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Semesterarbeit

The Asteroid Impact Threat
From Physical Parameters to Information

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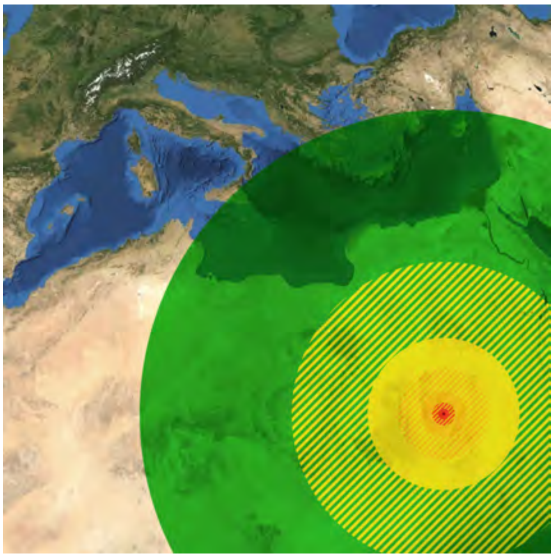

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Zusammenfassung

Das Ziel der vorliegenden Arbeit ist die Erstellung einer nicht-statistischen Skala für Einschläge von Asteroiden und anderen Himmelsobjekten, die für die Kommunikation mit Katastrophenschutzbehörden und der Öffentlichkeit verwendet werden kann.
Zunächst wird ein Überblick über die Folgen eines Einschlags dargestellt. Durch ein einfaches mathematisches Modell werden diese mit den Parametern des einschlagenden Objekts verknüpft. Mithilfe einer Analyse von bereits existierenden Skalen für Einschläge und für andere Bereiche wird daraus eine neue, auf Schadenszonen basierende Skala erstellt.

Abstract

The following paper aims to provide a non-probabilistic impact scale that can be used for communication with emergency agencies and the general public.
An overview is given on the effects of the impact of an asteroid or other celestial object. These are linked to the parameters of the impactor using a simple mathematical model. With the help of an analysis of existing scales regarding impacts and other domains, a new scale is proposed that is based on damage zones.

Contents

Figures

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Symbols

A_{deep}	m	initial wave amplitude
Δ	km	distance from earthquake epicenter to point of measurement
ϵ	-	fraction of impact energy converted into wave energy
η	-	luminous efficiency, fraction of impact energy converted to thermal radiation
μ	Pa	shear strength of the faulted rock
Φ	MJ/m^2	thermal exposure
ρ_i	kg/m^3	impactor density
ρ_t	kg/m^3	target density
ρ_{water}	kg/m^3	ocean water density
θ	°	impact angle
c_0	m/s	ambient speed of sound in air
d	m	average displacement on fault
E	Mt TNT, J	yield or impact energy
E_w	erg	wave energy
E_{kin}	J	kinetic energy
f	-	fraction of the fireball visible above the horizon
f_B	1/yr	annual background impact frequency
g_E	m^2	gravitational acceleration on Earth's surface
H	m	average tsunami height on the coast closest to the source
h	m	maximum wave amplitude on the coast measured foot to crest
h	m	maximum wave amplitude on the coast measured foot to crest
h_{deep}	m	ocean depth at the point of impact
h_{in}	m	Run-in, distance that the tsunami travels inland from the shore
H_{max}	m	maximum wave height observed on the shore or measured by mareograph

h_{up}	m	Run-up, height of the tsunami wave at the shore
I	-	Soloviev Tsunami Strength Scale value
L	m	impactor diameter before point of impact
L_0	m	impactor diameter before atmospheric entry
M	-	Imamura-Iida Tsunami Strength Scale value
m_b	-	Body-wave Magnitude Scale value
m_i	kg	impactor mass before atmospheric entry
M_L	-	Local Magnitude Scale value or Richter Scale value
M_O	10^{-7} Nm	Seismic Moment
M_S	-	Surface Wave Magnitude Scale value
M_t	-	Abe-Hatori Tsunami Strength Scale value
M_W	-	Moment Magnitude Scale value
M_{eff}	-	calculated Richter Scale Value at distance Δ from impact site
ML	-	Murty-Loomis Tsunami Strength Scale value
P_0	bar	ambient pressure
p_I	-	impact probability
p_x	bar	pressure at crossover point r_x
PS	-	Palermo Technical Hazard Scale value
r	m	distance to fireball center
R	-	relative risk
r_x	m	crossover point
R_{f*}	m	fireball radius
S	m^2	fault area
t	yr	time
v_0	m/s	impactor velocity before atmospheric entry
v_i	m/s	impactor velocity before point of impact

Acronyms

INES International Nuclear Event Scale
MMI Modified Mercalli Intensity Scale
JMA Japanese Meteorolocial Agency Seismic Intensity Scale
VEI Volcanic Explosivity Index

1. Introduction

For all of recorded history, there has never been a person that was killed by an impact of an asteroid or other celestial object [26]. Impacts are rare and large impacts even rarer, but nevertheless they possess an enormous potential for harm. In the event of an upcoming impact, it may be crucial to take appropriate measures. For this, emergency agencies and the general public - laymen with little knowledge of impacts and their consequences - need to know what to expect.

In order to characterize and communicate about emergencies, scales have proven a valuable tool. There have been several attempts to create scales for impact events, but for public communication, most of them are of limited usefulness.
The following pages provide an overview on impactors[1], impact effects and their correlation, analyze existing scales and use this information to propose a new scale for communication with emergency agencies and the general public.

[1] For simplicity, asteroids, meteroids, comets and other objects that enter the atmosphere will be called impactors, regardless of whether there is an impact on the ground or not.

2. Airburst and Impact Effects

An impact causes a variety of different effects, several of which are linked. This section provides a qualitative overview. A quantitative approach is given in section 4.

Due to lack of data on actual impact events, the resulting effects have historically been modeled after point-mass explosions like chemical and nuclear explosions. More recent calculations however have shown that this underestimates the impact effects (see [10]).

2.1. Thermal Radiation

Beyond a certain velocity, an impact typically causes an explosion. The thermal radiation released may ignite materials close to the impact site but its intensity drops quickly with distance.
When an explosion occurs, the temperature is such that the fireball is opaque at first. Only after it has expanded and cooled down, it transitions and becomes transparent. This means that there are two heatwaves from radiation: The first one of the opaque fireball and a more intense second one, when the confined radiation of the fireball is released. [4; 21]

Thermal radiation can be shielded by objects such as buildings or landscape features and at large distances, the fireball is shielded by the horizon. While the latter can easily be accounted for in mathematical models, the previous makes it difficult to predict the effects without detailed knowledge of the surroundings.

2.2. Air Blast

The air blast caused by the impact explosion can be broken down into two phenomena.
First is the pressure blast wave caused by the rapid expansion and compression of air during the explosion. Second is the wind following the pressure wave.
While most damage is induced by overpressure, objects with high drag are particularly vulnerable to the high winds.

2.3. Seismic Effects

Large impactors beyond several hundred meters in diameter cause noticeable seismic effects. These can be described by the same measures that are used for earthquakes. Richter-Scale and Mercalli-Scale values can be assigned to the seismic activity, see section 4.7.

Along with seismic effects, impactors may also trigger volcanic effects. Yet, the probability of such an event is much lower as this could only happen at very specific sites. Although a freak incident like an impact at the Yellowstone Caldera triggering a supervolcanic eruption is possible in theory, the likelihood of such an event is miniscule.

2.4. Cratering and Ejecta

Crater size plays a minor role compared to thermal radiation and air blast when looking at the hazard to human life since the latter have a larger range and very thorough effect. It does, of course, make a considerable difference when it comes to structures and infrastructure.

When it comes to crater size, two different kinds of craters can be defined: the so-called transient crater which is formed at the point of impact and the final crater that results from the subsequent collapse of the transient crater. For the purpose of damage assessment, the relevant crater size is that of the final crater. It indicates the region in which the ground has been reshaped.

For small impacts, the ejecta usually stay within the radius of the fireball. Only during large impacts with impact energies over 10^{18} J, where the fireball reaches the upper layers of the atmosphere, the ejecta may escape the dense lower layers and reach significantly wider distances [16].

2.5. Atmosphere Poisoning

Injection of dust and water vapor may play a significant role for larger impactors. The effects range from local ozone depletion to situations similar to what is widely known as „Nuclear Winter“, causing wide-scale extinction events.

2.6. Tsunami

More than 70% of the earth's surface is water [36]. Since the probability of an asteroid impact is generally the same everywhere on earth [32], the majority of impactors hit the ocean rather than land.

Considering that a large share of the world population lives at or near the coast (see fig. 2.1), tsunamis created by impact – also called cosmogenic tsunamis – pose a significant hazard.

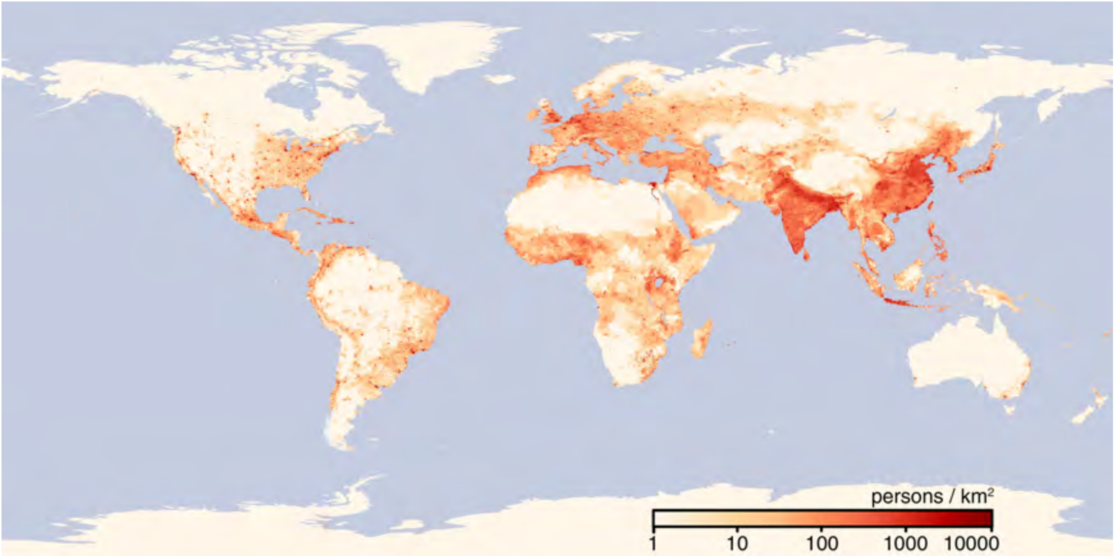


Fig. 2.1.: World Population Density Map (data from 2000) [28]

Tsunamis can be characterized by two parameters [3]:

- Run-up, which is the height of the tsunami wave at the shore.
- Run-in, which is the distance that the tsunami travels inland from the shore.

Since no cosmogenic tsunamis have been recorded yet, all known interaction models of impactors with water of different depths are purely theoretical and contain numerous uncertainties [25](p.295). The energy-carrying wave-spectrum components of cosmogenic tsunamis travel significantly slower than those of tsunamis caused by seismotectonic activity[1], which arguably leads to different behavior and different effects on the shore, such as less run-in.

2.7. Airburst

Some of the effects described in the previous sections assume a single, non-fragmented impactor. This is not necessarily the case. In fact, there are three possible instances:

- The impactor reaches the ground in one single piece.
- The impactor disintegrates and reaches the ground in several pieces.
- The impactor disintegrates and explodes in the atmosphere.

[1]by a factor of two for typical cases, see [25](p.303)

Whether an impactor fragments and to what degree depends a lot on its composition. Diameter does likely make a difference, but it is not clear in which way as there are opposing findings and opinions on this matter [4]. Very small objects however can be assumed to burn up in the atmosphere. It is not quite clear what the effect of an airburst above water is, but it is assumed that they do not cause a tsunami.
Existing models are quite complex and, due to the lack of real-life data, difficult to verify. This makes predictions difficult except for impactors with extreme parameters.

3. Parameters and Their Influence

For assessing the threat posed by it, an impactor can be described by the following parameters. Other existing impactor characteristics such as albedo may be relevant for determining some of the following parameters but do not significantly influence the impact process itself.
The influence of the parameters on kinetic energy varies. Kinetic energy and ultimately impact energy (i.e. kinetic energy at the point of impact) is the most important factor for characterizing impact effects.

3.1. Impactor Diameter

Along with mass, diameter may be considered the most important parameter of an impactor. It affects mass and therefore kinetic energy over-proportionally by the power of three and its value range is virtually unrestricted at the top. With optical and IR measurements, it is also one the easier parameters to determine. This is why diameter is often used to convey the destructive potential of an impactor in one single figure.

3.2. Impactor Density and Mass

Density is used to calculate mass from diameter. It typically ranges from roughly 600 kg/m^3 (porous ice) to 8000 kg/m^3 (solid iron) and is influenced by composition and porosity.
Along with diameter, mass may be considered the most important parameter of an impactor as it proportionally affects kinetic energy.

3.3. Impactor Velocity

After the tandem of diameter and mass, velocity is the next most significant parameter.
Velocity is limited to a range from 11 km/s to 72 km/s. Faster object surpass the escape velocity of the solar system and cannot be held in sun orbit which is typically required for a significant probability of a collision with earth. Slower objects are accelerated by gravity before collision. [16]
Velocity affects kinetic energy over-proportionally by the power of two.

3.4. Impact Angle

The impact angle ranges from 0° (tangential to earth's surface) to 90° (perpendicular). Empirical records place the most probable angle at 45°. [16]
While the impact angle obviously does not affect kinetic energy before entering the atmosphere, it has significant influence on the path through the atmosphere and how much of the impactor burns up before reaching the ground. Therefore, it also affects crater size and ejecta.
In case of a disintegrating impactor, for a low angle the breakup may occur at more than double the height compared to a steep angle. Impact energy varies by a factor of about two as well.

3.5. Impactor Porosity

Porosity, along with composition, is used to assess the density of an impactor. It can be as high as 35% (i.e. up to 35% of an impactor's volume can be void) [17]. This void can fill with gas and expand when heated during atmospheric entry. Combined with the lower structural integrity that typically comes with high porosity, this increases the likelihood of a breakup in the atmosphere.

3.6. Impactor Composition

Composition, along with porosity, is used to assess density.
Impactors can be classified according to their composition. In the case of meteorites, the top level categories are

- stony meteorites
- stony-iron meteorites
- iron meteorites

each of which consists of several sub-categories. These help to estimate the density of the impactor. [17]

3.7. Target Parameters

The topic of target parameters is a complex one and the exact influence of some of them is hard to quantify simply because of their sheer variety.
The most basic parameters include whether the impactor hits (respectively bursts above) land or water. In the first case, geological composition, porosity and density do play a role and typically range from ice (1000 kg/m^3) over porous rock

(1500 kg/m^3) to dense rock (3000 kg/m^3). In the latter case, the deciding factors are water depth and – except for small impactors or very deep water – the parameters of the ground beneath. These influence the properties of a potential tsunami, cratering, ejecta and amount of evaporation.

More difficult to put into numbers are the shape of the landscape and, for assessing the damage, differences in construction of man-made structures. An impact into a mountain range will have different effects than one into flatland. Also, the consequences to cities of European-style brick buildings would be different to those of third-world tin shacks or to those of Japanese earthquake resistant high-rise buildings.

4. Quantitative Translation between Parameters and Effects

In this section, a simple model is created that links the parameters of the impactor to the effects.

Since there is hardly any data available from actual impacts, these are usually modeled after chemical or nuclear explosions. However, these point-source explosion models tend to underestimate the effects of an impactor having high downward velocity [10].
Between chemical and nuclear explosions, there are differences due to energy density [21]. In terms of energy per unit mass, asteroids possess about four to twenty times that of TNT [16] while the one of nuclear explosion devices is larger by several magnitudes. Therefore, an impact is likely to be closer to a chemical explosion. Data on large explosions, however, is almost exclusively available for nuclear explosions which has to be kept in mind.

Large parts of the following quantitative translation are based on the Earth Impact Effects model by Collins et al. [16]. Since the aim is to aid creation of a one-dimensional warning scale which is only possible when neglecting less influential factors, the model is being simplified further.

A Matlab script of the model is provided in the appendix.

4.1. Kinetic Energy

The kinetic energy of an impactor before entering the atmosphere is given as

$$E_{kin} = \frac{1}{2} m_i v_0^2 = \frac{\pi}{12} \rho_i L_0^3 v_0^2 \tag{4.1}$$

with

m_i impactor mass before atmospheric entry,

v_0 impactor velocity before atmospheric entry,

ρ_i impactor density,

L_0 impactor diameter before atmospheric entry.

This kinetic energy is converted into thermal energy, seismic energy and kinetic energy of the target and the atmosphere during the process of an impact [16].

4.2. Atmospheric Entry

The three cases of atmospheric entry can be quantified as follows:

- The impactor reaches the ground in one single piece. The effects can be assessed from the impact energy.
- The impactor disintegrates and reaches the ground in several pieces. These pieces disperse over a larger area than an intact impactor would. The effects can be assessed from the cumulated impact energies of the pieces but due to the spread may differ from the effects of an intact impactor.
- The impactor disintegrates and explodes in the atmosphere. Large parts of the kinetic energy are converted into blast energy.

For impactors that do not disintegrate in the atmosphere, impact energy is generally in the same order of magnitude as the kinetic energy before atmospheric entry E_{kin}. How much it deviates depends mainly on impact angle.
Considering that most impact effects are typically insensitive to deviations within the order of a magnitude of E, the influence of atmospheric entry can be neglected for bigger, non-fragmenting impactors.
Modeling disintegrating impactors and airburst is quite complex and, similar to water impacts, only gives reliable results for numerical modeling and numerous input parameters [40].

For the sake of simplicity, only non-disintegrating impactors will be considered in the creation of the scale. Airbursts in particular depend on multiple factors that cannot be represented in a simple scale. It has to be noted, however, that for smaller impactors, which are much more common than large ones, disintegration and airbursts are likely outcomes [16].

4.3. Fireball & Thermal Radiation

When compared to actual impacts, the Earth Impact Effects model places the yield within the order of a magnitude of what has been determined by examining the effects. The exception are cases with unusual or extreme parameters where larger deviations are possible. [17]

Using yield scaling, the fireball radius in meters R_{f*} can be calculated as

$$R_{f*} = 0.002E^{1/3} \tag{4.2}$$

with the impact energy or yield E in Joules (which, for our purpose, we consider equal to the kinetic energy E_{kin}) [16]. This means that the fireball radius grows progressively slower with respect to the impact energy. Considering that the impactors in question have a kinetic energy in the order of Tera- to Petajoules

Tab. 4.1.: Ignition factors for 1 Mt explosion [16; 21]

	$\Phi_{ignition}$(1 Mt) in MJ/m^2)
Clothing	1.0
Plywood	0.67
Grass	0.38
Newspaper	0.33
Deciduous trees	0.25
Third degree burns	0.42
Second degree burns	0.25
First degree burns	0.13

and greater, impact energy deviations of a magnitude have little effect on fireball size.

The thermal exposure Φ at a distance r from the fireball can be calculated as

$$\Phi = \frac{\eta E}{2\pi r^2} \tag{4.3}$$

with

$\eta = 10^{-3}$ luminous efficiency[1], fraction of impact energy converted to thermal radiation

E impact energy, which for simplification we equate with the kinetic energy before atmospheric entry E_{kin}, see section 4.2

r distance to fireball center [16]

Shading due to the curvature of the earth is neglected as it is only significant at very large distances where thermal radiation does not play a major role any more.

Using table 4.1, the minimum thermal exposure at which different materials ignite can be computed as

$$\Phi_{ignition}(E) = \Phi_{ignition}(1Mt) \cdot E^{1/6} \tag{4.4}$$

with the impact energy E in Mt [16]. This can be compared to the thermal exposure at a specific place Φ (equation 4.3) to determine the effects.

[1] empirical data suggests a value between 10^{-2} and 10^{-4}, so 10^{-3} is assumed [16]

4.4. Airblast

A comprehensive analysis of damage to man-made structures from nuclear explosion is given by Glasstone and Dolan [21]. However, most of their analysis is based on early nuclear weapons tests and the detonations of Hiroshima and Nagasaki in 1945. Since then, construction has made significant progress, especially when it comes to earthquake-resistant buildings. As such, the question stands to which degree their analysis is valid for current structures.
To the knowledge of the author, more current data of similar scope is not available. Aside from the detonations in Japan, data on the effects of an explosion on actual large cities does not exist and the introduction of nuclear test ban treaties in the second half of the 20th century put an end to overground testing in most countries.

An empirical approximation to overpressure p from an explosion at a distance r is given as

$$p = \frac{E^{1/3} \cdot p_x r_x}{4r} \left(1 + 3\left(\frac{E^{1/3} \cdot r_x}{r}\right)^{1.3}\right) \tag{4.5}$$

with

E impact energy,

p_x = 0.75 bar pressure at crossover point r_x,

r_x = 290 m crossover point,

r distance from the explosion.

The effects of the pressure wave can then be assessed from table 4.2 with the previous paragraph in mind.
This expression only works for explosions on the ground and is not accurate for airbursts. Those will not be included here as they are complex and depend on multiple factors that cannot be incorporated into a one-dimensional scale.

The peak wind velocity following the pressure wave is

$$u = \frac{5p}{7P_0} \cdot \frac{c_0}{\left(1 + 6p/(7P_0)\right)^{0.5}} \tag{4.6}$$

with

p overpressure,

P_0 = 1 bar ambient pressure,

c_0 = 330 m/s ambient speed of sound in air [16].

The effects of the wind velocity can be estimated from the storm intensity scales in section 6.3.

Tab. 4.2.: Air blast damage with respect to distance from explosion [16; 21]

Overpressure p in Pa	**Description of air blast-induced damage**
426000	Cars and trucks will be largely displaced and grossly distorted and will require rebuilding before use.
379000	Highway girder bridges will collapse.
297000	Cars and trucks will be overturned and displaced, requiring major repairs.
273000	Multistory steel-framed office-type buildings will suffer extreme frame distortion, incipient collapse.
121000	Highway truss bridges will collapse.
100000	Highway truss bridges will suffer substantial distortion of bracing.
42600	Multistory wall-bearing buildings will collapse.
38500	Multistory wall-bearing buildings will experience severe cracking and interior partitions will be blown down.
26800	Wood frame buildings will almost completely collapse.
22900	Interior partitions of wood frame buildings will be blown down. Roofs will be severely damaged.
6900	Glass windows shatter.

4.5. Cratering

According to Collins et al. [16], the final crater diameter can be calculated as

$$D_{fr} = 1.45\left(\frac{\rho_i}{\rho_t}\right)^{\frac{1}{3}} L^{0.78} v_i^{0.44} g_E^{-0.22} \sin(\theta)^{\frac{1}{3}} \tag{4.7}$$

with

ρ_i impactor density,

ρ_t target density,

L impactor diameter before point of impact,

v_i impactor velocity before point of impact,

g_E = 9.81 m/s^2 gravitational acceleration on Earth's surface,

θ impact angle.

We will assume θ= 45° as the most probable impact angle, ρ_t = 2000 kg/m^3 as the average ground density and, using equation 4.1, approximate equation 4.7 as

$$D_{aprx} = 1.45\left(\frac{1}{\rho_t}\right)^{\frac{1}{3}} \cdot \left(\frac{12}{\pi}E\right)^{\frac{1}{4}} \cdot g_E^{-0.22} \sin(\theta)^{\frac{1}{3}} \tag{4.8}$$

$$= 1.8\left(\frac{1}{\rho_t}\right)^{\frac{1}{3}} \cdot E^{\frac{1}{4}} \cdot g_E^{-0.22} \tag{4.9}$$

which is a function of the single variable E (impact energy).
This is of course a very rough simplification, but sufficient for our purpose.

4.6. Atmosphere Poisoning

Atmosphere poisoning can be classified into three broad categories:

- As a lower limit, an impact energy of 10^{19} J (corresponding to an impactor diameter of roughly 1 km at typical velocity and density) is regarded as causing significant water vapor injections and regional ozone loss.
- At more than 10^{20} J (2 km), climatological effects are to be expected on a global scale. Nitrous oxide produced by the ejecta plume may destroy the ozone shield.

- Beyond 10^{21} J (few km), sulfate and dust levels in the atmosphere may reduce sunlight and halt photosynthesis. Reentering ejecta may cause further drop of light levels. [20]

4.7. Seismic Effects

According to experimental data, between 10^{-5} and 10^{-3} of the impact energy is transformed into seismic wave energy E_w [16]. For simplicity,

$$E_w = 10^{-4} E \tag{4.10}$$

is assumed.
The Richter Scale value can be calculated from the Gutenberg-Richter magnitude energy relation

$$M_L = 0.67 \log_{10} E_w - 5.87 \tag{4.11}$$

To account for distance from the impact site, the magnitude at the place of interest is computed as

$$M_{eff} = M_L - 0.0238\Delta \tag{4.12}$$

with the distance from the impact site in km Δ for $\Delta < 60$ km,

$$M_{eff} = M_L - 0.0048\Delta - 1.1644 \tag{4.13}$$

for 60 km $< \Delta <$ 700 km and

$$M_{eff} = M_L - 1.66 \log_{10} \Delta - 6.399 \tag{4.14}$$

for $\Delta >$ 700 km.

With table 6.1 in section 6.1.2, the respective value can be translated to a stage on the Modified Mercalli Scale allowing an estimation of expected damage.

Converting equations 4.10 and 4.11 and computing the impactor diameter from the impact energy, it can be shown that seismic effects are irrelevant for smaller impactors.
For example, even when using the maximum values[2] for velocity and density, the minimum diameter of an impactor to score a value of I on the Mercalli Intensity Scale (barely noticeable) at the impact site is about 200 m.
Seismic effects get more severe with larger impactors but remain insignificant in comparison to the other effects.

[2]velocity $v = 72\,\mathrm{km/s}$, density $\rho = 8000\,\mathrm{kg/m^3}$ (see sections 3.2 and 3.3)

4.8. Water Impacts

Descriptions of water impacts are highly complex and unreliable. Numerical models appear to provide better results but are difficult to verify as until today there is no real-life data from a water impact.
The model can be split into two sections:

- The impact itself and what part of the impact energy is being translated into cratering of the sea floor, thermal energy (vaporization) and tsunami wave energy. This depends mainly on water depth and the composition of both the impactor and the sea floor.
- The tsunami wave and its propagation. This depends mostly on the shape of the seafloor and the coast.

Since most of these factors are highly dependent on impact location, it is nearly impossible to make an accurate model of universal scope. However, Bailey [3] offers an analytical model that will be simplified further for our purpose of giving a very rough estimation.

The depth of a cavity caused by an impactor is

$$d_{cavity} = 3.84 \cdot \left(\frac{\epsilon}{\rho_{water} g_E}\right)^{1/4} E^{1/4} \tag{4.15}$$

with

ϵ = 0.15 fraction of impact energy converted into wave energy,

ρ_{water} = 1020 kg/m^3 sea water density,

g_E gravitational acceleration on Earth's surface,

E impact energy.

The initial wave amplitude can be calculated as

$$A_{deep} = d_{cavity}\left(1 + \frac{2r}{3d_{cavity}}\right)^{-1.53} \tag{4.16}$$

with

d_{cavity} cavity depth in the ocean (see equation 4.15),

r horizontal distance from the impact.

Tsunamis progressively build up in height when propagating into shallower water. The run-up or height of the tsunami wave at the shore is defined as

$$h_{up} = 1.09 \cdot A_{deep}^{4/5} h_{deep}^{1/5} \tag{4.17}$$

and run-in or distance that the tsunami travels inland from the shore as

$$h_{in} = 10\sqrt{g_E h_{up}}(\frac{3}{2}d_{cavity})^{0.375} \tag{4.18}$$

with

A_{deep} initial wave amplitude (see equation 4.16),

h_{deep} ocean depth at the point of impact,

g_E gravitational acceleration on Earth's surface.

The run-up can be translated to the corresponding stage of the Papadopoulos–Imamura Tsunami Intensity Scale (section 6.2.3) using table 4.3.
For the creation of the scale, we will assume h_{deep} = 3688 m as the average depth of the ocean [33]. This is, of course, a very coarse simplification. The actual depth and therefore run-up and run-in depend on the individual impact location.
Run-in is also highly dependent on terrain. In general, a mountainous coastline will stop a tsunami wave much sooner than a flat one.

Given the many uncertainties and simplifications, it has to be noted that the whole model is only able to provide an idea of the dimensions of the effects. The effects of an actual impact will very likely deviate from the model.

Tab. 4.3.: Simplified correlation between run-up and Papadopoulos–Imamura Tsunami Intensity Scale stages [30]

Run-up in m	<1	2	4	8	16	32
Stage number	I-V	VI	VII-VIII	IX-X	XI	XII

5. Threat Scales for Asteroid Impacts

So far, there have been several attempts at creating a scale for impact hazards. These scales vary in usefulness for communication with the general public.
Both the Torino Impact Hazard Scale and the Palermo Impact Hazard Scale are probabilistic. This poses a major problem for public communication and is generally discouraged, as can be seen in an excerpt from a risk communication guide by the U.S. Department of Health and Human Services:

> „A discussion of statistical probabilities and how they translate into a 'relatively minimal-risk scenario for the average citizen' might be fine for scientists, but for the general public such a discussion will only confuse the issue and fail to meet the goals of informing and easing concerns. If the risk is low, say, 'the risk to the public is low.' " [29]

With regard to impact hazards, the main difficulties are illustrated as follows:

> „One of the more difficult concepts to explain the lay audiences is the concept of risk and statistical probability. Statistically the risk of impact fatalities is high; however, the expectation of death due to impact within ones lifetime is very small [...] Percentages and probabilities are very difficult for people to understand – and reliance on them alone should be avoided when communicating with the public. 'Never a statistic without a story,' should be the rule of thumb, providing context to numbers. In addition, return period/recurrence intervals are easier to contextualize than are probabilities. However, it is essential to explain that, for example, 'on average an encounter should be expected every 100 years,' so that the population understands that if 100 years passes without an encounter, it does not necessarily mean the scientists are wrong – or that an encounter will happen on day 101." [18]

As such, there were voices among the scientist community demanding a new scale:

> „'We already have a couple of different scales, the Palermo scale, the Torino scale, but the viewpoint from those that have more background and expertise in communications with the public is that those scales are too complex[.] [...] They are just not understandable by the general public, and we needed a more simplified tool.' " [11]

A very simple scale called Broomfield Hazard scale was introduced with the goal to satisfy this request. It can be debated, however, how simple such a scale must be to be understood and how simple it may be before it loses its validity.

5.1. Torino Impact Hazard Scale

The Torino Impact Hazard Scale (fig. 5.1 and tab. 5.1) rates the hazard from a potential impactor event based on its kinetic energy and the probability of an impact. The probability of a potential impact changes with time due to new measurements and recalculations and gets more accurate, therefore a Torino Scale value is only meaningful in context with the potential impact date. [7]

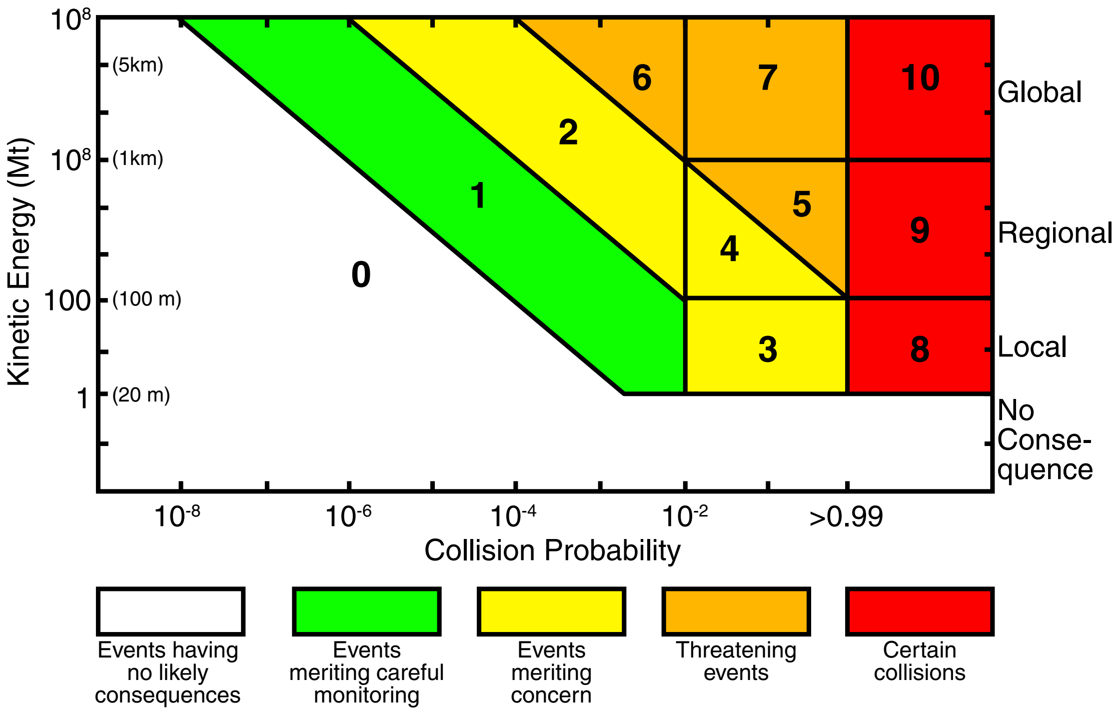


Fig. 5.1.: Torino Scale diagram [6]. For the respective description, see tab. 5.1

Due to the scale's probabilistic nature, it is of limited usefulness for its intended purpose, public communication. Apart from the issue of understanding (or not understanding) statistics, it can be difficult to convey why the scale value of a certain potential impactor can change over time. Without in-depth knowledge about the whole measuring process and concepts such as keyholes, this may be interpreted as incompetence on the part of scientists or emergency agencies – leading to a subsequent loss of public credibility.

5.2. Palermo Technical Impact Hazard Scale

The Palermo Technical Impact Hazard Scale is a logarithmic scale that compares the impact probability and expected yield of an object to the average risk posed by objects of the same size. It is computed as

Tab. 5.1.: Torino Scale according to [5; 27]

No Hazard	**0**	The likelihood of a collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bodies that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	**1**	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	**2**	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.
Threatening	**5**	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	**8**	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

$$PS = \log_{10} \cdot R \tag{5.1}$$

where the relative risk R is given as

$$R = \frac{p_I}{f_B \cdot t} \tag{5.2}$$

with the impact probability of the the object p_I and the time in years until impact t.

$$f_B = 0.03 \cdot E^{-4/5} \tag{5.3}$$

is the annual background impact frequency or the annual probability of an impact event with a yield E in Megatons TNT as big or bigger than the event in question. [15]
Events with values smaller than -2 are unlikely to have consequences, values between -2 and 0 merit monitoring and positive values may be cause for concern. An object classified with a value of 2 is one hundred times more likely to impact than statistically average. [15]

The Palermo Scale was created as an instrument to be used among experts. It lacks visualization, it is unintuitive and it requires extensive explanation for understanding. As such, it is not a useful tool for communication with the public.

5.3. Broomfield Hazard Scale

The Broomfield Hazard Scale (Fig. 5.2) was introduced in September 2014 as an attempt to create a non-probabilistic scale for communication with the general public [11; 24].

The scale is simple and easy to understand – at the cost of several issues:

- The scale is graded after one single impactor parameter: impactor size. It assumes average values or a small range of values for all other parameters (density and velocity) or neglects them.
- No differentiation between land and sea impacts. Target parameters are neglected.
- The descriptions of the impact hazard are vague and „subject to interpretation“ [24].
- The small number of classes results in energy potential differences of factor 20 within one class. It could be argued that impactors at either extreme of one class have vastly different effects and are hardly comparable.

Broomfield Hazard Scale

Class	Object size	Energy potential	Impact hazard	Color scale
1	<10 m	<50 kt	Visible fireball	
2	10 – 30 m	50 kt – 1 Mt	Localized damage possible	
3	20 – 80 m	1 – 20 Mt	City-wide damage	
4	60 – 230 m	20 – 500 Mt	Regional damage	
5	160 – 800 m	500 Mt – 20 Gt	Country-wide destruction	
6	>600 m	>20 Gt	Global destruction	

Sizes (in meters) are indications only: given size range is based on 3g/cc, the velocity range 15-25km [sic!]
Energy potential expressed in tons of TNT equivalent

Fig. 5.2.: Broomfield Hazard Scale [24]

This raises the question whether the Broomfield Hazard Scale is oversimplified and too constricted to be useful.
Some of these points have already been recognized by the creators of the scale and it has been suggested to include „blast radius information (distance plus severity of effects)“ [24].
Aside from these issues that come with the nature of the scale, the choice of colors leaves room for improvement: While the range from green to red and – to a certain degree – black is widely understood with respect to the severity of a signal or warning, this may less be the case for indigo when viewed on its own and without context.

5.4. Boslough Airburst Warning Scale

The Boslough Airburst Warning Scale or, more in line with the other impact hazard scales, Bucharest Airburst Warning Scale is a little known scale that was first proposed in 2011 [9; 19].
The scale only covers the aspect of airbursts. It lacks a quantitative translation from impactor parameters to scale values but consists of qualitative descriptions. In contrast to the other impact hazard scales, it contains instructions on how to react to a specific scale value, which is typically seen as helpful for public communication (see [42]). Therefore, parts of it may be used for improving existing scales or creating a new one.

Boslough Airburst Warning Scale [9]

1. High-altitude airburst with no possible damage. Bright light in sky followed by sonic boom. No recommended action.

2. High-altitude airburst with minor damage. Possible hazard from broken windows and dust from sonic boom, shaking of structures. Recommended action: avoid standing near windows and anticipate respiratory hazard from dust in buildings. 2008 TC3 would have probably been this class.
3. High-altitude airburst with major damage. Possible hazard from many broken windows and unsecured structures like trailers blowing down due to blast wave. Recommended action: take cover in basements or strong structures. Consider leaving area.
4. Low-altitude airburst with heavy blast damage: Tunguska-class event. Structures within blast zone destroyed. Recommended action: evacuate blast zone and take cover outside that zone.
5. Low-altitude airburst with heavy thermal damage: Libyan Desert Glass class event. Fireball zone surrounded by blast zone. Everything within fireball zone incinerated, everything within blast zone blown down. Recommended action: evacuate fireball and blast zones, and take cover outside those zones.

6. Scales and Descriptions of Other Domains

There is a variety of scales from other domains such as natural hazards. Most of them are phenomenological, specific to a certain location – so called intensity scales – and used for description and classification after an event. Scales that can be used to predict the severity of an event are usually confined to one single physical aspect instead of providing a comprehensive assessment of all the expected effects.

6.1. Earthquakes

6.1.1. Richter Scale & Moment Magnitude Scale

The Richter Scale or Local Magnitude Scale M_L is a logarithmic representation of seismograph amplitude. Whole number increases translate to tenfold increases in measured seismograph amplitude and 31-fold increases in released energy. [37]
Earthquakes with values below 2.0 are called „microearthquakes“, large earthquakes score 8.0 or higher.
The Richter Scale is not in use any more and has mostly been replaced by the Moment Magnitude Scale – despite the false notion in the media where Moment Magnitude Scale values are often designated as „... on the Richter Scale“. [37]

Aside from the disused Richter Scale, there are several Magnitude scales with different strengths and weaknesses for different purposes. Worth mentioning are the Surface Wave Magnitude Scale M_S, the Body-Wave Magnitude Scale m_b and the Moment Magnitude Scale M_W. The latter is currently the preferred scale to classify medium and large earthquakes.
Magnitude scales categorize the earthquake as a whole – in contrast to the intensity scales in the following sections 6.1.2 and 6.1.3 which describe the local effects at specific site. [37]

The Moment Magnitude Scale is given as

$$M_W = \frac{2}{3}\log(M_O) - 10.7 \tag{6.1}$$

The Seismic Moment M_O can be calculated along faults as

Tab. 6.1.: Modified Mercalli Scale [38; 39; 41]

Mercalli Intensity	Equivalent Richter Magnitude	Witness Observations and Damage Descriptions
I	1.0 to 2.0	Felt by very few people; barely noticeable.
II	2.0 to 3.0	Felt by a few people, especially on upper floors.
III	3.0 to 4.0	Noticeable indoors, especially on upperfloors, but may not be recognized as an earthquake.
IV	4.0	Felt by many indoors, few outdoors. May feel like heavy truck passing by.
V	4.0 to 5.0	Felt by almost everyone, some people awakened. Small objects moved. Trees and poles may shake.
VI	5.0 to 6.0	Felt by everyone. Difficult to stand. Some heavy furniture moved, some plaster falls. Chimneys may be slightly damaged.
VII	6.0	Slight to moderate damage in well built, ordinary structures. Considerable damage to poorly built structures. Some walls may fall.
VIII	6.0 to 7.0	Little damage in specially built structures. Considerable damage to ordinary buildings, severe damage to poorly built structures. Some walls collapse.
IX	7.0	Considerable damage to specially built structures, buildings shifted off foundations. Ground cracked noticeably. Wholesale destruction. Landslides.
X	7.0 to 8.0	Most masonry and frame structures and their foundations destroyed. Ground badly cracked. Landslides. Wholesale destruction.
XI	8.0	Total damage. Few, if any, structures standing. Bridges destroyed. Wide cracks in ground. Waves seen on ground.
XII	8.0 or greater	Total damage. Waves seen on ground. Objects thrown up into air.

$$M_O = \mu S d \quad (6.2)$$

with

μ shear strength of the faulted rock,

S fault area,

d average displacement on the fault. [37]

Comparing the Moment Magnitude Scale to the Richter Scale, the values are similar for medium earthquakes but deviate for small and large ones.

While neither of the Magnitude scales include verbal descriptions, their prevalence in the media has made them familiar to many people, particularly to those who live in regions regularly affected by earthquakes. The mathematical basis may not be understood by the general public, but many people are aware that values below 4.0 mean none to little harm while values of 7.0 and higher correspond to considerable damage in the vicinity of the epicenter.

6.1.2. Modified Mercalli Intensity Scale

The most widely used intensity scale for earthquakes is the Modified Mercalli Intensity Scale (MMI) (see tab. 6.1). Its twelve stages range from barely noticeable to complete destruction and are given for a specific location, not the earthquake itself. The MMI only ranks the visible effects of an earthquake and does not have a mathematical foundation [38]. However, rough translations between MMI ranks and the equivalent Richter Scale magnitudes (section 6.1.1) exist (see again tab. 6.1).

6.1.3. Japanese Meteorological Agency Seismic Intensity Scale

Analogous to the MMI (section 6.1.2), the Japanese Meteorolocial Agency Seismic Intensity Scale (JMA) (see tab. 6.2) is a non-mathematical scale that describes the local effects of an earthquake. Like the MMI, the JMA has been extended with time. Compared to its predecessor, the Japanese Seismic Intensity Scale (see [8]), stage 5 and 6 of the JMA have been split into „upper“ and „lower“ to provide finer graduation for more severe effects.
In addition to the categories of human perception and the general indoors and outdoors situation, there are multiple tables that describe the effects more specifically. These include scales covering the effects on reinforced-concrete buildings, wooden houses, large-scale structures such as skyscrapers, the situation of ground and slopes and the influence on utilities and infrastructure.

Tab. 6.2.: Japanese Meteorological Agency Seismic Intensity Scale [2]

Seismic intensity	Human perception and reaction	Indoor situation	Outdoor situation
0	Imperceptible to people, but recorded by seismometers.	-	-
1	Felt slightly by some people keeping quiet in buildings.	-	-
2	Felt by many people keeping quiet in buildings. Some people may be awoken.	Hanging objects such as lamps swing slightly.	-
3	Felt by most people in buildings. Felt by some people walking. Many people are awoken.	Dishes in cupboards may rattle.	Electric wires swing slightly.
4	Most people are startled. Felt by most people walking. Most people are awoken.	Hanging objects such as lamps swing significantly, and dishes in cupboards rattle. Unstable ornaments may fall.	Electric wires swing significantly. Those driving vehicles may notice the tremor.
5 Lower	Many people are frightened and feel the need to hold onto something stable.	Hanging objects such as lamps swing violently. Dishes in cupboards and items on bookshelves may fall. Many unstable ornaments fall. Unsecured furniture may move, and unstable furniture may topple over.	In some cases, windows may break and fall. People notice electricity poles moving. Roads may sustain damage.
5 Upper	Many people find it hard to move; walking is difficult without holding onto something stable.	Dishes in cupboards and items on bookshelves are more likely to fall. TVs may fall from their stands, and unsecured furniture may topple over.	Windows may break and fall, unreinforced concrete-block walls may collapse, poorly installed vending machines may topple over, automobiles may stop due to the difficulty of continued movement.
6 Lower	It is difficult to remain standing.	Many unsecured furniture moves and may topple over. Doors may become wedged shut.	Wall tiles and windows may sustain damage and fall.
6 Upper	It is impossible to remain standing or move without crawling. People may be thrown through the air.	Most unsecured furniture moves, and is more likely to topple over.	Wall tiles and windows are more likely to break and fall. Most unreinforced concrete-block walls collapse.
7		Most unsecured furniture moves and topples over, or may even be thrown through the air.	Wall tiles and windows are even more likely to break and fall. Reinforced concrete-block walls may collapse.

Tab. 6.3.: JMA for reinforced concrete buildings [2]

Seismic intensity	Reinforced-concrete buildings	
	High earthquake resistance	**Low earthquake resistance**
5 Upper	-	Cracks may form in walls, crossbeams and pillars.
6 Lower	Cracks may form in walls, crossbeams and pillars.	Cracks are more likely to form in walls, crossbeams and pillars.
6 Upper	Cracks are more likely to form in walls, crossbeams and pillars.	Slippage and X-shaped cracks may be seen in walls, crossbeams and pillars. Pillars at ground level or on intermediate floors may disintegrate, and buildings may collapse.
7	Cracks are even more likely to form in walls, crossbeams and pillars. Ground level or intermediate floors may sustain significant damage. Buildings may lean in some cases.	Slippage and X-shaped cracks are more likely to be seen in walls, crossbeams and pillars. Pillars at ground level or on intermediate floors are more likely to disintegrate, and buildings are more likely to collapse.

As an example, tab. 6.3 shows the scale for reinforced-concrete buildings. This scale clearly illustrates one of the problems in creating meaningful one-dimensional scales from a multitude of parameters: phrases such as „may form“, „are more likely to form“ and „are even more likely to form“ are highly subjective and hardly useful when assigning a scale value to an event.
Another difficulty demonstrated by the JMA is the existence of regional and also temporal differences. The scale is intended for the use in Japan and earthquakes with similar parameters might be categorized much differently in other countries due to variations in construction. Also, the scale has to be checked every five years and – if necessary – modified to account for constructional improvements in terms of earthquake resistance [2].

6.2. Tsunamis

6.2.1. Magnitude

Over the years, a number of scales for quantitative description of tsunamis have been developed.

One of the most simple scales for tsunami strength is the Imamura-Iida Scale which is calculated as

$$M = \log_2 H_{max} \tag{6.3}$$

with the maximum wave height in meters H_{max}, observed on the shore or measured by mareograph. This translates to a six-point scale from -1 to 4.

A more refined scale has been proposed by Soloviev:

$$I = \frac{1}{2} + \log_2 H \tag{6.4}$$

with the average tsunami height in meters on the coast closest to the source H. Both scales only consider one parameter and are insensitive to deviations of that parameter. This is why the scales are likely to continue to be used, particularly for the categorization of historic tsunamis of which not much data is available. However, this simplicity also limits their relevance.

The Abe-Hatori Scale on the other hand also accounts for the weakening of waves with increasing distance from the source:

$$M_t = a \log h + b \log \Delta + D \tag{6.5}$$

with

h maximum wave amplitude on the coast measured from the foot of the crest to the top in meters,

Δ distance from the earthquake epicenter to the point of measurement in kilometers

a, b, D constants that make the scale resemble the seismological magnitude scale (section 6.1.1).

A categorization based on the potential energy of the tsunami wave is put forward by the Murty-Loomis Scale:

$$ML = 2(\log E_w - 19) \tag{6.6}$$

with the wave energy in erg E_w.
While being the least ambiguous among the tsunami magnitude scales, this approach raises the problem of how to determine the wave energy. It should also be noted that the wave energy does not translate directly to the severity of destruction on the coast. As such, the scale is effective for physical description of the tsunami but not for the description of its effects. [25]

Neither of the four magnitude scales includes verbal descriptions and their values do not hold much meaning to non-experts. For public communication, the scales in the following sections 6.2.2 and 6.2.3 are better suited.

6.2.2. Sieberg–Ambraseys Tsunami Intensity Scale

The Sieberg–Ambraseys Tsunami Intensity Scale was one of the first attempts to categorize the effects of a tsunami. Therefore, it has less stages and is much less descriptive than the Papadopoulos–Imamura Tsunami Intensity Scale (section 6.2.3).
As an intensity scale, it only categorizes the effects at a specific site and is not based on parameters of the tsunami or the location.

Sieberg–Ambraseys Tsunami Intensity Scale [25](p.12)

1. **Very light.** Waves can only be registered by special tide gauges (mareographs).
2. **Light.** Waves noticed by those living along the shore. On very flat shores waves are generally noticed.
3. **Rather strong.** Waves generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coasts. In estuaries, reversal of the river flow some distance upstream.
4. **Strong.** Significant flooding of the shore. Buildings, embankments, dikes, and cultivated ground near coast damaged. Small and average vessels carried either inland or out to sea. Coasts littered with debris.
5. **Very strong.** General significant flooding of the shore. Quay-walls and solid structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land. Littering of the coast with floating items, fish, and sea animals thrown up on the shore. With the exception of big ships all other types of vessels carried inland or out to sea. Bores formed in estuaries of rivers. Harbor works damaged. People drowned. Wave accompanied by strong roar.
6. **Disastrous.** Partial or complete destruction of manmade structures for some distance from the shore. Strong flooding of coasts. Big ships severely damaged. Trees uprooted or broken. Many casualties.

6.2.3. Papadopoulos–Imamura Tsunami Intensity Scale

The Papadopoulos–Imamura Tsunami Intensity Scale describes the effects of a tsunami at a specific site according to the following criteria [25]:

a) influence upon people,

b) impact on natural and artificial objects, including boats of different sizes,

c) damage caused to buildings.

Like the Sieberg–Ambraseys Tsunami Intensity Scale (section 6.2.2), the Papadopoulos–Imamura Tsunami Intensity Scale is not based on parameters. It is structured into twelve stages.

Papadopoulos–Imamura Tsunami Intensity Scale [25](p.14)

I. **Not felt**[1]

a) Not felt even in most favorable circumstances;

b) No effect;

c) No damage;

II. **Scarcely felt**

a) Felt by some people in light boats. Not observed on the shore;

b) No effect;

c) No damage;

III. **Weak**

a) Felt by most people in light boats. Observed by some people on the shore;

b) No effect;

c) No damage;

IV. **Largely observed**

a) Felt by all people in light boats and some on large vessels. Observed by most people on shore;

b) Some light boats are slightly carried onto the shore;

c) No damage;

V. **Strong**

a) Felt by all people on large vessels. Observed by all people on shore. Some people are frightened and run-up elevations;

b) Many light vessels are carried inland over significant distances, some of them collide with each other or are overturned. The wave leaves layers of sand in places with favorable conditions. Limited flooding of cultivated land along the coast;

c) Limited flooding of coastal structures, buildings and territories (gardens, etc.) near residential houses;

VI. **Slightly damaging**

a) Many people are frightened and run-up elevations;

[1] Registered only by special instruments.

b) Most light vessels are carried inland over significant distances, undergo strong collisions with each other, or are overturned;

c) Some wooden structures are destroyed and flooded. Most brick buildings have survived;

VII. **Damaging**

a) Most people are frightened and try to run away onto elevations;

b) Most light vessels are damaged. Some large vessels undergo significant vibrations. Objects of varying dimensions and stability (strength) are overturned and shifted from their positions. The wave leaves layers of sand and accumulates pebbles. Some floating structures are washed away to sea;

c) Many wooden structures are damaged, some are totally wiped away or carried out to sea by the wave. Destructions of first degree and flooding of some brick buildings;

VIII. **Heavily damaging**

a) All people run-up elevations, some are carried out to sea by the wave;

b) Most light vessels are damaged, many are carried away by the wave. Some large vessels are carried upshore and undergo collisions with each other. Large objects are washed away. Erosion and littering of the coast. Widespread flooding. Insignificant damage in antitsunami plantations of trees. Many floating structures are carried away by the wave, some are partially damaged;

c) Most wooden structures are carried away by the wave or completely wiped off the earth's surface. Destructions of second degree in some brick buildings. Most concrete buildings are not damaged, some have undergone destruction of first degree and flooding;

IX. **Destructive**

a) Many people are carried away by the wave;

b) Most light vessels are destroyed and carried away by the wave. Many large vessels are carried inland over large distances, some are destroyed. Broad erosion and littering of the coast. Local subsidence of the ground. Partial destruction of antitsunami plantations of trees. Most floating structures are carried away, many are partially damaged;

c) Destructions of third degree in many brick buildings. Some concrete buildings have undergone destructions of second degree;

X. **Very destructive**

a) General panic. Most people are carried away by the wave;

b) Most large vessels are carried inland over large distances, many are destroyed or have undergone collisions with buildings. Small rocks (pebbles, stones) have been carried onshore from the seafloor. Vehicles are overturned and displaced. Petroleum spilt, fires. Widespread subsidence of ground;

c) Destructions of fourth degree in many brick houses, some concrete buildings have undergone destructions of third degree. Artificial dams (embankments) destroyed and harbor wavebreakers damaged.

XI. **Devastating**

b) Vital communications destroyed. Widespread fires. Reversed flows of water wash away to sea vehicles and other objects. Large rocks of different kinds are carried onshore from the seafloor;

c) Destructions of fifth degree in many brick buildings. Some concrete buildings suffer damage of fourth degree, many of third degree.

XII. **Completely devastating**

c) Practically all brick buildings are wiped out. Most concrete buildings have suffered destructions of degrees not lower than third.

6.3. Storms

6.3.1. Beaufort Wind Force Scale

The Beaufort Wind Force Scale (see tab. 6.4) has been used for more than two centuries, but only in the mid-20th century was extended to connect the stages and descriptions to wind speeds [12].
While today there are better means for determining wind speeds, the scale offers relatively clear distinctions in the descriptions of its stages so that an assessment can, for the most part, be made unambiguously.

6.3.2. Saffir–Simpson Hurricane Wind Scale

The Saffir–Simpson Hurricane Wind Scale connects to the upper end of the Beaufort Scale (section 6.3.1). It is mainly used to categorize hurricanes in the Atlantic Ocean and northeastern Pacific Ocean. In other areas, such storms are called „cyclones“ or „typhoons“ and are described by different scales.
Since the scale is only used for a specific region with relatively similar infrastructure and style of construction, the stage assessments can be considered more accurate than those of other scales used for events worldwide.

Tab. 6.4.: Beaufort Scale [12; 34]

Beaufort number	description	wind speed in knots	wind speed in kph	specification (sea surface)	specification (land area)
0	Calm	<1	<1	Sea like a mirror	Smoke rises vertically
1	Light air	1–3	1–5	Ripples with appearance of scales are formed, without foam crests	Direction shown by smoke drift but not by wind vanes
2	Light breeze	4–6	6–11	Small wavelets still short but more pronounced; crests have a glassy appearance but do not break	Wind felt on face; leaves rustle; wind vane moved by wind
3	Gentle breeze	7–10	12–19	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses	Leaves and small twigs in constant motion; light flags extended
4	Moderate breeze	11–16	20–28	Small waves becoming longer; fairly frequent white horses	Raises dust and loose paper; small branches moved.
5	Fresh breeze	17–21	29–38	Moderate waves taking a more pronounced long form; many white horses are formed; chance of some spray	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong breeze	22–27	39–49	Large waves begin to form; the white foam crests are more extensive everywhere; probably some spray	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Moderate gale (or near gale)	28–33	50–61	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind; spindrift begins to be seen	Whole trees in motion; inconvenience felt when walking against the wind.
8	Fresh gale (or gale)	34–40	62–74	Moderately high waves of greater length; edges of crests break into spindrift; foam is blown in well-marked streaks along the direction of the wind	Twigs break off trees; generally impedes progress.
9	Strong gale	41–47	75–88	High waves; dense streaks of foam along the direction of the wind; sea begins to roll; spray affects visibility	Slight structural damage (chimney pots and slates removed).
10	Whole gale (or storm)	48–55	89–102	Very high waves with long overhanging crests; resulting foam in great patches is blown in dense white streaks along the direction of the wind; on the whole the surface of the sea takes on a white appearance; rolling of the sea becomes heavy; visibility affected	Seldom experienced inland; trees uprooted; considerable structural damage
11	Storm (or violent storm)	56–63	103–117	Exceptionally high waves; small- and medium-sized ships might be for a long time lost to view behind the waves; sea is covered with long white patches of foam; everywhere the edges of the wave crests are blown into foam; visibility affected	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	>63	>117	Air is filled with foam and spray; sea is completely white with driving spray; visibility very seriously affected	Devastation

Tab. 6.5.: Saffir–Simpson Hurricane Wind Scale [13]

Category	Sustained Winds	Types of Damage Due to Hurricane Winds
1	64-82 kt 119-153 km/h	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles, likely will result in power outages that could last a few to several days.
2	83-95 kt 154-177 km/h	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	96-112 kt 178-208 km/h	Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	113-136 kt 209-251 km/h	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles,will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	137 kt or higher 252 km/h or higher	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Tab. 6.6.: Fujita and Enhanced Fujita scales [22]

Fujita-Scale			Enhanced Fujita-Scale	
F Number	Fastest 1/4-mile (mph)	3 Second Gust (mph)	EF Number	3 Second Gust (mph)
0	40-72	45-78	0	65-85
1	73-112	79-117	1	86-110
2	113-157	118-161	2	111-135
3	158-207	162-209	3	136-165
4	208-260	210-261	4	166-200
5	261-318	262-317	5	Over 200

6.3.3. Fujita Scale and Enhanced Fujita Scale

Like the Saffir–Simpson Scale (section 6.3.2), the Fujita Scale and the Enhanced Fujita Scale connect to the upper end of the Beaufort Scale (section 6.3.1). As intensity scales, they rely on damage to man-made structures to estimate wind speed and categorize a storm. The Enhanced Scale improves estimation of wind speed with the help of so-called damage indicators for more accurate damage assessment. It also reduces the wind speed span of each stage for finer graduation and tops out at lower wind speeds in return.

Several weaknesses have been recognized since the scales are in use [14]:

- The scales do not account for differences in construction style.
- The damage descriptions are subject to interpretation.
- The scales are based on damage to man-made structures. If no such structures are located in the vicinity of a storm, a proper assessment is difficult.
- The damage assessment is based on the worst damage, even if said damage is exclusive to one single structure.
- Wind speeds greater than stage 3 tend to be overestimated.

Due to these reasons, wind speeds are rough estimations rather than clear determinations and cannot fully be relied on.

6.4. Explosions and Nuclear Incidents

6.4.1. Volcanic Explosivity Index

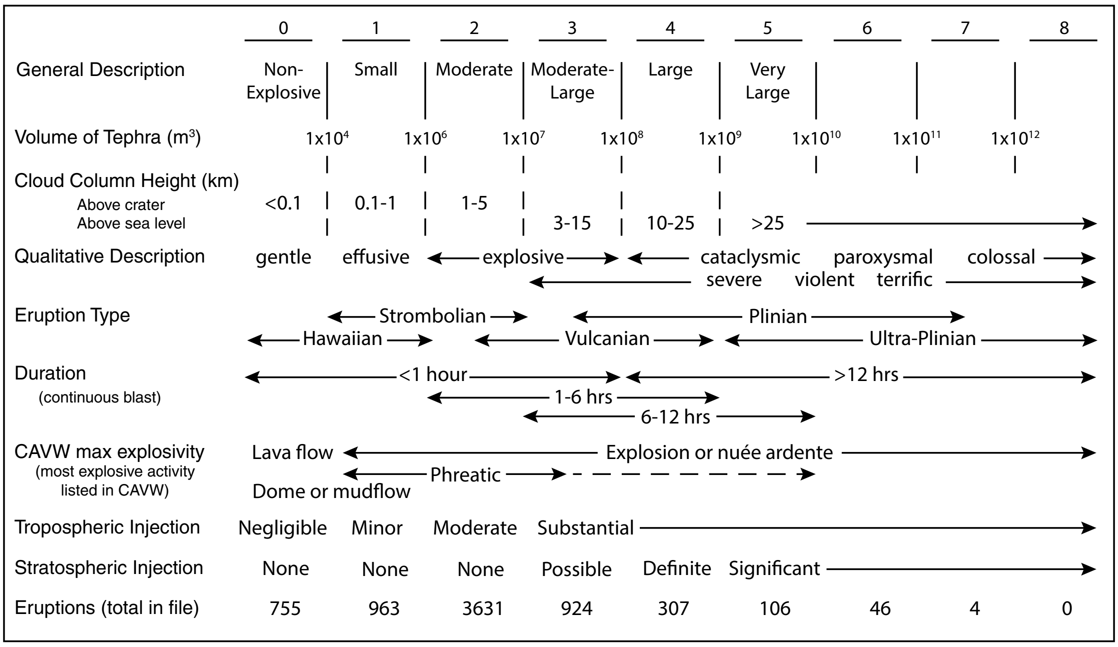


Fig. 6.1.: Volcanic Explosivity Index [31]

The logarithmic Volcanic Explosivity Index (VEI) (see fig. 6.1) is one of the few scales based on parameters rather than assessment of effects. It is mainly based on the volume of ash produced (tephra), the cloud column height and the duration of eruption [35]. This allows for clear and replicable categorization and is mostly free from subjective interpretation.
However, since the scale lacks a comprehensive description of the effects on the surroundings, it is of limited value for communication with the general public and better suited to be used among experts.

6.4.2. International Nuclear Event Scale

Intended for use for all kinds of non-military nuclear and radiological events, the International Nuclear Event Scale (INES) is a logarithmic scale with seven stages. For communication with the public, titles have been given to the stages that convey the severity of an event in a few words: These are 'anomaly', 'incident', 'serious incident', 'accident with local consequences', 'accident with wider consequences', 'serious accident' and 'major accident' [1].
In addition to extensive qualitative ones, the scale contains some quantitative descriptions (Sv and Sv/hr) which are not meaningful to the general public.

Description and INES Level	People and the environment	Radiological barriers and controls at facilities	Defence in depth
Major accident Level 7	- Major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures.		
Serious accident Level 6	- Significant release of radioactive material likely to require implementation of planned countermeasures.		
Accident with wider consequences Level 5	- Limited release of radioactive material likely to require implementation of some planned countermeasures. - Several deaths from radiation.	- Severe damage to reactor core. - Release of large quantities of radioactive material within an installation with a high probability of significant public exposure. This could arise from a major criticality accident or fire.	
Accident with local consequences Level 4	- Minor release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls. - At least one death from radiation.	- Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory. - Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure.	
Serious incident Level 3	- Exposure in excess of ten times the statutory annual limit for workers. - Non-lethal deterministic health effect (e.g. burns) from radiation.	- Exposure rates of more than 1 Sv/hr in an operating area. - Severe contamination in an area not expected by design, with a low probability of significant public exposure.	- Near accident at a nuclear power plant with no safety provisions remaining. - Lost or stolen highly radioactive sealed source. - Misdelivered highly radioactive sealed source without adequate radiation procedures in place to handle it.
Incident Level 2	- Exposure of a member of the public in excess of 10mSv. - Exposure of a worker in excess of the statutory annual limits.	- Radiation levels in an operating area of more than 50 mSv/h. - Significant contamination within the facility into an area not expected by design.	- Significant failures in safety provisions but with no actual consequences. - Found highly radioactive sealed orphan source, device or transport package with safety provisions intact. - Inadequate packaging of a highly radioactive sealed source.
Anomaly Level 1			- Overexposure of a member of the public in excess of statutory limits. - Minor problems with safety components with significant defence in depth remaining. - Low activity lost or stolen radioactive source, device or transport package.
No safety significance (Below scale/Level 0)			

Fig. 6.2.: International Nuclear Event Scale [1]

6.4.3. Chemical and Nuclear Explosions

In fact a metric rather than a scale, chemical and nuclear explosions are characterized by yield which is typically given in Tons TNT. Yield is the amount of released energy. Since there is usually no direct way to measure it, particularly in the case of nuclear explosions, determining yield can be complex and difficult and usually comes with a high level of uncertainty.

As a means of communication with the public, yield is not useful. While many people may have heard the unit „Tons TNT“ (or rather the multiples „Kilotons TNT“ or „Megatons TNT“), few have an intuitive understanding of how much a Ton TNT of released energy is and what extent of damage this relates to. Therefore it holds no more meaning than other energy units such as Joule.

7. Introducing a New Hazard Scale

7.1. General Issues

As can be seen in sections 5 and 6, the creation of a hazard scale often comes with several difficulties. The most significant are:

- Number of stages:
  With few stages, one stage encompasses a large variance of effects. Events classified as the same stage can therefore have vastly different consequences. If the severity of an event cannot accurately be told from the stage value, the scale loses its benefit. This issue comes into play all the more with impact hazard scales where effects cover a vast range from „shooting star“ to „global annihilation“.
  With more stages, chances are higher that predicted events are categorized incorrectly since small deviations and errors are more likely to make a difference. It also becomes more difficult to differentiate verbal descriptions of stages from one another to the point where the finer graduation may lose its meaning.

- Projection:
  Complex multidimensional models are hard to understand for the general public and have to be projected into a one-dimensional scale. This prompts the question which parts of a model can safely be simplified and to what degree before the scale becomes pointless.

- Regional differences:
  Despite similar parameters, the effects caused by an impactor may vary considerably among different regions. This is due to different geological conditions, construction styles and infrastructure.
  For illustration, one may consider the 2016 Kumamoto (Japan) earthquake and the the 2011 Haiti earthquake. Despite both of them scoring a 7.0 Magnitude and occuring in a densely populated area, the latter’s consequences were much more severe. In Kumamoto, around 50 people died and 3000 were injured whereas in Haiti the deathtoll alone was in the order of hundred thousands.

The proposed scale that is presented in the following section addresses the first and the second issue. The last issue cannot be solved generally for a scale of global scope. For better results, the scale would have to be adjusted to regional circumstances.

7.2. Description of the Scale

The scale consists of eleven stages representing zones. Each of these zones corresponds to a certain level of impact effect intensity. In the simplest case, the zones are circle-shaped and expand radially from the impact site in descending order of severity. As an example, see fig. 7.1.

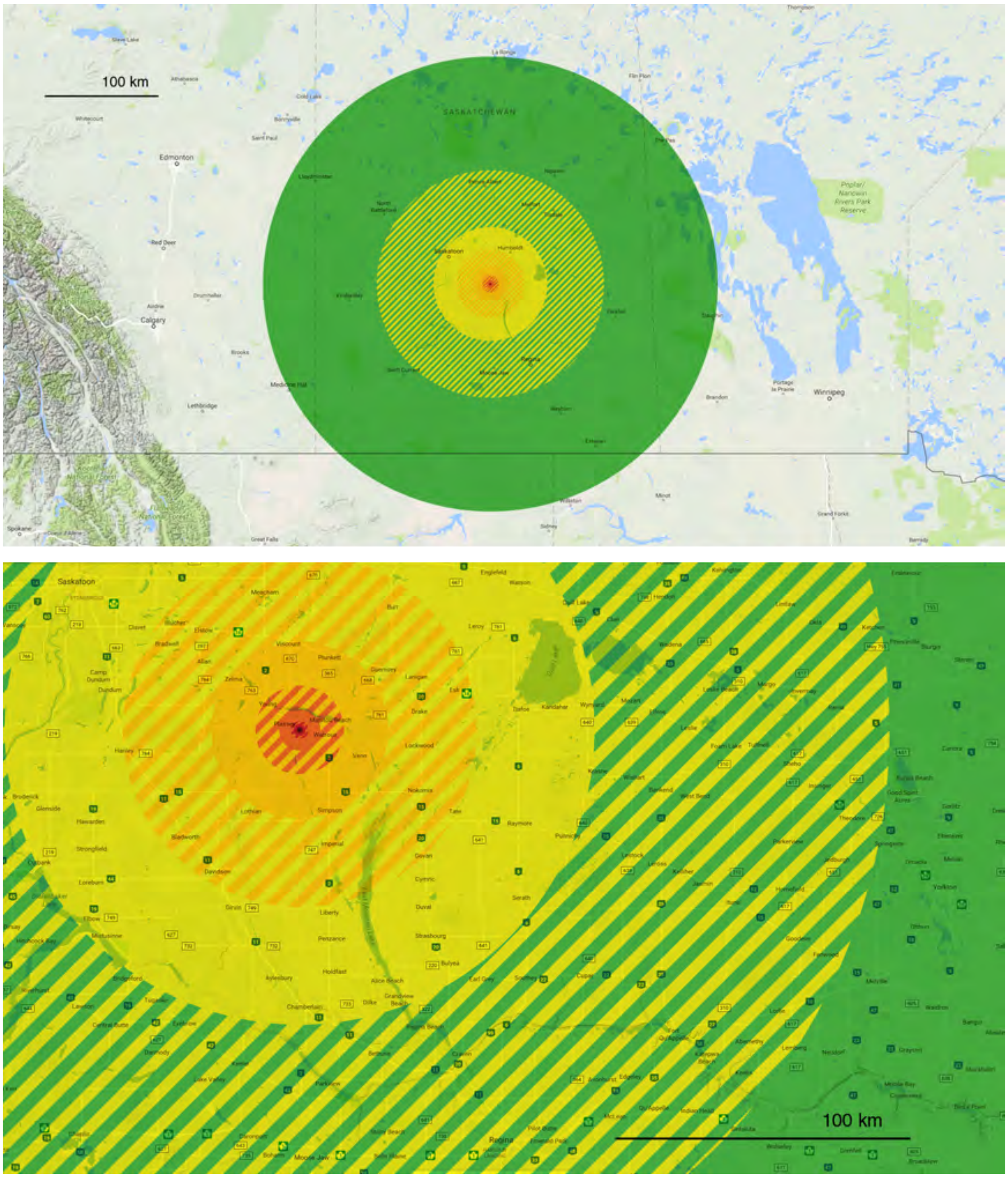


Fig. 7.1.: Zone map for impact of 10^{15} J impactor in Saskatchewan, Canada, at different magnification levels. The flat and relatively homogenous terrain is likely to provide circle-shaped zones. Map background: [23].

The scale is split into two sections: land impacts and water impacts. An exemplary zone map of the latter is shown in fig. 7.4. The typical range of each zone is shown in the mapping key (fig. 7.2).
Since the actual distribution of the zones depends a lot on ground parameters and terrain which are highly specific to the impact site, the mapping key is only to be taken as a guideline. With the knowledge of the excact impact site, a more accurate zone map could be created using numerical models that incorporate the local conditions. A qualitative example of what such a zone map could look like is shown in fig. 7.3.

Global effects such as atmosphere poisoning are not represented within the scale. Should the impactor be large enough for these to become relevant, this information would have to be provided additionally.

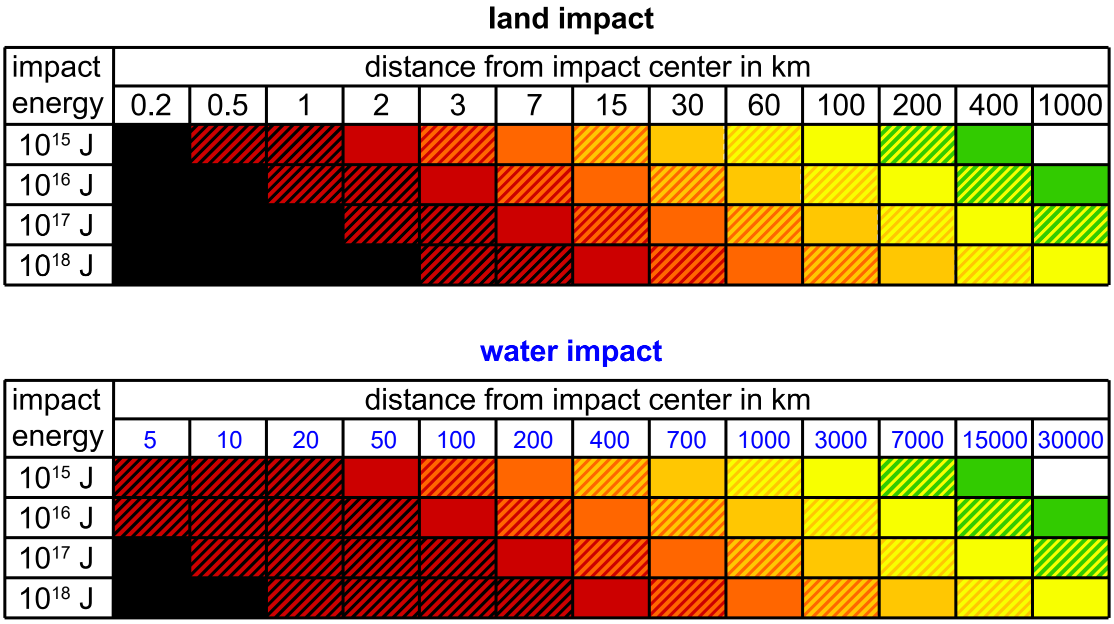


Fig. 7.2.: Mapping key for land and water impacts.
Water impact effects are based on an ocean depth of 3688 m at the impact site and may differ significantly depending on actual ocean depth and terrain.

Descriptions:

1. **harmless** (green)

   - **land impact**
     Noticeable heat.
     Beaufort number 1 winds (light air).

   - **water impact**
     Wave not felt, registerable only by special instruments. No damage.
     Papadopoulos–Imamura stage I tsunami (not felt).

2. **noticeable** (yellow - green)

- **land impact**
  Strong heat.
  Beaufort number 1 winds (light air).

- **water impact**
  Noticeable wave, but no damage.
  Papadopoulos–Imamura stage III tsunami (weak).

3. **weak** (yellow)

   - **land impact**
     First degree burns if exposed.
     Beaufort number 1 winds (light air).

   - **water impact**
     Noticeable wave, may be observed on the shore. Some light boats slightly carried onto the shore.
     Papadopoulos–Imamura stage IV tsunami (largely observed).

4. **detrimental** (orange - yellow)

   - **land impact**
     Third degree burns, grass and deciduous trees ignite if exposed.
     Beaufort number 3 winds (gentle breeze).

   - **water impact**
     Limited flooding of coastal land and structures. Many light vessels carried inland.
     Papadopoulos–Imamura stage V tsunami (strong).

5. **harmful** (orange)

   - **land impact**
     Clothing and trees ignite if exposed.
     Beaufort number 3 winds (gentle breeze).

   - **water impact**
     Many light vessels carried inland. Some wooden structures destroyed.
     Papadopoulos–Imamura stage VI tsunami (slightly damaging).

6. **severe** (dark orange - orange)

   - **land impact**
     Firestorm. Glass windows shatter.
     Beaufort number 8 winds (gale), Saffir-Simpson category 1 winds (very dangerous winds, some damage).

   - **water impact**
     Some people carried away to sea. Most light vessels damaged, some large vessels carried ashore. Many floating structures carried out to sea. Many wooden structures damaged or carried out to sea.
     Papadopoulos–Imamura stage VIII tsunami (heavily damaging).

7. **damaging** (dark orange)

   - **land impact**
     Devastation. Firestorm. Roofs are severely damaged, wood frame buildings collapse.
     Saffir-Simpson category 2 winds (extremely dangerous winds, extensive damage).

   - **water impact**
     Most people carried away. Most large vessels carried inland, vehicles overturned and displaced. Fires. Artificial dams destroyed, harbor wavebreakers damaged.
     Papadopoulos–Imamura stage X tsunami (very destructive).

8. **disruptive** (red - dark orange)

   - **land impact**
     Widespread devastation. Firestorm. Multistory wall-bearing buildings collapse.
     Saffir-Simpson category 5 winds (catastrophic damage).

   - **water impact**
     Vehicles carried out to sea. Most buildings severely damaged. Widespread fires.
     Papadopoulos–Imamura stage XI tsunami (devastating).

9. **destructive** (red)

   - **land impact**
     Near-complete devastation. Extreme firestorm. Steel-framed buildings suffer extreme distortions, all other buildings and most bridges collapse. Cars and trucks are overturned and displaced.

   - **water impact**
     Brick buildings wiped out, most concrete buildings severely damaged.
     Papadopoulos–Imamura stage XII tsunami (completely devastating).

10. **devastating** (black - red)

    - **land impact**
      Immediate vicinity of the fireball. Complete devastation. Extreme firestorm. All buildings and bridges collapse. Cars and trucks are largely displaced and grossly distorted.

    - **water impact**
      Immediate vicinity of the impact cavity. All buildings wiped out.

11. **annihilating** (black)

    - **land impact**
      Range of crater and fireball. Complete devastation without exception. Terrain is entirely reshaped.

- **water impact**
  Range of impact cavity. Complete devastation without exception. Ocean floor may be reshaped.

The referred scales are the Beaufort Wind Force scale (section 6.3.1), the Saffir-Simpson Hurricane Wind Scale (section 6.3.2) and the Papadopoulos–Imamura Tsunami Intensity Scale (section 6.2.3).

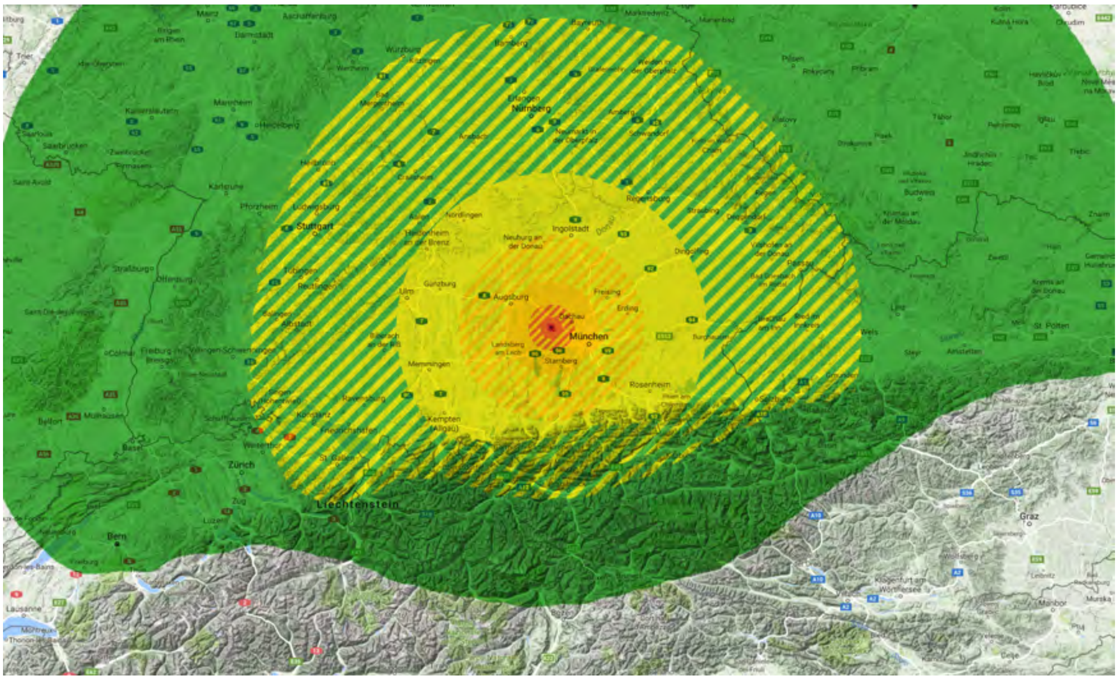


Fig. 7.3.: Zone map for impact of 10^{15} J impactor in Munich, Germany. Due to the Alps and other elevated areas, the zones are irregular in shape (zone shapes are qualitative). Map background: [23].

7.3. Advantages and Disadvantages

Of the existing impact hazard scales, the proposed scale most closely resembles the Broomfield Hazard Scale (section 5.3) as they both are non-probabilistic, making them more suitable for public communication. However, it differs in various important key points to reduce its weaknesses:

- The categorization subject is the area around the impact site instead of the impactor itself. This has two advantages:
  - Emergency agencies as well as the general public are mainly interested in the extent of destruction in a certain area. Whether said destruction is caused by a small or a large impactor is of secondary interest.
  - When using numerical models, the partitioning of the area into zones allows to create a zone map that considers the local conditions. This

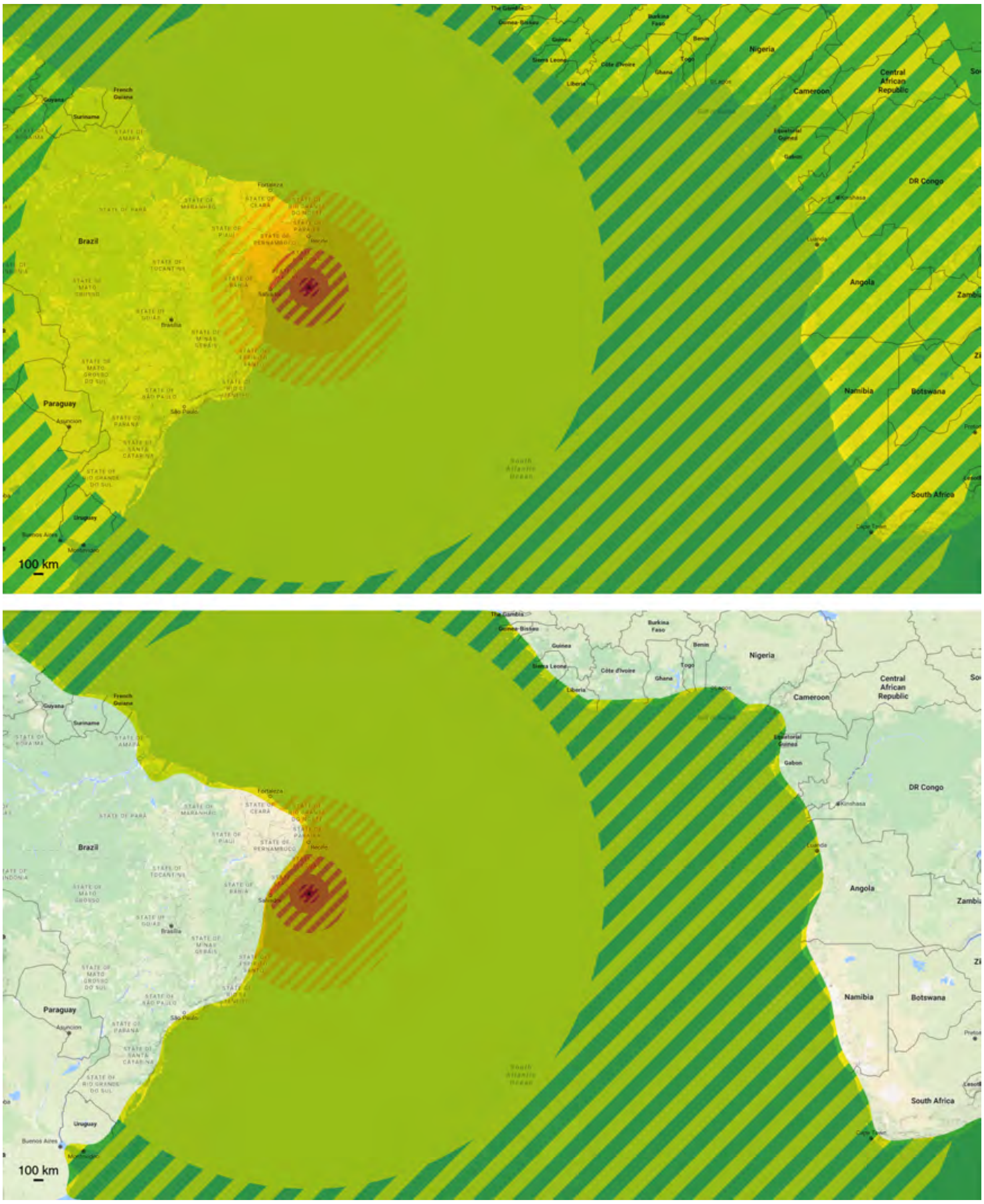


Fig. 7.4.: Zone map for impact of 10^{15} J impactor in the Southern Pacific (top). Since the tsunami only affects coastal regions, an alternative rendering (bottom) may be preferable to prevent confusion (affected coast area is qualitative). Map background: [23].

can provide a much higher accuracy and a better idea of the impact consequences.

- Instead of diameter, the scale is based on kinetic energy which is calculated from several parameters, one of which is diameter.
  It may be argued that diameter is more intuitive for the layman and easier to determine. This would certainly be the case if an impactor's diameter was easily recognizable for the general public which could then reproduce the classification. But since only experts have the means to detect and measure impactors long before impact, the classification of an impactor can only be done by experts in any case. At this point, using a more tangible physical property does not bring any advantage.
  While it may not be possible to determine some of the necessary parameters with high precision, this would still be more accurate than assuming average values.

- The scale provides a much higher number of stages. This allows for a more precise estimation of the damage extent. However, this also means that inaccurate input parameters or impact models are more likely to lead to an incorrect classification of an area.
  For a simpler, less detailed scale, stages can also be left out. The corresponding zones would then merge with the zones of the next-higher stages.

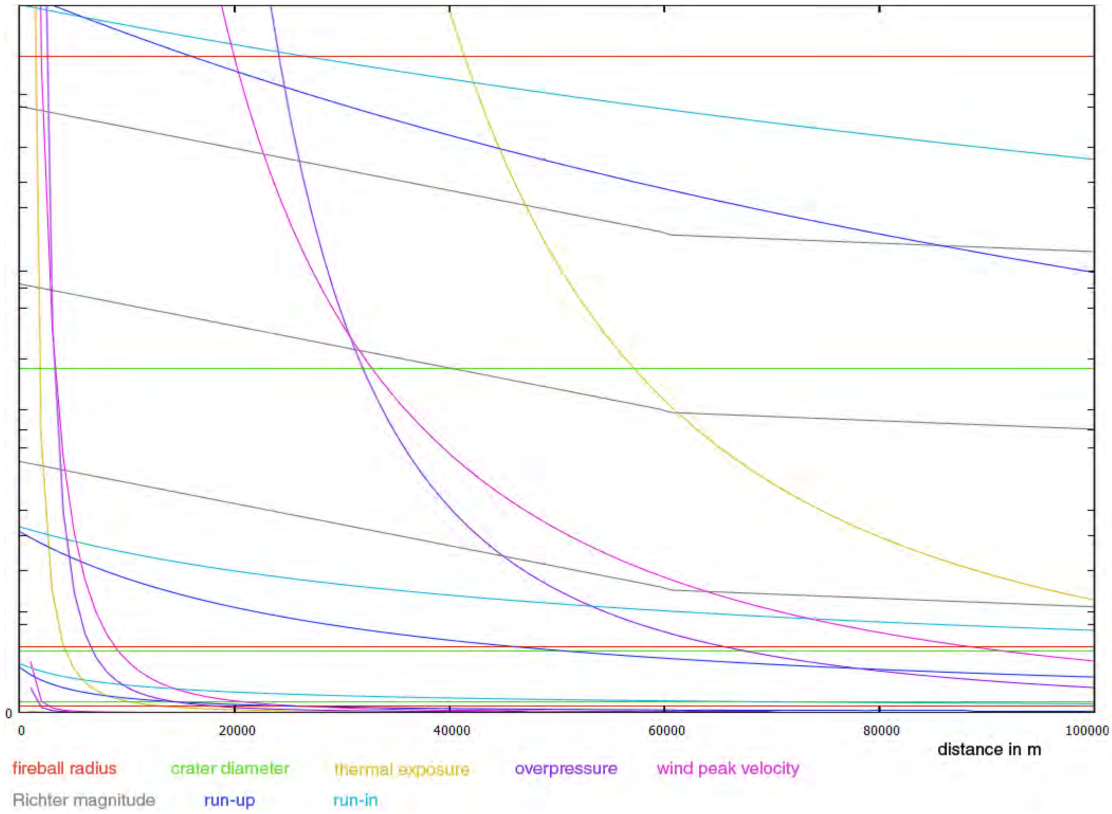
- With the exception of black which is universally understood, the stage colors are limited to the range of traffic light colors. To account for a higher number of stages, mixed colors are used. This allows a much more intuitive understanding when colors are viewed without context.

- The extent of destruction in the zones is described in-depth.
  Impacts are extremely rare. Unlike for storms, earthquakes, tsunamis and volcano eruptions in some parts of the world, there is no intuitive understanding of their consequences. So whenever applicable, the values of hazard scales from other, more common domains are referenced in order to provide a better idea of what to expect.

However, the advantage of zones and a high number of stages is also a handicap: For meaningful results, the exact impact location and the impactors parameters have to be known which is not always a given. Otherwise, a scale of such detail conjures the misleading impression of a high degree of accuracy which – in this case – is not sufficiently grounded in reality.

7.4. Quantitative Foundation

For illustration, the effects of three different impactors have been plotted according to the quantitative model in section 4. In order to cover a wide range, the impact energies were selected as $E = 10^{17}$ J, $E = 10^{20}$ J and $E = 10^{23}$ J. The



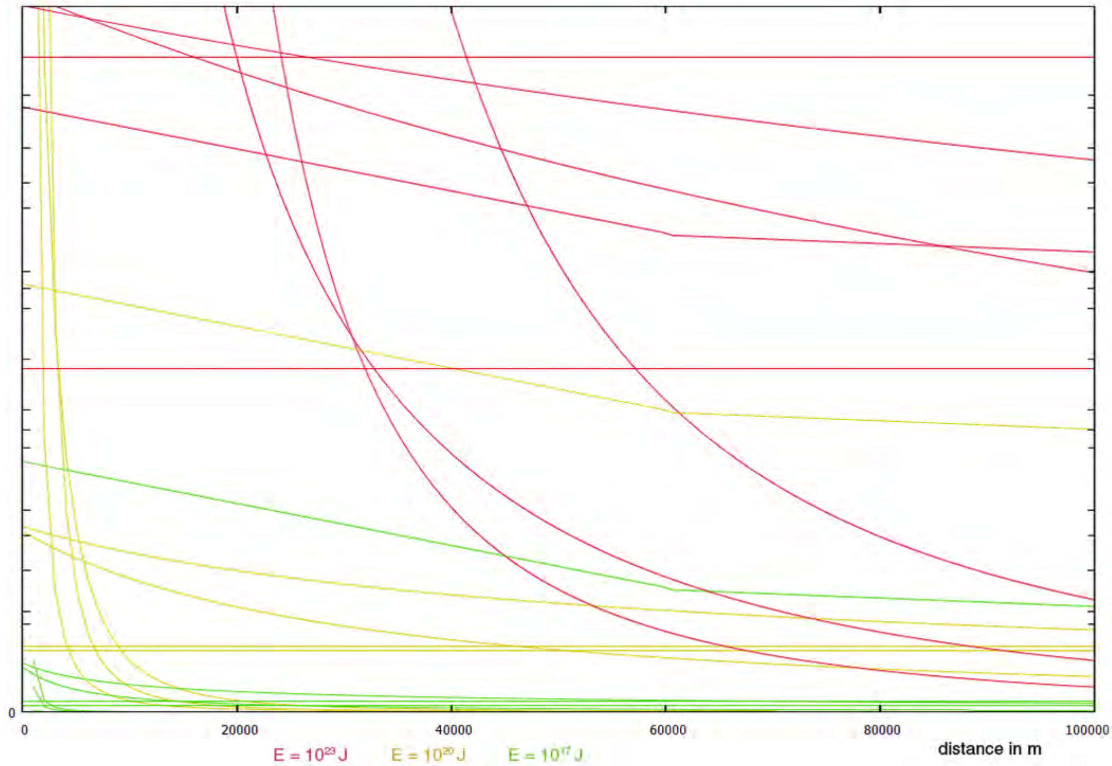


Fig. 7.5.: Effects over distance for three different impactors, color coded for effects (top) and impact energy (bottom)

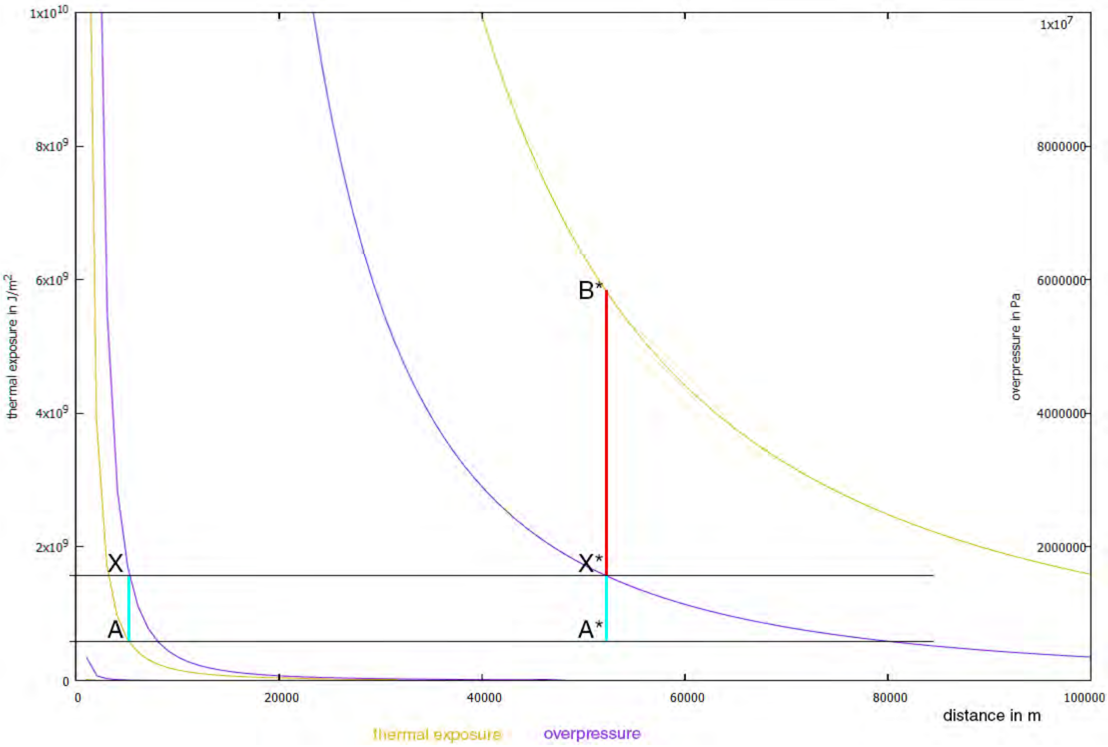


Fig. 7.6.: Comparison between overpressure and thermal exposure

lowest impact energy corresponds to that of the Tunguska event, whereas the highest is similar to that of the Chicxulub impactor.
A summary of the graphs is shown in fig. 7.5, single graphs for each effect are available in the appendix. Comparing the plots, it can be shown that the effects do not scale in proportion to each other.

In figure 7.6, thermal exposure and overpressure have been picked as an example while the other effects were discarded for a clearer view.
Choosing an arbitrary point X on the overpressure plot of the middle impactor, the corresponding thermal exposure at the same distance is visible at point A. The same overpressure value is selected for a higher impact energy which naturally puts the point X* at a greater distance from the impact. If the effects scaled proportionally, the corresponding thermal exposure value were to be expected at point A*. In reality, it is at point B* which, in this case, deviates from A* by a factor of ten.
Similar relationships can be observed between most of the effects. The exception are those that are linked directly, such as pressure p and wind peak velocity u.
The consequence is that between two differently sized impacts, the extent of single effects in the same zone will differ. Whether that difference is significant depends on the difference of the selected impact energies, which means that the zones are only reasonably accurate for a certain range of impact energies.
Since they are much more common, the zones are defined with respect to small impactors (10^{15} - 10^{16} J). It is also prudent to assume that the mathematical model fits smaller impactors much better since it has been created after rela-

tively small explosions. Data on very large explosions, let alone actual impacts, is even more limited and it is difficult to discern how the effects would behave.

For the mapping key (fig. 7.2), impact energies from 10^{15} J to 10^{18} J have been considered. The mapping key can be extended for impactors of higher impact energies. Impactors of lower impact energies are likely to burn up in the atmosphere which is why it makes little sense to cover them within this scale.

Since some of the effects described in section 2 dominate the others in terms of destructive potential, the scale is primarily adjusted with respect to those. An impact-induced earthquake, for example, does little damage compared to the overpressure caused by the same impactor and can therefore be neglected.
For land impacts, the dominating effects are overpressure and thermal exposure. In case of a water impact, the tsunami wave overpowers all the other effects, which is why there are separate mapping keys for land and water impacts.

8. Conclusion

Unlike previous scales, the proposed scale is suitable to provide an image of the damage extent of an impact by separating the affected area into multiple zones.

The accuracy of the scale hinges on the mathematical impact effects model which, to date, is rather primitive. Significant deviations from the effects of an actual impact are to be expected, especially for water impacts. This issue could be circumvented by using numerical models adjusted to individual impacts at the cost of significantly more effort and resources. Regardless of the mathematical model, the scale requires a precise impact location to give meaningful results.
Some effects have been neglected either because their destructive potential is diminutive in comparison or because they occur on a global level and cannot be fitted into a zone map. Since the effects scale disproportionately, the scale becomes less accurate for bigger impactors. It only covers impactors that reach the ground, so a question mark remains with respect to impactors that disintegrate into an airburst.

As is the case for all hazard scales, this scale can never paint the entire picture. For public communication, the scale should always be used as one tool among many.

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B. Appendix

B.1. Code

Matlab script of the impact effect model (section 4)

```
%% variables
rho_i = 5000  ; % impactor density in kg/m^3
L_0 = 500 ;  % impactor diamater in m
v_0 = 17000 ;  % impactor velocity in m/s
r = 2*10^3 ; % distance from impact in m
Phi_ignition_1Mt = 0.1 ; % ignition factor in Mt
rho_t = 2000 ; % target density in kg/m^3
E = 10^18 ; %kinetic energy/impact energy in J

%% factors
eta = 0.001 ; % luminous efficiency
p_x = 75000  ; % pressure at crossover point in Pa
r_x = 290 ; % crossover point in m
P_0 = 100000 ; % ambient pressure in Pa
c_0 = 330 ; % speed of sound (air) in m/s
g_E = 9.81 ; % gravitational acceleration in m/s
epsilon = 0.15 ; % fraction of impact energy conv. into wave energy
rho_water = 1020 ;  % water density in kg/m^3
h_deep = 3688 ; % ocean depth in m

%% kinetic energy = impact energy (atmospheric entry is neglected)
% (calculate only if E is not given)
E = pi/12 *rho_i *L_0^3 *v_0^2 ;

%% fireball and thermal radiation
% fireball radius
R_f = 0.002* E^(1/3) ;
% thermal exposure
Phi = eta *E /2 /3.14 /r^2 ;
% ignition
Phi_ignition_E = Phi_ignition_1Mt *(E)^(1/6) ;

Phi = Phi_ignition_E;
```

```
%% airblast
% overpressure
p = E^(1/3)/10^4 *p_x *r_x /4 /r *(1+3*( E^(1/3)/10^4 *r_x /r )^1.3 ) ;

% wind peak velocity
u = 5 *p /7 /P_0 *c_0 /(1 +6*p/(7*P_0))^(0.5) ;

%% cratering
%crater diameter
D_fr = 1.8 *rho_t^(-1/3) *E^(1/4) *g_E^(-0.22) ;

%% seismic effects
% seismic wave energy
E_w = 10^(-4) *E ;

% magnitude
M_L = 0.67 *log10(E_w)-5.87 ;

if r<60000
M_eff = M_L - 0.0238*r *10^(-3) ;
elseif 60000 <= r < 700000
M_eff = M_L -0.0048*r*10^(-3) -1.1644  ;
else
M_eff = M_L -1.66 *log10(r*10^(-3)) -6.399 ;
end

%% water impacts
% cavity depth
d_cavity = 3.84* (epsilon /rho_water /g_E *E)^(1/4) ;
% wave amplitude
A_deep = d_cavity *(1+ 2*r/3/d_cavity)^(-1.53) ;
% run-up
h_up = 1.09 *A_deep.^(4/5) *h_deep^(1/5) ;
% run-in
h_in = 10 *sqrt(g_E *h_up) *(3/2 *d_cavity)^0.375 ;
```

B.2. Figures

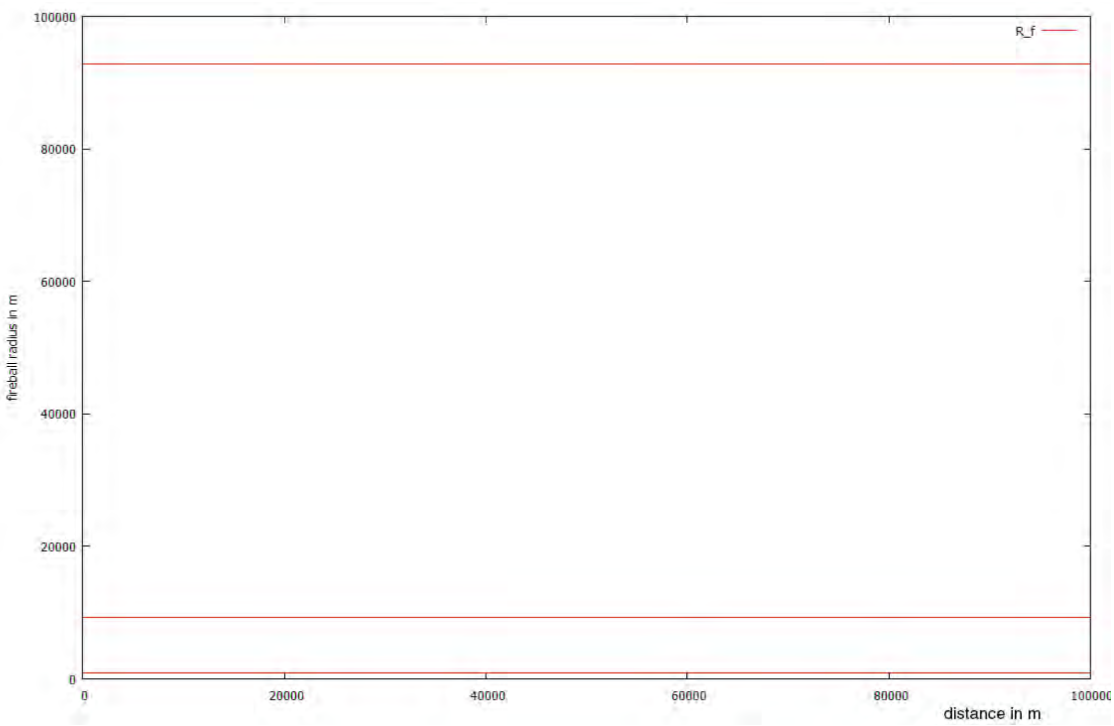

Fig. B.1.: Fireball radius for three different impactors

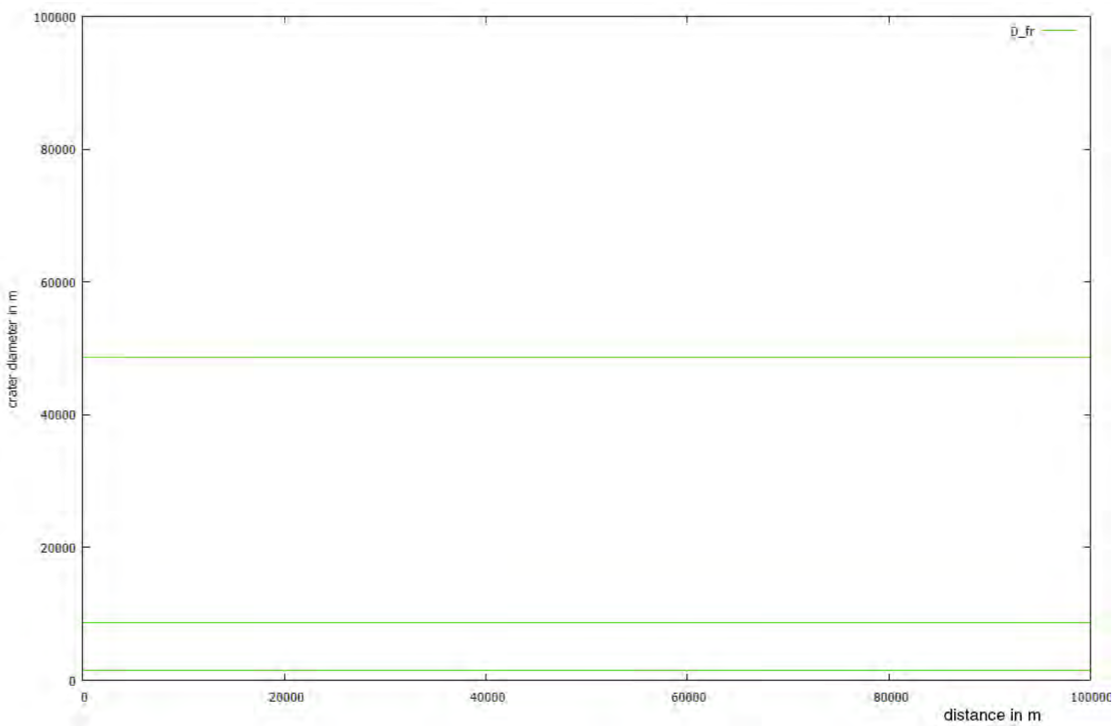

Fig. B.2.: Crater diameter for three different impactors

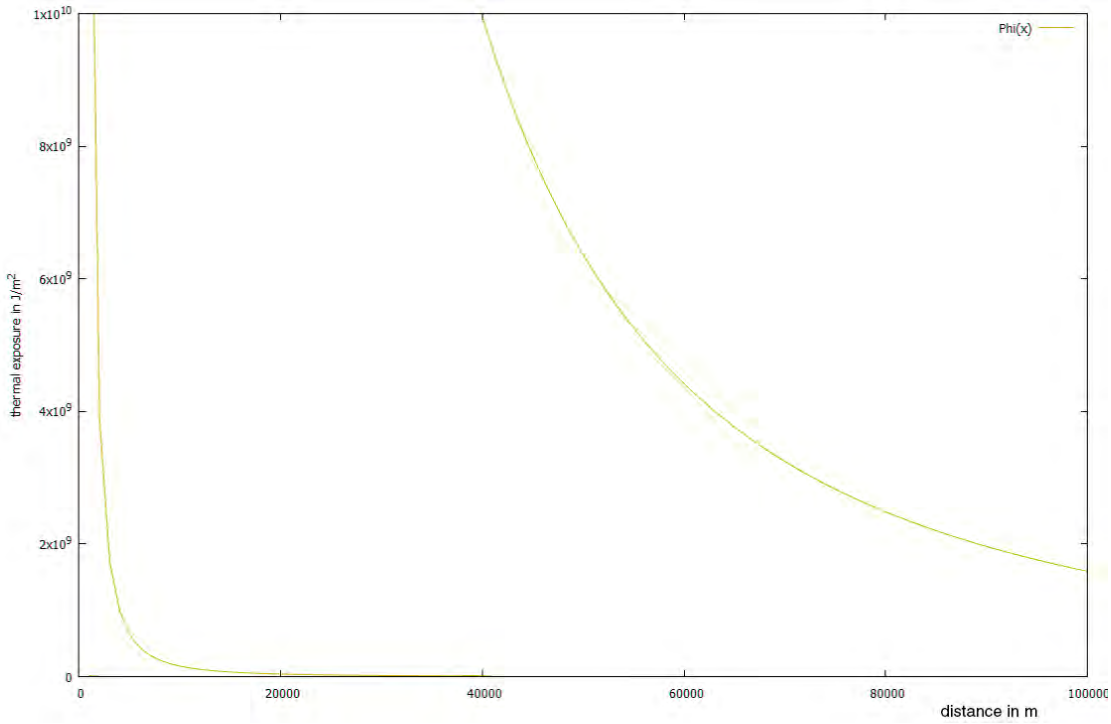

Fig. B.3.: Thermal exposure over distance for three different impactors

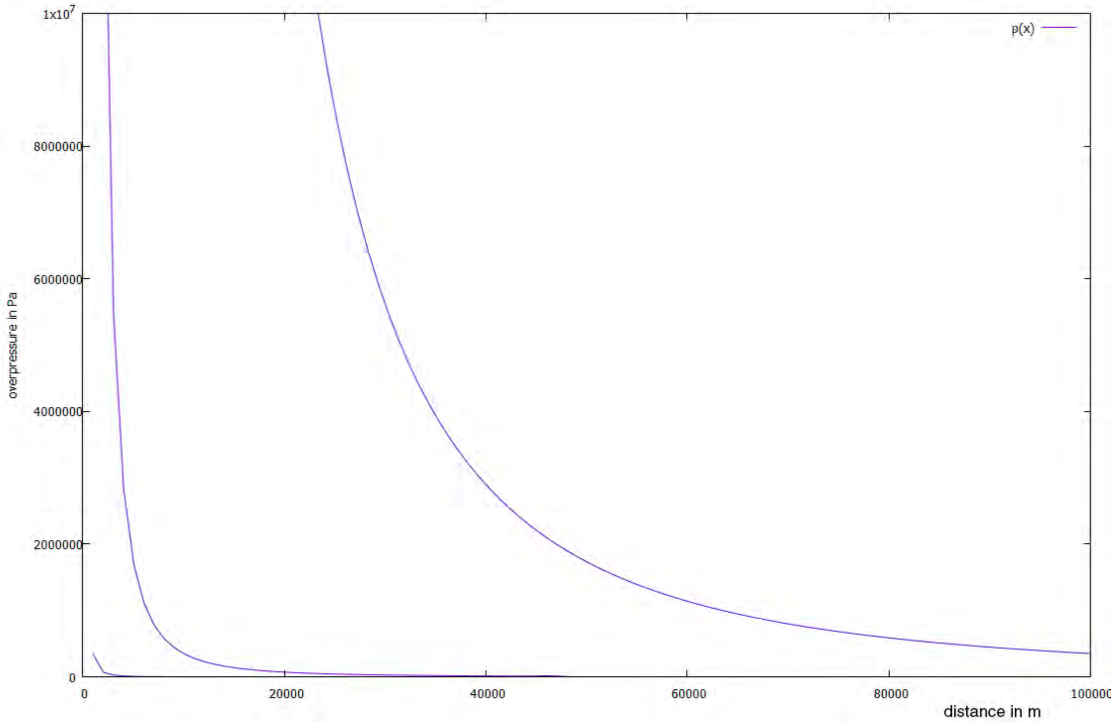

Fig. B.4.: Overpressure over distance for three different impactors

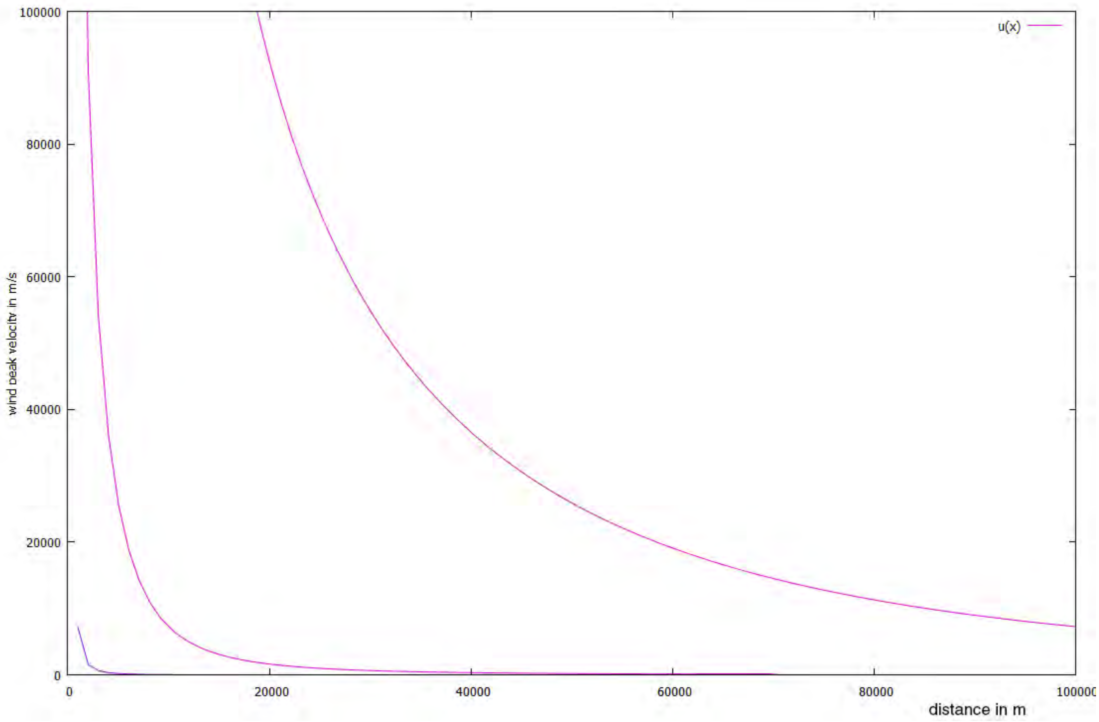

Fig. B.5.: Wind peak velocity over distance for three different impactors

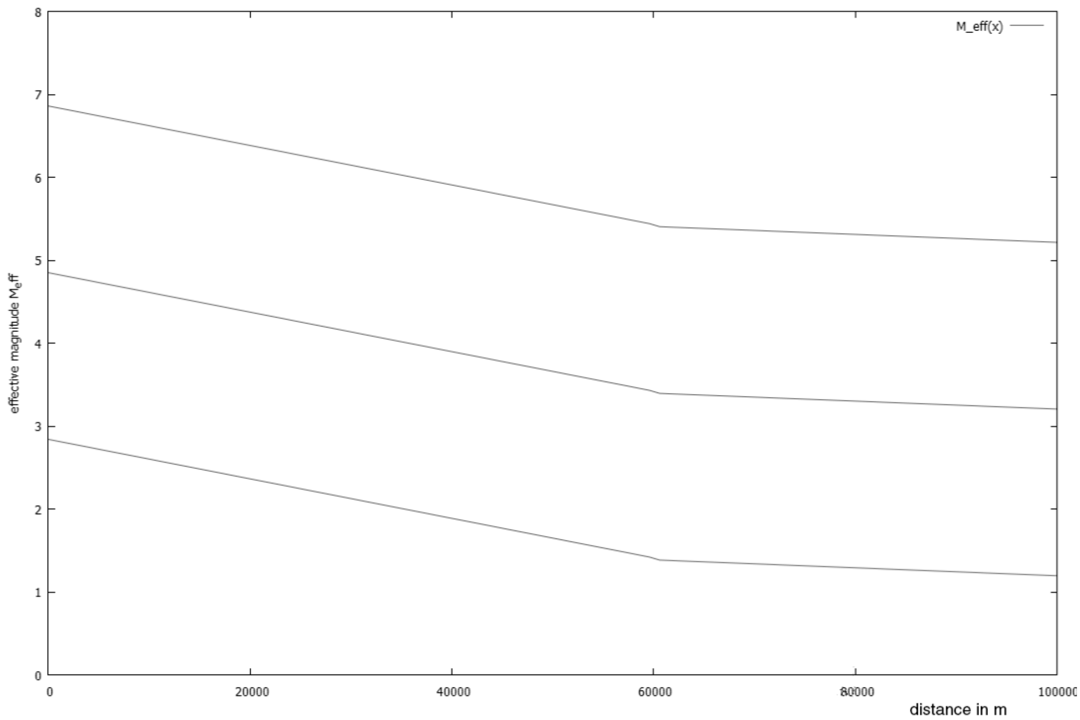

Fig. B.6.: Richter magnitude over distance for three different impactors

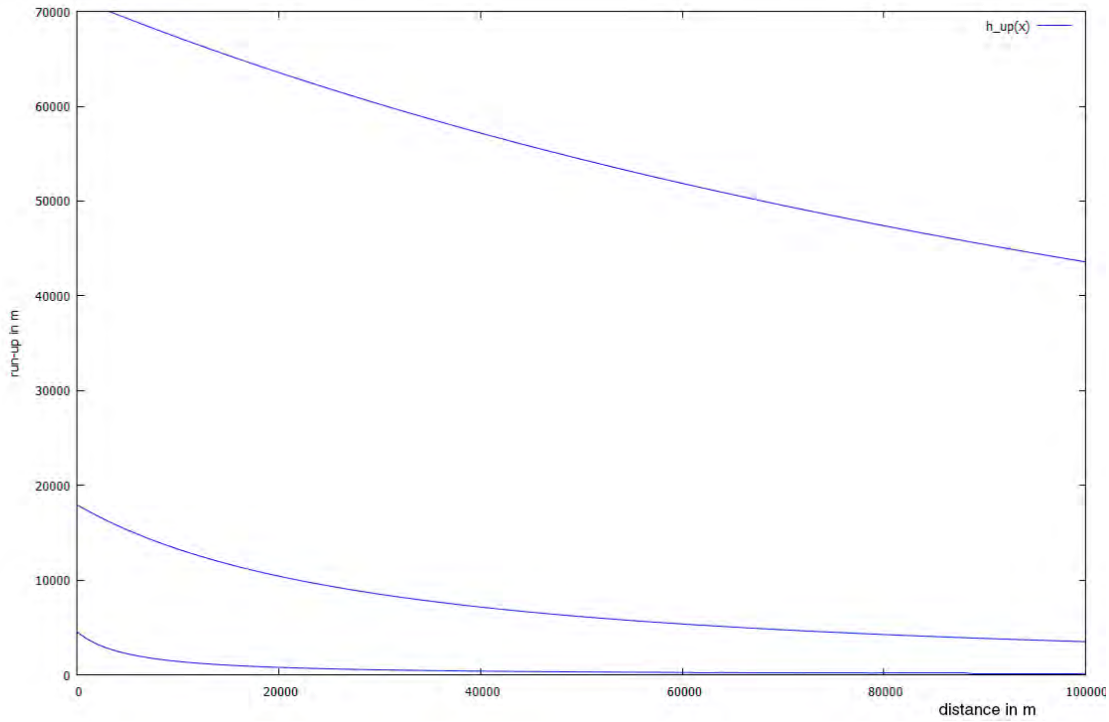

Fig. B.7.: Run-up over distance for three different impactors

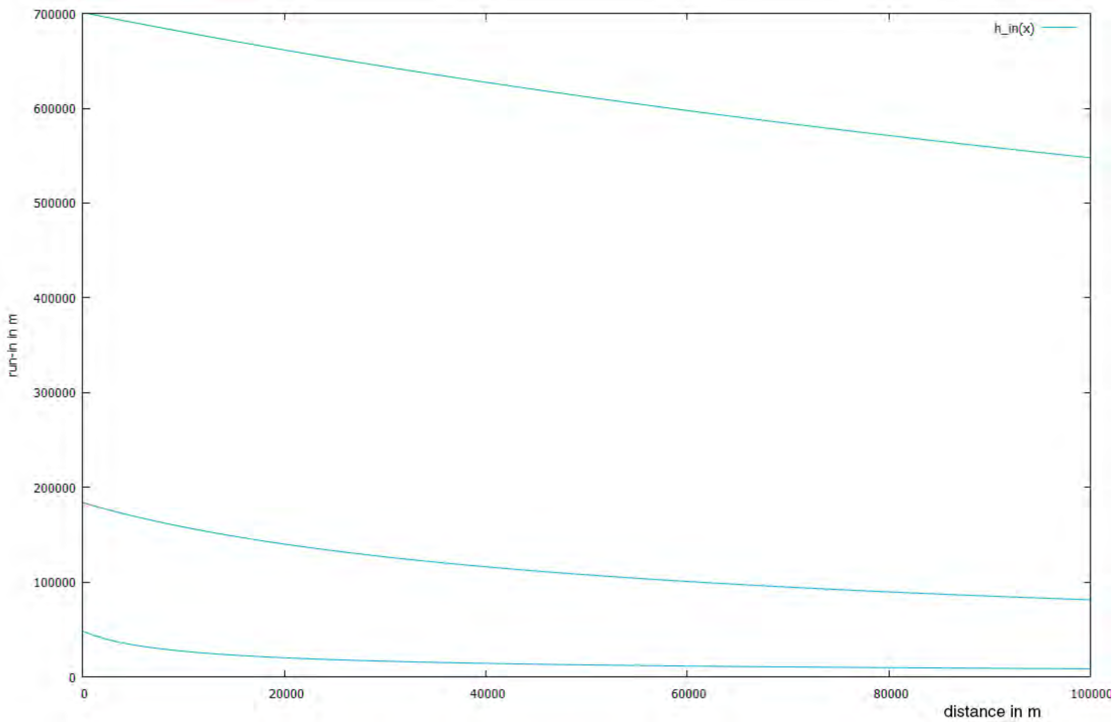

Fig. B.8.: Run-in over distance for three different impactors