expected Value of Annual Damage ($M)	**$ 10.58**

Now the question emerges: Where is there a decision to be made concerning this model?

The answer: Ongoing asteroid search programs identify PHAs on a regular basis. Once a PHA has been identified, a decision analysis framework based on an economic damage model can provide insight as to how to best respond to the threat of impact.

But first, an important conclusion results from this analysis. It has become possible using the model above to create an equation that relates economic damage to the size of the PHA. The equation for expected economic damage as a function of asteroid diameter uses the following list of variables, parameters and equations. Again, the logic behind these equations is discussed in the previous section.

Variables:
R_a = Radius of the asteroid or PHA
R_c = Radius of the impact crater
R_i = Radius of infrastructure damage
R_p = Radius of production disruption (one year of output loss is assumed)
GDP_{km} = Average GDP per square kilometer (including oceans)
d = Discount rate (8% is assumed)
P(i) = Probability of impact for the given PHA
Pi = 3.14159
T = Expected impact time from present (in years)

Parameters:
ID = Estimated economic impact damage
PVID = Present value of impact damage
EVID = Expected value of impact damage

Equations:
$R_c = 20 * R_a$
$R_i = 10 * R_c$
$R_p = 100 * R_c$
$ID = Pi*R_i^2 * (7*GDP_{km}) + Pi*R_p^2 * GDP_{km}$
PVID = ID/(1+d)^T
EVID = PVID * P(i)

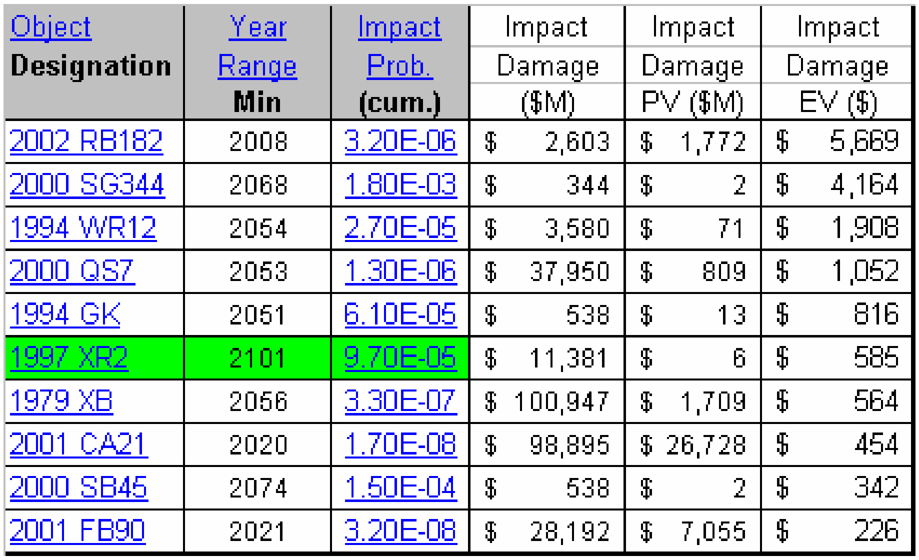
Thus; $\mathbf{EVID = [P(i)*Pi*(200R_a)^2 *(7*GDP_{km}) + Pi*(2000R_a)^2 *GDP_{km}]/(1+d)\text{^}T}$

The equation above relates expected economic damage to probability of impact, asteroid radius, time to impact, discount rate and GDP per square kilometer. All of these variables are well characterized for a given PHA.

Applying The Economic Damage Model To The List Of 46 PHAs

The NASA Jet Propulsion Laboratory (JPL) maintains a Near-Earth Object office that is responsible for the current list of potentially hazardous asteroids. There are currently 46 known objects that are considered potentially hazardous, as shown in Appendix 2 (see JPL, 2003b). The economic model has been applied to this data, estimating ID, PVID and EVID for each of these 46 elements, also shown in Appendix 2. The top ten PHAs as sorted by the EVID metric were extracted and are shown below in Table 2. These ten objects will become the input data set for the decision model. In other words, the optimal decision with respect to how to respond to these threats will be the expected result of the decision model.

Table 2. List of Top ten PHAs showing ID, PVID and EVID metrics.



Object **Designation**	Year Range **Min**	Impact Prob. **(cum.)**	Impact Damage ($M)	Impact Damage PV ($M)	Impact Damage EV ($)
2002 RB182	2008	3.20E-06	$ 2,603	$ 1,772	$ 5,669
2000 SG344	2068	1.80E-03	$ 344	$ 2	$ 4,164
1994 WR12	2054	2.70E-05	$ 3,580	$ 71	$ 1,908
2000 QS7	2053	1.30E-06	$ 37,950	$ 809	$ 1,052
1994 GK	2051	6.10E-05	$ 538	$ 13	$ 816
1997 XR2	2101	9.70E-05	$ 11,381	$ 6	$ 585
1979 XB	2056	3.30E-07	$ 100,947	$ 1,709	$ 564
2001 CA21	2020	1.70E-08	$ 98,895	$ 26,728	$ 454
2000 SB45	2074	1.50E-04	$ 538	$ 2	$ 342
2001 FB90	2021	3.20E-08	$ 28,192	$ 7,055	$ 226

COSTING AND PROBABILITIES FOR THREE PRIMARY DECISIONS

The next section of this analysis will posit three primary decisions that can be made with respect to a clearly identified hazardous asteroid. The decisions are: 1) Whether or not to conduct telescopic observation; (2) Whether or not to conduct a spacecraft reconnaissance mission; And (3) Whether or not to conduct a hazard mitigation space mission. Unit costs have been estimated for each of these decisions as elaborated below.

The Telescopic Observation Decision

Unit detection costs for PHA telescopic observation is estimated at a value of $1,000 per hour. This cost is assumed to account for overhead, salaries and maintenance expenses and is assumed to be a marginal cost (that is, does not account for amortized capital infrastructure cost). It is assumed that one hour of telescope time has a 95% likelihood of decreasing the probability of impact by an order of magnitude, and a 5% likelihood of increasing the probability of impact by a factor of 2.

The Spacecraft Reconnaissance Decision

A *spacecraft reconnaissance mission* would provide precise orbital data regarding the PHA, further refining the estimate of probability of impact. In addition, a rendezvous with an asteroid would characterize the size; spin rate and composition of the body, providing valuable data for a mitigation mission. The Near Earth Asteroid Rendezvous (NEAR) mission cost $150 Million. For the purposes of this analysis, it is assumed that a NEAR-like spacecraft would be adequate for the purposes of orbital refinement and physical property delineation. The probability of a successful mission is assumed to be 85%. The result of a ‘successful’ spacecraft reconnaissance mission would be to decrease the probability of impact by two orders of magnitude. The likelihood of an ‘unsuccessful’ mission is assumed to be 15%, with the result of a fivefold increase in the probability of impact.

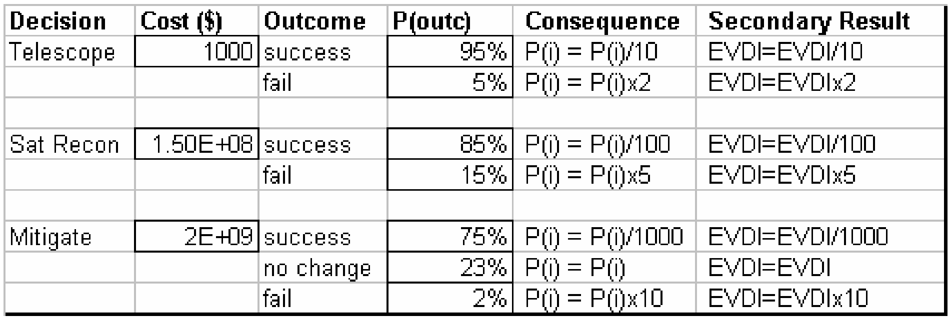
The Hazard Mitigation Mission Decision

A mission to avert a highly probable asteroid impact is defined as a *hazard mitigation mission*. For the purposes of this paper, a simple mission will be hypothesized. It is assumed that the use of two nuclear devices in succession could alter the trajectory of an asteroid. The first would employ a shaped charge to burn a tunnel into the asteroids subsurface (perhaps a hundred feet). The second device would be emplaced within the hole and when detonated would blast a sizable portion of the asteroid in a pre-specified direction, modifying the orbit of the larger body. The total estimated cost for this type of mitigation strategy is assumed to be $2 Billion dollars, and it is assumed to be available in time to mitigate the approaching hazard. The likelihood of ‘success’ of this theoretical mitigation mission is assumed to be 75%, and is assumed to reduce the probability of impact by three orders of magnitude. The likelihood of ‘no change’ for the mitigation mission is assumed to be 23%, and would leave the probability of impact unchanged. The likelihood of ‘failure’ of the mitigation mission is assumed to be 2%, and would increase the probability of impact by an order of magnitude.

DECSION ANALYSIS PROBLEM FORMULATION

The preceding discussion has been summarized by integrating the various assumptions into Table 3 below. An important simplifying assumption was made – that the reduction or increase in impact probabilities would map directly into final values. Thus, the decision model only considers the likelihood of success or failure of each decision.

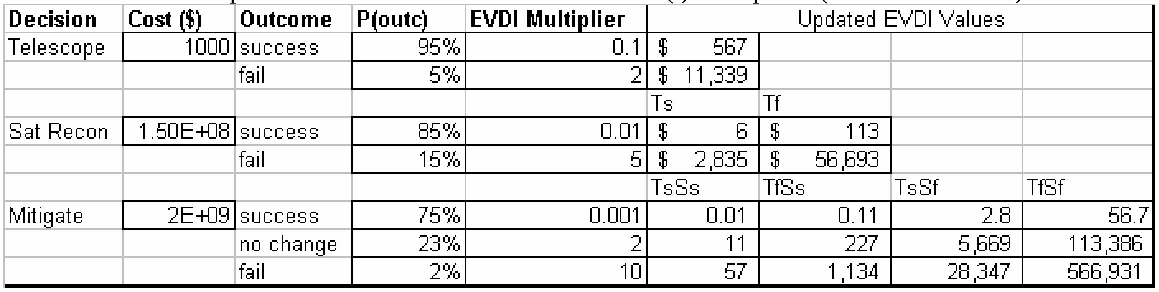
Table 3. Assumptions used to build decision model.



Decision	Cost ($)	Outcome	P(outc)	Consequence	Secondary Result
Telescope	1000	success	95%	P(i) = P(i)/10	EVDI=EVDI/10
		fail	5%	P(i) = P(i)x2	EVDI=EVDIx2
Sat Recon	1.50E+08	success	85%	P(i) = P(i)/100	EVDI=EVDI/100
		fail	15%	P(i) = P(i)x5	EVDI=EVDIx5
Mitigate	2E+09	success	75%	P(i) = P(i)/1000	EVDI=EVDI/1000
		no change	23%	P(i) = P(i)	EVDI=EVDI
		fail	2%	P(i) = P(i)x10	EVDI=EVDIx10

A sample of the results of applying these value multipliers is shown below in Table 4 for the case of a PHA named ‘2002 RB182.’ Note that this asteroid is at the top of the JPL list shown in Table 2.

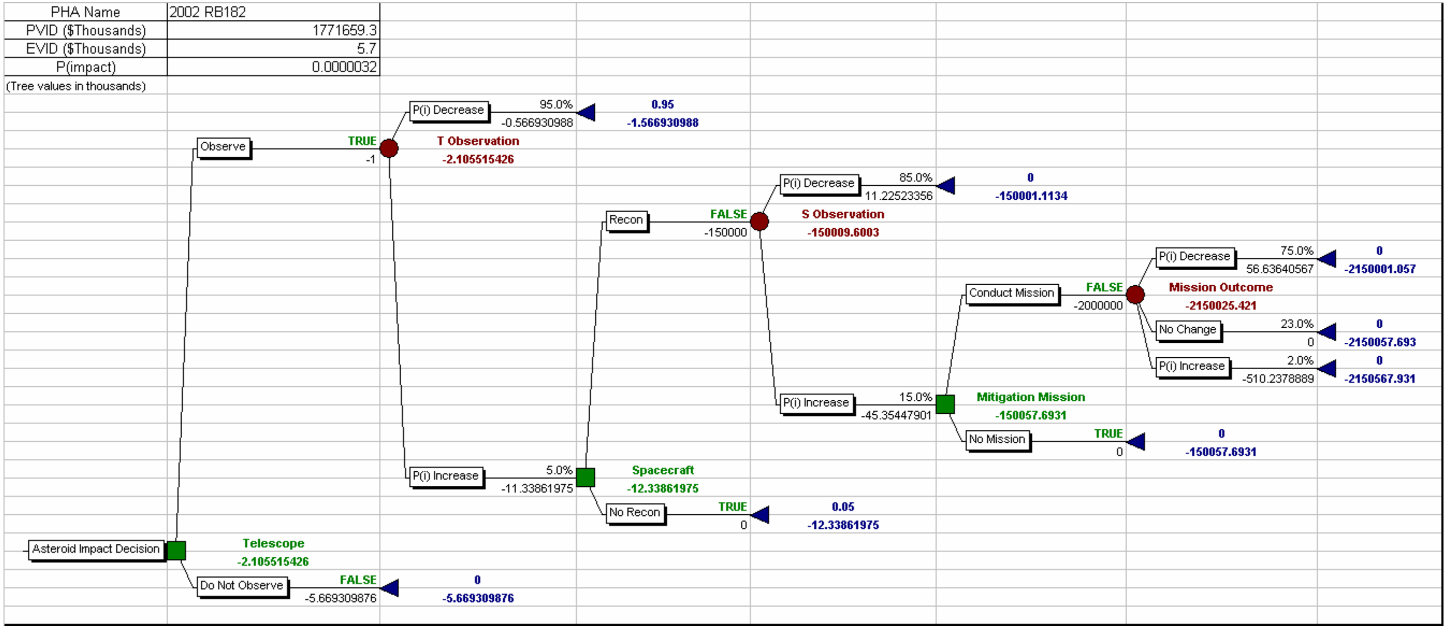
Table 4. Expected values associated with assumed P(i) multipliers (Value shown in $).



Decision	**Cost ($)**	**Outcome**	**P(outc)**	**EVDI Multiplier**	Updated EVDI Values			
Telescope	1000	success	95%	0.1	$ 567			
		fail	5%	2	$ 11,339			
					Ts	Tf		
Sat Recon	1.50E+08	success	85%	0.01	$ 6	$ 113		
		fail	15%	5	$ 2,835	$ 56,693		
					TsSs	TfSs	TsSf	TfSf
Mitigate	2E+09	success	75%	0.001	0.01	0.11	2.8	56.7
		no change	23%	2	11	227	5,669	113,386
		fail	2%	10	57	1,134	28,347	566,931

Finally, these values and their associated likelihoods are mapped into a decision tree. Results of the decision tree formulation are shown below as Figure 2.

Figure 2. Decision tree for PHA ‘2002 RB182.’



PHA Name	2002 RB182
PVID ($Thousands)	1771659.3
EVID ($Thousands)	5.7
P(impact)	0.0000032

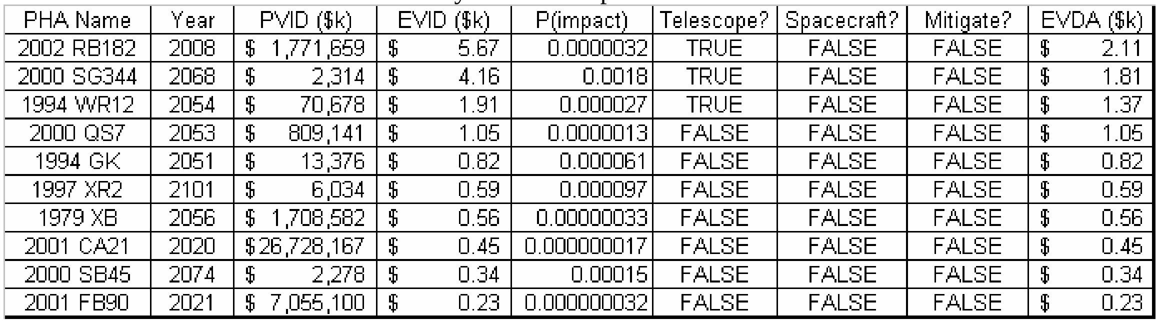
(Tree values in thousands)

Note that the decision tree recommends telescopic observation of the asteroid, with a 95% likelihood of reducing the expected damage figure by a factor of ten. Further, no spacecraft reconnaissance or mitigation is recommended. This is not a surprising result, as the expected value of impact damage (EVID) is just over $5,600. Note that this PHA represents the highest EVID on the current hazard list. Therefore, no spacecraft recon or mitigation is recommended with respect to *any known* asteroid hazard.

RESULTS OF DECSION ANALYSIS

As is shown on the previous page, the highest known asteroid hazard merits one hour of telescopic observation. Results are summarized in Table 5 below for the other nine members of the PHA hazard list derived from Table 2. Note that telescopic observation is only recommended for the top three. Also note that the expected value resulting from decision analysis (EVDA) is lower than the EVID metric in those three cases. This is due to the 95% likelihood of a tenfold decrease in P(i) as reflected by a lower expected damage figure.

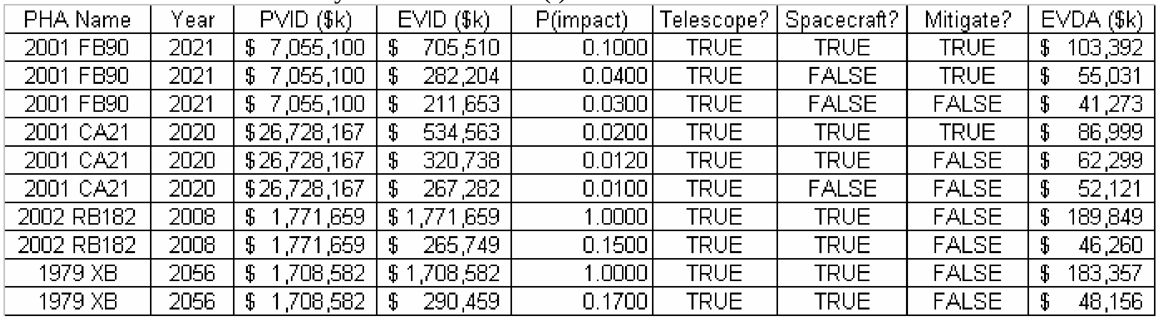
Table 5. Results of decision analysis for the top ten asteroid hazards.



PHA Name	Year	PVID ($k)	EVID ($k)	P(impact)	Telescope?	Spacecraft?	Mitigate?	EVDA ($k)
2002 RB182	2008	$ 1,771,659	$ 5.67	0.0000032	TRUE	FALSE	FALSE	$ 2.11
2000 SG344	2068	$ 2,314	$ 4.16	0.0018	TRUE	FALSE	FALSE	$ 1.81
1994 WR12	2054	$ 70,678	$ 1.91	0.000027	TRUE	FALSE	FALSE	$ 1.37
2000 QS7	2053	$ 809,141	$ 1.05	0.0000013	FALSE	FALSE	FALSE	$ 1.05
1994 GK	2051	$ 13,376	$ 0.82	0.000061	FALSE	FALSE	FALSE	$ 0.82
1997 XR2	2101	$ 6,034	$ 0.59	0.000097	FALSE	FALSE	FALSE	$ 0.59
1979 XB	2056	$ 1,708,582	$ 0.56	0.00000033	FALSE	FALSE	FALSE	$ 0.56
2001 CA21	2020	$26,728,167	$ 0.45	0.000000017	FALSE	FALSE	FALSE	$ 0.45
2000 SB45	2074	$ 2,278	$ 0.34	0.00015	FALSE	FALSE	FALSE	$ 0.34
2001 FB90	2021	$ 7,055,100	$ 0.23	0.000000032	FALSE	FALSE	FALSE	$ 0.23

It must be reiterated that less than 20% of the estimated PHA population has been discovered to date. The utility of this type of decision analysis model may be in evaluating what to do if a ‘real problem’ is discovered in the near future. A recent example may illustrate the potential for trouble. On December 6, 2003, an asteroid named ‘2003 XJ7’ passed within 150,000 kilometers of Earth (40% of the distance to the Moon – a very close call) traveling nearly 17 kilometers per second. We did not see it coming. It was estimated to be between 15 and 33 meters in size. It could have caused a sizable amount of trouble had it impacted an urban area. It is the nearest miss that has been observed to date. 2003 XJ7 and similar near misses are used by the scientific community as rationale to step up the discovery rate for PHAs. Provided the asteroid assessment rate increases, potential hazard discoveries could emerge that challenge the decision maker. The utility or value of the current decision analysis model will next be explored by a series of ‘what if’ questions. The premise is simple. What if the likelihood of impact for four of the known PHAs was higher? Table 6 below lists the assumed values for increased likelihood, as well as the decisions recommended by the model.

Table 6. What-if analysis for increased P(i) likelihood for four known PHAs.



PHA Name	Year	PVID ($k)	EVID ($k)	P(impact)	Telescope?	Spacecraft?	Mitigate?	EVDA ($k)
2001 FB90	2021	$ 7,055,100	$ 705,510	0.1000	TRUE	TRUE	TRUE	$ 103,392
2001 FB90	2021	$ 7,055,100	$ 282,204	0.0400	TRUE	FALSE	TRUE	$ 55,031
2001 FB90	2021	$ 7,055,100	$ 211,653	0.0300	TRUE	FALSE	FALSE	$ 41,273
2001 CA21	2020	$26,728,167	$ 534,563	0.0200	TRUE	TRUE	TRUE	$ 86,999
2001 CA21	2020	$26,728,167	$ 320,738	0.0120	TRUE	TRUE	FALSE	$ 62,299
2001 CA21	2020	$26,728,167	$ 267,282	0.0100	TRUE	FALSE	FALSE	$ 52,121
2002 RB182	2008	$ 1,771,659	$ 1,771,659	1.0000	TRUE	TRUE	FALSE	$ 189,849
2002 RB182	2008	$ 1,771,659	$ 265,749	0.1500	TRUE	TRUE	FALSE	$ 46,260
1979 XB	2056	$ 1,708,582	$ 1,708,582	1.0000	TRUE	TRUE	FALSE	$ 183,357
1979 XB	2056	$ 1,708,582	$ 290,459	0.1700	TRUE	TRUE	FALSE	$ 48,156

Table 6 clearly shows that the decision analysis model does indeed recommend spacecraft and mitigation missions, given a significant enough likelihood of impact. To aid in understanding the model results, Appendix 3 shows the decision model outcomes for the asteroid '2001 CA21' (expected to travel nearby Earth in the year 2020) for assumed likelihood of impact values of 2%, 1.2% and 1%. Note that these are the values that trigger the mitigation decision, the spacecraft decision and the telescope decision, respectively.

CONCLUSIONS

The list of know PHAs offer very low likelihoods for impact. This fact is well represented by the EVID metric, which is well below $10,000 for all members of the list. However, the chance that a future discovery may uncover a real hazard will remain high until the catalogue of PHAs is more complete. Therefore, the decision analysis model and economic damage estimation procedure are offered as a straightforward method of modeling a proper response to future hazards.

RECOMMENDATIONS

This model is relatively simplistic, and was constructed in a short period of time. Further work would improve the results substantially. Note that this paper has focused on the decision analysis framework rather than a comprehensive treatment of economic damage. For that reason, these preliminary results are framed as a process to follow, and should not be considered authoritative. More work is recommended.

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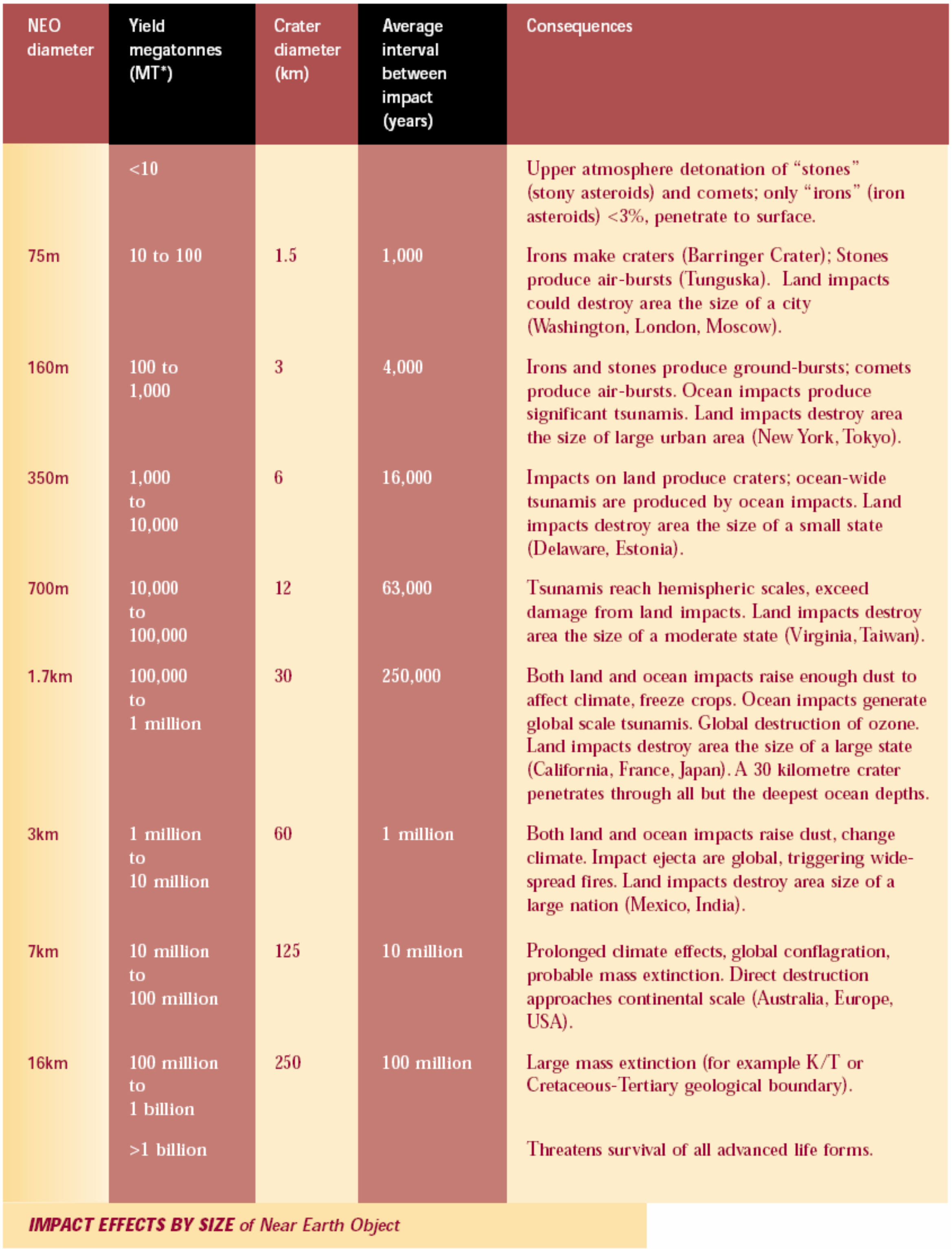
APPENDIX 1: Diagram from Atkinson (2000).



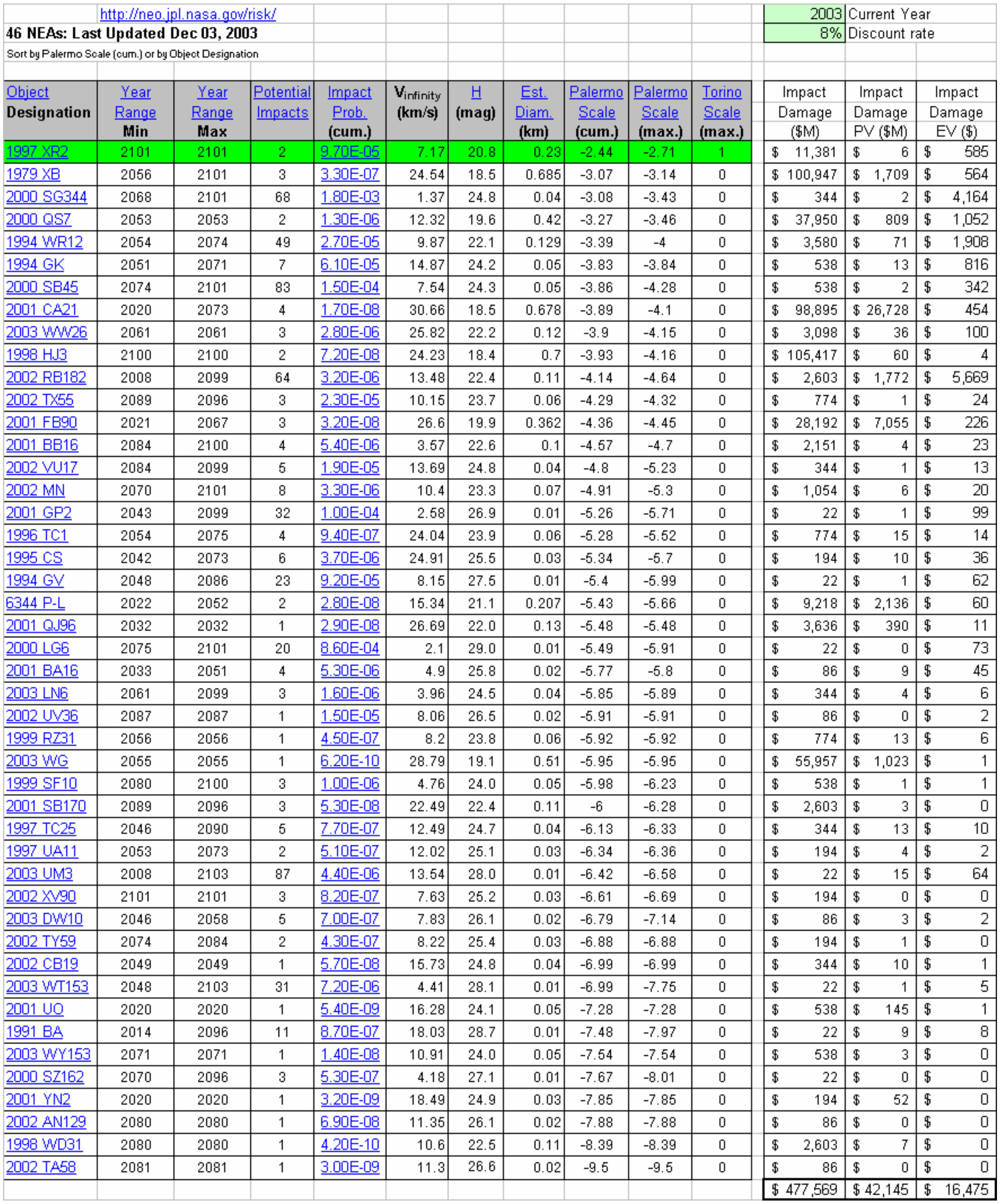
NEO diameter	Yield megatonnes (MT*)	Crater diameter (km)	Average interval between impact (years)	Consequences
	<10			Upper atmosphere detonation of "stones" (stony asteroids) and comets; only "irons" (iron asteroids) <3%, penetrate to surface.
75m	10 to 100	1.5	1,000	Irons make craters (Barringer Crater); Stones produce air-bursts (Tunguska). Land impacts could destroy area the size of a city (Washington, London, Moscow).
160m	100 to 1,000	3	4,000	Irons and stones produce ground-bursts; comets produce air-bursts. Ocean impacts produce significant tsunamis. Land impacts destroy area the size of large urban area (New York, Tokyo).
350m	1,000 to 10,000	6	16,000	Impacts on land produce craters; ocean-wide tsunamis are produced by ocean impacts. Land impacts destroy area the size of a small state (Delaware, Estonia).
700m	10,000 to 100,000	12	63,000	Tsunamis reach hemispheric scales, exceed damage from land impacts. Land impacts destroy area the size of a moderate state (Virginia, Taiwan).
1.7km	100,000 to 1 million	30	250,000	Both land and ocean impacts raise enough dust to affect climate, freeze crops. Ocean impacts generate global scale tsunamis. Global destruction of ozone. Land impacts destroy area the size of a large state (California, France, Japan). A 30 kilometre crater penetrates through all but the deepest ocean depths.
3km	1 million to 10 million	60	1 million	Both land and ocean impacts raise dust, change climate. Impact ejecta are global, triggering wide-spread fires. Land impacts destroy area size of a large nation (Mexico, India).
7km	10 million to 100 million	125	10 million	Prolonged climate effects, global conflagration, probable mass extinction. Direct destruction approaches continental scale (Australia, Europe, USA).
16km	100 million to 1 billion	250	100 million	Large mass extinction (for example K/T or Cretaceous-Tertiary geological boundary).
	>1 billion			Threatens survival of all advanced life forms.

IMPACT EFFECTS BY SIZE *of Near Earth Object*

** 1 MT = explosive power of 1 megatonne of TNT. The Hiroshima atomic bomb was about 15 kilotonnes; and the hydrogen device on the Bikini atoll about 10 MT.*

After D Morrison et al, p 71, Hazards *(T Gehrels, Ed) 1994, including data from Alan Harris in the graph on page 17.*

APPENDIX 2. JPL (2003b) list of 46 Potentially Hazardous Asteroids (PHAs).



http://neo.jpl.nasa.gov/risk/

46 NEAs: Last Updated Dec 03, 2003

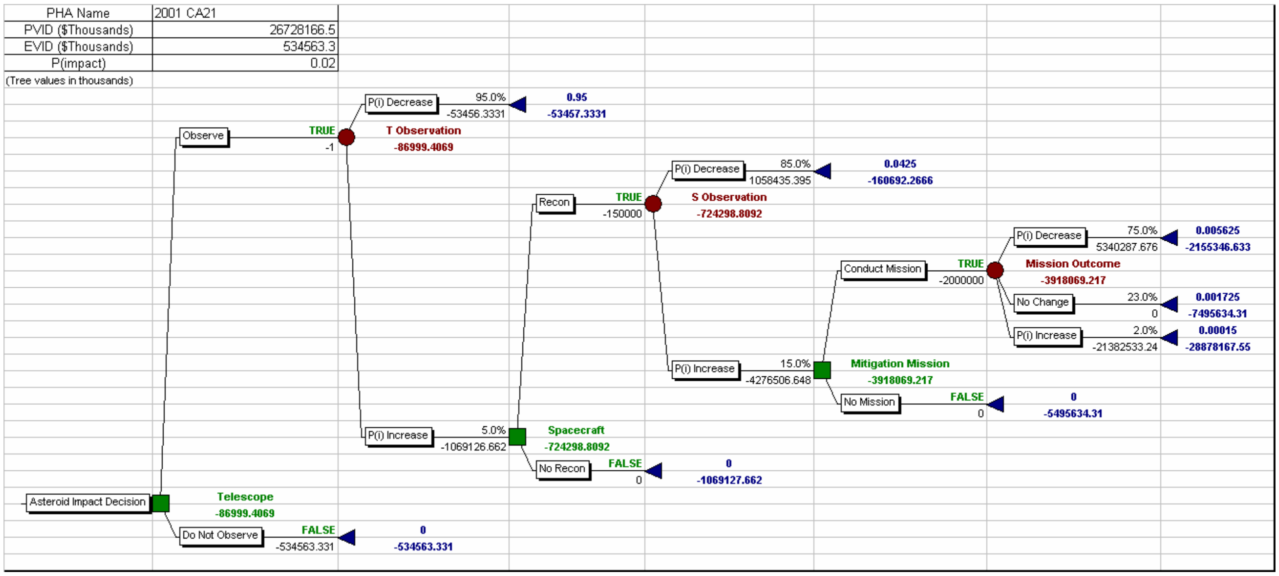
Sort by Palermo Scale (cum.) or by Object Designation

2003 Current Year

8% Discount rate

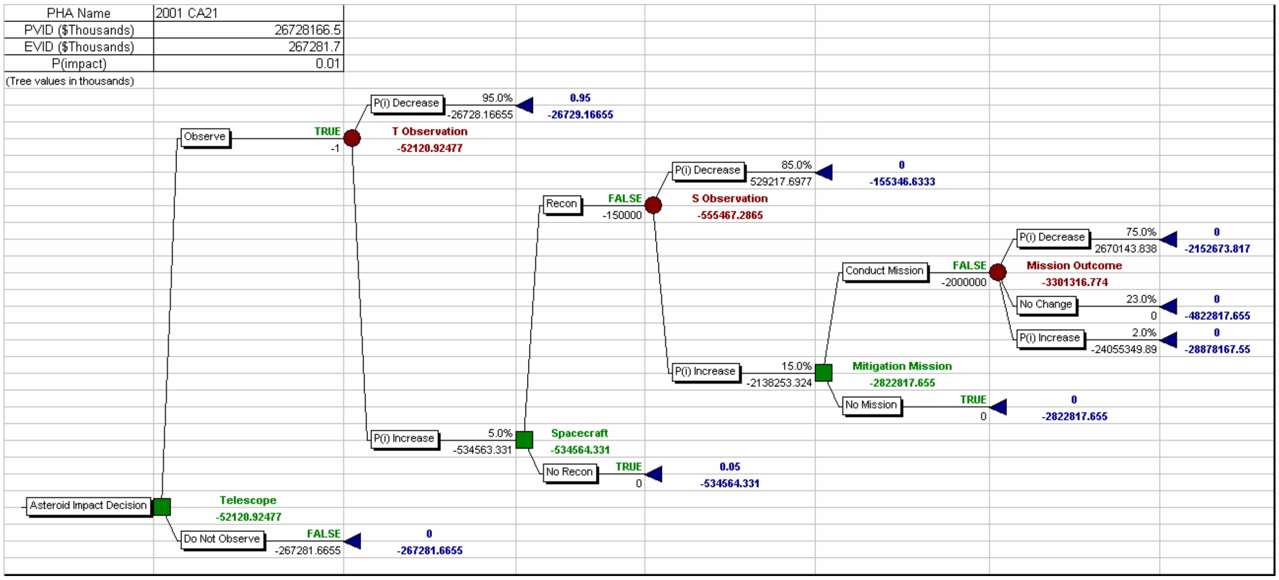
Object **Designation**	Year Range **Min**	Year Range **Max**	Potential Impacts	Impact Prob. **(cum.)**	**$V_{infinity}$ (km/s)**	H **(mag)**	Est. Diam. **(km)**	Palermo Scale **(cum.)**	Palermo Scale **(max.)**	Torino Scale **(max.)**	Impact Damage ($M)	Impact Damage PV ($M)	Impact Damage EV ($)
1997 XR2	2101	2101	2	9.70E-05	7.17	20.8	0.23	-2.44	-2.71	1	$ 11,381	$ 6	$ 585
1979 XB	2056	2101	3	3.30E-07	24.54	18.5	0.685	-3.07	-3.14	0	$ 100,947	$ 1,709	$ 564
2000 SG344	2068	2101	68	1.80E-03	1.37	24.8	0.04	-3.08	-3.43	0	$ 344	$ 2	$ 4,164
2000 QS7	2053	2053	2	1.30E-06	12.32	19.6	0.42	-3.27	-3.46	0	$ 37,950	$ 809	$ 1,052
1994 WR12	2054	2074	49	2.70E-05	9.87	22.1	0.129	-3.39	-4	0	$ 3,580	$ 71	$ 1,908
1994 GK	2051	2071	7	6.10E-05	14.87	24.2	0.05	-3.83	-3.84	0	$ 538	$ 13	$ 816
2000 SB45	2074	2101	83	1.50E-04	7.54	24.3	0.05	-3.86	-4.28	0	$ 538	$ 2	$ 342
2001 CA21	2020	2073	4	1.70E-08	30.66	18.5	0.678	-3.89	-4.1	0	$ 98,895	$ 26,728	$ 454
2003 WW26	2061	2061	3	2.80E-06	25.82	22.2	0.12	-3.9	-4.15	0	$ 3,098	$ 36	$ 100
1998 HJ3	2100	2100	2	7.20E-08	24.23	18.4	0.7	-3.93	-4.16	0	$ 105,417	$ 60	$ 4
2002 RB182	2008	2099	64	3.20E-06	13.48	22.4	0.11	-4.14	-4.64	0	$ 2,603	$ 1,772	$ 5,669
2002 TX55	2089	2096	3	2.30E-05	10.15	23.7	0.06	-4.29	-4.32	0	$ 774	$ 1	$ 24
2001 FB90	2021	2067	3	3.20E-08	26.6	19.9	0.362	-4.36	-4.45	0	$ 28,192	$ 7,055	$ 226
2001 BB16	2084	2100	4	5.40E-06	3.57	22.6	0.1	-4.57	-4.7	0	$ 2,151	$ 4	$ 23
2002 VU17	2084	2099	5	1.90E-05	13.69	24.8	0.04	-4.8	-5.23	0	$ 344	$ 1	$ 13
2002 MN	2070	2101	8	3.30E-06	10.4	23.3	0.07	-4.91	-5.3	0	$ 1,054	$ 6	$ 20
2001 GP2	2043	2099	32	1.00E-04	2.58	26.9	0.01	-5.26	-5.71	0	$ 22	$ 1	$ 99
1996 TC1	2054	2075	4	9.40E-07	24.04	23.9	0.06	-5.28	-5.52	0	$ 774	$ 15	$ 14
1995 CS	2042	2073	6	3.70E-06	24.91	25.5	0.03	-5.34	-5.7	0	$ 194	$ 10	$ 36
1994 GV	2048	2086	23	9.20E-05	8.15	27.5	0.01	-5.4	-5.99	0	$ 22	$ 1	$ 62
6344 P-L	2022	2052	2	2.80E-08	15.34	21.1	0.207	-5.43	-5.66	0	$ 9,218	$ 2,136	$ 60
2001 QJ96	2032	2032	1	2.90E-08	26.69	22.0	0.13	-5.48	-5.48	0	$ 3,636	$ 390	$ 11
2000 LG6	2075	2101	20	8.60E-04	2.1	29.0	0.01	-5.49	-5.91	0	$ 22	$ 0	$ 73
2001 BA16	2033	2051	4	5.30E-06	4.9	25.8	0.02	-5.77	-5.8	0	$ 86	$ 9	$ 45
2003 LN6	2061	2099	3	1.60E-06	3.96	24.5	0.04	-5.85	-5.89	0	$ 344	$ 4	$ 6
2002 UV36	2087	2087	1	1.50E-05	8.06	26.5	0.02	-5.91	-5.91	0	$ 86	$ 0	$ 2
1999 RZ31	2056	2056	1	4.50E-07	8.2	23.8	0.06	-5.92	-5.92	0	$ 774	$ 13	$ 6
2003 WG	2055	2055	1	6.20E-10	28.79	19.1	0.51	-5.95	-5.95	0	$ 55,957	$ 1,023	$ 1
1999 SF10	2080	2100	3	1.00E-06	4.76	24.0	0.05	-5.98	-6.23	0	$ 538	$ 1	$ 1
2001 SB170	2089	2096	3	5.30E-08	22.49	22.4	0.11	-6	-6.28	0	$ 2,603	$ 3	$ 0
1997 TC25	2046	2090	5	7.70E-07	12.49	24.7	0.04	-6.13	-6.33	0	$ 344	$ 13	$ 10
1997 UA11	2053	2073	2	5.10E-07	12.02	25.1	0.03	-6.34	-6.36	0	$ 194	$ 4	$ 2
2003 UM3	2008	2103	87	4.40E-06	13.54	28.0	0.01	-6.42	-6.58	0	$ 22	$ 15	$ 64
2002 XV90	2101	2101	3	8.20E-07	7.63	25.2	0.03	-6.61	-6.69	0	$ 194	$ 0	$ 0
2003 DW10	2046	2058	5	7.00E-07	7.83	26.1	0.02	-6.79	-7.14	0	$ 86	$ 3	$ 2
2002 TY59	2074	2084	2	4.30E-07	8.22	25.4	0.03	-6.88	-6.88	0	$ 194	$ 1	$ 0
2002 CB19	2049	2049	1	5.70E-08	15.73	24.8	0.04	-6.99	-6.99	0	$ 344	$ 10	$ 1
2003 WT153	2048	2103	31	7.20E-06	4.41	28.1	0.01	-6.99	-7.75	0	$ 22	$ 1	$ 5
2001 UO	2020	2020	1	5.40E-09	16.28	24.1	0.05	-7.28	-7.28	0	$ 538	$ 145	$ 1
1991 BA	2014	2096	11	8.70E-07	18.03	28.7	0.01	-7.48	-7.97	0	$ 22	$ 9	$ 8
2003 WY153	2071	2071	1	1.40E-08	10.91	24.0	0.05	-7.54	-7.54	0	$ 538	$ 3	$ 0
2000 SZ162	2070	2096	3	5.30E-07	4.18	27.1	0.01	-7.67	-8.01	0	$ 22	$ 0	$ 0
2001 YN2	2020	2020	1	3.20E-09	18.49	24.9	0.03	-7.85	-7.85	0	$ 194	$ 52	$ 0
2002 AN129	2080	2080	1	6.90E-08	11.35	26.1	0.02	-7.88	-7.88	0	$ 86	$ 0	$ 0
1998 WD31	2080	2080	1	4.20E-10	10.6	22.5	0.11	-8.39	-8.39	0	$ 2,603	$ 7	$ 0
2002 TA58	2081	2081	1	3.00E-09	11.3	26.6	0.02	-9.5	-9.5	0	$ 86	$ 0	$ 0
											$ 477,569	$ 42,145	$ 16,475

APPENDIX 3. DA formulations for PHA ‘2001 CA21’ given P(i)=2%, 1.2% and 1%.



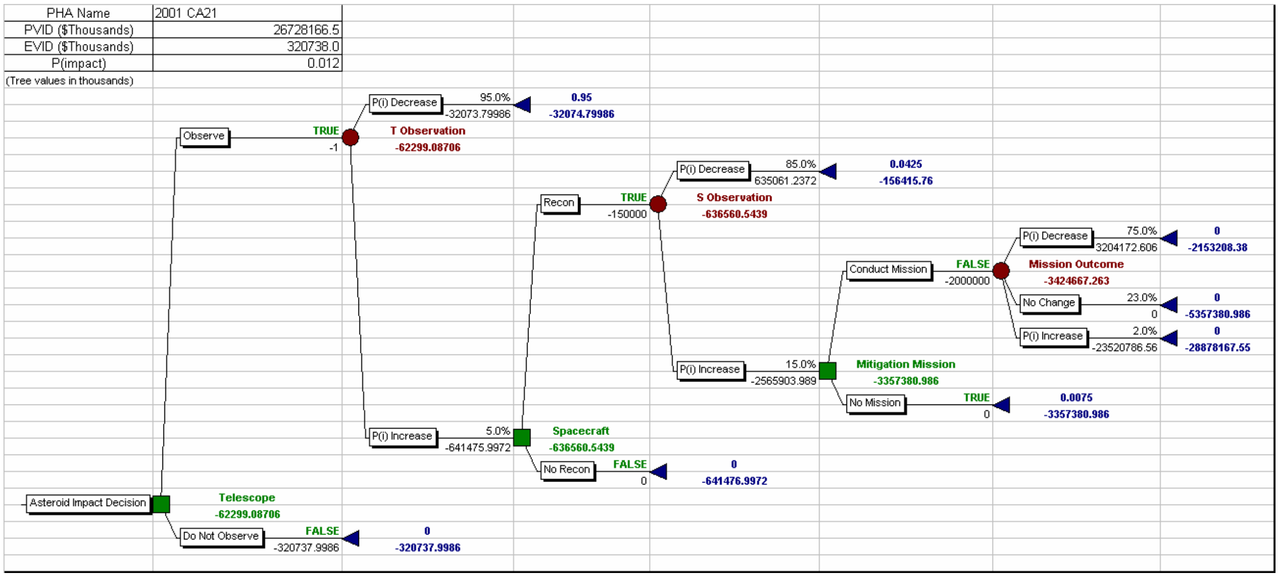
PHA Name	2001 CA21
PVID ($Thousands)	26728166.5
EVID ($Thousands)	534563.3
P(impact)	0.02

(Tree values in thousands)



PHA Name	2001 CA21
PVID ($Thousands)	26728166.5
EVID ($Thousands)	267281.7
P(impact)	0.01

(Tree values in thousands)



PHA Name	2001 CA21
PVID ($Thousands)	26728166.5
EVID ($Thousands)	320738.0
P(impact)	0.012

(Tree values in thousands)