P WMA 12/T30/00/5212/12

water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA

DIRECTORATE: OPTIONS ANALYSIS

FEASIBILITY STUDY FOR THE MZIMVUBU WATER PROJECT

FEASIBILITY DESIGN:
NTABELANGA DAM
APPENDICES

OCTOBER 2014

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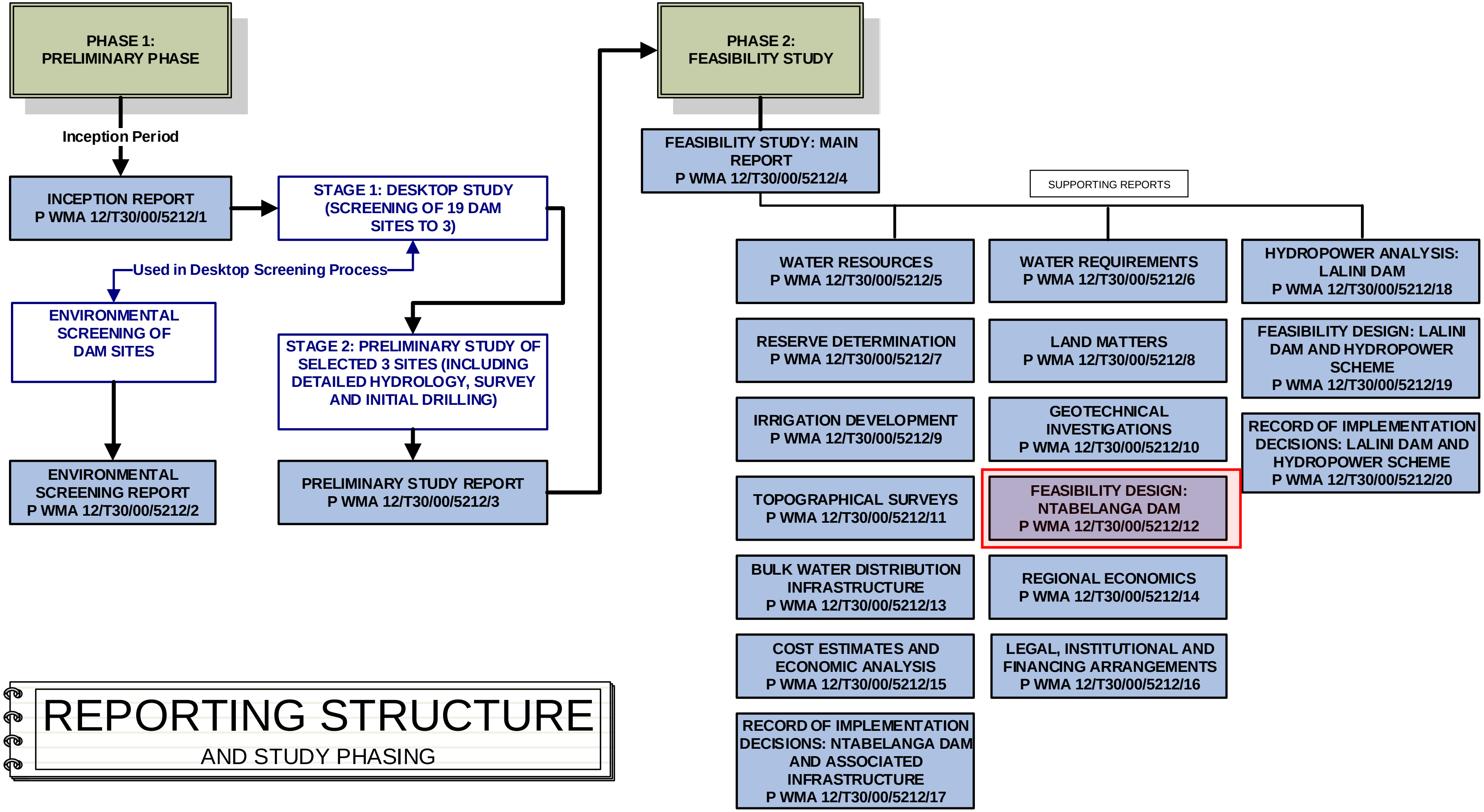
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REPORTING STRUCTURE
AND STUDY PHASING

REFERENCE

This report is to be referred to in bibliographies as:

Department of Water and Sanitation, South Africa (2014). ***Feasibility Study for the Mzimvubu Water Project: Feasibility Design: Ntabelanga Dam: Appendices***

DWS Report No: P WMA 12/T30/00/5212/12

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Note on Departmental Name Change:

In 2014, the Department of Water Affairs changed its name to the Department of Water and Sanitation, which happened during the course of this study. In some cases this was after some of the study reports had been finalized. The reader should therefore kindly note that references to the Department of Water Affairs and the Department of Water and Sanitation herein should be considered to be one and the same.

Note on Spelling of Laleni:

The settlement named Laleni on maps issued by the Surveyor General is locally known as Lalini and both names therefore refer to the same settlement.

APPENDICES

APPENDIX A

DESIGN FLOOD HYDROLOGY REPORT

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A. DESIGN FLOOD HYDROLOGY

As part of the Mzimvubu Water Resources project, the Ntabelanga Dam site was selected as the preferred site at which to construct a dam. As part of the dam feasibility design process, the dam spillway needs to be sized in accordance to the guidelines published by the South African National Council on Large Dams (SANCOLD) in (SANCOLD, 1991). This section provides the SANCOLD design requirements for the Ntabelanga Dam as well as methodologies undertaken to determine peak discharge values used to determine the Recommended Design Flood (RDF) and Safety Evaluation Flood (SEF) for the design of the Ntabelanga Dam spillway.

The potential flood damage that could be inflicted on a hydraulic structure may be related to one or more of the following parameters:

- High Flood Level – the maximum water level reached during a flood event;
- Peak Discharge – the maximum flow rate during a flood event;
- Maximum Flow Velocity – the maximum calculated flow velocity associated with a given flow rate;
- Flood Volume – the volume of water that is released from a catchment during a flood event; and
- Flood Duration – the period of time when the discharge associated with a flood event exceeds a specified limit.

Peak discharge is the most useful parameter in design calculation requirements for structures to resist potential damage imposed by flood events. The peak discharge of a catchment is directly related to the characteristics of the storm event and characteristics of the contributing catchment area. The requirements for the design of the proposed Ntabelanga Dam spillway, as per the SANCOLD guidelines, are presented in the following section.

A.1 Design Flood Guidelines

Guidelines on dam safety in relation to floods was published by the SANCOLD (1991) to facilitate the requirements for the determination of flood values for the purposes of dam design. This was undertaken to ensure that the risk of failure through inadequacy of the spillway system could be kept to acceptable levels, hence, these guidelines were used in this investigation. The guidelines outline the requirements for the Recommended Design Flood (RDF) and the Safety Evaluation Flood (SEF). The spillway should be designed such that it can safely discharge the peak flow rate associated with the RDF, without any damage to the dam wall or spillway. The SEF is used to ensure that the spillway is designed to sufficiently to discharge the SEF associated peak flow rate without catastrophic failure of the dam wall or spillway (some damage is tolerated), whilst making no allowance for freeboard, thus maintaining the dam’s integrity until such a time as it can be repaired.

The SANCOLD Guidelines used to determine the RDF and SEF requirements for the design of the Ntabelanga Dam spillway are presented in Tables A-1 to A-6. These guidelines were applied under the assumption that the Ntabelanga Dam is going to be in the order of a 1.5 MAR impoundment, which results in a large dam wall (> 30 m high), an assumed potential loss of life greater than 10 people and a great potential economic loss.

Table 0-1: Dam Size Classification

Size Class	Maximum Wall Height (m)
Small	More than 5 and less than 12
Medium	Equal to or more than 12 but less than 30
Large	Equal to or more than 30

Table 0-2: Hazard Classification

Hazard Rating	Potential Loss of Life	Potential Economic Loss
Low	None	Minimal
Significant	Not more than 10 lives	Significant
High	More than 10 lives	Great

Table 0-3: Dam Safety Categorisation

Dam Size Class	Hazard Rating		
	Low	**Significant**	**High**
Small	1	2	2
Medium	2	2	3
Large	3	3	3

Table 0-4: Recommended Design Flood Values

Dam Size Class	Hazard Rating		
	Low	**Significant**	**High**
Small	$0.5Q_{50} - Q_{50}$	Q_{100}	Q_{100}
Medium	Q_{100}	Q_{100}	Q_{200}
Large	Q_{200}	Q_{200}	Q_{200}

Table 0-5: Safety Evaluation Flood Values

Dam Size Class	Hazard Rating		
	Low	**Significant**	**High**
Small	$RMF_{-\Delta}$	$RMF_{-\Delta}$	RMF
Medium	$RMF_{-\Delta}$	RMF	$RMF_{+\Delta}$
Large	RMF	$RMF_{+\Delta}$	$RMF_{+\Delta}$

In each of the Tables A-1 to A-5, the assumptions relating to the Ntabelanga Dam are highlighted in yellow. A summary of this information is provided in Table A-6. From this it is evident that the Ntabelanga Dam will be classed as a Category III Dam, therefore the RDF and SEF used to size the dam spillway will be equal to the 1:200 year design flood event and the Regional Maximum Flood (RMF; Kovacs, 1988) plus a category, respectively.

Table 0-6: Information and Categories Applicable to Ntabelanga Dam

Size Classification	Large	Downstream wall height ≥ 30m
Hazard Classification	High	Great potential economic loss
Dam Safety Categorisation	**3**	
Recommended Design Flood Values	$\mathbf{Q_{200}}$	
Safety Evaluation Flood Values	$\mathbf{RMF_{+\Delta}}$	

A.2 Catchment Characteristics

The Ntabelanga Dam and Tsitsa River catchment outlet are located approximately 55 km North of Umtata and 20 km east of Maclear in the Eastern Cape of South Africa. The dam is situated on the Tsitsa River, which in turn is fed by the Mooi and Pot Rivers. The dam catchment area consists of five quaternary catchments T35A, T35B, T35C, T35D and T35E, as depicted in Figure A-1. The dam catchment area is partially developed, with approximately 10 % of the catchment area under afforestation, 5 % under subsistence agriculture and approximately 80 % of the catchment under grasslands (NLC, 2000). The average Mean Annual Precipitation (MAP) of the contributing catchment area was calculated to be 907 mm, based on the Design Rainfall Utility (Smithers and Schulze, 2000).

Four streamflow gauges, located in the area of the proposed Ntabelanga Dam, were used in this study. These are Gauging Weir T3H005 located at the outlet of Quaternary Catchment T34H on the Tina River, T3H006 located at the outlet of Quaternary T35K on the Tsitsa River, T3H007 located at the outlet of Quaternary Catchment T33G on the Mzimvubu River and T3H009 located at the outlet of Quaternary Catchment T35C on the Mooi River at Maclear. The relative location of these flow gauges to the proposed dam site is indicated in Figure A-1. Table A-7 contains the catchment specific characteristics used in peak discharge calculations.

Table 0-7: Ntabelanga Dam Catchment Characteristics

Catchment Area (km^2)	Stream Length (km)	Slope (m/m)	Time of Concentration (hours)*	Distance to Catchment Centroid (km^2)
1971.78	114.90	0.005	19.52	61.29

* Time of concentration calculated using the method developed by the US Soil Conservation Service (Roads Drainage Manual, 2006)

A.3 Design Rainfall

Design rainfall for the catchment is required as an input into Deterministic Methods used to calculate peak discharge values. Appropriate methods include the Rational Method and the Unit Hydrograph Method. In order to develop design rainfall values for the Ntabelanga Dam catchment the following methodology was undertaken:

- The contributing catchment area was divided into three parts, namely upper (higher altitude area of the catchment), middle (mid-section of the catchment area) and lower (catchment area including the proposed Ntabelanga Dam), as depicted in Figure A-2;
- Each of the above mentioned sections were then further sub-divided into three sections. A point was then identified at the centre of each sub-section, resulting in nine points dispersed throughout the catchment area, as depicted in Figure A-2;
- In addition to the nine points described previously, the value at the centroid of the Ntabelanga Dam catchment was also used in the analysis;
- Design rainfall for each of the above mentioned points was then extracted using the Design Rainfall Utility developed by Smithers and Schulze (2003); and
- Comparisons of the extracted design rainfall from each of the identified points was then undertaken and representative design rainfall depths chosen (the centroid value was selected as it provided the most representative value) for the contributing catchment area.

The Design Rainfall Utility developed by Smithers and Schulze (2000) utilises a regionalised L-moment Algorithm and scale invariance to estimate design rainfall at any 1' × 1' grid interval in South Africa. Comparisons of the design rainfall depths for the ten design rainfall assessment points dispersed throughout the catchment area was undertaken. These design rainfall depths were compared to values extracted for the centroid of the Ntabelanga Dam catchment, revealing that the design rainfall depths for the centroid of the catchment provided representative values of the entire catchment area. The resultant design rainfall depths for the catchment centroid are presented in Table A-8.

Table 0-8: Design Rainfall of the Catchment Centroid

Duration	Return Period (Years) Design Rainfall Depth (mm)						
	1:2	1:5	1:10	1:20	1:50	1:100	1:200
5 min	11.5	15.8	18.9	22.3	27.2	31.3	35.8
10 min	15.7	21.4	25.7	30.3	36.9	42.4	48.5
15 min	18.7	25.6	30.7	36.2	44.1	50.7	58.0
30 min	23.5	32.2	38.6	45.5	55.5	63.8	73.0
45 min	26.9	36.8	44.2	52.1	63.4	73.0	83.5
1 hour	29.6	40.5	48.6	57.3	69.8	80.3	91.8
1.5 hour	33.9	46.3	55.6	65.5	79.8	91.8	105.0
2 hour	37.3	50.9	61.2	72.0	87.8	101.0	115.5
4 hour	43.2	59.0	70.9	83.5	101.8	117.1	133.9
6 hour	47.1	64.3	77.3	91.1	111.0	127.7	146.0
8 hour	50.1	68.4	82.2	96.8	118.0	135.8	155.2
10 hour	52.5	71.7	86.2	101.5	123.7	142.4	162.8
12 hour	54.6	74.6	89.6	105.6	128.6	148.0	169.2
16 hour	58.1	79.3	95.3	112.2	136.8	157.4	179.9
20 hour	60.9	83.2	99.9	117.7	143.4	165.0	188.7
24 hour	63.3	86.5	103.9	122.4	149.1	171.6	196.2
1 day	53.7	73.3	88.1	103.8	126.5	145.5	166.4
2 day	68.2	93.1	111.9	131.7	160.6	184.7	211.2
3 day	78.4	107.0	128.6	151.5	184.6	212.4	242.9
4 day	84.8	115.8	139.2	163.9	199.8	229.9	262.8
5 day	90.2	123.1	148.0	174.3	212.4	244.4	279.5
6 day	94.8	129.5	155.6	183.2	223.3	257.0	293.8
7 day	98.9	135.1	162.3	191.2	233.0	268.1	306.5

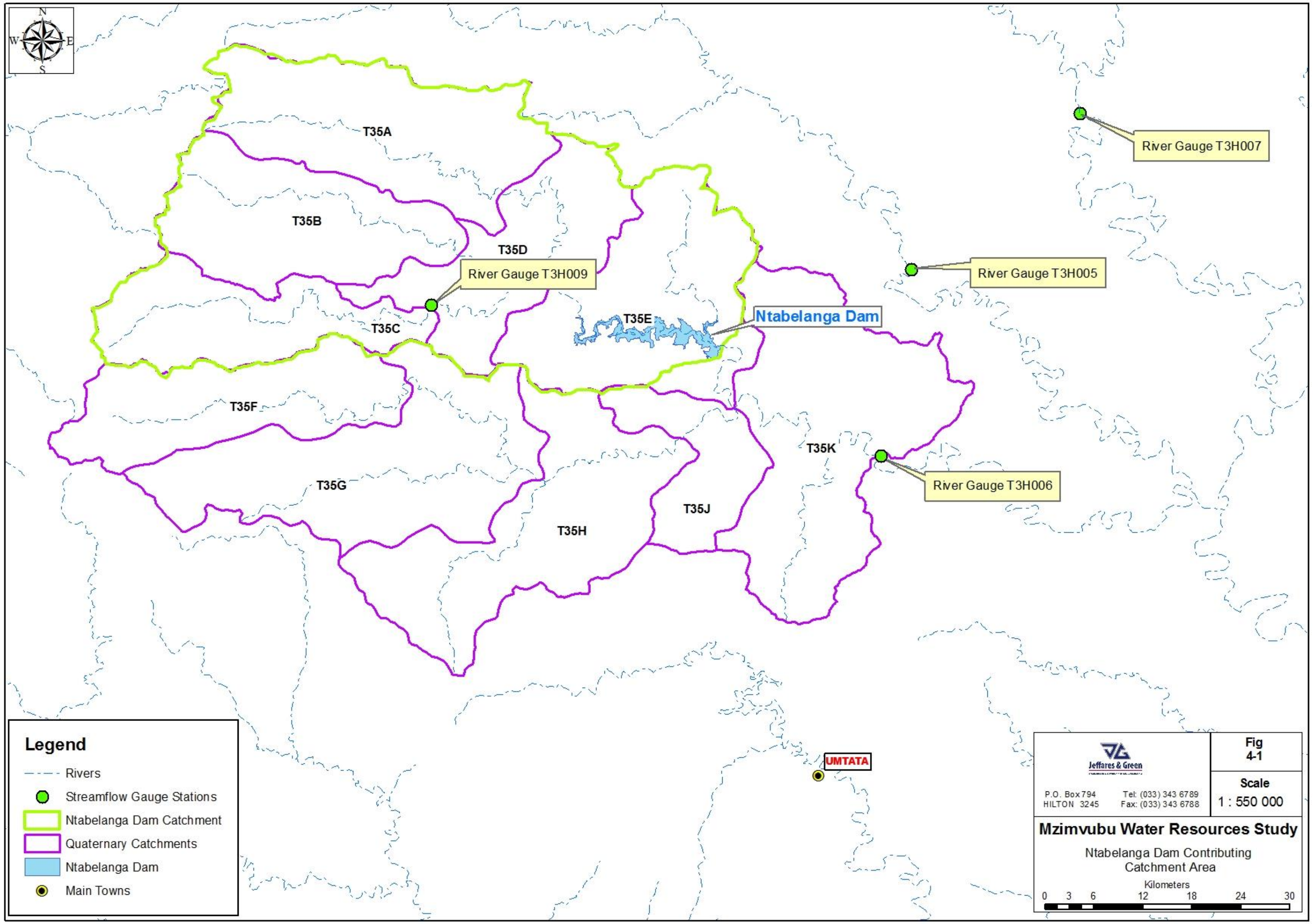

Figure 0-1: Ntabelanga Contributing Catchment Area

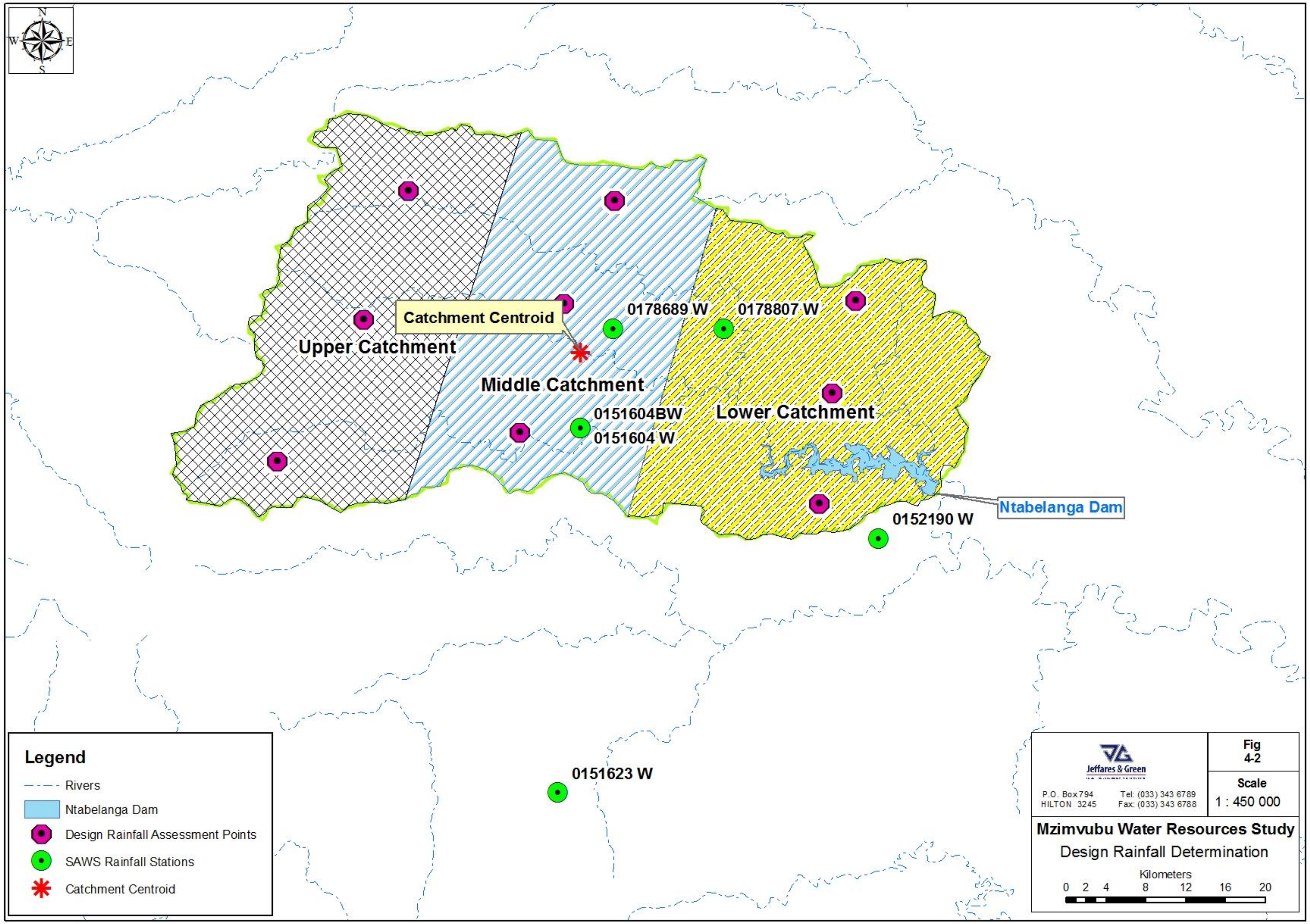

Figure 0-2: Design Rainfall Points Assessed

A.4 Design Flood Hydrology Methods

SANCOLD (1991) specifies that for new Category III dams site specific hydrological calculations need to be used to estimate the design floods. A number of approaches are available to estimate design floods in South Africa, as shown in Figure A-3 (after Smithers and Schulze, 2001). These include the analysis of gauged flow data (flood frequency analysis) and the regionalisation of results to enable the estimation of floods at ungauged sites, the use of flood envelopes (Regional Maximum Flood Method) and use of design rainfall and event based deterministic models, for example the Rational method. The methods used to determine the design flood hydrology for the Ntabelanga Dam were as follows:

- Statistical Methods
  - Probability Distribution Fitting to Observed Streamflow Data
- Deterministic Methods
  - Synthetic Unit Hydrograph (SUH)
  - Rational Method
- Empirical Methods
  - Catchment Parameter Method (CAPA)
  - HRU 1/71
  - Midgely and Pitman Method (MIPI)
  - Standard Design Flood (SDF)
  - Regional Maximum Flood (TR 137)

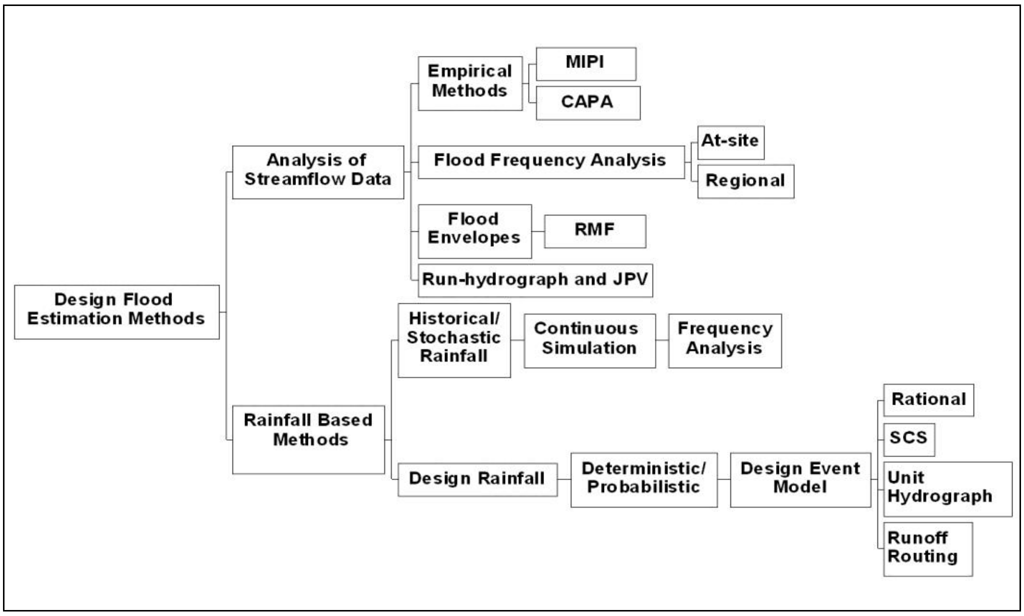

Figure 0-3: Design Flood Estimation Approaches

A.4.1 Statistical Methods

The PSP undertook an analysis of all streamflow gauges (as per the DWS streamflow monitoring network) in the area of the proposed Ntabelanga Dam. From the streamflow gauges assessed, four gauges had sufficient record lengths and sufficiently reliable data for further analysis. The gauges selected for further analysis included gauges T3H005, T3H006, T3H007 and T3H009, as presented in Table A-1.

Gauges T3H006 and T3H009 are located on the Tsitsa/Mzimvubu River system, upstream and downstream of the proposed Ntabelanga Dam. Unfortunately neither of the two gauges on this river system are located at the proposed position of the Ntabelanga Dam wall.

Gauge T3H005 is located in the catchment adjacent to the Tsitsa Catchment on the Tina River and the Gauge T3H006 is located on the Mooi River approximately 48 km north east of the proposed Ntabelanga Dam Wall. All of the above mentioned gauges do, however, fall within the greater Mzimvubu River Catchment.

As presented in Table A-9, data from Gauges T3H005 and T3H007 contain high levels of missing data. Data from Gauge T3H006 has a moderate to low level of missing data and Gauge T3H009 has a low level of missing data. The level of missing data associated with a particular gauge directly affects the reliability of results obtained through statistical analysis of its recorded data. In addition to missing data, rating tables used to determine flow rates at Gauges T3H006 and T3H005 were exceeded on a number of occasions, as presented in Table A-10. As a result, capped (and therefore incorrect) flow rates were recorded. This further reduces the confidence of results obtained through statistical analysis of the gauge data. Table A-11 presents a summary of the Annual Maximum Series (AMS) data for gauges T3H005, T3H006, T3H007 and T3H009.

Table 0-9: Streamflow Gauges Assessed

Flow Gauge Station	River Name	Catchment Area (Km^2)	Years of Record	Missing Data (%)
T3H005	Tina River	2 597	1951-09-20 to 2013-05-16	21.5
T3H006	Tsitsa River	4 268	1951-10-16 to 2013-05-16	14.0
T3H007	Mzimvubu River	6 906	1984-09-20 to 2013-04-05	30.0
T3H009	Mooi River	307	1964-08-15 to 2013-03-27	1.7

Table 0-10: Overtopping of Streamflow Gauge Rating Tables

Gauge	Date	Level (m)	Rating Table Level (m)	% overtopped
T3H006	1972 - 02 - 25	3.09	2.68	15
T3H006	1976 - 03 - 21	3.48	2.68	30
T3H006	1976 - 10 - 05	3.07	2.68	15
T3H006	1996 - 01 - 26	2.77	2.68	3
T3H005	1976 - 03 - 21	4.18	3.93	6
T3H005	1996 - 01 - 26	4.70	3.93	20

Table 0-11: Observed AMS from Gauges A3H005, A3H006, A3H007 and A3H009

T3H005				T3H006				T3H007				T3H009			
Date	Flow Level (m)	Peak Discharge (m3/s)	Code	Date	Flow Level (m)	Peak Discharge (m3/s)	Code	Date	Flow Level (m)	Peak Discharge (m3/s)	Code	Date	Flow Level (m)	Peak Discharge (m3/s)	Code
19510930	0.63	50.30	M	19510101			M	19840923	0.15	3.00	M	19640917	0.34	5.60	M
19520304	1.15	135.60	M	19511027	0.72	59.70	M	19850119	1.00	65.00	>	19650201	2.35	63.50	
19530403	1.08	122.50	M	19530406	0.95	102.40	M	19860106	1.40	115.60	>	19660120	2.78	91.70	
19540710	0.11	2.60	M	19531212	0.98	109.70	M	19870323	1.96	208.10	M	19670216	3.13	120.70	
19550221	1.23	154.10	M	19550425	1.24	186.90	M	19871001			M	19680208	1.16	22.70	
19551130	0.75	67.10	M	19551130	1.00	115.20	M	19881001			M	19690307	3.22	129.00	
19561226	1.27	160.80		19561207	1.22	178.80	>	19900404	1.57	84.70	M	19700930	3.00	109.30	
19571230	1.23	154.10	M	19580113	1.22	178.80	>	19910209	2.46	291.80	>	19701013	4.16	251.30	
19590518	2.68	610.70	M	19590520	1.46	266.70	>	19911022	1.78	123.70	M	19720225	4.93	405.40	
19591210	1.06	119.10		19591212	1.21	175.00		19930315	1.84	136.30	M	19721127	1.82	42.40	
19610413	1.49	214.70	M	19601031	0.67	52.70	M	19940207	3.00	469.40	M	19740306	4.62	336.50	
19620306	1.76	288.70		19620311	1.62	332.70		19950219	1.90	148.70	M	19750311	2.62	80.00	
19630311	2.56	562.10	M	19630311	2.40	788.80	M	19960126	4.91	1305.00	M	19760322	3.82	199.40	
19631112	1.75	285.80	M	19640619	1.92	485.50		19970127	3.41	628.70		19761006	3.38	145.60	
19650913	0.24	10.30	M	19650208	1.58	316.20		19980215	3.99	887.80		19780328	2.25	58.30	
19651117	0.72	63.20	M	19660120	1.63	338.10	M	19990322	2.71	368.50	M	19781210	2.21	56.70	
19670620	0.20	7.90	M	19670328	1.93	490.00	M	20000306	6.55	2066.70	M	19791224	1.13	22.30	M
19671031	0.63	51.00	M	19680401	0.94	101.20	M	20010207	3.53	679.00		19810217			M
19690331	0.84	80.80	M	19690306	1.71	377.10	M	20011118	2.54	315.80		19820202	4.22	260.90	
19700930	0.95	98.70	M	19700930	1.54	296.40	M	20030305	1.84	136.80		19821101	2.31	61.20	
19701012	1.43	199.10		19701012	2.21	659.80		20040129	2.34	256.60	E	19840108	2.17	55.10	
19720225	3.25	861.60	M	19720225	3.09	1016.40	A	20041221	3.04	483.00	>	19850210	2.61	79.40	
19730930	0.08	1.70	M	19730219	1.34	220.00	M	20060926	3.11	510.70		19851102	4.50	312.80	
19740121	2.05	378.80	M	19740412	1.59	320.20	M	20061018	2.58	327.60		19870930	3.29	135.80	
19741219	1.25	158.00	M	19750312	1.52	290.10	M	20071121	1.98	166.50	?	19880222	4.58	329.10	
19760321	4.18	1212.20	M	19760321	3.48	1016.40	M	20090313	2.89		M	19890217	4.27	270.10	
19761005	2.78	651.10	M	19761005	3.07	1016.40	A	20100226	3.12		Z	19891129	4.00	224.90	M
19771230	1.78	295.40	M	19780422	2.59	935.20	M	20110105	2.80		Z	19910215	3.06	113.90	M
19781210	1.39	189.80		19781025	0.80	73.60	M	20120808	2.68		Z	19911022	1.64	36.20	
19800319	0.57	43.60	M	19800302	0.86	83.80	M	20130211	3.39		M	19921210	1.24	24.30	
19801203	0.34	18.30	M	19801001			M					1993			
19811001			M	19811001			M					19940207	3.38	145.40	
19830824	0.03	0.40	M	19830925	0.13	1.10	M					19950302	2.60	78.80	M
19840129	1.43	200.10	M	19840307	1.44	258.00	M					19960126	3.81	198.20	M
19850210	1.97	352.30	>	19850209	2.47	839.60	M					19970127	3.99	224.10	
19860128	1.81	304.60		19851206	1.74	391.70						19980217	3.78	193.70	
19861123	1.74	282.90	>	19870929	1.52	291.70	M					19990130	2.77	90.90	M
19880302	2.69	613.10	M	19880303	2.52	878.20						20000117	3.33	140.10	
19890216	1.86	318.40	M	19890218	2.56	907.60	M					20010214	3.43	151.50	
19891129	1.55	229.30		19891129	2.15	621.70						20011116	2.99	107.90	M
19910208	1.25	158.20		19910220	0.84	79.60	M					20030110	1.35	27.00	

19911216	1.23	153.20		19920109	1.46	263.90	M
19921213	0.43	27.00		19930212	0.91	93.90	
19940207	1.73	280.90		19940207	1.98	516.60	E
19950302	1.10	126.50	>	19950115	1.39	238.40	M
19960126	4.70	1212.20	M	19960126	2.77	1016.40	>
19970127	2.39	495.50	M	19970612	1.82	430.70	M
19980217	2.35	483.70	M	19980301	2.22	665.10	M
19990131	2.29	483.60	M	19990129	2.39	752.10	
20000306	3.51	1259.50	M	20000316	2.49	844.00	
20010323	1.95	338.80	M	20010214	1.83	361.00	
20011223	2.25	464.80		20020910	2.54	889.10	
20021223	1.48	183.80		20030111	1.13	94.10	
20040321	1.63	226.90		20040926	1.97	443.50	
20050228	1.98	351.80	?	20050123	2.06	500.60	
20060927	1.75	267.30		20060927	2.46	813.20	
20061102	1.85	301.50		20061127	1.99	450.40	
20080322	1.84	298.30	M	20080224	2.30	675.90	
20090216	2.11	403.90	M	20090215	2.50	855.40	Q
20100223	2.21	449.20	Q	20100226	1.68	281.90	Q
20110105	2.95	854.10	Q	20110106	2.08	515.60	Q
20120123	2.28	478.40	Q	20120113	1.98	448.50	Q
20121224	2.78	747.50	M	20121213	2.19	593.40	M

20040224	2.97	106.30	
20050120	2.39	65.80	
20060210	2.79	91.80	
20061226	2.61	79.60	E
20080115	2.36	64.20	M
20090216	4.56	324.80	Q
20100127	2.50	72.20	Q
20110105	3.49	157.80	Q
20120122	3.24	131.30	Q
20130130	3.30	137.60	M

Note:
“A” denotes flow d0epth above the rating curve
“Z” denotes no infomation for stage/discharge determination
“M” denotes missing data
“?” denotes unreliable value
“E” denotes estimated data
“>” denotes greater than
“Q” denotes data not audited
“[yellow]“ denotes > 10 % missing data during the wet season
“[orange]“ denotes rating table exceeded

Due to the high levels of missing streamflow data associated with the gauges used in this study, additional analysis of the data relating to each of the respective gauges was undertaken. This analysis included assessing when data is missing, with particular reference to defining the level of missing data during the wet season. The rationale behind this approach is that it is possible that AMS may not include extreme events if a period of missing data occurred in the wet season (October to April). As depicted in Table A-11, AMS data associated with a hydrological year that contained more than 10 % of missing data in the wet season was flagged (highlighted in yellow).

A.4.2 Extreme Value Distribution

Two sets of statistical analysis were undertaken using data from each of the respective flow gauges. The first analysis was based on all available AMS data, and no adjustment to the AMS data was done to account for events when the flow depth exceeded the rating tables. The second analysis was based on a “refined” set of AMS data. The AMS data was refined by firstly eliminating all AMS data that coincided with more than 10 % of missing data during the wet season (all values highlighted in yellow in Table A-11) for a particular hydrological year. In addition AMS data that exceeded the respective gauge’s rating table was adjusted through extending the rating table by fitting a curve to the height versus flow of recorded data.

For each of the above mentioned sets of analysis, several probability distributions were fitted to the AMS data, these included:

- Gumbel (EV1);
- Log-Pearson III (LP III); and
- Log-Normal (LN).

The above mentioned distributions were plotted against the observed data using the Cunnane Plotting Position. The distribution that provided the best fit of the observed data was the LP III distribution, as presented in Figure A-4 to Figure A-11. Alexander (1990, 2001) confirms that the LP III distribution should be used in South Africa.

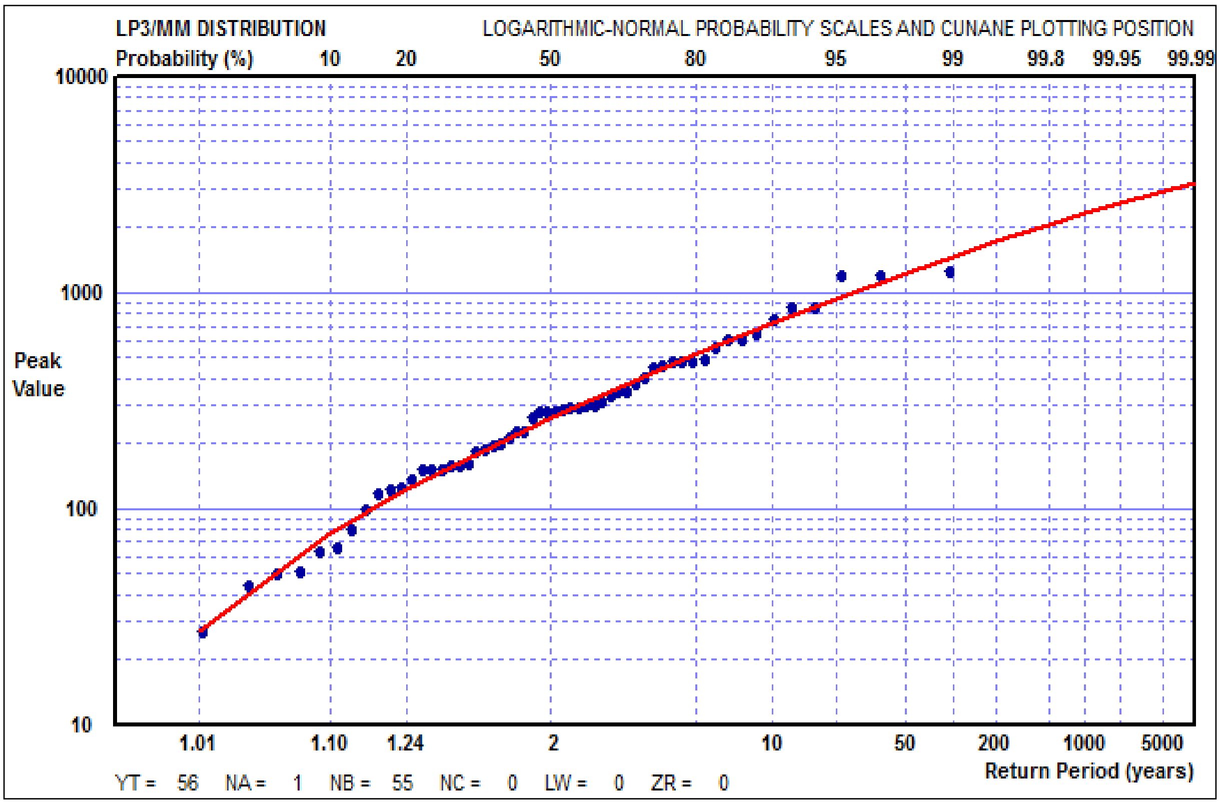

Figure 0-4: Gauge T3H005 LP III Probability Distribution: Original AMS Data

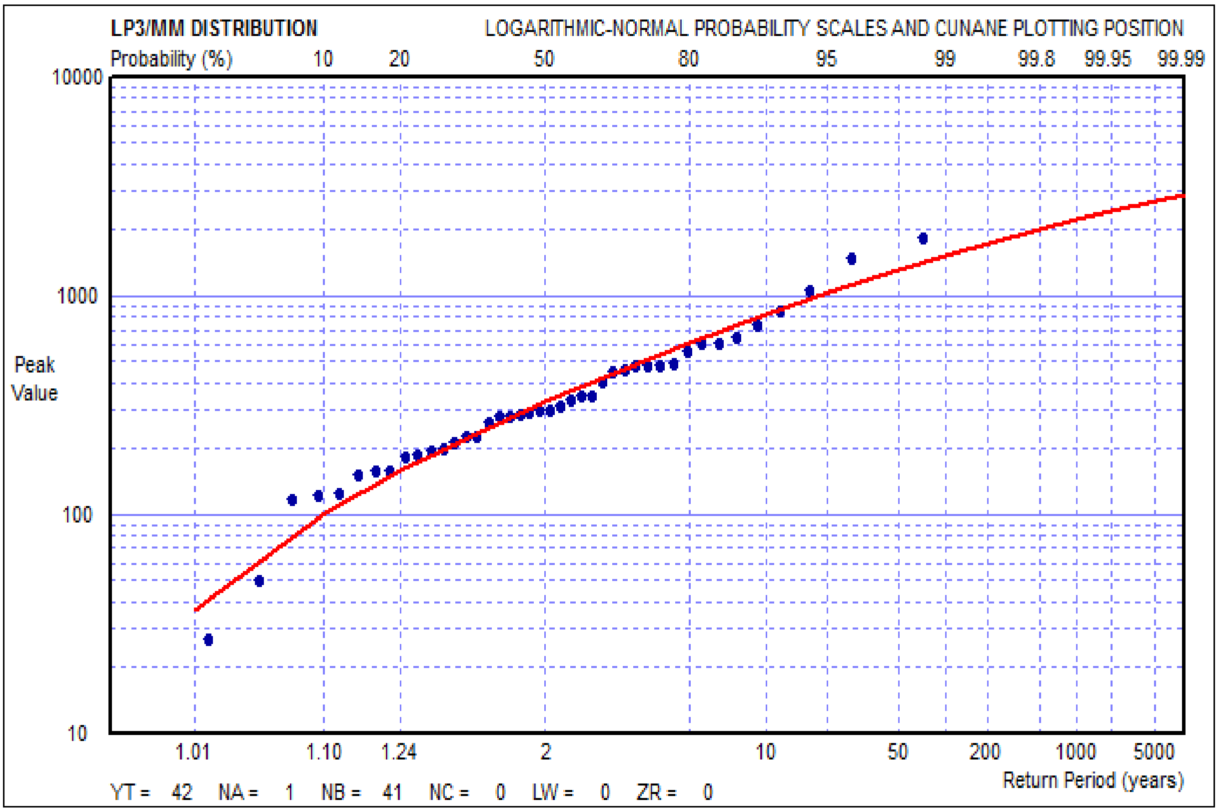

Figure 0-5: Gauge T3H005 LP III Probability Distribution: Refined AMS Data

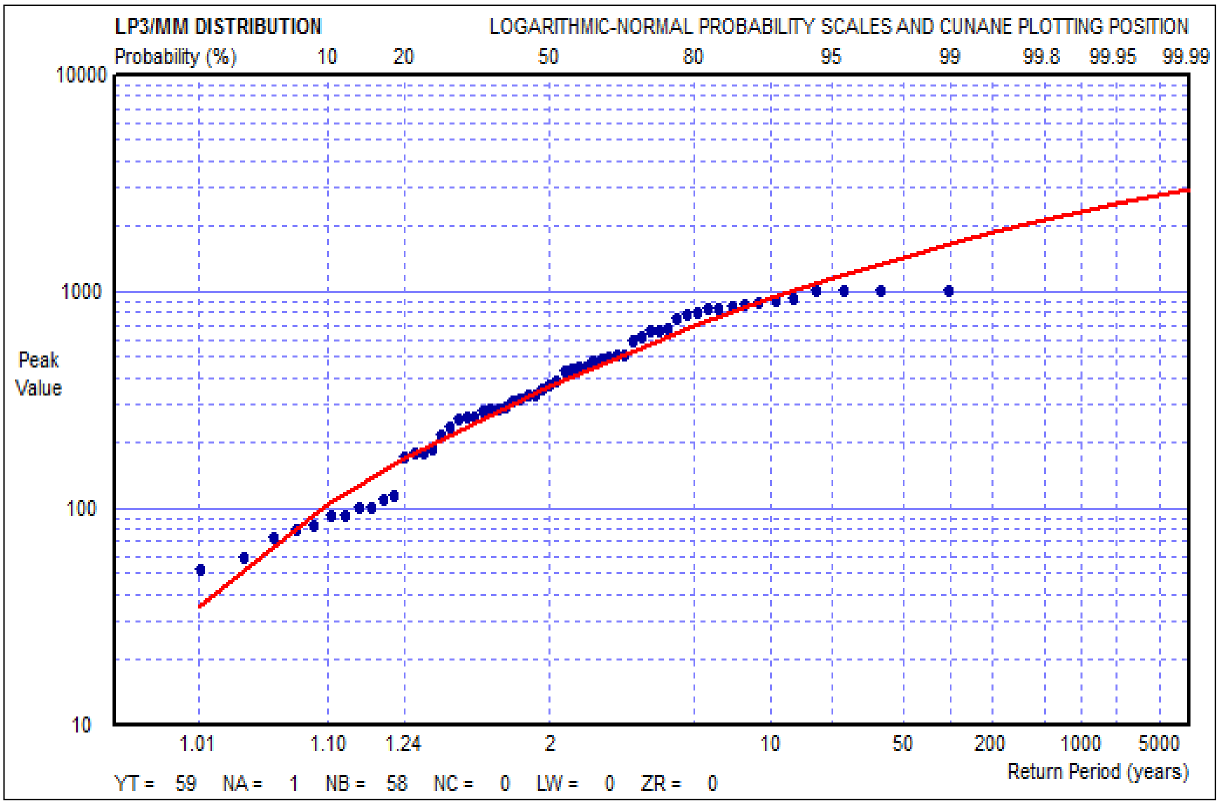

Figure 0-6: Gauge T3H006 LPIII Probability Distribution: Original AMS Data

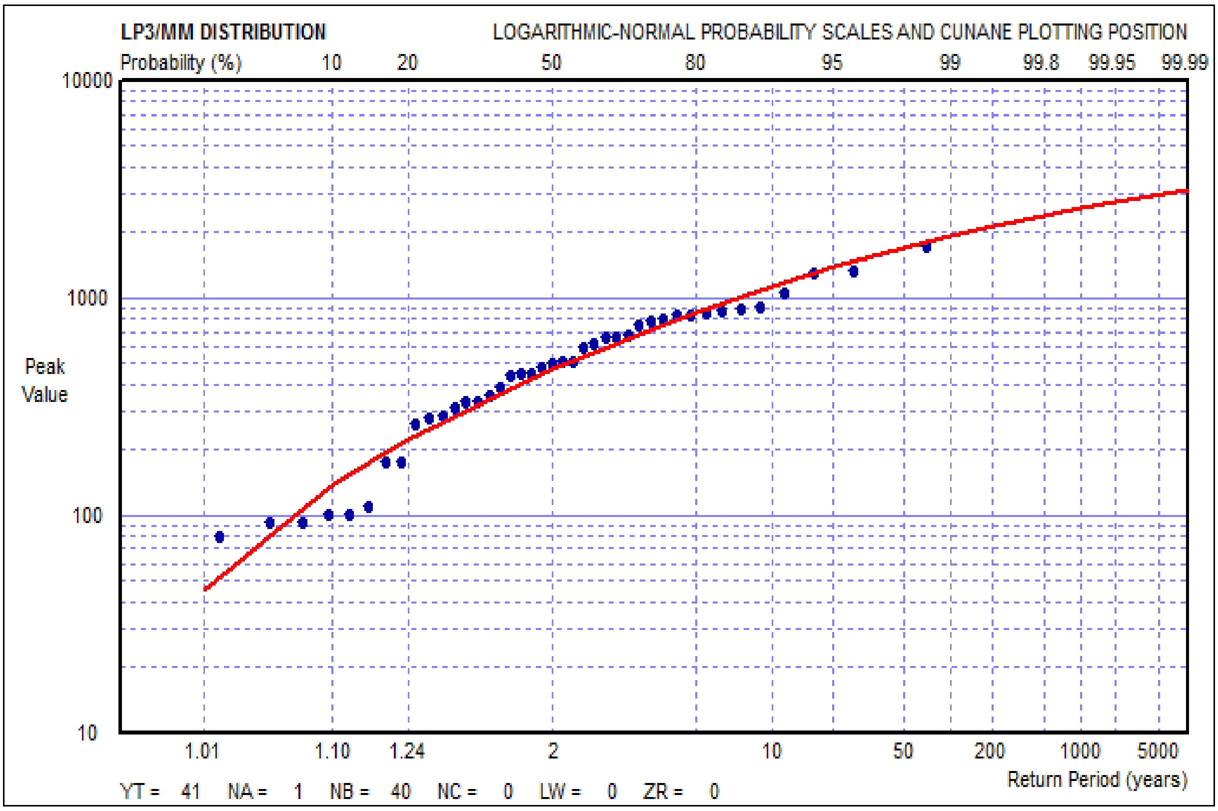

Figure 0-7: Gauge T3H006 LP III Probability Distribution: Refined AMS Data

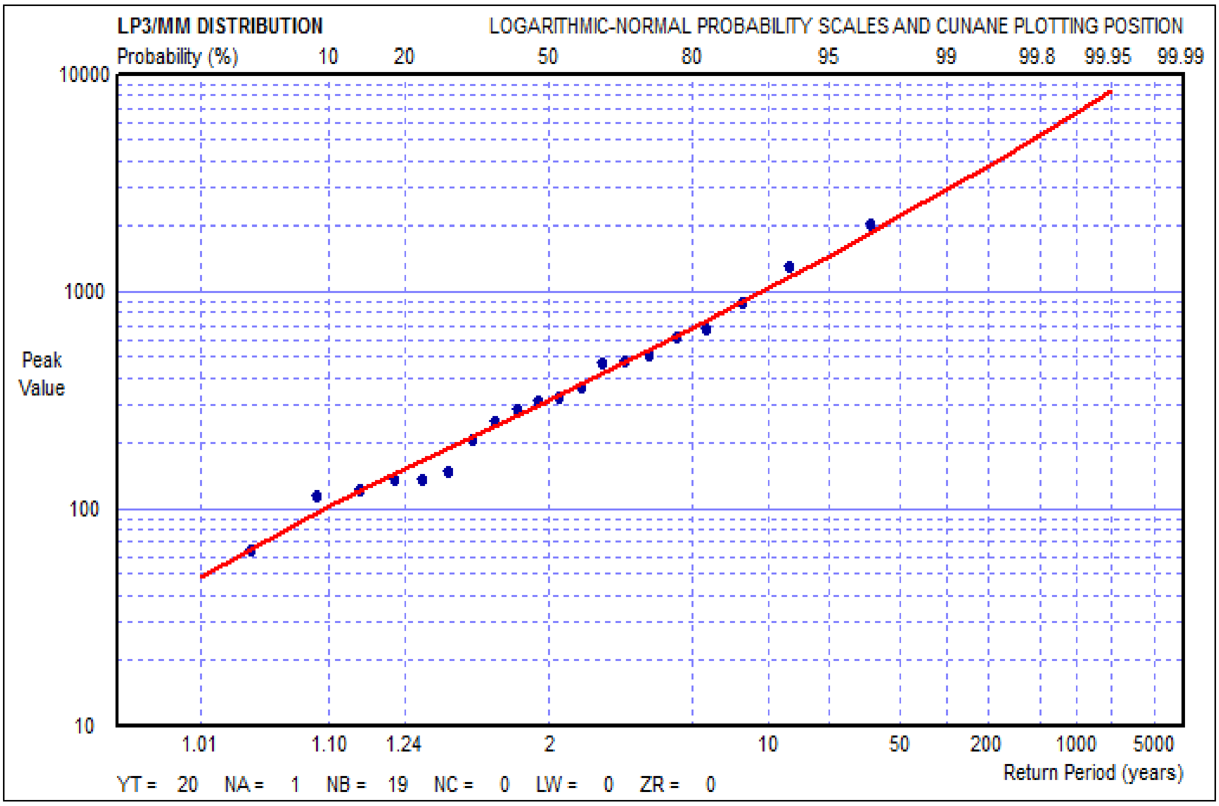

Figure 0-8: Gauge T3H007 LP III Probability Distribution: Original AMS Data

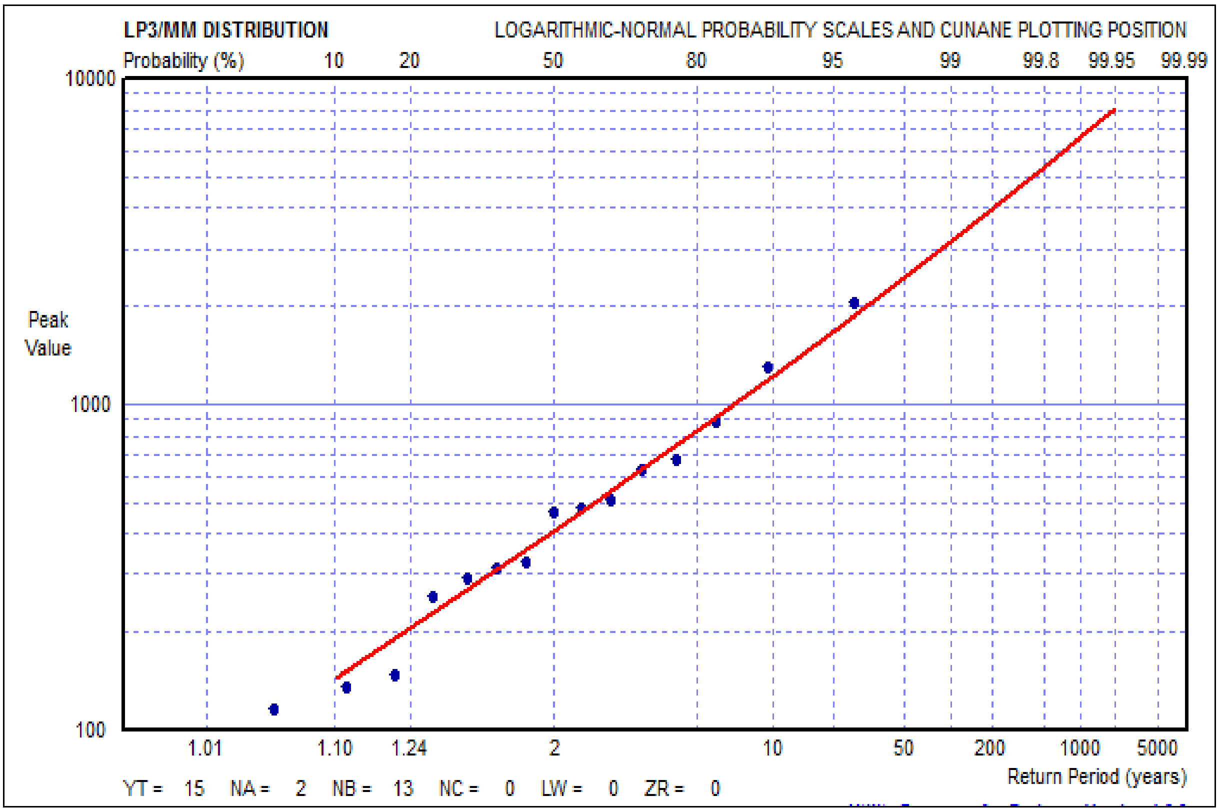

Figure 0-9: Gauge T3H007 LP III Probability Distribution: Refined AMS Data

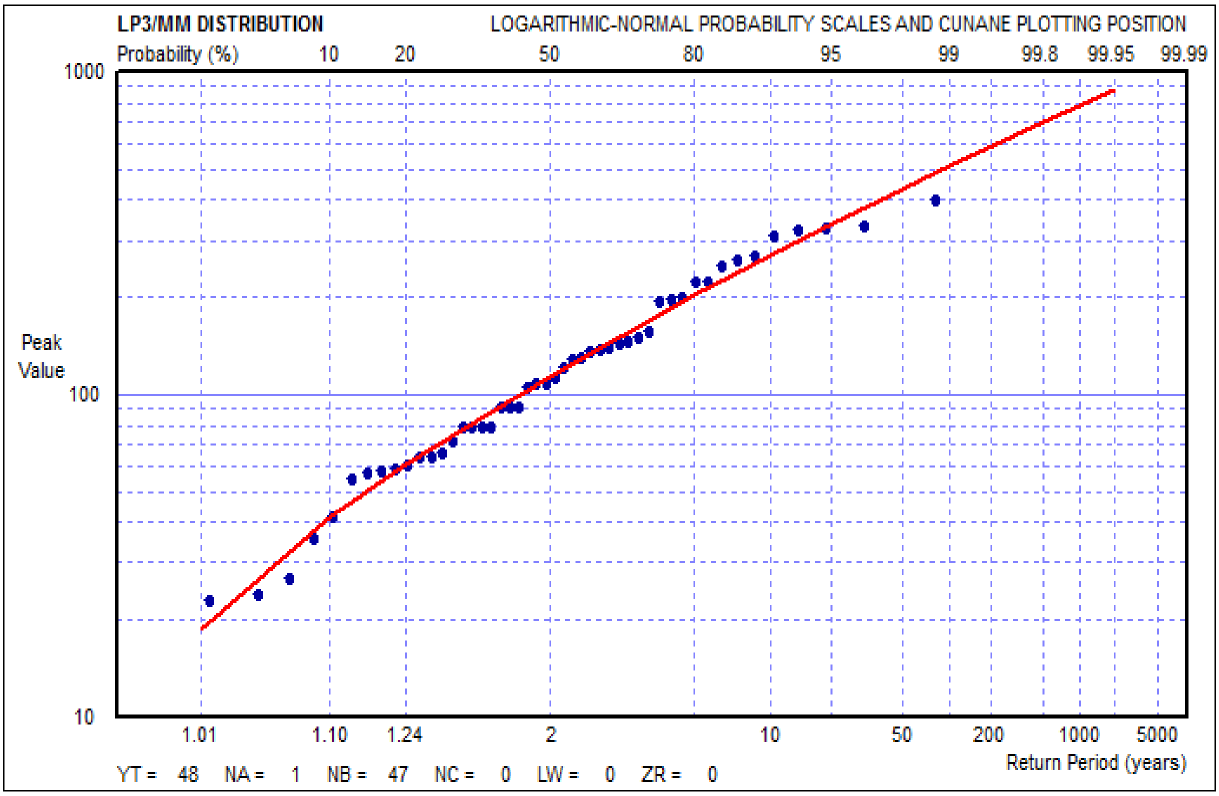

Figure 0-10: Gauge T3H009 LP III Probability Distribution: Original AMS Data

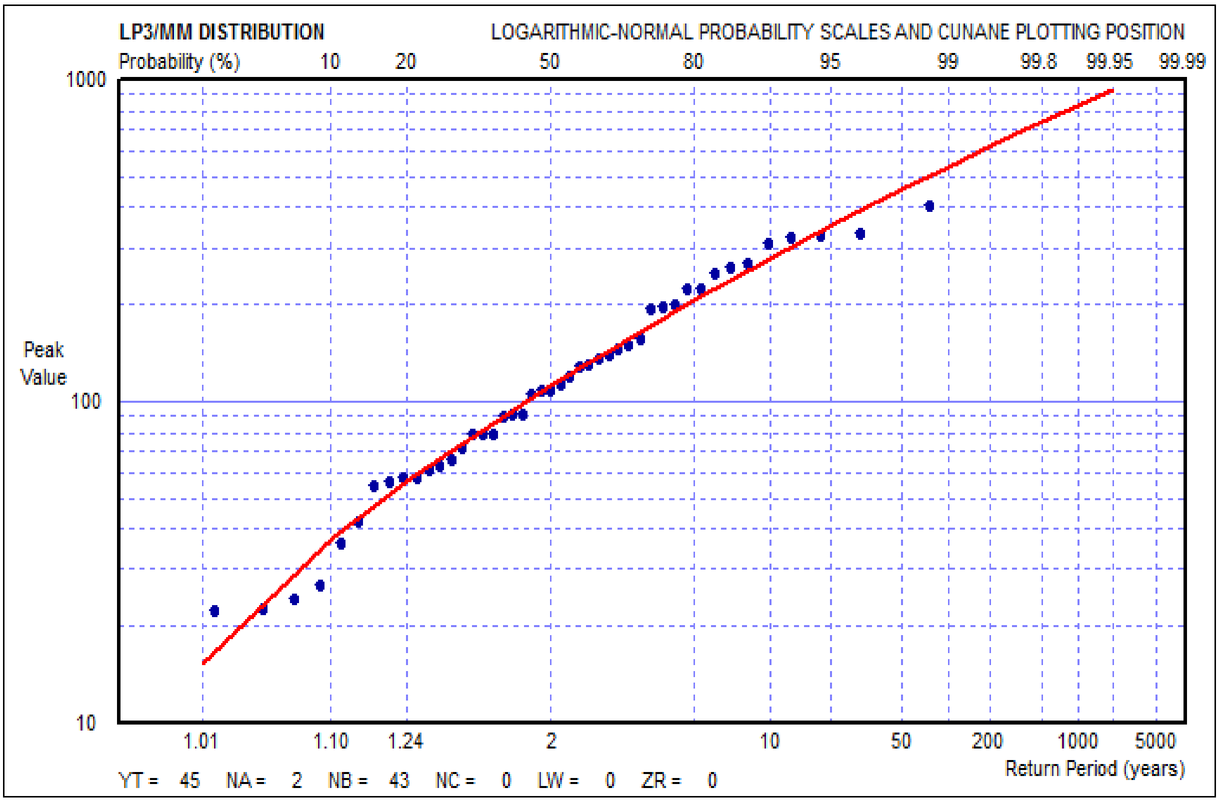

Figure 0-11: Gauge T3H009 LP III Probability Distribution: Refined AMS Data

The peak discharge values per gauge analysed, based on the original AMS data and the LP III distribution, are summarised in Table A-12. The peak discharge values per gauge analysed, based on the refined AMS Data are presented in Table A-13. Due to the fact that AMS values were removed due to missing data, a conditional probability adjustment was applied to the revised peak discharges (Barfield *et. al.,* 1983). The results of the conditional probability adjusted peak discharges based on the refined streamflow gauge data set are presented in Table A-14.

Table 0-12: Peak Discharge Values: Original AMS and LP III Distribution (m^3/s)

Streamflow Gauge	Catchment Area (km^2)	Fitted Distribution	Return Period (Years)					
			1:2	1:10	1:20	1:50	1:100	1:200
T3H005	2597	LP3	265	730	945	1 243	1 479	1 725
T3H006	4268	LP3	367	926	1156	1 450	1 666	1 879
T3H007	6906	LP3	315	1031	1474	2 228	2 955	3 846
T3H009	307	LP3	113	269	338	434	510	599

Table 0-13: Peak Discharge Values: Refined AMS and LP III Distribution (m^3/s)

Streamflow Gauge	Catchment Area (km^2)	Fitted Distribution	Return Period (Years)					
			1:2	1:10	1:20	1:50	1:100	1:200
T3H005	2597	LP3	329	827	1038	1317	1528	1740
T3H006	4268	LP3	471	1136	1390	1704	1928	2139
T3H007	6906	LP3	408	1214	1681	2445	3155	3998
T3H009	307	LP3	111	278	353	457	538	623

Table 0-14: Conditional Probability Adjusted Peak Discharge Values: Refined AMS and LP III Distribution (m^3/s)

Streamflow Gauge	Catchment Area (km^2)	Fitted Distribution	Return Period (Years)					
			1:2	1:10	1:20	1:50	1:100	1:200
T3H005	2597	LP3	219	619	756	1162	1387	1598
T3H006	4268	LP3	314	858	1221	1526	1775	1996
T3H007	6906	LP3	272	753	1268	1897	2541	3269
T3H009	307	LP3	74	259	334	436	519	603

When comparing the results presented in Table A-13 (Refined AMS) to the results presented in Table A-12 (original data), it is evident that by excluding AMS data with more than 10 % of missing values in the wet season, and by adjusting the peak discharge values in instances where a flood event exceeded a gauge rating table, estimated peak discharge values increased. However, Table A-14 shows that by applying the conditional probability adjustment to the revised peak discharge values, the resultant estimated peak discharge values are less than those obtained from the original AMS dataset. Conditional probability adjustment is usually used in instances where there is a maximum of 25 % of missing data (IACWD, 1982). Due to the fact that in refining the AMS data, three of the four gauges assessed required approximately 30 % of AMS data removed it was decided that the results obtained from the original AMS data would be used for further analysis.

A.4.3 Regionalised Growth Curve

In order to estimate peak discharge values at the proposed Ntabelanga Dam wall, the index flood method was used to scale statistically estimated peak discharge values obtained from gauges T3H005, T3H006, T3H007 and T3H009. The index flood method uses a growth curve established by scaling the design values at a gauged site by an index value and then developing relationships to estimate the index value at an ungauged site. This approach assumes that relatively homogeneous flood response zones can be identified where the distribution of floods are similar after site specific scaling. In this study the 1:2 year return period flood event was used as the index flood.

Peak discharge values presented in Table A-12 (based on the original AMS dataset and the LP III distribution) were used to develop growth factors and a growth curve, as presented in Table A-15 and Figure A-12 respectively. Growth factors are determined by dividing the estimated design peak discharge by the 1:2 year peak discharge for the same catchment. As depicted in Figure A-12, the growth curve developed for Gauge T3H007 is somewhat different to those developed for Gauges T3H005, T3H006 and T3H009. Due to these differences, and that it was the furthest gauge from the dam site, streamflow gauge T3H007 was not used in developing the regional growth factors.

The resultant regression curve, based on the 1:2 year return period peak discharge values and the contributing catchment areas for streamflow gauges T3H005, T3H006 and T3H009, is presented in Figure 4-13. As depicted on Figure 4-13, the R^2 value for the regression curve is 0.99, which is indicative of a particularly good fit and can therefore be confidently applied in determining the peak discharge values at the proposed Ntabelanga Dam wall, based on the assumption that the data used in the analysis (T3H005, T3H006 and T3H009) contain accurate measurements of large floods at those sites. The design peak discharge values at the proposed Ntabelanga Dam wall are therefore obtained by multiplying the 2 year return period index flood at the Ntabelanga Dam, estimated using the regression equation presented in Figure A-13, and the regional growth factors summarised in Table A-15.

Table 0-15: Flood Growth Factors

Streamflow Gauge	Return Period (Years)					
	1:2	**1:10**	**1:20**	**1:50**	**1:100**	**1:200**
T3H005	1.0	2.8	3.6	4.7	5.6	6.5
T3H006	1.0	2.5	3.2	4.0	4.5	5.1
T3H007	1.0	3.3	4.7	7.1	9.4	12.2
T3H009	1.0	2.4	3.0	3.8	4.5	5.3
Regional Growth Factors Based on Gauges T3H005, T3H006 and T3H009	**1.0**	**2.6**	**3.3**	**4.2**	**4.9**	**5.6**

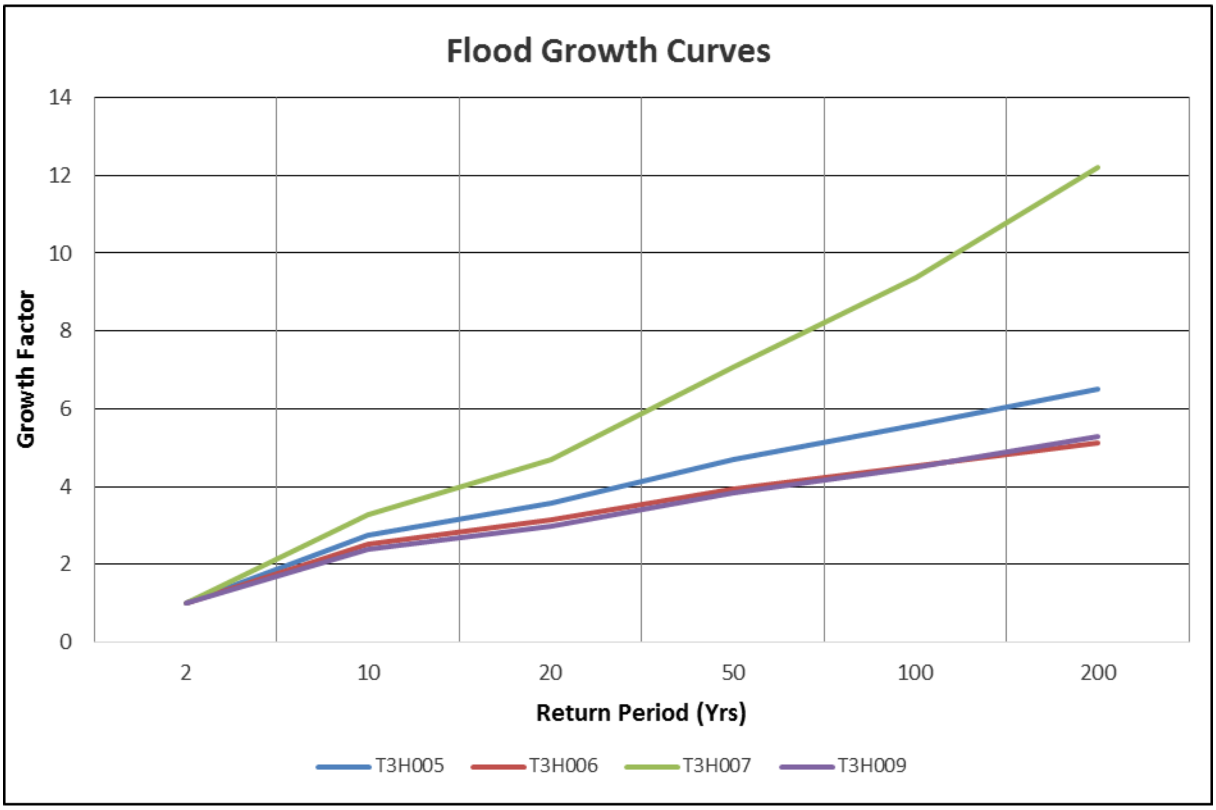

Figure 0-12: Growth Curves Derived using 1:2 Year Return Period Flood as the Index Value

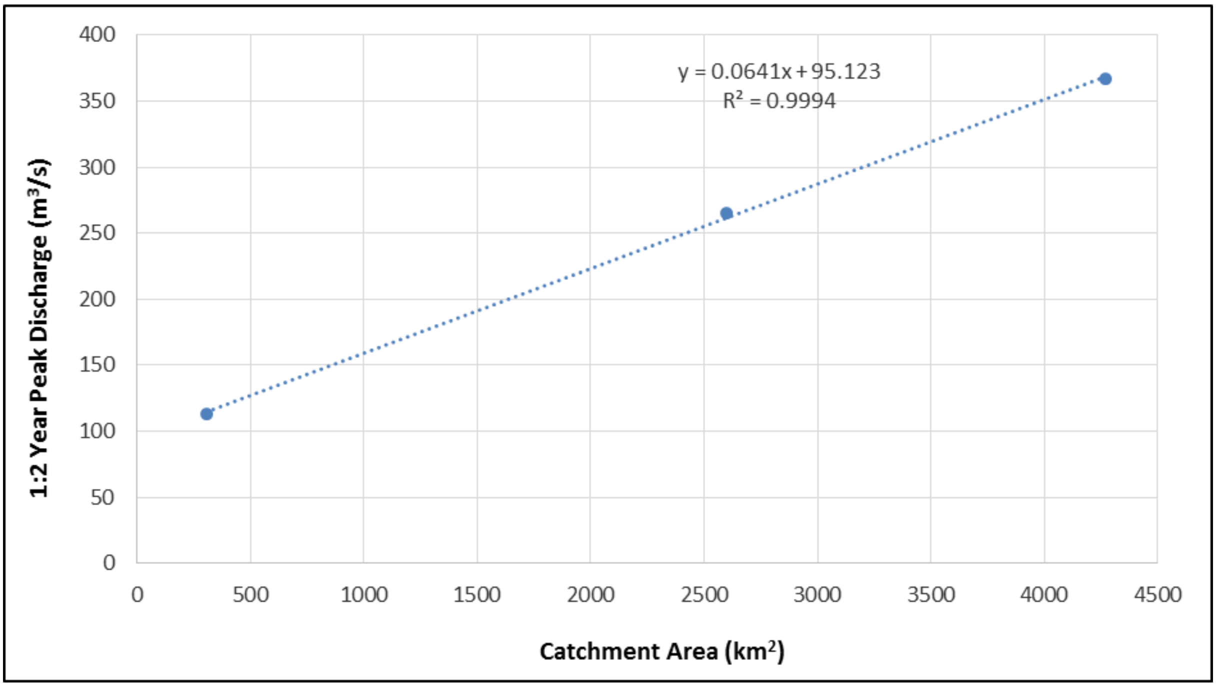

Figure 0-13: Regression Curve: 1:2 Year Return Period Peak Discharge Values: Gauges T3H005, T3H006 and T3H009

A.4.4 Rational Method

The Rational Method is widely used throughout the world for both small rural and urban catchments (Alexander, 2001; Pilgrim and Cordery, 1993), is the most widely used method of estimating design flood peak discharges using design rainfall as input and it is easy to understand and simple to use (Parak and Pegram, 2006). The method assumes that the peak discharge occurs when the duration of the rainfall event is equal to the time of concentration of the catchment and that the rainfall intensity does not vary and is distributed uniformly over the catchment.

The rainfall intensity was estimated for a duration equal to the Time of Concentration (T_c) of 19.52 hours. Time of concentration was calculated using the method developed by the US Soil Conservation Service (Roads Drainage Manual, 2006). The runoff coefficient was estimated using slope, permeability and vegetation sub-factors, as presented in Table A-16. The return period adjustment factor suggested by Van der Spuy and Rademeyer (2010) was used to adjust the runoff coefficient for a given return period. An areal reduction factor was applied to reduce the point design rainfall intensity into a catchment intensity using an algorithm proposed by Alexander (2001). The resultant input variables used to calculate peak discharge values based on the Rational Method are presented in Table A-17.

Table 0-16: Rational Method C Factor Calculation

Catchment Characteristics	Classification				Data Source
	Variable	% of Variable	Recommended C Value	Calculated C Value	
Slope	Y < 3	10.1	0.05		Calculated in ARCMap Based on 1:50 000 Topographic Map Sheet 20 Metre Contours
	3 - 10	39.2	0.11		
	10 - 30	42.6	0.20		
	30 - 100	8.1	0.30		
C_Y =				**0.158**	
Permeability of soil	Very Permeable (A)		0.05		Areas calculated in ARCMap Permeability Class Based on SCS-SA Textural Classification
	A/B		0.08		
	Permeable (B)	45.0	0.10		
	B/C		0.15		
	Semi-Permeable (C)		0.20		
	C/D	55.0	0.25		
	Impermeable (D)		0.30		
C_P =				**0.183**	
Vegetation	Dense Bush Forest	13.6	0.05		Calculated in ARCMap based on NLC (2000) Land Use Distributions
	Thin Bush, Cultivated land	4.8	0.15		
	Grass land	81.3	0.26		
	Bare Surface	0.3	0.30		
C_V =				**0.226**	
Total Catchment C Factor				**0.566**	

Table 0-17: Rational Method Peak Discharge Calculation

Rational Method Required Inputs	Return Period (Years)			
	1:10	50	100	200
Time of Concentration (hours)	19.52	19.52	19.52	19.52
Point Rainfall (mm)	99.30	142.60	164.10	187.60
Average Rainfall Intensity (mm/h)	5.10	7.30	8.40	9.60
Areal Reduction Factor (%)	82.80	82.80	82.80	82.80
Catchment Rainfall Intensity (mm)	4.20	6.00	7.00	8.00
Catchment C Factor	0.57	0.57	0.57	0.57
Adjustment Factor (Ft)	0.85	0.95	1.00	1.00

In order to verify the C Factor determined for the Ntabelanga Dam catchment, calibrated C Factors for the catchment areas contributing to streamflow gauges T3H005, T3H006, T3H007 and T3H009 were determined. These calibrated C Factors were based on the 1:200 year peak discharge values obtained using the original AMS data for each respective gauges, and the fitted LP III probability distributions. No particular pattern can be deduced from the calibrated C Factors presented in Table A-18, due to significant differences in C Factors between the respective gauges and their respective catchments. This variability may be due to the high level of missing data associated with gauge data.

The calibrated C Factor for the streamflow gauge T3H009 (with the most reliable set of data), located upstream of the proposed Ntabelanga Dam, is 0.585, which is very close to that determined for the proposed Ntabelanga Dam catchment. Although this value suggests the C Factor determined for the proposed Ntabelanga Dam Catchment (C Factor equal to 0.566) is appropriate, the variability of the calibrated C Factors for the other streamflow gauges assessed, does not allow for a firm conclusion to be drawn.

Table 0-18: Calibrated C Factors for 200 year return period

Catchment Name	Catchment Area (km2)	Time of Concentration (hours)	Applied Rainfall Intensity (mm)	Calibrated Catchment C Factor	Calibrated? Rational Peak Discharge (m^3/s)	LP III Peak Discharge (m^3/s)
T3H005	2 573	21.8	6.0	**0.355**	1 725	1 725
T3H006	4 295	23.3	4.9	**0.280**	1 879	1 879
T3H007	6 929	33.7	2.9	**0.607**	3 846	3 846
T3H009	307	12.0	10.3	**0.598**	5 99	599

A.4.5 Unit Hydrograph Method

The Unit Hydrograph method is suitable for the determination of flood peaks as well as flood hydrographs for medium-sized rural catchments of between 15 and 5 000 km^2. The method is based on regional analyses of historical data, and is independent of personal judgement. The results are reliable, although some natural variability in the hydrological occurrences is lost through the broad regional divisions and the averaged form of the hydrographs (Road Drainage Manual, 2006). The specific recommended method is described in detail in Report 1/72 of the Hydrological Research Unit (Pitman and Midgley, 1971).

The catchment variables used in the Unit Hydrograph Method are presented in Table A-19 and Table A-20. Peak discharge values were calculated for six durations, including a 5 hour, 10 hour, 12 hour, 13.2 hour (equal to lag time), 15 hour and 20 hour hydrograph. The resultant peak discharge values are presented in Table A-21.

Table 0-19: Unit Hydrograph Catchment Parameters

Catchment MAP (mm)	907
Veld Type Zone	5
Lag Time (hours)	13.23
Catchment Index	99 592
Coefficient (Ku)	0.351
Peak Discharge of Unit Hydrograph (m^3/s)	52.31

Table 0-20: Unit Hydrograph Input Variables

Variable	Return Period (Years)			
	1:20	1:50	1:100	1:200
Storm duration (hours), T_{SD} - 5 hour	5.0	5.0	5.0	5.0
Storm duration (hours), T_{SD} - 10 hour	10.0	10.0	10.0	10.0
Storm duration (hours), T_{SD} - 12 hour	12.0	12.0	12.0	12.0
Storm duration (hours), T_{SD} - 13.2 hour	13.2	13.2	13.2	13.2
Storm duration (hours), T_{SD} - 15 hour	15.0	15.0	15.0	15.0
Storm duration (hours), T_{SD} - 20 hour	20.0	20.0	20.0	20.0
Point Rainfall (mm), P_T - 5 hour	87.3	106.4	122.4	140.0
Point Rainfall (mm), P_T - 10 hour	101.5	123.7	142.4	162.8
Point Rainfall (mm), P_T - 12 hour	105.6	128.6	148.0	169.2
Point Rainfall (mm), P_T - 13.2 hour	108.1	131.7	151.5	173.2
Point Rainfall (mm), P_T - 15 hour	110.6	134.8	155.1	177.2
Point Rainfall (mm), P_T - 20 hour	117.7	143.4	165.0	188.7
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 5 hour	17.5	21.3	24.5	28.0
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 10 hour	10.2	12.4	14.2	16.3
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 12 hour	8.8	10.7	12.3	14.1
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 13.2 hour	8.2	10.0	11.5	13.1
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 15 hour	7.4	9.0	10.3	11.8
Point Intensity (mm/hour), P_{IT} (=P_T/T_{SD}) - 20 hour	5.9	7.2	8.3	9.4
Area Reduction Factor ARF_{iT} - 5 hour	76.0	76.0	76.0	76.0
Area Reduction Factor ARF_{iT} - 10 hour	80.0	80.0	80.0	80.0
Area Reduction Factor ARF_{iT} - 12 hour	80.2	80.2	80.2	80.2
Area Reduction Factor ARF_{iT} - 13.2 hour	80.7	80.7	80.7	80.7
Area Reduction Factor ARF_{iT} - 15 hour	81.4	81.4	81.4	81.4
Area Reduction Factor ARF_{iT} - 20 hour	84.0	84.0	84.0	84.0
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 5 hour	66.3	80.9	93.0	106.4
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 10 hour	81.2	99.0	113.9	130.2
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 12 hour	84.7	103.1	118.7	135.7
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 13.2 hour	87.2	106.3	122.3	139.8
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 15 hour	90.0	109.7	126.2	144.3
Average rainfall (mm), P_{AvgiT} (=P_T x ARF_{iT}) - 20 hour	98.9	120.5	138.6	158.5
Flood run-off factor (%), f_{iT} - 5 hour	27.0	30.0	32.0	34.5
Flood run-off factor (%), f_{iT} - 10 hour	29.5	34.0	36.0	39.5
Flood run-off factor (%), f_{iT} - 12 hour	30.0	35.0	37.0	40.0
Flood run-off factor (%), f_{iT} - 13.2 hour	30.0	34.5	37.0	40.0
Flood run-off factor (%), f_{iT} - 15 hour	31.0	36.0	38.5	41.5
Flood run-off factor (%), fi_T - 20 hour	32.5	39.5	40.0	44.5
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 5 hour	17.9	24.3	29.8	36.7
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 10 hour	24.0	33.6	41.0	51.4
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 12 hour	25.4	36.1	43.9	54.3
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 13.5 hour	26.2	36.7	45.2	55.9
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 15 hour	27.9	39.5	48.6	59.9
Effective rain (mm), he_{iT}, (= f_{iT} x P_{AvgiT}) - 20 hour	32.1	47.6	55.4	70.5

Table 0-21: Unit Hydrograph Results

	Return Period (Years)			
	1:20	**1:50**	**1:100**	**1:200**
Peak Discharge (m^3/s) - 5 hours	848	1148	1409	1736
Peak Discharge (m^3/s) - 10 hours	**857**	**1204**	**1467**	**1840**
Peak Discharge (m^3/s) - 12 hours	835	1187	1444	1784
Peak Discharge (m^3/s) - 13.2hours	834	1169	1442	1783
Peak Discharge (m^3/s) - 15 hours	825	1168	1437	1770
Peak Discharge (m^3/s) - 20 hours	798	1181	1377	1751

A.4.6 Empirical Methods

Empirical methods are based primarily on the catchment area and location. A number of empirical methods were used to determine peak discharge rates at the proposed Ntabelanga Dam wall, these included:

- Catchment Parameter Method (CAPA) (McPherson, 1983).
- HRU 1/71 (Pitman and Midgley, 1971).
- Midgely and Pitman Method (MIPI) (Midgley, 1967).
- Standard Design Flood (SDF) (Alexander, 2002).
- Regional Maximum Flood (RMF) (Kovacs, 1988).

The CAPA method, developed by McPherson (1983) is based on flow, rainfall and physical geography data from more than 140 catchments in South Africa. The method requires four variables as input, including Catchment Area (km^2), MAP (mm), Mean Catchment Slope and a Catchment Shape parameter, which is the river length divided by the square root of the catchment area.

The HRU 1/71 method developed by Pitman and Midgley (1971) based on the results of the Unit Hydrograph Method, is a simple method also requiring four input variables. These variables include Catchment Area (km^2), MAP (mm), a combined coefficient dependent on the meteorological region, veld type zone and return period and, lastly, a catchment parameter incorporating catchment area and catchment index to reflect the response time of the catchment in terms of area and shape.

The MIPI method, developed by Pitman and Midgley (1967), can be described as an empirical-probabilistic method. It is implemented by determining a MIPI-flood region (in this case Region 2), and reading off a nomograph peak discharge rates relating to the various return period events.

The SDF method developed by Alexander (2002) is a simple and robust method which provides a uniform approach to flood calculations. The method is based on a calibrated Rational discharge coefficient for a specific recurrence period. The calibrated discharge parameters are based on historical data that were determined for 29 homogeneous basins in South Africa. The Ntabelanga Dam falls within Drainage Basin 23.

The RMF method (TR 137) was developed by Kovacs (1988). The method requires the determination Francou-Rodier (K_e) number. This value was determined by plotting the Ntabelanga Dam Catchment onto the TR 137 Flood Region Map derived by Kovacs (1988), which showed that catchment is located within Kovacs K region 5.

Thus, the RMF was based on a K region of 5. As per the SANCOLD Guidelines, the SEF is determined by adding an adjacent category to the determined Kovacs K-Factor ($RMF_{+\Delta}$) due to the dam being provisionally classified as a Category 3 impoundment. As per this requirement, the Ntabelanga Dam SEF was determined by using a K-Factor of 5.2.

A.5 Summary of Results

The peak discharge rates for each of the flood hydrology methods used in this study are presented in Table A-22. Based upon SANCOLD Guidelines, the proposed Ntabelanga Dam spillway needs to be designed using a RDF equal to the 1:200 year return period event.

Table 0-22: Peak Discharge Calculations Results at Ntabelanga Dam

Method Applied	Return Period (Years)				Maximum Floods	
	1:20	1:50	1:100	1:200	RMF	SEF ($RMF_{+\Delta}$)
Unit Hydrograph (m^3/s) (10 hour)	857	1204	1467	**1 840**		
Rational Method (m^3/s)	1 539	1 976	2 160	**2 470**		
MIPI (m^3/s)	690	1 500	1 800	**2 100**		
HRU 1/71 (m^3/s)	875	1 646	2 076			
CAPA (m^3/s)	1 070	2 082	2 562			
Statistical (Regional Growth Curve) (m^3/s)	565	921	1 080	**1 249**		
SDF (m^3/s)	850	1 804	2 319	**2 900**		
RMF (m^3/s)	1 342	2 060	2 511	**2 991**	**4 440**	**5 532**

From Table A-22, the 1:200 year peak discharge values range from 1 249 m^3/s (determined using statistical methods based on gauged streamflow data using a Regional Growth Curve) to 2 991 m^3/s (based on the RMF method). The peak discharge values obtained using gauged streamflow data (Index Flood method) are significantly lower than the peak discharge results obtained from other methods, as presented in Table A-22. Typically, statistical methods are the preferred means in determining peak discharge values used for design purposes. However, in this study it was found that the gauged streamflow data used to determine the AMS (upon which the statistical methods are based) contained significant levels of missing data as well as instances where flood events exceeded gauge rating tables. It is postulated that due to the level of missing and/or capped AMS data, the resultant probability distributions provide low estimates of design peak discharge values, and therefore are viewed with caution in this study.

The difference in the 1:200 year peak discharge results obtained from deterministic methods, namely the Unit Hydrograph and Rational Methods, were found to be notable. This is, however, to be expected due to the fact that the Ntabelanga Dam contributing catchment area is bigger than that for which the Rational Method was developed (normally used for catchment areas of less than 15 km^2). Slight changes in the input variables such as the areal reduction factor or the catchment C Factor can result in significant changes in the resultant peak discharge value. The Unit Hydrograph Method, on the other hand, was developed for catchment areas ranging between 15 and 5 000 km^2. The results of this method were found to be less conservative than those obtained from the Rational Method.

The 1:200 year peak discharge results obtained from the empirical methods range from 2 100 m^3/s (MIPI Method) to 2 991 m^3/s (RMF Method). The RMF and SDF results presented in Table A-22 are considered conservative due to the fact that they are developed using upper envelope methods. Unfortunately 1:200 year return period peak discharges were not available using the CAPA and HRU 1/71 methods, due to the fact that the K_t (HRU 1/71 method) and K_p (CAPA method) values were only available for return periods up to the 1:100 year return period flood event. However, by comparing the 1:100 year peak discharge values for all the empirical methods used (from Table 4-22), it appears that the MIPI method corresponds to the lowest estimated values, and the CAPA method would result in the highest estimated peak discharge.

The SEF was determined by adding a category to the adopted Kovacs K-Factor ($RMF_{+\Delta}$), based on the TR 137 Flood Region Map derived by Kovacs (1988). The RMF for the Ntabelanga Catchment was 4 440 m^3/s, and the SEF was determined to be 5 532 m^3/s.

A.6 Recommended Peak Discharge Value for the RDF and SEF

Based on the 1:200 year return period peak discharge results obtained from Statistical, Empirical and Deterministic flood calculation methods, it is recommended that a RDF peak discharge value of 2 500 m^3/s is adopted for the proposed Ntabelanga Dam spillway design. This RDF value is less than the 1:200 year return period peak discharge value estimated using the scaled RMF and SDF method, however, it is greater than the estimated 1:200 year return period peak discharge values obtained using deterministic methods (Rational and Unit Hydrograph Methods). The results obtained from the Statistical Method, based on gauged streamflow data, were not considered in determining the final RDF peak, due to the high level of missing data associated with the streamflow gauges. It was concluded that the missing and capped AMS data from the gauges resulted in low estimated peak discharge values.

The SEF, based on a Kovacs K-Factor of 5.2 and a catchment area of 1 971 km^2, was determined to be 5 532 m^3/s. It is therefore recommended that this value also be used in the design of the Ntabelanga Dam spillway.

A.7 References

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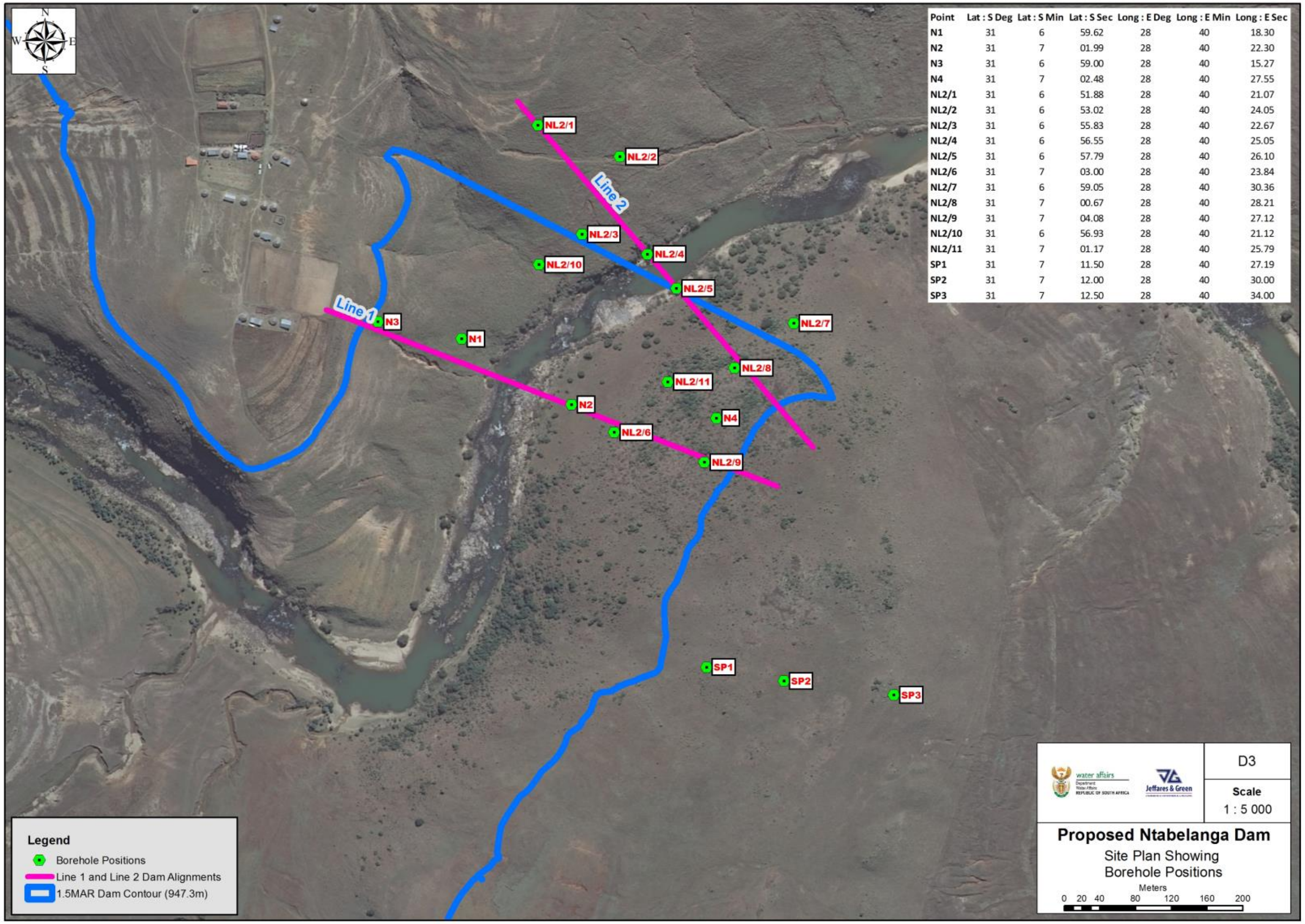
APPENDIX B

LOCATIONS OF GEOTECHNICAL INVESTIGATIONS AND MATERIALS SOURCES



Point	Lat : S Deg	Lat : S Min	Lat : S Sec	Long : E Deg	Long : E Min	Long : E Sec
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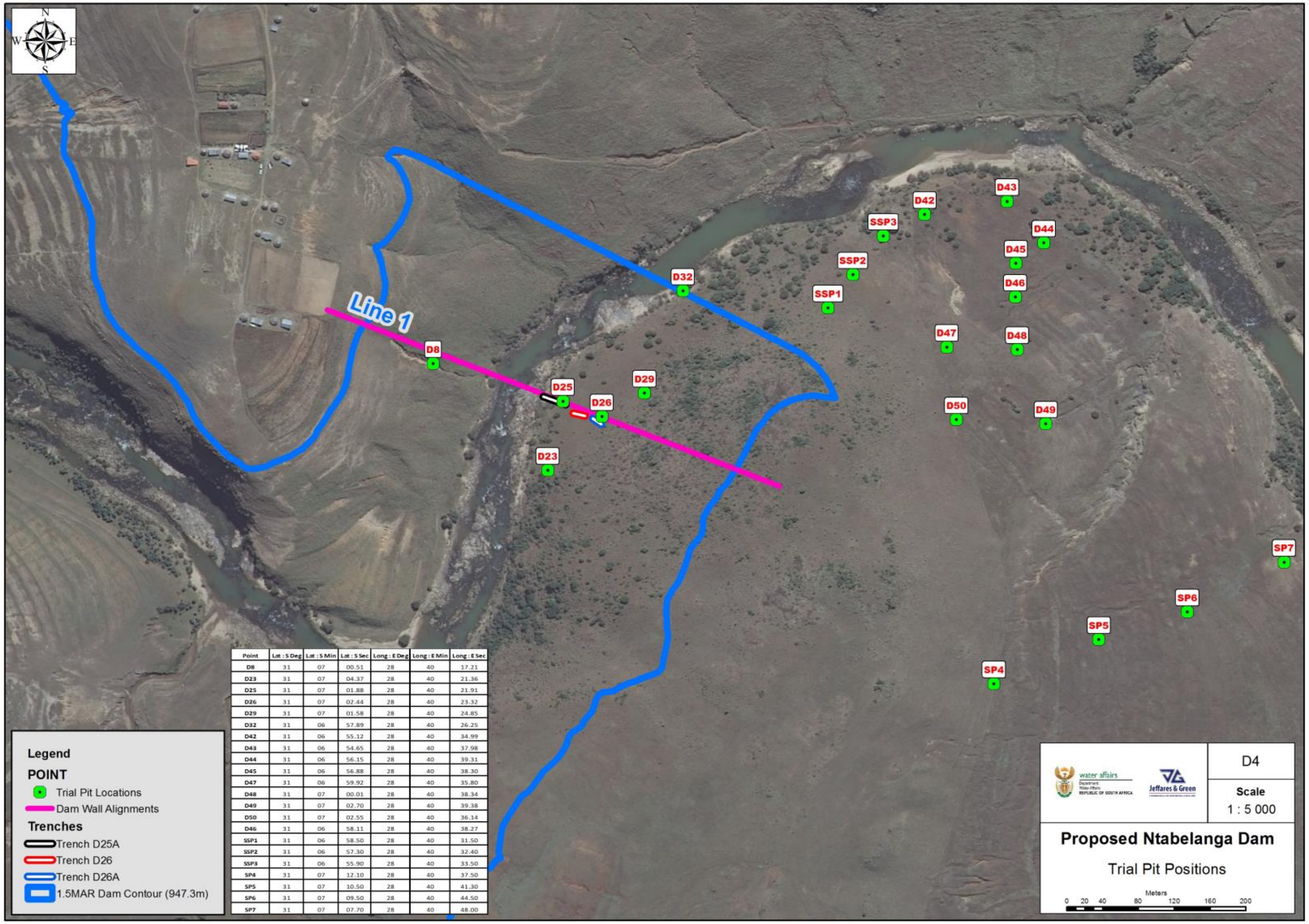
N2	31	7	01.99	28	40	22.30
N3	31	6	59.00	28	40	15.27
N4	31	7	02.48	28	40	27.55
NL2/1	31	6	51.88	28	40	21.07
NL2/2	31	6	53.02	28	40	24.05
NL2/3	31	6	55.83	28	40	22.67
NL2/4	31	6	56.55	28	40	25.05
NL2/5	31	6	57.79	28	40	26.10
NL2/6	31	7	03.00	28	40	23.84
NL2/7	31	6	59.05	28	40	30.36
NL2/8	31	7	00.67	28	40	28.21
NL2/9	31	7	04.08	28	40	27.12
NL2/10	31	6	56.93	28	40	21.12
NL2/11	31	7	01.17	28	40	25.79
SP1	31	7	11.50	28	40	27.19
SP2	31	7	12.00	28	40	30.00
SP3	31	7	12.50	28	40	34.00

Figure A-1: Location of Core Drilling Holes at Ntabelanga Dam Site



Point	Lat : S Deg	Lat : S Min	Lat : S Sec	Long : E Deg	Long : E Min	Long : E Sec
D8	31	07	00.51	28	40	17.21
D23	31	07	04.37	28	40	21.36
D25	31	07	01.88	28	40	21.91
D26	31	07	02.44	28	40	23.32
D29	31	07	01.58	28	40	24.85
D32	31	06	57.89	28	40	26.25
D42	31	06	55.12	28	40	34.99
D43	31	06	54.65	28	40	37.98
D44	31	06	56.15	28	40	39.31
D45	31	06	56.88	28	40	38.30
D47	31	06	59.92	28	40	35.80
D48	31	07	00.01	28	40	38.34
D49	31	07	02.70	28	40	39.38
D50	31	07	02.55	28	40	36.14
D46	31	06	58.11	28	40	38.27
SSP1	31	06	58.50	28	40	31.50
SSP2	31	06	57.30	28	40	32.40
SSP3	31	06	55.90	28	40	33.50
SP4	31	07	12.10	28	40	37.50
SP5	31	07	10.50	28	40	41.30
SP6	31	07	09.50	28	40	44.50
SP7	31	07	07.70	28	40	48.00

Figure A-2: Trial Pit Locations to Sample Materials and Check Dolerite Upper Horizon

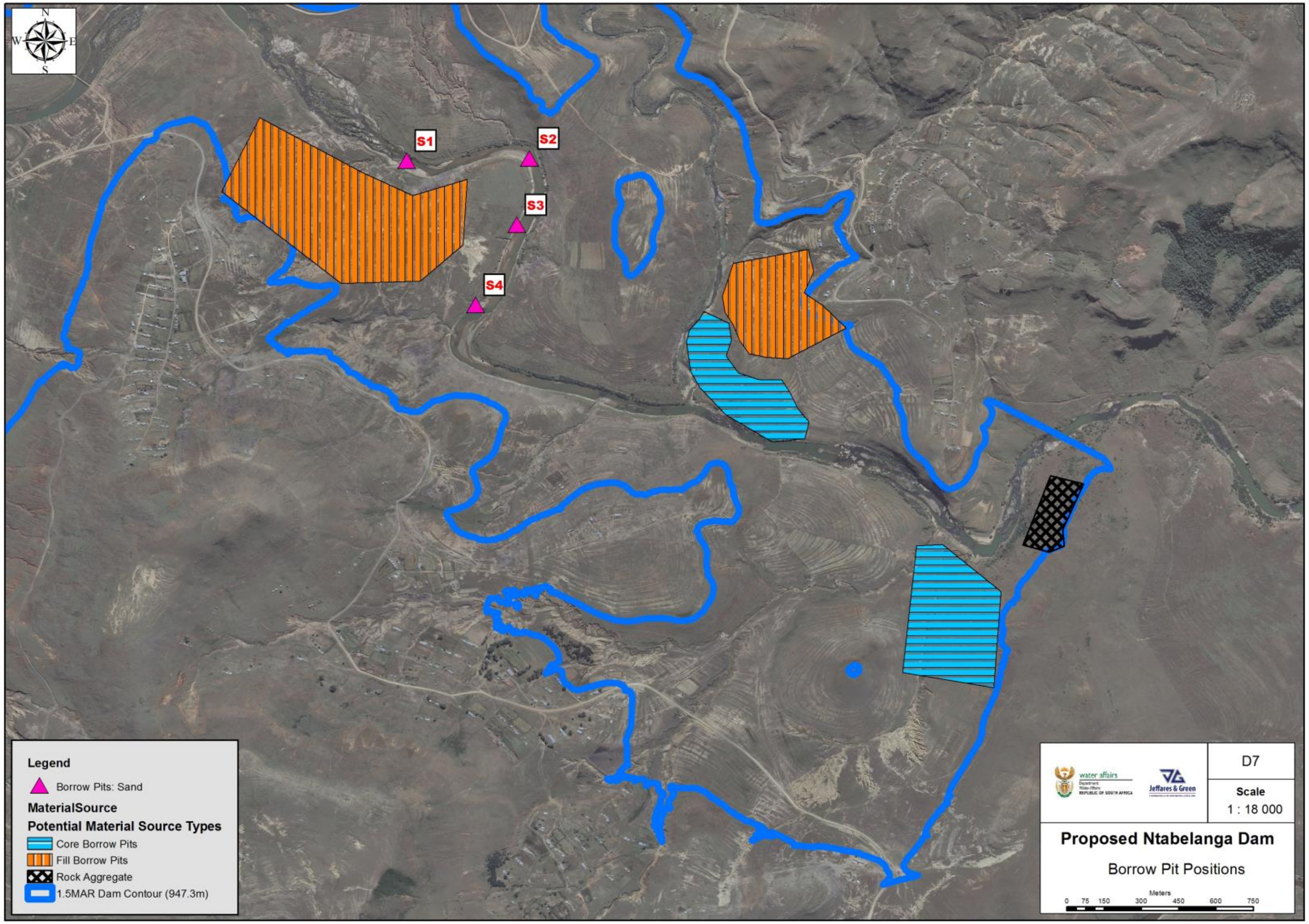


Figure A-3: Borrow Pit Locations: Core Material, Rock, Sand and Fill: All Within Dam Basin

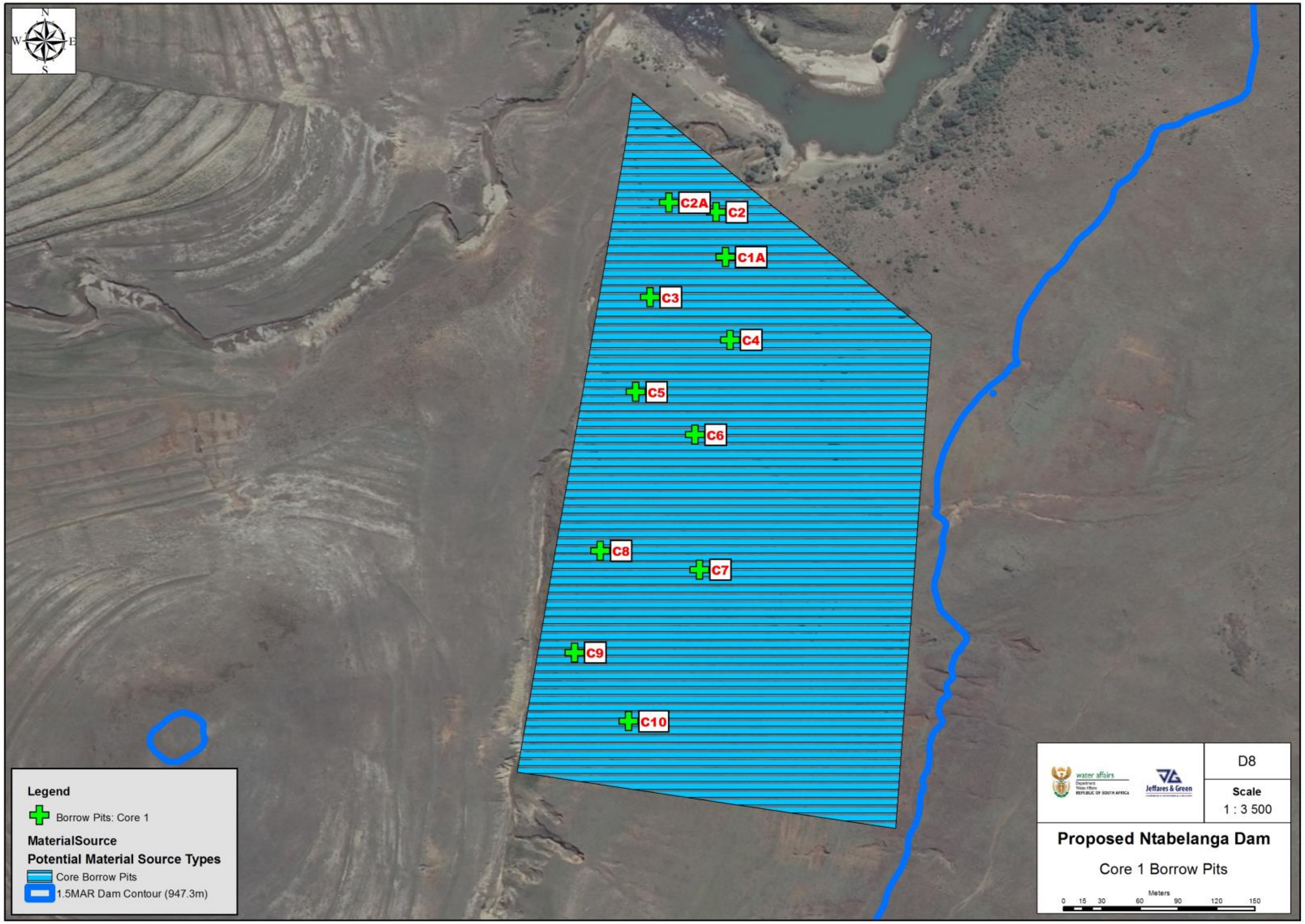


Figure A-4: Core Material Pits: Sampling Locations 1 of 2

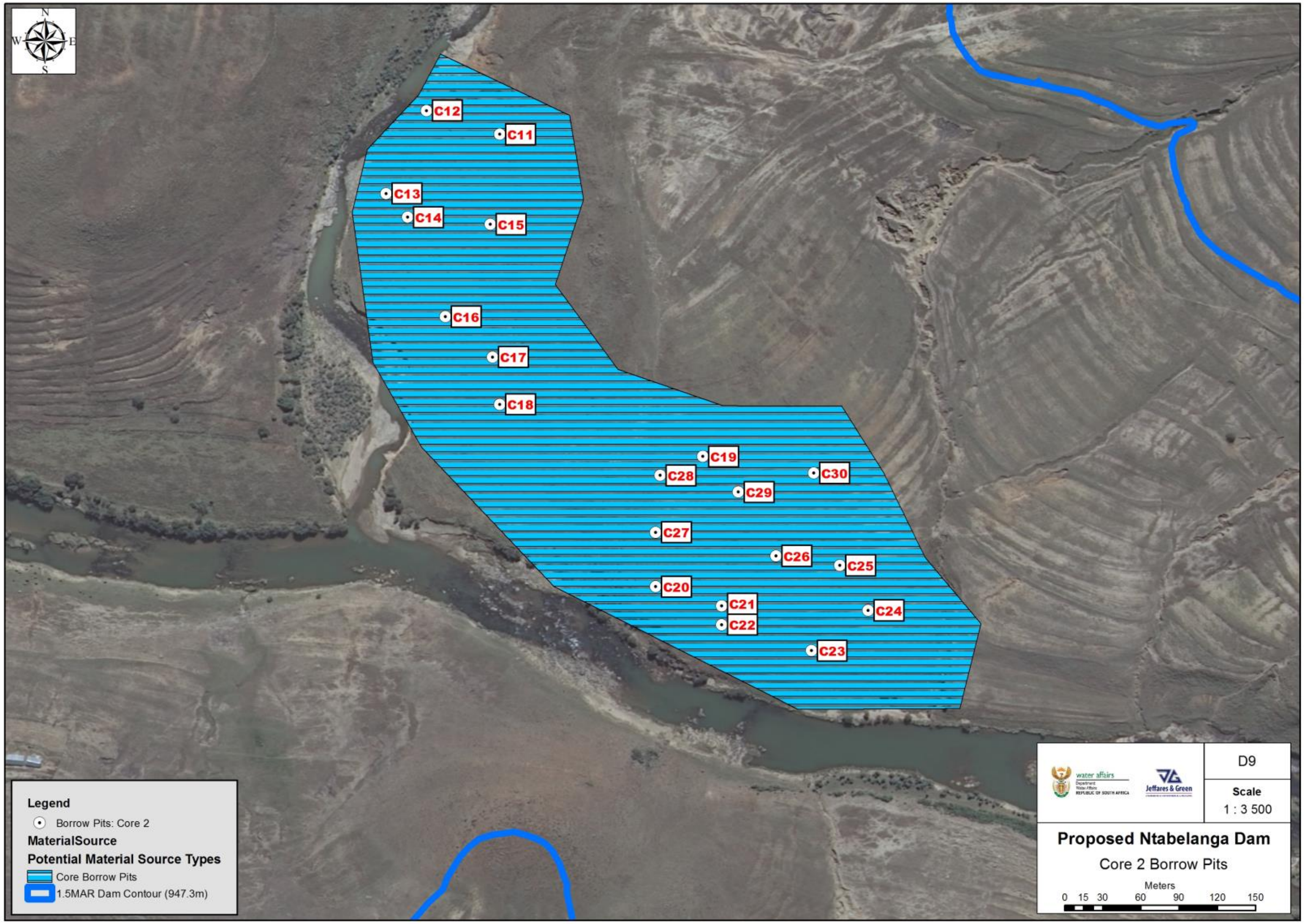


Figure A-5: Core Material Pits: Sampling Locations 2 of 2

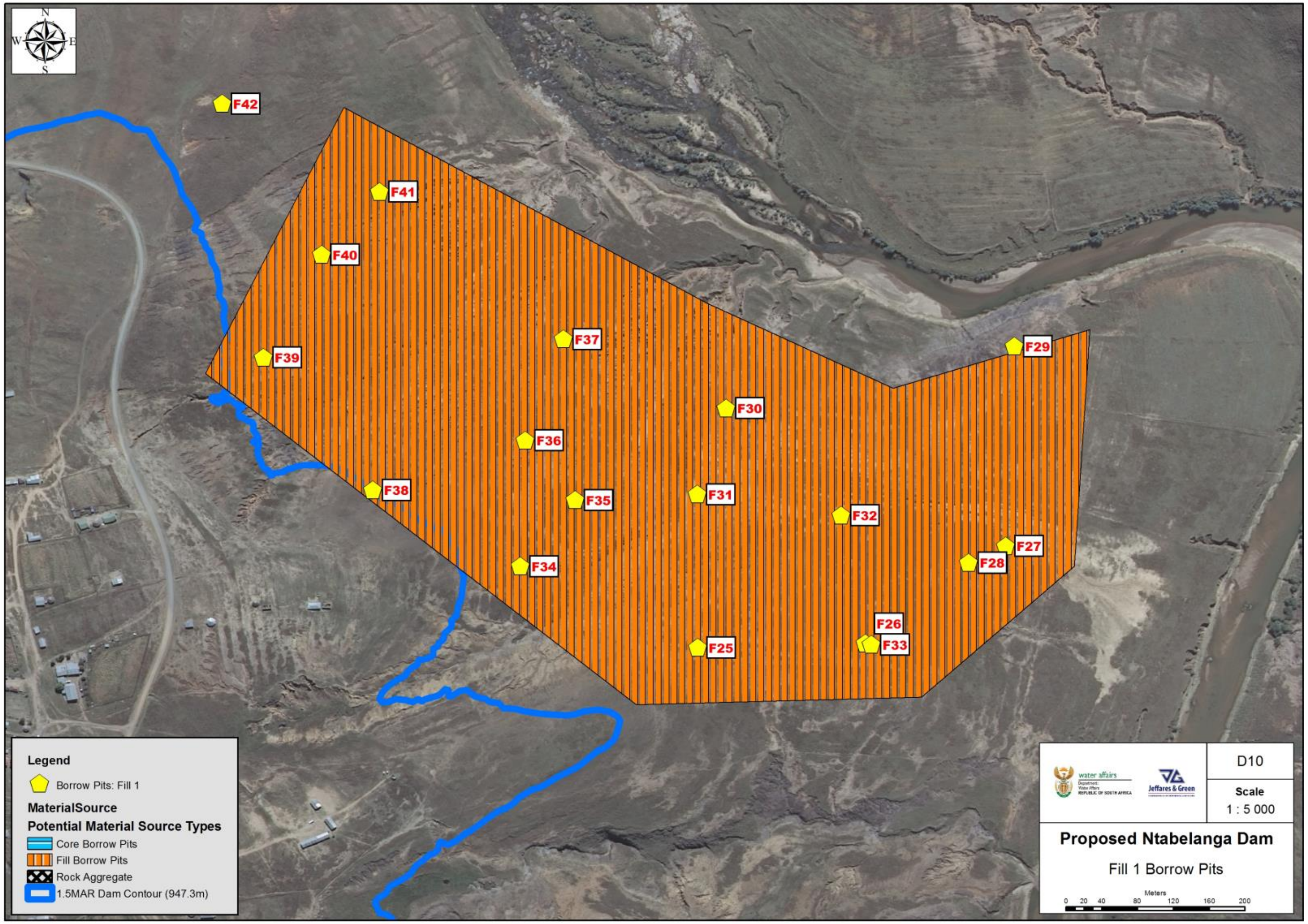


Figure A-6: Embankment Earthfill Material Pits: Sampling Locations 1 of 2

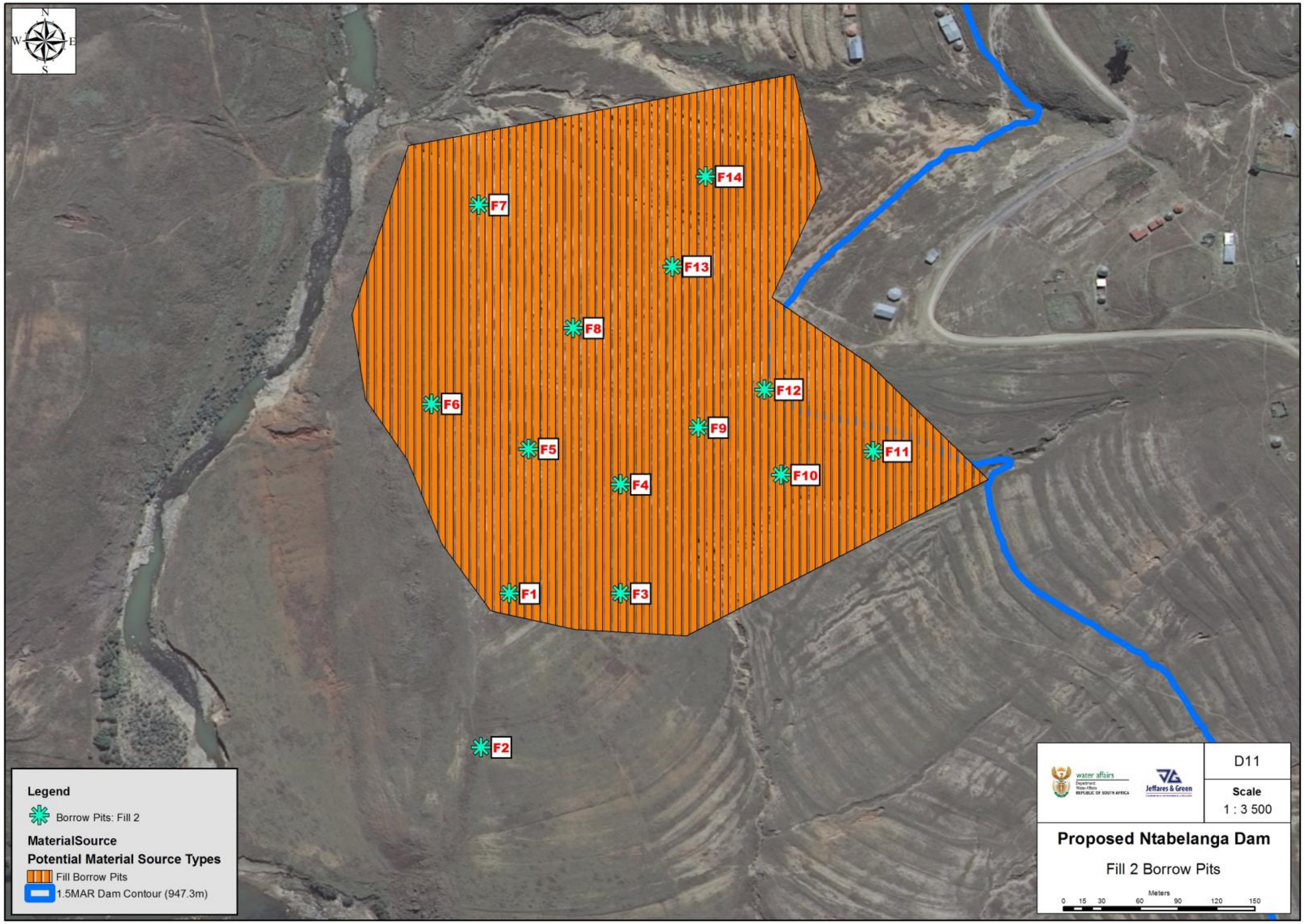


Figure A-7: Embankment Earthfill Material Pits: Sampling Locations 2 of 2

APPENDIX C

DRAFT SCOPE OF WORK FOR DETAILED DESIGN

INTRODUCTION

Background on Project

The Mzimvubu River catchment in the Eastern Cape of South Africa is within one of the poorest and least developed regions of the country. Development of the area to accelerate the social and economic upliftment of the people was therefore identified as one of the priority initiatives of the Eastern Cape Provincial Government.

Harnessing the water resources of the Mzimvubu River, the only major river in the country which is still largely unutilised, is considered by the Eastern Cape Provincial Government as offering one of the best opportunities in the Province to achieve such development. In 2007, a special-purpose vehicle (SPV) called AsgISA-Eastem Cape (Pty) Ltd (AsgiSA-EC) was formed in terms of the Companies Act to initiate planning and to facilitate and drive the Mzimvubu River Water Resources Development.

The five pillars on which the Eastern Cape Provincial Government and AsgiSA-EC proposed to model the Mzimvubu River Water Resources Development are:

- Afforestation.
- Irrigation.
- Hydropower.
- Water transfer.
- Tourism.

As a result of this the Department of Water Affairs (DWS) commissioned the Mzimvubu Water Project with the overarching aim of developing water resources schemes (dams) that can be multi-purpose reservoirs in order to provide benefits to the surrounding communities and to provide a stimulus for the regional economy, in terms of irrigation, forestry, domestic water supply and the potential for hydropower generation amongst others.

Following several previous water resources development studies in the region, DWS are currently undertaking a Feasibility Study to determine the best dam development option to implement as a high priority

This Feasibility Study commenced in January 2012 and was completed in October 2014 in three stages as follows:

- Inception;
- Phase 1 – Preliminary Study; and
- Phase 2 – Feasibility Study.

The purpose of the Feasibility Study is not to repeat or restate the research and analyses undertaken on the several key previous studies described below, but to make use of that information previously collected, to update and add to this information, and to undertake more focussed and detailed investigations and feasibility level analyses on the dam site options that have then been identified as being the most promising and cost beneficial.

Feasibility Study Phase 1 - Preliminary Study

The objective of this phase was to review available data and information from previous studies undertaken on the Mzimvubu river catchment, and, using this existing information at desktop level, to undertake a screening process of 19 potential dam sites, and make a recommendation on the best dam development project within the study area.

The selection was to be based upon, but not limited to, water requirements, environmental impact, social impact, hydrology, technical evaluation and stakeholder consultation.

The following key previous studies were the main reference documents used in the selection of the best dam development option:

- Republic of Transkei Mzimvubu Basin Development :1987.
- DWS Assessment of the Ultimate Potential Future Marginal Cost of Water Resources in South Africa, 2010
- DWA Water Resources Study to assist ASGISA-EC: 2010 (BKS).
- ASGISA-EC Business Case for Water Related Opportunities – 2010 (Ingerop).

The DWA Water Resources Study to assist ASGISA-EC in 2010 was undertaken at a conceptual/desktop level and identified 19 possible dam sites throughout the Mzimvubu River catchment and assessed each dam in terms of their use for hydropower, irrigation, domestic water supply, inter catchment transfers and overall economic stimulus.

Following this study an additional study was undertaken by Ingerop, called the ASGISA-EC Business Case for Water Related Opportunities – 2010. This report, also undertaken at conceptual level, looked at the same 19 dam sites plus one additional site (Tsitsa Dam Site) and undertook a dam site screening process based on a set of criteria that included the following:

- Capex / MW produced;
- Agriculture potential (irrigation);
- Forestry potential;
- Population;
- Accessibility / proximity to main transport infrastructure; and
- Potential use of dams in long term water transfer schemes.

Based on these criteria the two highest ranked dams were taken forward into a Business Case Study. These two sites were the Ntabelanga and Tsitsa Falls/Laleni Sites.

Phase 1 of the ongoing Feasibility Study revisited the above reports and also included detailed topographical surveys, some core drilling, and the undertaking of detailed yield hydrology, on three "finalist" dam site options on the Kinira and Tsitsa River, to check for any fatal flaws at each site.

The screening process also included updated costings, environmental screening, and further cost-benefit analyses, and this process has confirmed and recommended that the Ntabelanga Dam site development on the Tsitsa River be implemented.

Phase 2 of the Feasibility Study is currently proceeding with the objective of optimising and undertaking the Feasibility Design of this dam at Ntabelanga which has a gross storage capacity equal to 1.5 x the Mean Annual Runoff (MAR) at that point on the Tsitsa River.

The purposes of the Ntabelanga Dam will be:

i. To guarantee the supply of the potable water requirements of all communities that can be viably served by the dam
ii. To provide raw water to develop irrigated agriculture in the region
iii. To possibly generate hydropower at the dam which could be fed into the grid, or used for operational and/or local usage
iv. To regulate the river flow downstream of the dam as part of an integrated conjunctive use scheme with the potential Laleni Dam/Tsitsa Falls hydropower project (which latter scheme will be investigated and developed under a separate study)

Other purposes that might result following construction could be aquaculture development and tourism in the dam basin itself.

It is also possible that the dam could be part of a national water transfer scheme in the longer term, but this is unlikely to occur before the middle part of this century.

Dam Locality

Figure 1 below shows the locality plan for Ntabelanga Dam

Figure 1 – Ntabelanga Dam Locality Plan

The dam wall is located approximately 31 kms east of Maclear in the Eastern Cape, and can be accessed via a gravel road which branches off the R396 national road between Maclear and Tsolo.

Feasibility Study Reports
The Feasibility Study concluded with the delivery of the reports listed below:

REPORT TITLE	**DWS REPORT NUMBER**
Inception Report	P WMA 12/T30/00/5212/1
Environmental Screening	P WMA 12/T30/00/5212/2
Preliminary Study	P WMA 12/T30/00/5212/3
Feasibility Study: Main Report	P WMA 12/T30/00/5212/4
Volume 1: Report	
Volume 2: Book of Drawings	
FEASIBILITY STUDY: SUPPORTING REPORTS:	
Water Resources	P WMA 12/T30/00/5212/5
Water Requirements	P WMA 12/T30/00/5212/6
Reserve Determination	P WMA 12/T30/00/5212/7
Volume 1: River	
Volume 2: Estuary: Report	
Volume 3 :Estuary: Appendices	
Land Matters	P WMA 12/T30/00/5212/8
Irrigation Development	P WMA 12/T30/00/5212/9
Geotechnical Investigations	P WMA 12/T30/00/5212/10
Volume 1: Ntabelanga, Somabadi and Thabeng Dam Sites: Report	
Volume 2: Ntabelanga, Somabadi and Thabeng Dam Sites: Appendices	
Volume 3: Lalini Dam and Hydropower Scheme: Report	
Volume 4: Lalini Dam and Hydropower Scheme: Appendices	
Topographical Surveys	P WMA 12/T30/00/5212/11
Feasibility Design: Ntabelanga Dam	**P WMA 12/T30/00/5212/12**
Bulk Water Distribution Infrastructure	P WMA 12/T30/00/5212/13
Regional Economics	P WMA 12/T30/00/5212/14
Cost Estimates and Economic Analysis	P WMA 12/T30/00/5212/15
Legal, Institutional and Financing Arrangements	P WMA 12/T30/00/5212/16
Record of Implementation Decisions: Ntabelanga Dam and Associated Infrastructure	P WMA 12/T30/00/5212/17
Hydropower Analysis: Lalini Dam	P WMA 12/T30/00/5212/18
Feasibility Design: Lalini Dam and Hydropower Scheme	P WMA 12/T30/00/5212/19
Record of Implementation Decisions: Lalini Dam and Hydropower Scheme	P WMA 12/T30/00/5212/20

All of these reports should be made available to the detailed design PSP.

Implementation Programme
The latest version of an Implementation programme should be made available to the design PSP.

OBJECTIVE OF ASSIGNMENT

The objective of this assignment is to undertake the detail design, preparation of contractor prequalification and construction tender documents in accordance with DWS requirements, assisting DWS with the prequalification process, assisting DWS with the construction tendering process, undertaking the tender evaluations and adjudication, preparation of construction drawings, and the administration, management, and supervision of the construction of the works.

GENERAL PROJECT INFORMATION

Administration of Task

The Department of Water Affairs (DWS) is the client for the task. The contract will be administered by the {DWS Directorate: Infrastructure Branch……………………..}

Project Programme

The duration of this appointment is expected to span a period of ** months, from *** to (estimated) ***.

This period includes the 12 months defects notification period.

Preliminary Dam Information

The development of a multi-purpose dam on the Tsitsa River at Ntabelanga is a Strategic Infrastructure Project in this region, and therefore has very high priority.

For this reason, the detailed design and implementation process is to commence before the completion of the ongoing Feasibility Study, and will have an extremely tight programme.

The currently ongoing Feasibility Study tasks are focusing on finalizing water requirements for potable water supplies, irrigated agriculture, EWR, and downstream flow regulation. Geotechnical investigations of dam foundation conditions, grouting requirements, and construction materials are also underway. Dam type investigations commenced on 01 August. The identification of land issues, as well as investigating the institutional, financial and legal aspects of project development, are also a part of the Feasibility Study tasks.

At this stage, the optimum dam type has not been confirmed. Analyses are being undertaken to compare the following dam types:

- Roller Compacted Concrete (RCC) Dam
- Concrete Faced Rockfill Dam
- Embankment Dam (clay core)

Various spillway and stilling basin arrangements are also being investigated including:

- River centre-line uncontrolled ogee spillway integrated into dam wall
- Side channel spillway and discharge chute
- Separate rock cutting through right-hand flank abutment, and discharge chute

It is expected that a decision on optimum dam type and spillway arrangement will only be made in October 2013.

Therefore bidders should prepare their technical & financial proposals based upon undertaking the detailed design of any one of the above possible solutions.

DAM CHARACTERISTICS

The proposed Ntabelanga Dam has the following characteristics:

Full Supply Level (FSL):	*947.3 m.a.s.l.*
Non-Overspill Crest Level – right flank (NOCL):	*953.8 m.a.s.l.*
Minimum bed level in river at dam:	*886.7 m.a.s.l.*
Crest width:	*6 m*
Minimum operating level (MOL):	*918.00 m.a.s.l.*
Emergency drawdown minimum outlet level:	*907.00 m.a.s.l.*
Maximum dam wall height to NOC:	*66.1 m*
Wall crest length (incl. spillway):	*407 m*
Spillway crest length:	*150 m*
Gross stored volume at FSL:	*490 million* m^3
Mean Annual Runoff at dam:	*415 million* m^3
Storage below MOL (V_{50} *sedimentation):*	*37 million* m^3
Surface area of lake behind dam:	*31.5* km^2
Backwater reach upstream of dam:	*15.5 km*

The dam wall height, impoundment volume, and downstream risk factors for the Ntabelanga Dam put this structure into a Category 3 dam under Gazetted Dam Safety Guidelines.

The flood criteria for design of this dam are as follows:

1 in 200 year return period Design Flood:	*2 500* m^3*/sec*
Safety Evaluation Flood (SEF):	*5 530* m^3*/sec*

Flow released from Ntabelanga Dam will need to be accurately regulated and measured as the dam will be used conjunctively with another planned dam and hydropower scheme at Laleni, which dam location would be some 30 km from the Ntabelanga Dam and located just above the Tsitsa Falls.

Basin Morphology

The dam basin has variable topography comprising mainly sedimentary rocks of the Tarkastad Formation, with dolerite intrusions forming positive relief features.

Geological Influence at Dam Site

The dam site is on a dolerite sill outcropping in the river section. Dolerite outcrops and sub-outcrops are present up the entire right flank. Dolerite on the left flank occurs beneath a cover of soil. The top of the left flank is underlain by sandstone.

A report on the geotechnical dam site and materials investigations is available from DWS. This includes core drilling at the proposed dam site, geophysics (seismic) at the dam site, some core drilling at potential quarries, as well as trial pitting and laboratory testing of other dam construction materials in the local area.

Information Available to Tenderers During the Tendering Period
The following information is provided in electronic format as a part of this Request for Proposals:

- The suite of Feasibility Study Reports described above
- Ntabelanga Dam locality plan
- Plan showing full supply level inundated areas for the 1.5 MAR sized dam
- Contoured plan covering the dam site and adjacent areas
- Borehole logs and core photos of two holes drilled at Ntabelanga Dam site in Phase 1 of the Feasibility Study
- Provisional Implementation Programme

Information to be Made Available to the Successful PSP

- LiDAR survey DTM and imagery of inundated areas of dam to NOC level, and dam site and surrounds – 0.5 m contour interval
- Latest drafts of Feasibility Study Reports listed above – this will include recommendations for dam type choice and general arrangements of the selected dam type and spillway arrangements
- Will also include the results and interpretation of geotechnical dam site and materials investigations
- WRYM yield models used in the Feasibility study with data files

Co-ordination With Other Related Studies

EIA and EMP PSP
DWS are currently procuring and Independent PSP who will be tasked with the undertaking of a full EIA for this project, the obtaining of Environmental approvals, and the development of an approved EMP for the implementation phase. This will include a review of the Environmental Water Requirements of the proposed system.

This EIA PSP assignment will also deal with the social impacts of the project including any resettlement, compensation and other mitigation measures that might be required. The EIA PSP will lead and manage the public consultation and participation process throughout the project, and all other PSPs will need to co-ordinate and co-operate continuously with the EIA PSP in this regard. The Detailed Design PSP must allow for attendance and participation at such public meetings and workshops that might be arranged by the EIA PSP.

Other Studies and Projects
The Ntabelanga Dam and its supply area predominately falls within the OR Tambo District Municipality's area of jurisdiction, but with a small portion of the supply areas falling with the Joe Qcabi DM. OR Tambo DM are very active in the development of water supplies in the areas to be served by the Ntabelanga Dam. Much of the planning, design, and implementation of water supplies in this area are being undertaken through Amatole Water, as the Implementing Agent, and various PSPs.

The largest of these regional water supply schemes is at various stages of development, and the latest thinking is that a centralized water treatment works will be constructed close to the Ntabelanga Dam, which will treat the raw water from the dam and then distribute potable water to the communities within and without of the watershed on both sides of the Tsitsa River, as well as (possibly) an area upstream of the dam wall.

The Ntabelanga Dam PSP will need to liaise and co-operate with the DM, its Implementing Agent and its PSPs to ensure efficient integration of these various schemes with the dam works.

PROJECT NUMBER {**********}**

SCOPE OF SERVICES

SCOPE OF SERVICES

Areas of expertise required

The Professional Service Provider (PSP) must provide information to demonstrate their expertise and experience for the various activities, namely:

- Project management & administration
- Design of large earth embankment, rockfill, and RCC dams
- Design of spillways and other flood control works
- Design of outlet works
- Design of advance infrastructure
- Economic, financial and risk analysis abilities
- Tender documentation and requirements for civil engineering projects
- Tendering procedures and tender evaluation
- Construction and engineering works management, co-ordination and liaison
- Site supervision of civil engineering projects
- Site supervision of electrical and mechanical engineering projects
- Quantity surveying and cost control
- Report writing – meeting DWS standards and guidelines

The PSP will also need to liaise with the DWS-appointed EIA PSP, and must therefore also demonstrate an awareness and understanding of the requirements and procedures for:

- Evaluation of the environmental and social impacts and obtaining EIA approvals
- Preparation and implementation of environmental management plans for civil engineering works

Normal Services Required

Inception Report

The PSP will be required to gather all relevant information available, which will include the outputs from the ongoing Feasibility Study.

Upon reviewing the above the PSP will prepare an Inception Report summarizing the following:

- Review of data and information gathered and available for the assignment
- Revised methodology and scope of work if required
- Detailed project work plan and schedule showing key deliverable and decision-making milestones
- Updated human resources schedule and organogram
- Updated project budget and monthly cashflow projections

This Report must be submitted **within one month** of the signing of the Contract Agreement.

Given the urgency of this project, the other activities described below will commence from day one of the contract and will therefore run in parallel to the Inception Period activities.

Feasibility Design Review

The PSP will utilize all information available to review the dam type analyses and feasibility design of the Ntabelanga Dam undertaken in the Feasibility Study.

If the PSP considers that a change in dam type or design details are warranted, then such findings and recommendations must be fully motivated and justified within this review period, having undertaken such review closely in liaison with the Feasibility Study PSP and its DWS Study Management Team.

Once consensus has been reached and DWS acceptance given on the best dam type to be implemented, approval will be given to proceed with the Preliminary and Detailed Designs of the works.

Such a decision must be reached by the **end of month two** of the programme.

Additional Geotechnical Investigations

The above process should also include whether or not the PSP considers that additional geotechnical investigations should be undertaken before finalization of the dam and spillway design.

If this is the case, such investigations should be specified, quantified and a cost estimate prepared, so that such investigations can be procured in a timely manner, using Provisional Sums allowed in the contract.

The PSP should allow sufficient time and cost for adequate supervision of these site investigations plus the preparation of an interpretive report on findings thereof.

It is expected that, if required, these additional geotechnical investigations should be completed by the **end of month 5**. The PSP will prepare a Record of Implementation Decision Report covering this Feasibility Design Review process.

During this same stage, the PSP shall advise DWS as to the necessity for further surveys, special visits, use of specialist consultants, setting out or staking out the work, and arranging for such to be carried out at the DWS's expense.

Preliminary Design Phase

The PSP will undertake the Preliminary Design of the following works, based on the decisions made above:

- The dam wall
- Spillway and discharge chutes, with stilling basin if required
- Drawoff and outlet works as described in Section 3.2 above, including the raw water pumping station and pipeline to the water treatment works inlet (WTW to be by undertaken others and this point will be one of the contract limits)
- Hydropower plant if considered to be viable
- Power supplies
- Other Mechanical & Electrical works
- Cofferdams/river diversion and associated temporary works
- Temporary and permanent access and haul roads
- Power supplies, communications, water supply and sanitation facilities required during construction
- Other temporary works – construction camp areas, quarries and borrow pits, crushing and screening plant and concrete batching plant areas, storage, laydown and stockpiling areas, areas for offices and site accommodation.
- Realignments and extension of rural access roads and bridges affected by the inundation
- Permanent administration and operational buildings
- Downstream gauging weir

- Other construction-related or mitigation works as might be required, including relocation of existing buildings, structures and services, as well as landscaping and remediation.

The outputs from this process will be presented in the form of a Preliminary Design Report including general arrangement and other drawings to a level of detail that a reviewer can clearly understand all of the component functions, materials and sizes, as well as the proposed construction methodology. The report will the basis of design, record of decisions, and criteria used, including key design calculations including hydraulic capacities of components, stability and seepage analyses, including checks for seismic activity (earthquake) safety factors, structural calculations, freeboard aspects and dealing with the Design Flood and SEF, and the operational and maintenance requirements once the works have been completed.

The report will also contain a Preliminary Bill of Quantities, cost estimate, updated implementation programme, and implementation cashflow projection.

The Preliminary Design Report shall be presented in draft form by the end of month 4, with the objective to discuss, review and finalize the Report by the **end of month 5**.

Modeling of Hydraulic Structures

The behavior of hydraulic structures such as outlet works, spillways, chutes and stilling basins under both normal and extreme flow conditions is a critical design optimization and safety issue.

It is expected that the PSP will undertake suitable Computation Fluid Dynamics and physical modeling of these structures in order to ensure that their design is optimized and that operational problems are avoided.

These activities must be programmed into what is a very short design period, and costs for undertaking these studies must be included in the tenderer's Financial Proposals. Tenderers are encouraged to check whether the DWS or other laboratories are available to undertake such physical modeling in the short time period allowed. It is conceivable that if more time is required to undertake such modeling, the finalization of the detailing of these critical hydraulic structures could even be undertaken during the construction tender process and final drawings only issued upon award of the contract, but this must be explained in the construction tender documents to avoid claims.

Draft Tender Documentation

Running in parallel to the above activities, the PSP will prepare draft tender documentation assuming that the construction Conditions of Contract will be FIDIC "Red Book".

The PSP will also prepare Specifications based upon those used on recent projects involving similar dam types and size, and associated works, preferably based on projects undertaken by or on behalf of DWS.

Similarly, the Standard Method of Measurement to be used should also be agreed with DWS before preparation of any Bills of Quantity commences.

Close liaison with DWS's Infrastructure Division will be required to produce an acceptable set of draft Tender documents.

This draft documentation should initially be based on the Preliminary Designs and submitted no later than the **end of month 5**, from which time it will be reviewed and amended to incorporate the Detailed Design of the works.

Contractor Prequalification

The PSP will prepare Contractor Prequalification Documentation so that DWS can undertake a fair and transparent Contractor shortlisting process. This should be structured such that only those Contractors that meet appropriate qualification criteria would succeed, and this will include their capacity, available human, plant and financial resources, experience on similar projects, compliance with financial, regulatory, and anti-corruption requirements, as well as well as other preferential procurement aspects.

These documents should be submitted to DWS in draft form no later than the **end of month 4** so that the prequalification process can commence no later than the **end of month 5**.

DWS will undertake the prequalification process, but the PSP will need to allow for providing assistance to DWS to respond to queries and clarifications during the process, as well as assisting DWS with the evaluation and shortlisting process.

Detailed Design & Final Tender Documentation

Following the discussion, review, and approval of the Preliminary Design Report and associated outputs, the PSP will be instructed to proceed with the Detailed Design & Final Tender Documents preparation.

This will involve the final refinement and optimization of designs using a value engineering approach, the preparation of more detailed drawings and Bills of Quantity to a level of detail suitable for a reliable tendering process where the tenderers fully understand the requirements for each and every component of the scheme without ambiguity.

The objective will be for the successful tenderer to only need to be issued with the final construction drawings limited to reinforced concrete details and bar bending schedules.

Mechanical and Electrical plant such as power supplies, transformers, penstocks, cranes, pumps, valves, hydropower plant, control systems, and associate ancillary works will require detailed functional specification at tender stage, rather than specifying actual manufacturers, to avoid contravening competitive tendering rules, and the construction tenderers proposals will need to be carefully scrutinized at tender adjudication to ensure that this equipment meets the defined quality and specified requirements.

Care will need to be taken to avoid the use of inferior quality materials, plant and equipment, and all such materials, plant and equipment should have proof of a reliable track record on previous similar projects in South Africa, as well as locally available spares and back-up services.

The final draft of the detailed design report and tender documents should be submitted no later than the **end of month 7**, so that these documents can be discussed, reviewed, and finalized by the **end of month 8**.

The report should also include an updated, accurate, cost estimate for the works, mitigation measures, and associated professional services, plus an updated implementation programme and quarterly cashflow projection, which shall include for inflation effects and VAT.

The report should also contain operations, maintenance and other life cycle costs, and financial implications thereof.

It is a requirement that all of the works designed and detailed under this contract must be developed, overseen, checked, and signed off by an Approved Professional Person (APP) who has suitable experience related to the type of dam and associated works being designed, who is preferably a member of SANCOLD, and who is on DWS's list of APPs.

All "signed-off" designs and details prepared under this Contract will need to be submitted to DWS's Dam Safety Office for their review, comments and approval prior to proceeding with the Construction stage.

Construction Tendering and Evaluation Process

The PSP will provide DWS with sufficient hard and soft copies of the Tender Documents and Drawings to be issued to the prequalified tenderers.

The PSP will prepare and present a detailed overview of the project and its requirements to the tenderers at a pre-tender briefing session, and will also conduct the pre-tender site visit on behalf of the DWS.

Assistance will also be given by the PSP to DWS during the tendering period (2.5 months) which will include responding to requests for clarification and the issuing of tender addenda if required.

This process could include advice to the DWS in any alternative designs and tenders, but excluding detailed inspection, reviewing and checking of alternative designs and drawings not prepared by the PSP and submitted by any contractor or potential contractor. If the latter is required, this will be at additional time and cost.

The PSP will also assist DWS with the evaluation of tenders received and recommendations for the award of the contract.

It is expected that the Contract Agreement for Construction with the successful tenderer will be signed before the **end of month 13**, which currently is expected to be in mid-December 2014.

Further Working Drawings

As has been stated above, it is expected that the PSP will provide tender drawings and documents that will require very few additional working drawings for the construction to proceed.

Following the DWS's instructions to proceed, the PSP will be responsible for the preparation of any further plans, designs and drawings, excluding shop details, which may be necessary for the execution of the works.

In the case of reinforced concrete works, working drawings must include reinforcement details and bending schedules.

In the case of structural steel works, working drawings and details provided by the PSP must include full information, dimensions and specifications on all sections, connections, plates, fasteners, bolts and welding, to such an extent that no further designs by contractors or other parties are required.

The PSP need not provide shop drawings for the manufacture of the structural steel works, as this will be a contractor requirement.

Construction Stage

The PSP will be responsible for the overall contract administration and co-ordination, as well as construction monitoring of the execution of the works in accordance with the contract, including all or any of the following:

i. Advice to the DWS as to any revisions or updates to the contract documents and preparation of such updates of the contract documents in consultation with the DWS.
ii. Overall contract administration and co-ordination, as well as construction monitoring of the execution of the works for compliance with the contract and attending site meetings on a combined average frequency of at least one day every two weeks for the duration of the construction of the specific works for which the PSP is engaged or at such more frequent intervals as the PSP may deem necessary.
iii. Directing construction monitoring operations, as provided for below.
iv. Checking contractor's drawings of structures, plant, equipment and systems for the works for conformity with designs requirements, but excluding detailed checking of manufacture and installation details for erection or installation fit.
v. Advice to the DWS on any further alternative designs, but excluding detailed inspection, reviewing and checking of alternative designs and drawings not prepared by the PSP and submitted by any contractor.
vi. Issuing instructions to contractors on behalf of the DWS.
vii. Issuing certificates or recommendations for payment of contractors and submitting regular reports regarding works finances and anticipated completion dates and final costs.
viii. Advice to the DWS in regard to or the resolution of disputes or differences that may arise between the DWS and the contractor, except mediation, arbitration and/or litigation.
ix. Preparation of and issuing variation orders on behalf of and after consultation with the DWS.
x. General inspection of materials and equipment for compliance with the original design and tender, including checking of marks or documentation for adherence to National and International standards and advice to the DWS regarding further inspections and testing of such materials and equipment as may be necessary and arranging for such inspections and testing to be carried out on behalf of and at the DWSs expense.
xi. Making arrangements on behalf of the DWS for the provision and reproduction at the DWSs expense of such drawings and documents as may be required by the contractors and site staff for the execution of the works.
xii. Agreeing final quantities with contractors, compiling final accounts and issuing final payment certificates.
xiii. Prepare and, on completion of the works, provide the DWS with record drawings. Making arrangements for the contractor to supply detailed operation, operating and maintenance manuals as part of the contractor's contractual obligations, receiving such and handing it over to the DWS. Both sets of documents shall be in formats as agreed to with the DWS.
xiv. Evaluating results of contractor's commissioning procedures and testing and witnessing final performance or acceptance tests on site, only, but excluding day-to-day routine tests.

Construction Monitoring

The duties of the PSP are as follows:

The construction monitoring staff shall:-

Maintain a full time presence on site to constantly review:

- Work procedures;
- Construction materials,

for compliance with the requirements of the plans and specifications and review completed work prior to enclosure or on completion as appropriate.

The PSP shall:

- carry out such administration of the project as is necessary on behalf of the DWS;
- be available to provide the contractor with technical interpretation of the plans and specifications;
- provide capacity building mentoring for DWS personnel in line with DWS's employee capacity building initiatives.

Occupational Health and Safety Act, 1993 (Act No. 85 of 1993)

The DWS requires the PSP to undertake duties falling under the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993) and the Construction Regulations in terms thereof, on behalf if the DWS and the additional services include the following:

i. The PSP must arrange, formally and in writing, for the contractor to provide documentary evidence of compliance with all the requirements of the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993).

ii. The PSP must execute the duties of the DWS, as his appointed agent, as contemplated in the Construction Regulations of the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993).

Project Management & Liaison Requirements

The PSP will designate a Project Manager who will be the main point of contact with DWS for the project. A deputy project manager will also be designated who will stand-in for the Project Manager when he or she is not available for whatever reason.

Progress and Steering Committee Meetings and Reporting

The PSP will allow for the time and cost of attending a monthly Project Management meeting with the DWS management team, which will be held in DWS's Pretoria offices.

The PSP will draw up the agenda, present progress and technical issues, take minutes and issue these to attendees and other relevant stakeholders.

Steering Committee Meetings will be held approximately every two months and will be held in East London or Mthatha.

The PSP will draw up the agenda, present progress and technical issues, take minutes and issue these to attendees and other relevant stakeholders.

Allowance should also be made to attend other ad-hoc meetings including the public consultation and participation/stakeholder meetings to be arranged by the Independent EIA PSP.

Progress Reports

Three types of progress reports are required to be prepared by the PSP:

i) "Short" version to accompany **each monthly invoice**
ii) "Technical" version to report actual progress on tasks and issues pertaining to them, as well as adherence to programme, which will be required **every two months**
iii) "Strategic" version to inform senior DWS management of overall project status – required **quarterly**
iv) *All three types must include a section on invoicing, cashflow and HDI participation.*

APPENDIX D

SEISMICITY REPORT

APPENDIX D
PROBABILISTIC SEISMIC HAZARD ANALYSIS

Author: Prof Andrzej Kijko, the Director of the University of Pretoria Natural Hazard Centre

EXECUTIVE SUMMARY

The feasibility study of the Probabilistic Seismic Hazard Analysis (PSHA) has been performed for site of the Ntabelanga Dam, Eastern Cape. All earthquakes located within a radius of 320 km from the site were used in the assessment. The PSHA was performed using the Cornell-McGuire procedure which can be broken down into two phases: (1) spatial delineation of seismogenic sources within 320 km from the site and (2) integration of all possible earthquake scenarios from each source to obtain probabilities of exceedance of specified ground motion parameters.

The applied procedure requires knowledge of the regional geology, tectonics, paleo- historic and instrumentally recorded seismicity.

The applied procedure requires knowledge of regional geology, tectonics, paleo- historic and instrumentally recorded seismicity. The information about regional geological model and tectonics of the future dam location was provided by Jeffares & Green (Pty) Ltd.

All calculations are repeated twice, each for a different ground motion prediction equation (GMPE):
- *AB06 (Atkinson and Boore, 2006)*
- *BA08 (Boore and Atkinson, 2008).*

The first, AB06 GMPE, (Atkinson and Boore, 2006) was developed for the central and eastern United States which is situated in a type of tectonic environment known as an intraplate region, or equivalently, stable continental area. Because of the limited number of strong-motion records in the stable continental areas, the attenuation relation (horizontal component) has been developed mainly by help of stochastic modelling.
The second applied GMPE, denoted as BA08, (Boore and Atkinson, 2008) is appropriate for predicting the earthquake generated horizontal component of ground motions in active tectonic regions with shallow crustal seismicity. It was derived by empirical regression of a strong-motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation) project. For frequency of ground motion exceeding 1 Hz, the analysis used 1,574 records from 58 earthquakes in the distance range of 0 km to 400 km (Boore and Atkinson, 2008).

The PSHA was performed using conventional, Cornell-McGuire procedure (Cornell, 1968; McGuire, 1976; 1978), where the integration across the uncertainty in the peak ground acceleration (PGA) prediction equation is an integral part of the methodology.

In accordance to the current seismic regulations as e.g. Eurocode 8 (2004) and ASCE (2005), three seismic designed levels were considered: Operating Basis Earthquake (OBE), Maximum Design Earthquake (MDE) and Maximum Credible Earthquake (MCE).

Given the existence of 594 tectonic faults in vicinity of the dam site (information provided by Jeffares & Green (Pty) Ltd), an investigation of the effect of potential seismic activity of the faults on the seismic hazard assessment was performed.

The results of the PSHA are given in terms of mean return periods and probabilities of being exceeded for horizontal component of the PGA.

Based on the logic tree formalism, the expected values of horizontal component of OBE, MDE and MCE for the site of Mzimvubu Dam, Eastern Cape are:

OBE (Return Period 144 years): ***0.018 ± 0.003g***
MDE (Return Period 475 years): ***0.039 ± 0.012g***
MCE (Return Period 10,000 years): ***0.159 ± 0.043g***

According to the applied guidelines, the site of the future dam is rated as low risk.
The uniform acceleration response spectra (horizontal component) are also provided.
A simple procedure for conversion of PSHA characteristics from horizontal to vertical component of PGA and spectra is described in Annex G.

All results of calculations are based on the assumption that the dam structures are founded on rock (NEHRP site class B/C, or equivalently to shear velocity 760 m/sec, averaged over the upper 30 m). If such an assumption is incorrect, results of the calculations must be corrected for the actual ground conditions. Annex H describes in detail how such a correction can be implemented. Finally, Annex I provides the fundamentals of a PSHA and its interpretation.

The lack of the regional ground motion prediction equation, reliable local seismotectonic model and information about seismic potential of tectonic faults in vicinity of the site of the Mzimvubu Dam are the main sources of uncertainty in this PSHA assessment. Incorporation of such information (especially information about capable tectonic faults in vicinity of the dam location) can significantly affect the provided hazard assessments.

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DEFINITION OF TERMS, SYMBOLS AND ABBREVIATIONS

Acceleration	The rate of change of particle velocity per unit time. Commonly expressed as a fraction or percentage of the acceleration due to gravity (*g*), where $g = 9.81$ m/s^2.
Acceleration Response Spectra (ARS)	Spectral acceleration is the movement experienced by a structure during an earthquake.
Annual Probability of Exceedance	The probability that a given level of seismic hazard (typically some measure of ground motions, e.g., seismic magnitude or intensity), or seismic risk (typically economic loss or casualties)
Area-specific mean seismic activity rate (λ_A)	Mean rate of seismicity for the whole selection area in the vicinity of the site for which the PSHA is performed.
Attenuation	A decrease in seismic-signal amplitude as waves propagate from the seismic source. Attenuation is caused by geometric spreading of seismic-wave energy and by the absorption and scattering of seismic energy in different earth materials.
Attenuation law - ground motion prediction equation (GMPE)	A mathematical expression that relates a ground motion parameter, such as the peak ground acceleration, to the source and propagation path parameters of an earthquake such as the magnitude, source-to-site distance, fault type, etc. Its coefficients are usually derived from statistical analysis of earthquake records. It is a common engineering term known as ground motion prediction equation (GMPE).
b-value (*b*)	A coefficient in the frequency-magnitude relation, $\log N(m) = a - bm$, obtained by Gutenberg and Richter (1941; 1949), where *m* is the earthquake magnitude and *N(m)* is the number of earthquakes with magnitude greater than or equal to *m*. Estimated *b*-values for most seismic sources fall between 0,6 and 1,2.
Capable (active) fault	A mapped fault that is deemed a possible site for a future earthquake with magnitude greater than some specified threshold.
Catalogue (seismic events)	A chronological listing of earthquakes. Early catalogues were purely descriptive, i.e., they gave the date of each earthquake and some description of its effects. Modern catalogues are usually quantitative, i.e., earthquakes are listed as a set of numerical parameters describing origin time, hypocenter location, magnitude, focal mechanism, moment tensor, etc.
Design Earthquake	The postulated earthquake (commonly including a specification of the ground motion at a site) that is used for evaluating the earthquake resistance of a particular structure.
Elastic design spectrum (or spectra)	The specification of the required strength or capacity of the structure plotted as a function of the natural period or frequency of the structure appropriate to earthquake response at the required level. Design spectra are often composed of straight line segments (Newmark and Hall, 1982) and/or simple curves, for example, as in most building codes, but they can also be constructed from statistics of response spectra of a suite of ground motions appropriate to the design earthquake(s). To be implemented, the requirements of a design spectrum are associated with allowable levels of stresses, ductilities, displacements or other measures of response.
Earthquake	Ground shaking and radiated seismic energy caused most commonly by sudden slip on a fault, volcanic or magmatic activity, or other sudden stress changes in the Earth.
Epicentre	The epicentre is the point on the earth's surface vertically above the hypocenter (or focus).
Epicentral distance(Δ)	Distance from the site to the epicentre of an earthquake.
Fault	A fracture or fracture zone in the Earth along which the two sides have been displaced relative to one another parallel to the fracture. The accumulated displacement may range from a fraction of a meter to many kilometres. The type of fault is specified according to the direction of this slip. Sudden movement along a fault produces earthquakes. Slow movement produces a seismic creep.
Focal depth(*h*)	Focal depth is the vertical distance between the hypocentre and epicentre.
Frequency	The number of cycles of a periodic motion (such as the ground shaking up and down or back and forth during an earthquake) per unit time; the reciprocal of period. Hertz (Hz), the unit of frequency, is equal to the number of cycles per second.

Ground motion	The movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.
Ground motion parameter	A parameter characterizing ground motion, such as peak acceleration, peak velocity, and peak displacement (peak parameters) or ordinates of response spectra and Fourier spectra (spectral parameters).
Heterogeneity	A medium is heterogeneous when its physical properties change along the space coordinates. A critical parameter affecting seismic phenomena is the scale of heterogeneities as compared with the seismic wavelengths. For a relatively large wavelength, for example, an intrinsically isotropic medium with oriented heterogeneities may behave as a homogeneous anisotropic medium.
Hypocenter	The hypocenter is the point within the earth where an earthquake rupture starts. The epicentre is the point directly above it at the surface of the Earth. Also commonly termed the focus.
Hypocentral distance (r)	Distance from the site to the hypocenter of an earthquake.
Induced earthquake	An earthquake that results from changes in crustal stress and/or strength due to man-made sources (e.g., underground mining and filling of a water reservoir), or natural sources (e.g., the fault slip of a major earthquake). As defined less rigorously, “induced” is used interchangeably with “triggered” and applies to any earthquake associated with a stress change, large or small.
Local Magnitude (M_L)	A magnitude scale introduced by Richter (1935) for earthquakes in southern California. M_L was originally defined as the logarithm of the maximum amplitude of seismic waves on a seismogram written by the Wood-Anderson seismograph (Anderson and Wood, 1925) at a distance of 100 km from the epicentre. In practice, measurements are reduced to the standard distance of 100 km by a calibrating function established empirically. Because Wood-Anderson seismographs have been out of use since the 1970s, M_L is now computed with simulated Wood-Anderson records or by some more practical methods.
Magnitude	In seismology, a quantity intended to measure the size of earthquake and is independent of the place of observation. Richter magnitude or local magnitude (M_L) was originally defined in Richter (1935) as the logarithm of the maximum amplitude in micrometers of seismic waves in a seismogram written by a standard Wood-Anderson seismograph at a distance of 100 km from the epicentre. Empirical tables were constructed to reduce measurements to the standard distance of 100 km, and the zero of the scale was fixed arbitrarily to fit the smallest earthquake then recorded. The concept was extended later to construct magnitude scales based on other data, resulting in many types of magnitudes, such as body-wave magnitude (m_b), surface-wave magnitude (M_S), and moment magnitude (M_W). In some cases, magnitudes are estimated from seismic intensity data, tsunami data, or duration of coda waves. The word “magnitude” or the symbol M, without a subscript, is sometimes used when the specific type of magnitude is clear from the context, or is not really important.
Maximum Regional Earthquake Magnitude (m_{max})	Upper limit of magnitude for a given seismogenic zone or entire region. Often also referred to as the maximum credible earthquake (MCE).
Operating Basis Event (OBE)	Event with an average return period in the order of 145 years i.e. 50 % probability of exceedance in 100 years.
Oscillator	In earthquake engineering, an oscillator is an idealized mass-spring system used as a model of the response of a structure to earthquake ground motion. A seismograph is also an oscillator of this type
Peak Ground Acceleration (PGA)	The maximum acceleration amplitude measured (or expected) of an earthquake.
Probabilistic Seismic Hazard Analysis (PSHA)	Available information on earthquake sources in a given region is combined with theoretical and empirical relations among earthquake magnitude, distance from the source and local site conditions to evaluate the exceedance probability of a certain ground motion parameter, such as the peak acceleration, at a given site during a prescribed period.
Response spectrum	The response of the structure to a specified acceleration time series of a set of single-degree-of-freedom oscillators with chosen levels of viscous damping, plotted as a function of the undamped natural period or undamped natural frequency of the system. The response spectrum is used for the prediction of the earthquake response of buildings or other structures.

Seismic Hazard	Any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land use, man-made structure and socio-economic systems that have the potential to produce a loss. It is also used without regard to a loss to indicate the probable level of ground shaking occurring at a given point within a certain period of time.
Seismic Wave	A general term for waves generated by earthquakes or explosions. There are many types of seismic waves. The principle ones are body waves, surface waves, and coda waves.
Seismic zone	An area of seismicity probably sharing a common cause.
Seismogenic	Capable of generating earthquakes.
Site-specific mean activity rate (λ)	Mean activity rate of the selected ground motion parameter experienced at the site.
Strong ground motion	A ground motion having the potential to cause significant risk to a structure's architectural or structural components, or to its contents. One common practical designation of strong ground motion is a peak ground acceleration (PGA) of 0.05g or larger.
GMPE	Ground motion prediction equation

D.0 TERMS OF REFERENCE

The Natural Hazard Assessment Consultancy (NHAC) Centurion, was requested by Director, Mr Jan Morris, Jeffares & Green (Pty) Ltd, Engineering & Environmental Consulting 6 Pin Oak Avenue, Hilton, Pietermaritzburg, 3201, South Africa, P.O. Box 794, Hilton, Pietermaritzburg, KwaZulu-Natal, 3245, South Africa, (e-mail of November 25, 2013), to provide a probabilistic seismic hazard analysis (PSHA) for site of future location of the Ntabelanga Dam. The Ntabelanga Dam site is located in Eastern Cape, South Africa and has approximate geographical coordinates, latitude 31.117^0 S and longitude 28.673^0 E.

In general, the hazardous effects of earthquakes can be divided into three categories:

1. Those resulting directly from a certain level of ground shaking
2. Those at the site resulting from surface faulting or deformations
3. Those triggered or activated by a certain level of ground shaking such as the generation of a tsunami or landslide.

This study covers Category 1 only and in case of PSHA is limited to the following investigations:

1. Selection of earthquakes within a radius of 320 km from the site.
2. Assessment of earthquake recurrence parameters for the area.
3. Discussion on applicable ground motion prediction equations (GMPEs) used in this study.
4. PSHA calculations and provision of seismic hazard curves in terms of Peak Ground Acceleration (PGA) and Uniform (acceleration) Response Spectra (URS).
5. PGA calculation for the Operating Basis Earthquake (OBE), Maximum Design Earthquake (MDE) and the Maximum Credible Earthquake (MCE). In this report, the OBE is defined as PGA having return period of 144 years or equivalently having a 50% probability of exceedance in 100 years. The MCE is suggested as PGA having return period of 10,000 years. In addition, following e.g. regulation ER No. 1110-2-1806, (1995), Eurocode 8 (2004), or ASCE 7-05 (2005), the MDE is calculated as PGA having a return period of 475 years or equivalently having a 10% probability of exceedance in 50 years.
6. The classic Newmark and Hall (1982) elastic design spectra for 5% damping anchored at the OBE, MDE and MCE values.

The PSHA was performed using conventional, Cornell-McGuire procedure (Cornell, 1968; McGuire, 1976; 1978), where the integration across the uncertainty in the ground motion prediction equation is an integral part of the methodology.

The procedure used in this seismic hazard assessment consists of two steps. The first step is applicable to seismic sources (known also as seismogenic sources or seismic zones) in the vicinity of the site, for which the seismic hazard analysis is required. The procedure requires an estimation of the *seismic source parameters*. The second step is applicable to a specified *site*, and consists of assessing the *site-specific parameters*, which describe the amplitude distribution of ground motion parameter PGA.

The PGA is the maximum acceleration of the ground shaking during an earthquake. Spectral acceleration is the movement experienced by a *structure* during an earthquake. The acceleration is expressed in units of gravity, *g*, which is equal to 9.81 m/s^2.

The results are given in terms of mean return periods and probabilities of being exceeded for specified values of *horizontal* component of PGA. Simple procedure of conversion of the above results from the *horizontal* to the *vertical* component of PGA is described in the paper by Abrahamson and Litehiser, Annex G.

Lists of all seismic events used in the study are given in Annex A. The procedure for PSHA as applied in this work is described in Annex B.

Lists of seismic hazard occurrence parameters for three seismogenic zones and for background seismicity are given in Annex C. Annex D provides information on the applied GMPEs.

Appendices E-F shows the results of the PSHA calculations for the site of the dam. It contains details of the computations, input data, respective hazard characteristics and their uncertainties. Annex G provides the paper by N.A. Abrahamson and J.J. Litehiser on the attenuation of the vertical peak acceleration.

The results of all the calculations are based on the assumption that the dam structures are founded on hard rock. If this assumption is incorrect, the calculations must be corrected for ground conditions.

Annex H describes in details how such corrections can be implemented.

Finally, Annex I provides the fundamentals of a PSHA and its interpretation.

D.1 INTRODUCTION

The objective of a PSHA is to obtain the probabilities of the occurrence of seismic events of a specified size in a given time interval. The methodology used in most PSHA was first defined by Cornell (1968). There are four basic steps in a PSHA:

- Step 1 is the definition of seismotectonic sources. Sources may range from small faults to large seismotectonic provinces.
- Step 2 is the definition of earthquake parameters for each source, where each source is defined by an earthquake probability distribution or earthquake recurrence relationship. A recurrence relationship indicates the chance of an earthquake of a given size occurring anywhere inside the source during a specified period. An upper bound for the earthquakes for each source is chosen, which represents the source characteristic, maximum possible earthquake magnitude.
- Step 3 is the estimation of the earthquake effects, using several GMPEs, each relating a ground motion parameter, such as PGA with distance and earthquake magnitude.
- Step 4 is the determination of the hazard at the site. The effects of all earthquakes of different sizes occurring at different locations in different earthquake sources at different probabilities of exceedance are integrated into one hazard curve that shows the probability of exceeding different levels of ground motion (such as PGA) at the site during a specified period of time.

The PSHA was performed using the conventional, Cornell-McGuire procedure (Cornell, 1968; McGuire, 1976; 1978), where the integration across the uncertainty in the ground motion prediction equation is an integral part of the methodology.

D.2 SEISMIC SOURCES AND THEIR PARAMETERS

Figure D.1 shows the distribution of all known seismic events with magnitude M_W=3.0 and stronger, that occurred within a radius of 320 km from the dam location. Only the largest events within a radius of 320 km from the site were used in the analysis, as only these events can be considered to contribute to the seismic hazard at the site. Events at larger distances from the dam site are not likely to generate PGA's large enough to be of engineering concern.

The seismic event catalogue used in this study was compiled from several sources. After critical analysis of each of the data sources, the main contribution to pre-instrumentally recorded seismicity come from Brandt *et al.* (2005). The instrumentally recorded events are mainly selected from databases provided by the Council for Geosciences, Pretoria, and the International Seismological Centre in UK.

This figure also shows the location and seismogenic zones used in this study. The future dam location is shown as a blue square.

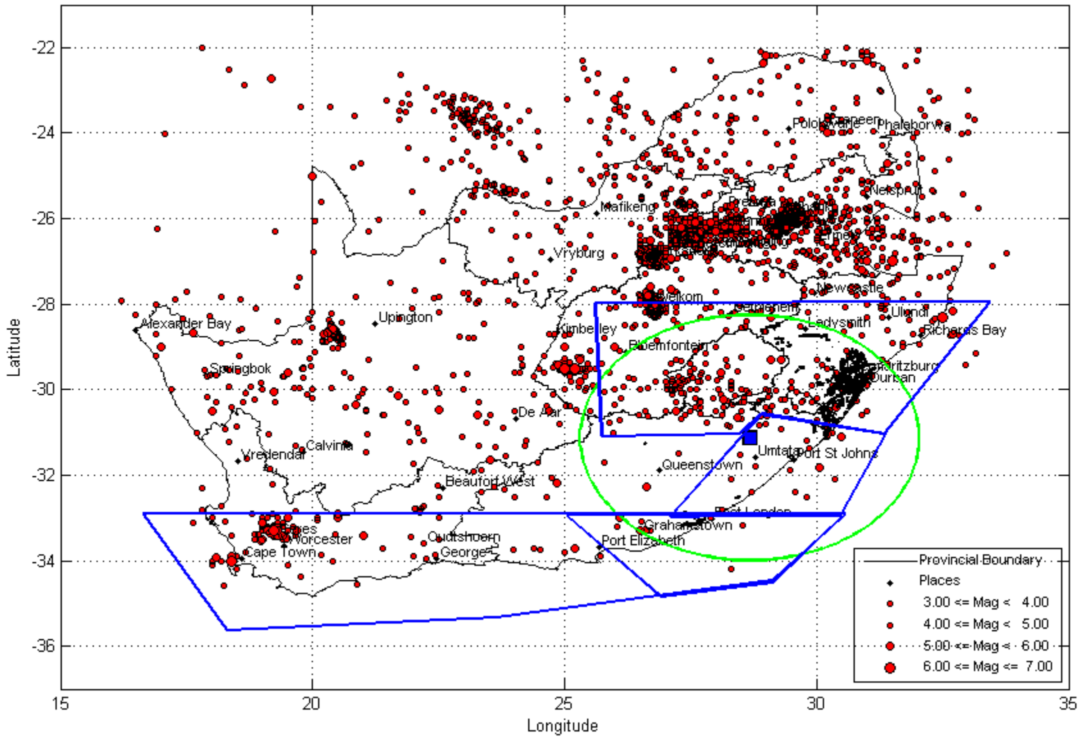

Figure C-1: Distribution of Largest Seismic Events within 320 Km Radius of Ntabelanga Dam

The close-up view of all identified faults and the three seismogenic source zones in vicinity of Mzimvubu dam (information provided by Jeffares & Green), is shown in Figure D-2. The dam location is shown as a blue square.

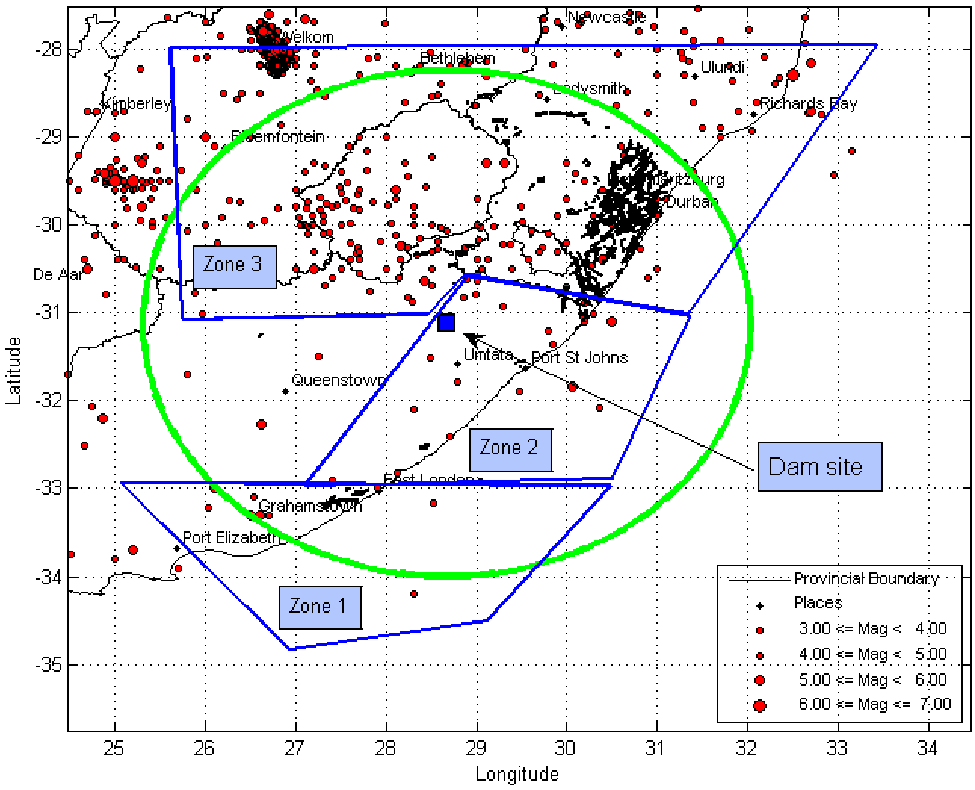

Figure C-2: Close-Up View of all Identified Faults in Vicinity of Ntabelanga Dam Site

It is assumed that magnitudes of earthquakes recorded within the specified area are distributed according to the Gutenberg-Richter relation

$$\log n(m) = a - b \cdot m, \quad \text{(Eq 1)}$$

Where *a* is a constant, *b* refers to the slope of the line, *m* is the earthquake magnitude and *n* the cumulative number of earthquakes occurring annually within a magnitude interval <*m*, *m* +Δ *m*>, or the number of earthquakes equal or larger than *m*. The parameter *a* is the *measure of the level of seismicity*, whereas the parameter *b*, which is typically close to 1, describes the *ratio* between number of small and large magnitude events.

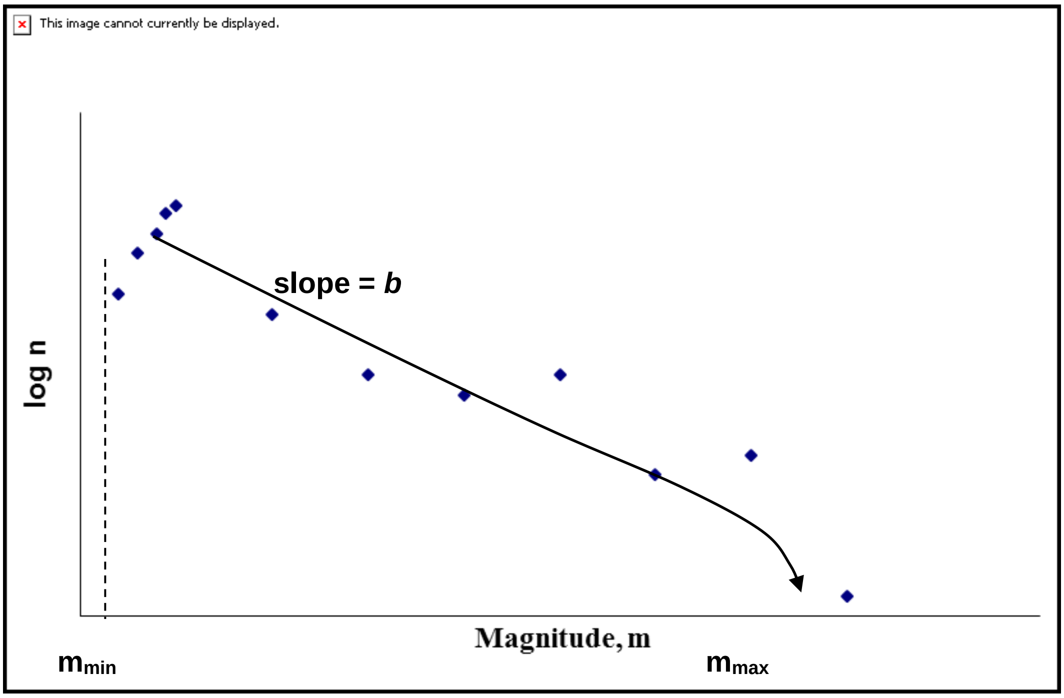

Figure C-3: Schematic Illustration: Doubly Truncated Frequency-Magnitude Gutenberg-Richter Relation

Acceptance of the classic frequency-magnitude Gutenberg-Richter relation (Eq 1) is equivalent to the assumption that the cumulative distribution function (CDF) of earthquake magnitude distribution is of the form

$$F_M(m) = \frac{\exp(-\beta m_{\min}) - \exp(-\beta m)}{\exp(-\beta m_{\min}) - \exp(-\beta m_{\max})}. \quad \text{(Eq 2)}$$

In Figure D-3 and equation (Eq 2), m_{min} is the minimum earthquake magnitude for which the earthquake catalogue is considered complete, m_{max} is the regional characteristic, maximum possible earthquake magnitude, and $\beta = b \cdot \ln(10)$, where *b* is the parameter of the frequency-magnitude Gutenberg-Richter relation (6.1).

The slope of the curve is described by parameter b, known as the b-value of the Gutenberg-Richter. Value mmin is the minimum earthquake magnitude to be considered and m_{max} is the regional characteristic, maximum possible earthquake magnitude.

Following Cornell (1968), each seismic source is described by three parameters: the mean seismic activity rate λ, Gutenberg-Richter *b*-value, and m_{max}.

The mean seismic activity rate λ, is defined as the ratio

$$\lambda = \frac{Number\ of\ earthquakes\ with\ m \geq m_{\min}}{Time\ span\ of\ observations} \quad , \qquad \text{(Eq 3)}$$

or equivalently as

$$\lambda = \frac{n(m \geq m_{\min})}{t}$$

Where *n* is the number of earthquakes of magnitude m_{min} and greater that occurred within a specified time interval *t.*

One can show that parameters *a* and *b,* level of completeness m_{min} and the mean activity rate λ, are linked together, and the following equation holds

$$a = \log_{10} \lambda + b \cdot m_{\min} \qquad \text{(Eq 4)}$$

Following the respective guidelines, the first action required in the determination of PSHA is the generation of a **data-driven** seismotectonic model that divides the investigated region into areas of similar seismic potential, called *seismogenic zones*. The first attempt to create the seismotectonic model for South Africa was done independently by Du Plessis (1996), Partridge (1995) and Hartnady (1996). The most recent attempt to develop a seismotectonic model for South Africa is described in two papers by Singh *et al*. (2009; 2011).

Unfortunately, all above attempts to build such a model have significant shortcomings and can be treated only as models of first-order and are not used in this study. In this report an alternative approach, as applied in the construction of the seismic hazard map for the United States (Frankel *et al*., 1996, 2002), has been used.

For the site, the area of 320 km radius was divided into 25 km x 25 km ‘point seismic sources’. Then, for each point seismic source the parameters λ, *b*-value and m_{max} were calculated. The parameters of the three seismogenic zones, (information provided by Jeffares & Green, Figures D-1 and D-2), were calculated separately and are provided in Annex C. One has to note that often, the seismicity outside the seismogenic zones is called “diffuse” or “background” seismicity.

In this investigation the recurrence parameters: the mean activity rate λ, *b*-value of Gutenberg-Richter and seismic source characteristic m_{max} are calculated according to maximum likelihood procedure developed Kijko and Sellevoll (1992) and Kijko (2004). The applied approach accounts for incompleteness and uncertainty in the seismic event catalogues. More details can be found in the description of the applied methodology in Annex B.

D.2.1 Tectonic Settings of the Mzimvubu Dam

The African plate, on which South Africa is situated, includes the East African Rift System, southern Africa and ends in the Indian Ocean. Plate boundaries in both the continental and oceanic lithosphere (including the African wide-plate boundary) are hundreds and thousands of kilometres wide. It is in fact cover roughly 15% of Earth’s total surface area (Gordon and Stein, 1992). This plate is considered one of the most tectonically stable areas and is bounded, by the South West Indian Ridge (SWIR) in the east, the Antarctic ridge (south), the mid-Atlantic ridge (west), the Hellenic arc (subduction zone) in the north and the Gulf of Aden/Afar triple junction in the north-east.

The southern African region can be sub-divided into the following tectonic provinces (Silver *et al*., 2001) and is depicted in Figure D-4:

- Zimbabwe Craton
- Limpopo Mobile Belt
- Kheis Thrust Belt
- Kaapvaal Craton (includes the Bushveld complex)
- Namaqua-Natal Mobile Belt
- Cape Fold Belt.

Evidence of tectonic uplift in southern Africa during the last 3 Ma (mega-annum) may be inferred from the uplift of Neogene diamond-bearing marine deposits and the relationship between onshore denudation and offshore sedimentation in, for example, KwaZulu Natal (Hartnady and Partridge, 1995). These authors subsequently speculated that the diapir plumes that buoy up a large part of East Africa have also affected South Africa.

The African wide-plate boundary is characterised by belt-like zones of seismicity surrounding relatively aseismic blocks. The seismicity in South Africa appears to portray the same spatial style and supports the notion that the wide-plate boundary extends into South Africa. The rift between the Nubia (west section) and the Somalia (east section) plate, south of 20ºS off the coast of Mozambique, is along the southwest Indian Ridge (Lemaux *et al*., 2002).

These two plates are extending in at a slow rate and are commonly known as the East African Rift System (EARS). Seismicity is observed in the EARS as far as the southern part of Africa. It is also theorized that this extension connects to the southwest Indian ridge (Bird, 2003; Hartnady, 2002; Rudolf, 2002). Some scientists believe the opposite i.e. the rift would follow their boundaries (Stein and Wysession, 2003). Hence, even though South Africa may be influenced by the wide-plate boundary between the Nubian and Somalian plates, the rift itself does not extend into the country.

Recent studies on the distribution of earthquake epicentres have identified the existence of two stable blocks namely the Okavango Rift (Botswana), the rift-grabens (Mozambique) and the Senqu Seismic Belt. This belt is discrete zone of seismicity observed in South Africa (Hartnady, 2002) as seen in Figure 2 (Malephane, 2007).

The Senqu belt is seismically active and stretches from the Koffiefontein seismic cluster to the southern Lesotho and the southern part of Mozambique. This relatively aseismic block within the wide Nubia- and Somalia plate boundary zone is recently identified as a potential 'Trans-Gariep micro-plate' (Hartnady, 1998) and includes the southern boundary of the Kaapvaal province, the Namaqua-Natal province, the Karoo basin and ends in the Cape basin (Brandt, 2000).

The provinces are modified from the South African Seismic Experiment Project (Malephane, 2007). The regions are defined as a) Kheis thrust belt, b) Cape fold belt, c) Zimbabwe Craton, d) Limpopo mobile belt, e) Kaapvaal Craton and f) Namaqua-Natal mobile belt.

The numbers in red denote the seismicity regions. Region 1 is the Okavango rift; region 2 is the Mozambique rift-grabens; region 3 represents the mines of South Africa; region 4 is the Koffiefontein cluster which together with region 5 in southern Lesotho, form the Senqu Seismic Belt; region 6 is the Ceres-Tulbagh region. (Source: Malephane, 2007).

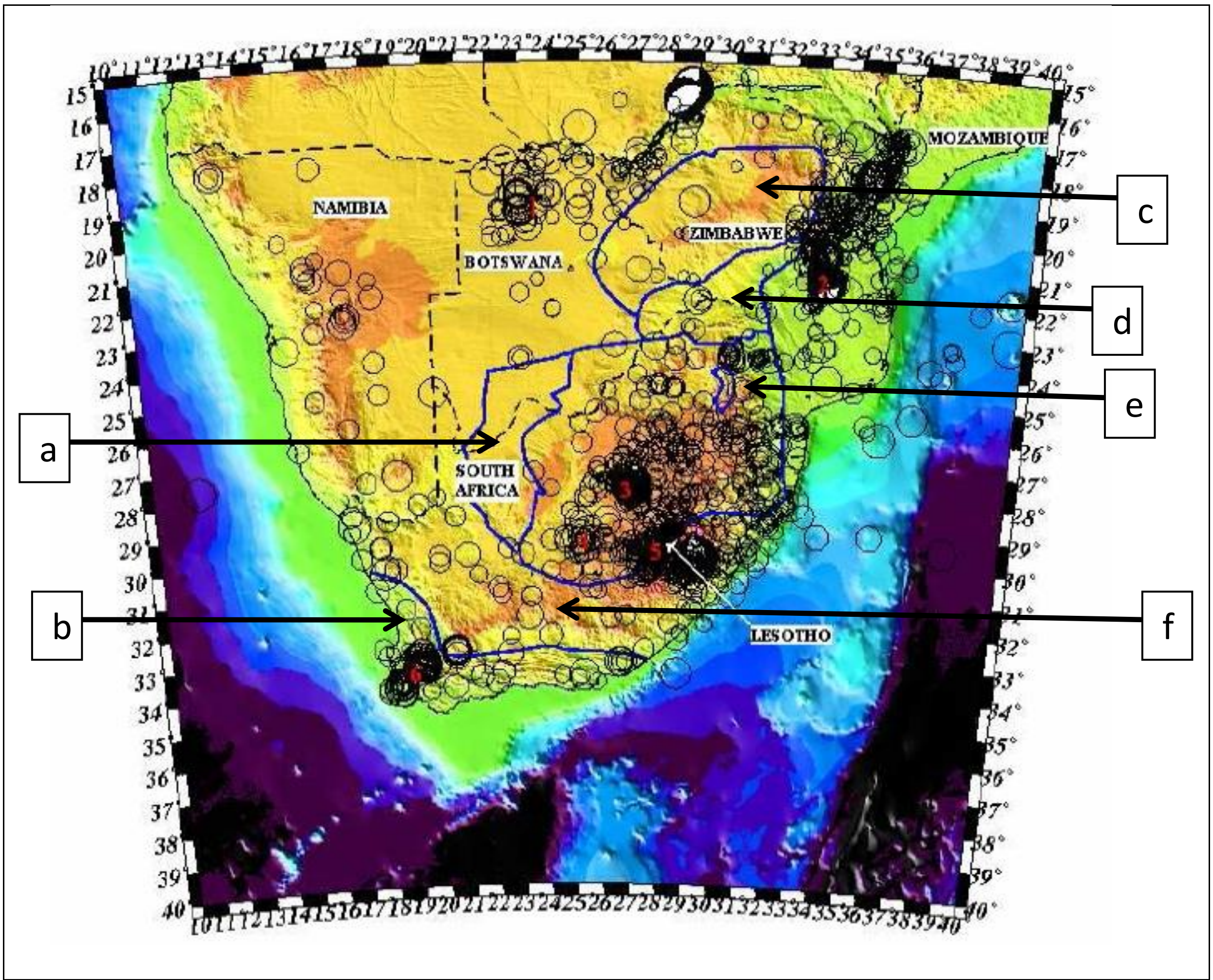

Figure C-4: Tectonic Provinces and Earthquake Distribution Map for Southern Africa (1620 To 2006)

Geologically speaking, the site of the Ntabelanga Dam is situated at the region known as the Namaqua-Natal mobile belt tectonic province.

Following the respective guidelines, the first action required in the determination of PSHA is the generation of a **data-driven** seismotectonic model that divides the investigated region into areas of similar seismic potential, called *seismogenic zones*. Probably, the first attempt to create the seismotectonic model for South Africa was done independently by Du Plessis (1996), Partridge (1995) and Hartnady (1996).

Despite of the fact that the three models were developed independently they are in surprisingly good agreement. Since the Du Plessis model (Figure D-5) provides more details, especially on the seismic clusters, it is preferable for the application in probabilistic seismic hazard analysis. Du Plessis (1996) work distinguishes four major regions displaying diffuse enhanced seismicity:

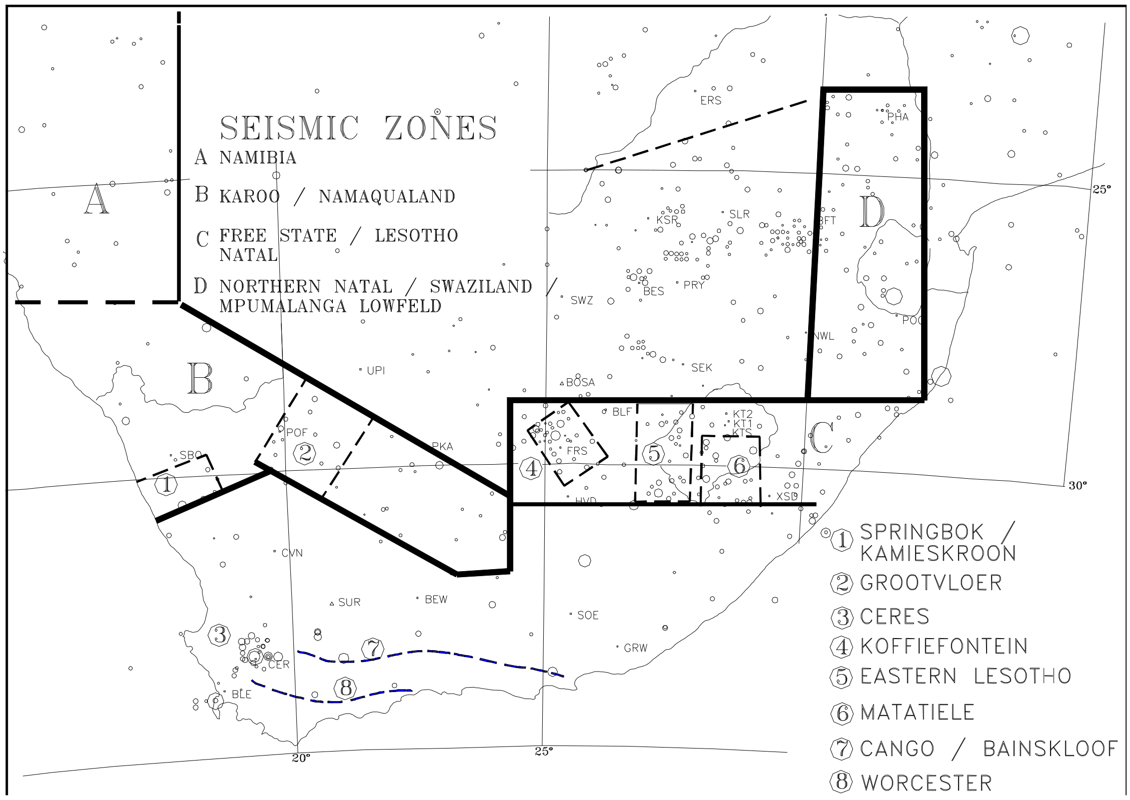

Figure C-5: Seismotectonic Provinces after Du Plessis (1996)

A **The Namibia Zone** which covers that country from the coast inland to 18°E.

B **The Karoo/Namaqualand Zone** which extends from approximately 25°E between 30°S and 32°S (200 km wide) in a mainly north-easterly direction towards Namibia with its southern boundary at 31.5°S on the west coast.

C **The Free State/Lesotho/Natal Zone** which is located between 29°S and 31°S (200 km wide) extending from Koffiefontein in the west eastwards to the coast and is almost coincident with the Cedarville Province of Hartnady (1996).

D **The Northern Natal/Swaziland/Mpumalanga and Northern Province Low field Zone** which extends northwards from 28°S between the longitudes of 30°E and 32°E (200 km wide) and which is largely coincident with the Mpumalanga Province of Hartnady (1996).

One has to note, that since the introduction of the Du Plessis model in 1996, the diffuse seismicity has become more populated, however, with the updated earthquake catalogue there is no significant deviation to the original model with respect to delineation of capable faults and 'new' seismic event clusters.

The most recent and the most comprehensive seismotectonic model for South Africa is described in two papers by M. Singh, A. Kijko and R. Durrheim: "*Seismotectonic Models for South Africa. Synthesis of Geoscientific Information, Problems and Way Forward*", Seismol Res Lett, **80,** 70–80), and "*First-Order Regional Seismotectonic Model for South Africa*", Natural Hazards, **59,** 383–400, (Singh *et al*., 2009; 2011).

Probably, the first seismic event in South Africa was reported in 1620 by the early Dutch settlers. The improvement in the recording methods of seismic events as well as investigations into the seismic nature of South Africa indicated that this area behaves typically of an intraplate region.

The intraplate earthquakes tend to have longer recurrence times and higher stress drops than interplate earthquakes. In most cases, the underlying cause of intraplate seismic activity is difficult to understand (e.g. Kanamori and Anderson, 1975). In addition, **the correlation between seismic event location and the surface expression of major geological features is not clear (Fernandez and Guzman, 1979a and b)**. Even in case of location of a few seismic events in the vicinity of identified tectonic fault, often, a significant correlation could not be established due to the poor quality of location. The earthquake locations in the studied area have a considerable error, often order of 100 km, especially for the events located prior 1971 (Saunders *et al.*, 2008).

The largest historically and instrumentally known earthquake in South Africa took place in vicinity of the Ceres-Tulbagh on September 29, 1969. According to Van Wyk and Kent (1974), the magnitude of this earthquake was 6.3 with the maximal intensity VIII on the Mercalli Modified Scale. The greatest damage occurred in the intensively farmed Groot-Winterhoek Valley. Extensive damage also occurred in the neighbouring town of Ceres, Tulbagh and Wolseley.

The earthquake was felt as far as Durban, in distance ca. 1 200 km. The earthquake was followed by a long sequence of aftershocks, the most severe of which had a magnitude of 5.7. Epicentral distribution of the aftershocks indicates fracturing along a near vertical northwest striking plane connecting the Saron and Groenhof faults (Keyser, 1974). The focal mechanism of the September 29, 1969 event and distribution of its aftershocks were investigated by Green and McGarr (1972).

D.2.2 Seismicity in vicinity of the Ntabelanga Dam

The Ntabelanga Dam site is located in Eastern Cape, on the Tstitsa River, a tributary of the Mzimvubu River. It lies about 50 km, NNW of the city of Mtata, about 30 km east of Maclear and about 22 km NW of Tsolo. The seismicity of tectonic origin observed in the area is relatively low as expected from an intraplate region. The intraplate earthquakes tend to have longer recurrence times and higher stress drops than interplate earthquakes. The underlying cause of intraplate seismic activity is difficult to understand (e.g. Kanamori and Anderson, 1975).

The seismicity of tectonic origin surrounding the Ntabelanga Dam is low. Recently recorded seismicity includes the 27 January 2002 seismic event of magnitudes $M_L \cong 4.6$ ($M_W = 4.7 \sim 4.9$) that occurred in central-southern Lesotho (Malephane, 2007). A magnitude $M_L = 5.1$ ($M_W \cong 5.2$) earthquake in 1986 occurred in the southern part of Lesotho. The largest earthquake in the area (but in the distance exceeding 320 km for location of the Mzimvubu Dam) is the Koffiefontein event of 1 July 1976 of magnitude $m_b = 5.9$.

To the north-east of the dam location is the site of the powerful seismic event (M_L between 6.3 and 6.8) of 31 December 1932 on the offshore of Cape St Lucia. This event rocked the KwaZulu-Natal coast and was widely felt throughout the whole country. A homestead collapsed in Masunzeni near Newcastle with other less severe structural and non-structural damage observed near the epicentre. A cattle train derailed after the railway embankment failed near Mtubutuba (www.geoscience.org.za). Further north the massive seismic event of $M_w = 7.0$ occurred on 22 February 2006 in Mozambique. This event was felt in the rest of Southern Africa (Fenton and Bommer, 2007) but caused little damage.

The database of seismic events for South Africa is incomplete, due to the fact that large parts of the area were very sparsely populated and the detection capabilities of the seismic network are far from uniform.

The catalogue used in the analysis spans a period of ca. 153 years; from 1 January 1850 to 1 January 2013. The catalogue is divided into an incomplete (largest events only) and five complete parts, (Table D-1).

Table C-1: Division of the Catalogue Used in the Analysis

Type of Catalogue	Span	m_{min}	SE
Incomplete (largest events only)	1850/01/01 – 1970/12/31	-	0.3
Complete #1	1971/01/01 – 1980/12/31	4.0	0.3
Complete #2	1981/01/01 –1990/12/31	3.8	0.2
Complete #3	1991/01/01 –2002/12/31	3.5	0.2
Complete #4	2003/01/01 –2010/12/31	3.3	0.2
Complete #5	2011/01/01 –2013/01/31	3.0	0.1

Note: m_{min} = Level of completeness; SE = standard error (assumed uncertainty in earthquake magnitude determination).

Since current knowledge of the area does not provide information on potential movement of the 594 neotectonic origin (Quaternary) faults in radius of 320 km from the dam site (information provided by Jeffares & Green), an investigation of the effect of potential seismic activity of the faults on the seismic hazard assessment was performed.

No relationships between instrumentally recorded or historic seismicity and fault location could be established. Also, no information on paleo-seismicity of the area was available. Therefore, in this report, the assessment of the maximum possible earthquake magnitude m_{max}, which can be generated by the identified faults, is based on its length. Our procedure of m_{max} estimation for a fault consists from two steps: (1) estimation of the most probable rupture length of the fault, and (2) estimation of the maximum possible fault-characteristic earthquake magnitude m_{max} based on empirical equations relating surface rupture length with moment magnitude.

In step one, estimation of the most probable rupture length of the fault was carried out according to procedure developed by Slemmons and Chung (1982). Slemmons and Chung (1982) has show that in average, fraction of a fault that ruptures, increases linearly with fault length according to formula $PRC(L) = 15.76 + 0.012 \cdot L$, where $PRC(L)$ is percent of total fault length that ruptures and L is total fault in km.

In Step 2, we input estimated rupture length into well known Wells and Coppersmith (1994) empirical equation, relating surface rupture length to moment magnitude. So estimated earthquake magnitude is considered as a fault characteristic, maximum earthquake magnitude m_{max}. The other two hazard recurrence parameters (the Gutenberg-Richter b-value and the mean activity rate λ) for each source fault has been estimated according to procedure developed by Kijko and Sellevoll (1992) and are based on knowledge of seismicity of the area.

All characteristics of all 594 faults (Figure D-1), as coordinates of its edges, total fault length, segment length with corresponding maximum earthquake magnitude, seismic parameters of the seismogenic zones within radius of 320 km from the dam site, seismic characteristics of three seismogenic zones and parameters of the “diffuse” (background) seismicity point seismic sources are given in Annex C.

D.3 GROUND MOTION PREDICTION EQUATIONS (GMPES)

Attenuation is the reduction in amplitude or energy of seismic waves caused by the physical characteristics of the transmitting media or system. It usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from the source.
Attenuation relationships known as ground motion prediction equations (GMPEs) for the investigated area established on the basis of strong motion data are practically non-existent (Minzi *et al*., 1999).

Three attempts to establish the horizontal component of PGA attenuation for the Eastern and Southern Africa are published: one by Jonathan (1996), one by Twesigomwe (1997) and more recently by Mavonga (2007). Jonathan's GMPE is based on the random vibration theory and is scaled by seismic records recorded by local seismic stations. Twesigomwe's equation is a modification of GMPE by Krinitzky *et al*. (1988). Comparison of the two regional GMPE with the e.g. global equation by Joyner and Boore (1988), Boore *et al.*, 1993; 1994) shows relatively good agreement between regional attenuations and used globally.

Finally, the most recent GMPE by Mavonga (2007) is based on well known procedure (Frankel, 1995; Irikura, 1986) of simulation of the ground motion of large earthquakes using recordings of small earthquakes. Seismic records of small earthquakes adjacent to the expected large earthquakes have been treated as an empirical Green's function. The advantage of the procedure is that predicted ground motion contain information on the site response, details of path effects, etc., therefore often they can produce realistic time histories. Unfortunately, all three GMPEs are derived only for PGA, and are not applicable to short, below 10 km distances.

The lack of reliable regional GMPE is one of the biggest sources of uncertainty in this seismic hazard assessment.

In this study, all assessments of seismic hazard are based on two, recent and well studied models of ground motion prediction equations.

The first applied GMPE of horizontal component (Atkinson and Boore, 2006), was developed for the central and eastern United States which is situated in a type of tectonic environment known as an intraplate region, or equivalently, stable continental area. The GMPE is denoted as AB06.

The second GMPE, belonging to the family of "Next Generation Attenuation" equations (NGA), (Boore and Atkinson, 2008), is appropriate for predicting earthquake generated horizontal component of ground motions in active tectonic regions with shallow crustal seismicity. Itwas derived by empirical regression of strong-motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation Attenuation) project.

For frequency of ground motion exceeding 1 Hz, the analysis used 1,574 records from 58 earthquakes in the distance range from 0 km to 400 km (Boore and Atkinson, 2008). The GMPE is denoted as BA08.

The two selected GMPEs, including their functional form and respective coefficients, are provided in Annex D.

D.4 PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR THE MZIMVUBU DAM SITE

In order to determine the seismic hazard curve for the site, i.e. probabilities of exceedance of specified values of PGA, the earthquake recurrence parameters obtained for each seismic source, together with the applied GMPE are integrated. Details of the applied procedure are described in Annex B.

Taking into account that very little is known about seismic potential of 594 identified faults in vicinity of the dam site (Figures D-1 and D-2), two scenarios regarding their seismic activity were considered:

(a) All faults identified in vicinity of 320 km from the dam site are not active. It means that the seismic activity of seismogenic zone delineated by the mapped faults is determined only by past seismic activity.
(b) The identified faults are active. It was assumed that faults activities can double the current activity of the area. The assumption is moderately conservative and equivalent to the postulation that in vicinity of the dam site, in average, one can expect, occurrence of fault-associated seismic event of magnitude 4.0 and stronger, approximately every 4 years, or equivalently, event of magnitude 5.0 every 40 years.

The respective seismic hazard curves (the annual probabilities of exceedance of median value of PGA at the dam site) for two applied GMPEs, AB06 and BA08, and two seismic activity scenarios are shown in Figures D-6 to D-9. Figures D-10 to D-13 show the respective return periods of specified values of median PGA. These are calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006).

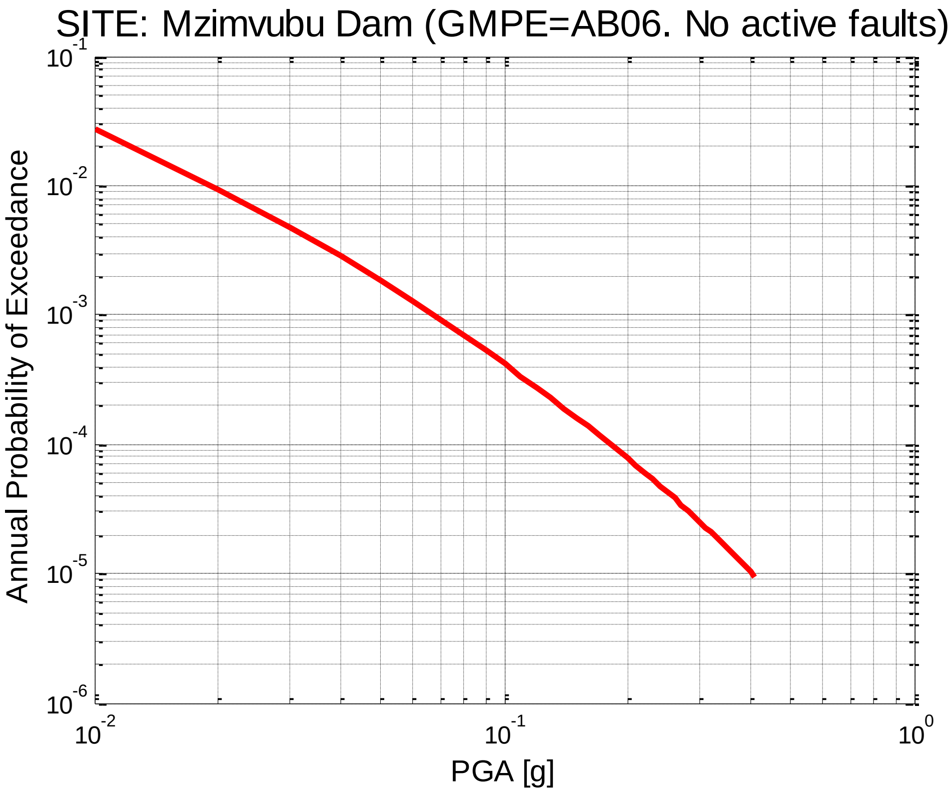

Figure C-6: Annual probability of exceedance of median value of horizontal PGA at dam site. Scenario #1: all known faults in vicinity of the dam are not active.

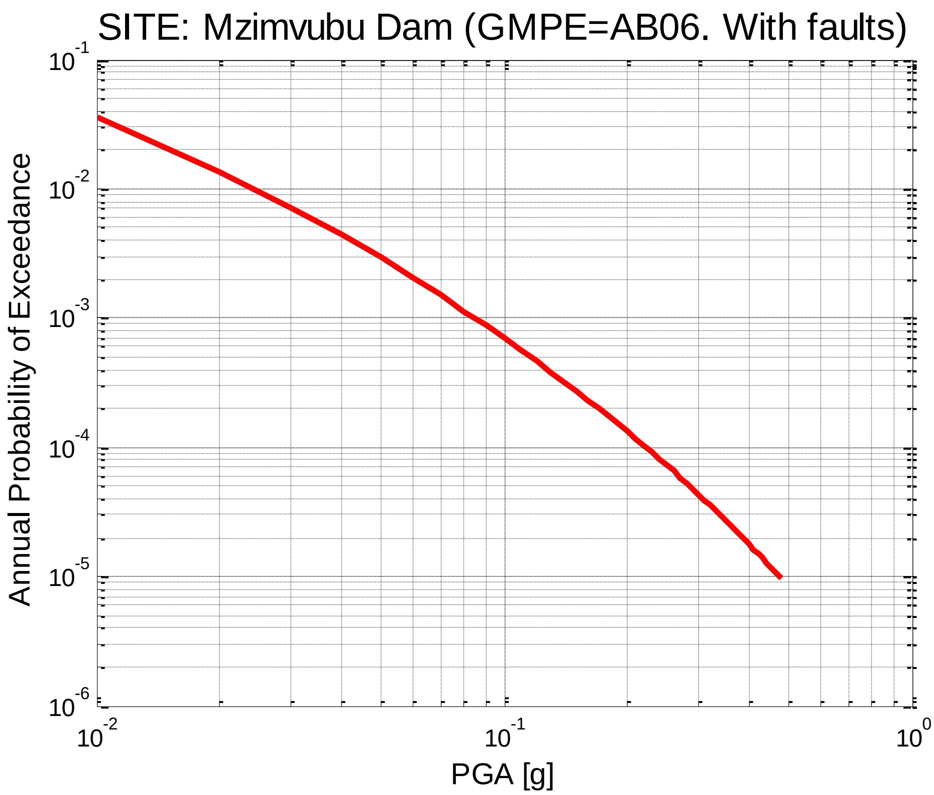

Figure C-7: Annual probability of exceedance of median value of horizontal PGA at dam site. Scenario #2: all known faults in vicinity of the dam are active.

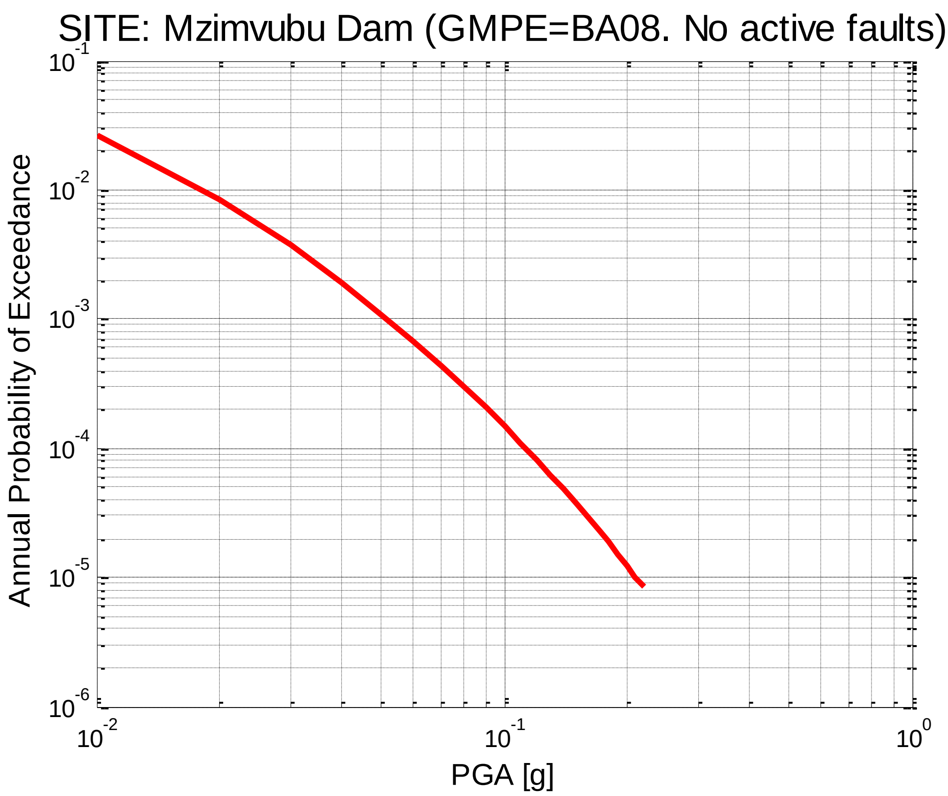

Figure C-8: Annual probability of exceedance of median value of horizontal PGA at dam site, Scenario #1: all known faults in vicinity of the dam site are not active.

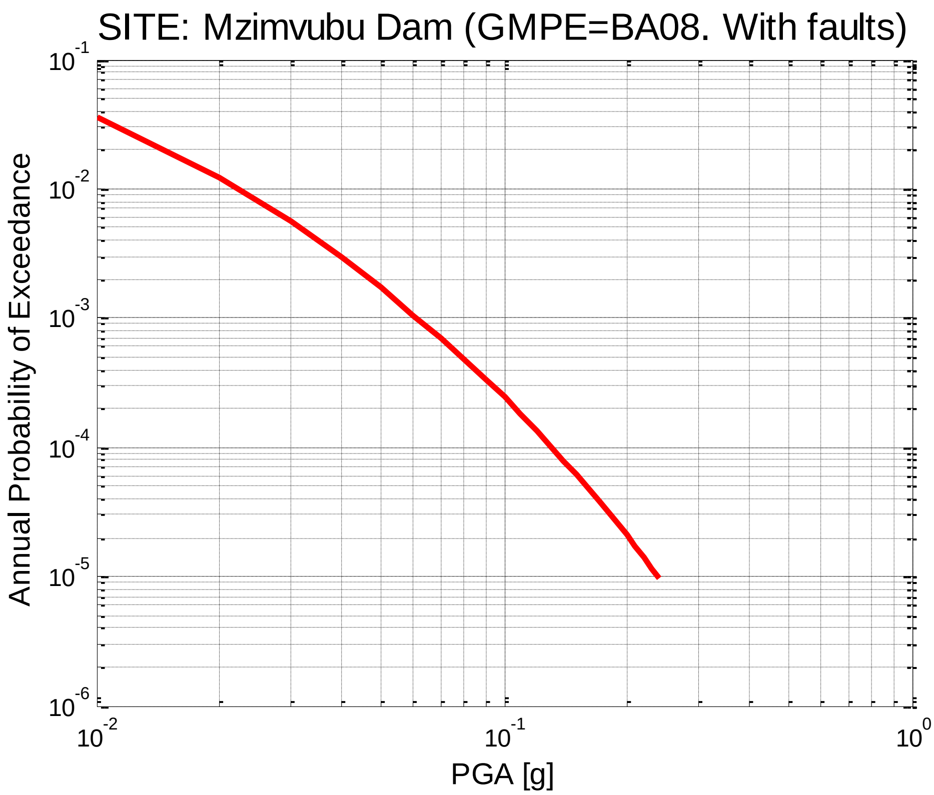

Figure C-9: Annual probability of exceedance of median value of horizontal PGA at the dam site. Scenario #2: all known faults in vicinity of the dam site are active.

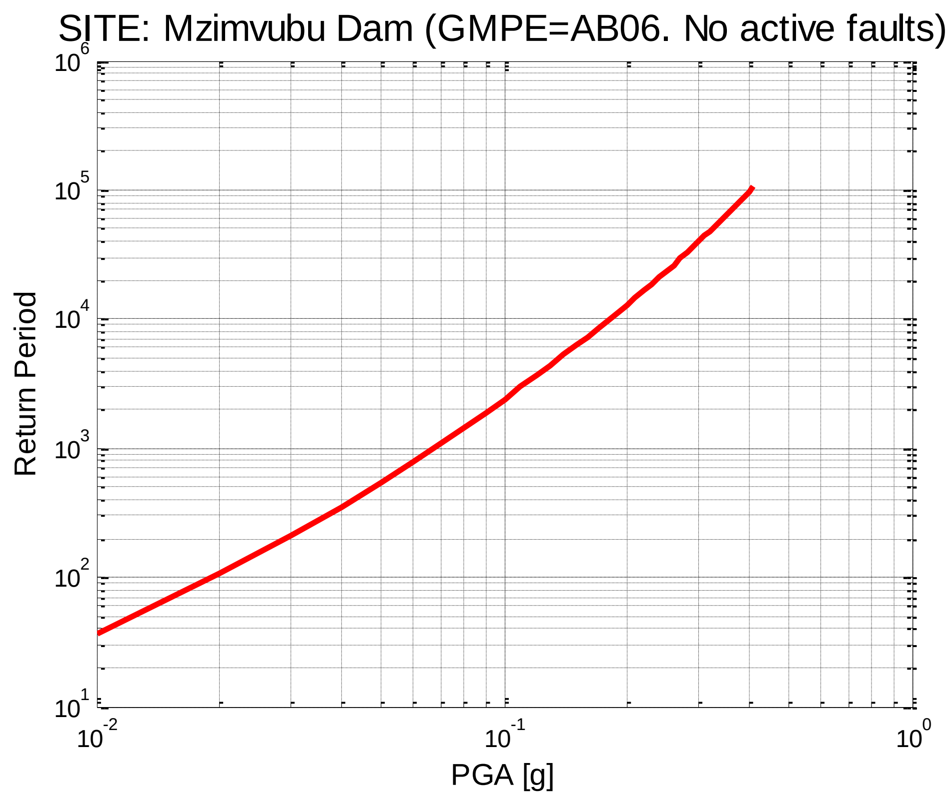

Figure C-10: Mean return period of median value of horizontal PGA at the dam site. Scenario #1: all known faults in vicinity of the dam site are not active.

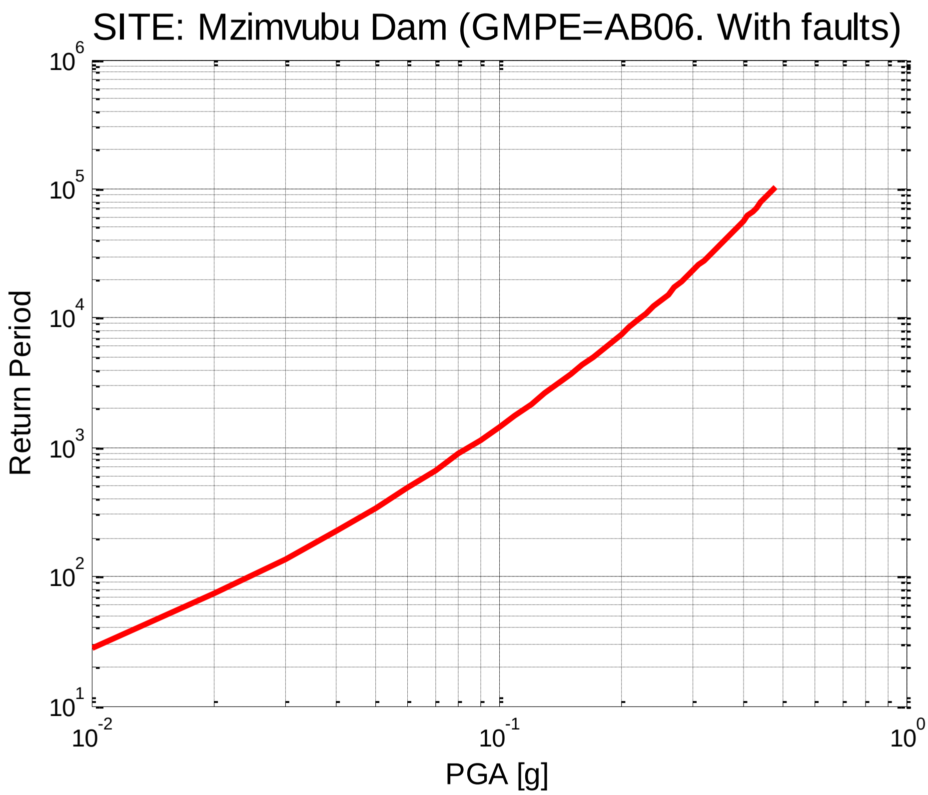

Figure C-11: Mean return period of median value of horizontal PGA at the dam site. Scenario #2: all known faults in vicinity of the dam site are active.

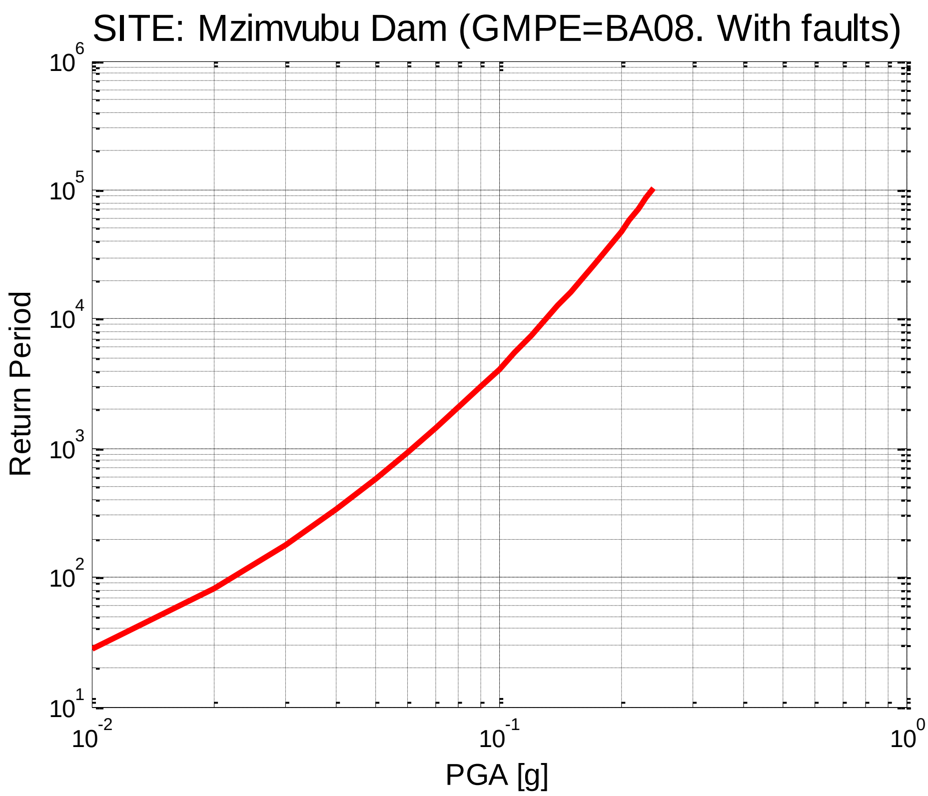

Figure C-12: Mean return period of median value of horizontal PGA at the dam. Scenario #1: all known faults in vicinity of the dam site are not active.

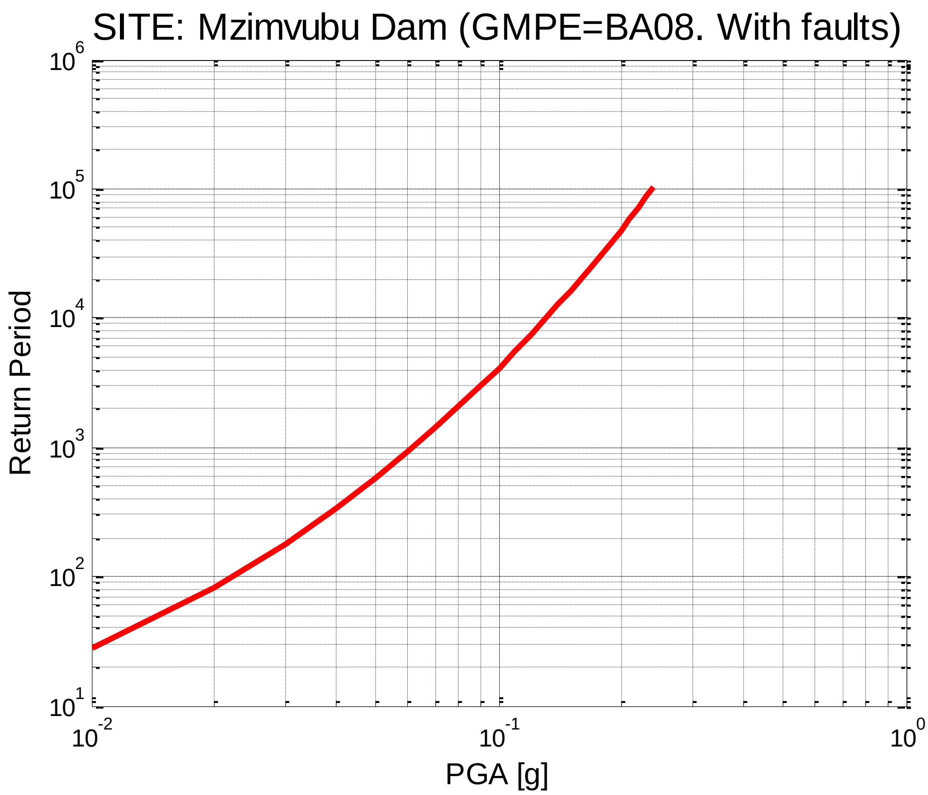

Figure C-13: Mean return period of median value of horizontal PGA at the dam. Scenario #2: all known faults in vicinity of the dam site are active.

All above results are also listed in the Annex E**.** Plots of the same hazard curves and return periods, including their confidence intervals are shown in Annex F. Simple conversion procedure of above results from *horizontal* to *vertical* component of PGA is described in Annex G.

D.4.1 Design Earthquake Criteria

In this report, three levels of ground motion at the dam site are considered, Maximum Credible Earthquake (MCE), Maximum Design Earthquake (MDE) and Operating Basis Earthquake (OBE).

The *Operating Basis Earthquake* (OBE) represents the level of ground motion at the dam site at which only minor damage is acceptable. The dam operation should remain functional and damage easily is repairable from the occurrence of earthquake shaking not exceeding the OBE (ICOLD, 1989; *Engineering and Design*, ER 1110, 1995). The quoted documents specifies that for civil works projects like the Ntabelanga Dam, one could use for the OBE a 50% probability of not being exceeded in 100 years, or equivalently, PGA with return period of 144 years.

The *Maximum Design Earthquake* (MDE) is the maximum level of ground motion for which a structure is designed. The associated performance requirement is that the structure performs without catastrophic failure, although severe damage or economic loss may be tolerated. For critical structures, the MDE is the same as the MCE. For all other structures, the MDE can be selected lower than the MCE (*Engineering and Design*, ER 1110-2-1806; 1995). In this report MDE is defined as earthquake with a return period of 475 years, or equivalently as PGA with 10% probability of exceedance within 50 years.

The *Maximum Credible Earthquake* (MCE) is the largest conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. In this report MCE is defined, as the PGA having a return period of 10,000 years, or equivalently, 0.5% probability of exceedance in 50 years. The selected time period of 10,000 years is standard for critical structures for areas with low to moderate seismicity, ICOLD (1989); *Engineering and Design*, ER 1110-2-1806 (1995).

Table 8-1 lists the OBE, MDE and MCE estimates for the two scenarios and two applied GMPEs. The OBE value for the two GMPEs is within range 0.014g – 0.023g. The MDE values fall within range 0.025g - 0.059g and MCE values fall within range of 0.112g to 0.220g.

Table C-2: OBE, MDE and MCE estimates (horizontal component) for two considered scenarios and two GMPEs

	Scenario # 1 – Faults are not Active	**PGA [g]** **GMPE AB06**	**PGA [g]** **GMPE BA08**
OBE	Return period of 144 years (equivalent to 50% probability of exceedance in 100 years)	0.017	0.014
MDE	Return period of 475 years (equivalent to 10% probability of exceedance in 50 years)	0.039	0.025
MCE	Return periodof 10 000 years (equivalent to 0.5% probability of exceedance in 50 years)	0.178	0.112
	Scenario #2: Faults are active	**PGA [g]** **GMPE AB06**	**PGA [g]** **GMPE BA08**
OBE	Return period of 144 years (equivalent to 50% probability of exceedance in 100 years)	0.023	0.016
MDE	Return period of 475 years (equivalent to 10% probability of exceedance in 50 years)	0.059	0.034
MCE	Return period of 10 000 years (equivalent to 0.5% probability of exceedance in 50 years)	0.220	0.125

According to the applied guidelines, the site of the future dam is rated as low risk.

D.4.2 Uniform Hazard Spectra

The Uniform Hazard Spectrum (UHS) represents a constant probability or uniform hazard (response) spectrum. Essentially, it shows ground motion amplitudes over a number of oscillator periods of engineering interest at the same return period or probability of exceedance.

The Uniform Hazard Spectrum, (UHS), known also as a uniform acceleration response spectrum is actually a lateral slice of an ensemble of hazard curves for a given probability of exceedance (or equivalent return period), where each curve represents the acceleration at a particular frequency.

The UHS does not reflect the shape of the spectrum of any particular earthquake, but provides a combination of contributions from distant large magnitude events and nearer, smaller ones. This is a drawback if the spectrum is to be used directly for multi-mode analysis or to generate a strong motion record. However, for normal buildings, in low seismicity areas, the main need is to provide a single, frequency dependent indicator of lateral strength requirement, for which refinement of considering multi-modes is not necessary. Moreover, the UHS can be used as an envelope criterion for the spectra from a set of real time histories which can be used in more advanced designs.

Figures D-14 to D-17 show horizontal UHS for the Ntabelanga Dam site calculated for two scenarios and two GMPEs: AB06 (Atkinson and Boore, 2006) and BA08 (Boore and Atkinson, 2008). The UHSs are calculated as a function of a ground motion vibration frequency for 3 probabilities, 0.5% (service), 0.1% (abnormal) and 0.01% (extreme). The same results expressed in terms of both the ground motion vibration frequency and ground motion vibration period are shown in Annex E.

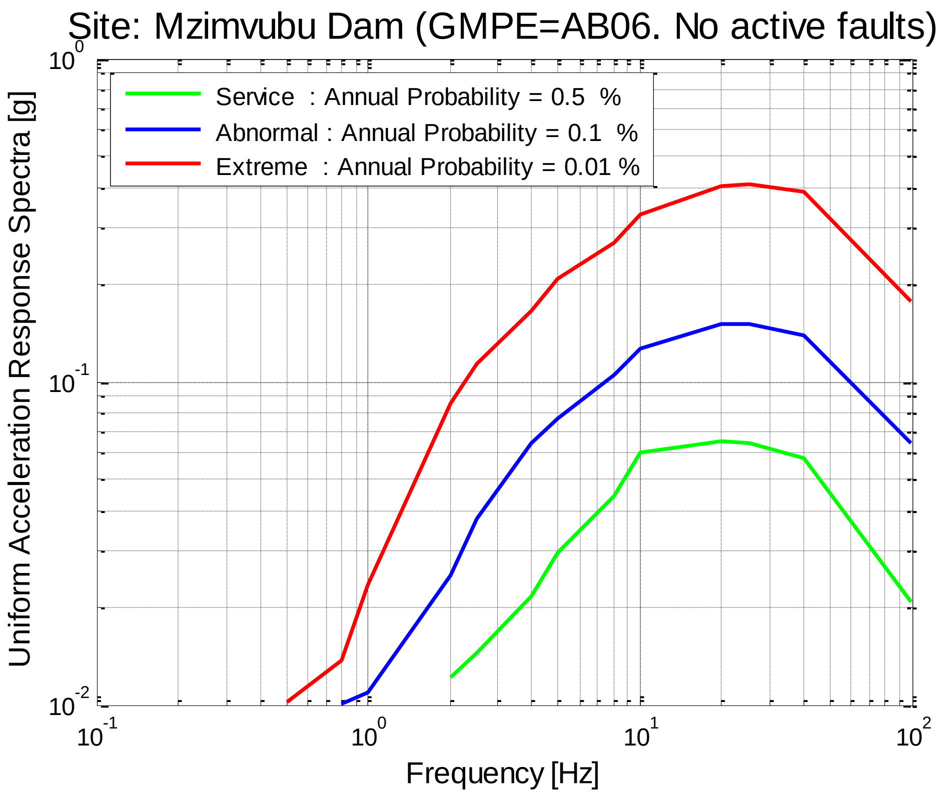

Figure C-14: Horizontal Uniform Acceleration Response Spectra. Scenario #1: all known faults in vicinity of the dam site are not active.

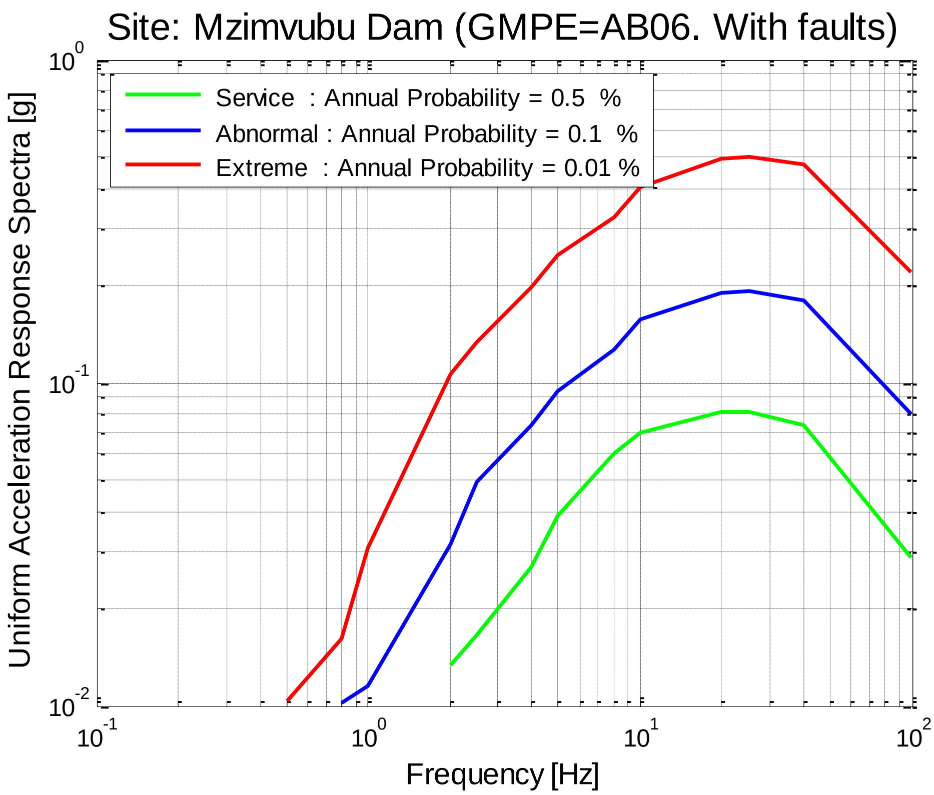

Figure C-15: Horizontal Uniform Acceleration Response Spectra. Scenario #2: all known faults in vicinity of the dam site are active.

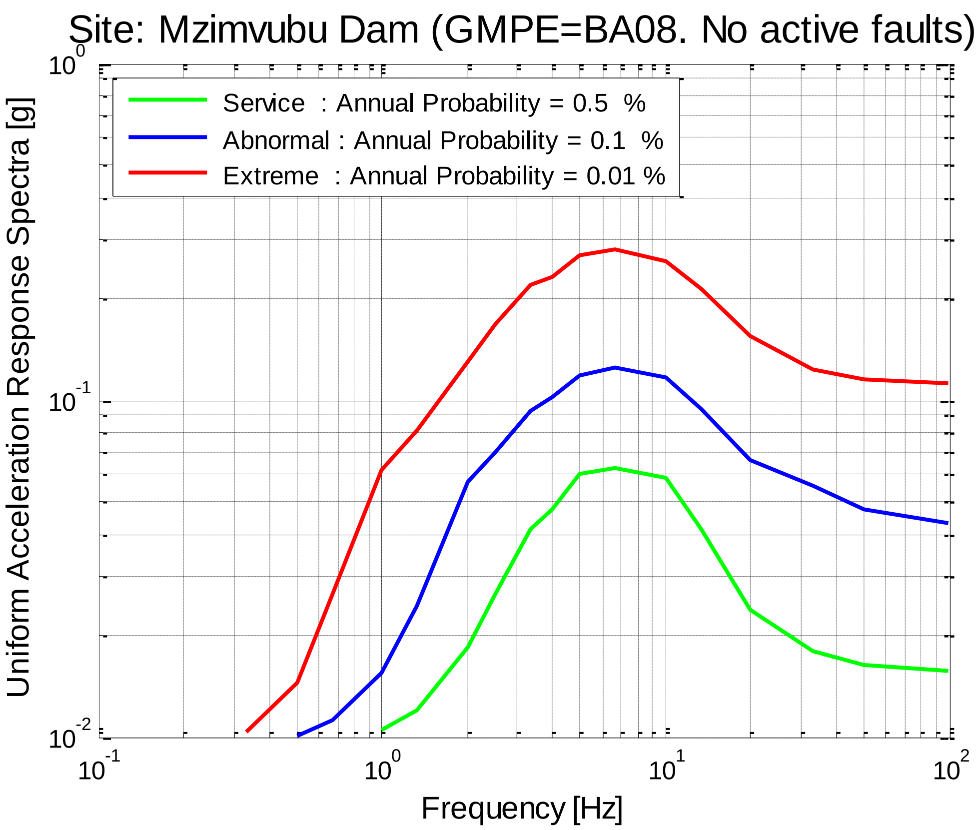

Figure C-16: Horizontal Uniform Acceleration Response. Scenario #1: all known faults in vicinity of the dam site are not active.

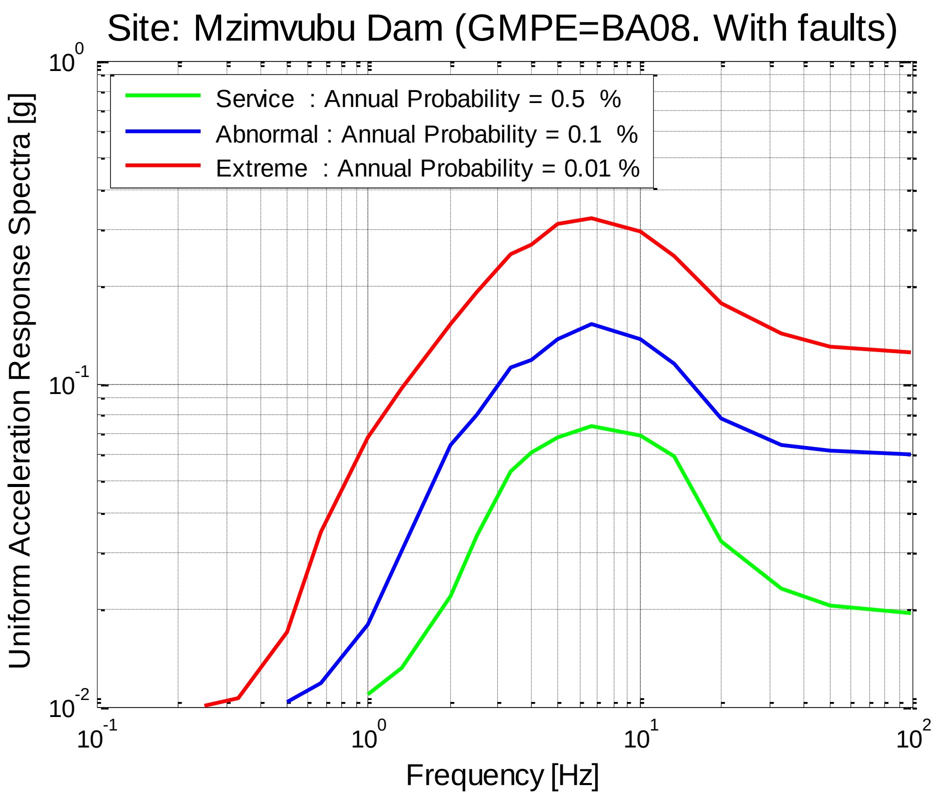

Figure C-17: Horizontal Uniform Acceleration Response. Scenario #2: all known faults in vicinity of the dam site are active.

D.5 ACCOUNT OF UNCERTAINTIES: LOGIC TREE APPROACH

The purpose of this section is to provide an interpretation of uncertainties associated with the PSHA assessment performed for site of the Mzimvubu Dam.

The development of any complexity seismotectonic model needed by PSHA requires several essential assumptions about its parameters, parameters which are uncertain and allow a wide range of interpretations.

There are two types of uncertainty (variability) that can be included in PSHA. These are aleatory and epistemic (e.g. Budnitz *et al*., 1997; Bernreuter *et al*., 1989).

Aleatory variability is uncertainty in the data used in an analysis which accounts for randomness associated with the prediction of a parameter from a specific model, assuming that the model is correct. For example, standard deviation of the mean value of ground motion represents typical aleatory variability. Aleatory variability is included, by default, in the PSHA calculations by means of mathematical integration, which are an integral part of the applied methodology.

Epistemic variability accounts for incomplete knowledge in the predictive models and the variability in the interpretations of the data. Epistemic uncertainty is included in the PSHA by account of alternative hypothesis and models. For example, the alternative hypothesis accounts for uncertainty in earthquake source zonation, their seismic potential, seismic source hazard parameters and GMPE's.

Let us apply formalism of the logic tree to the three levels of required ground motion (OBE, MDE and MCE) at the future dam location, by account of uncertainty of the GMPEs and seismic potential of identified faults in vicinity of the dam.

Let us assume that that the probability of being correct for each one of the two GMPEs is: 0.5 (AB06) and 0.5 (BA08).

Following information provided by Jeffares & Green Pty, Ltd, the subsequent assumptions were made regarding seismic potential of all identified faults in radius of 320 km of the dam:

Probability [faults are not active] = 0.5
Probability [faults are active] = 0.5.

Based on the logic tree formalism and Table 8-1, the expected values and standard deviations of horizontal component of OBE, MDE and MCE for the site of Ntabelanga Dam are:

OBE (Return Period 144 years) =
0.5 * 0.5 * 0.017g + 0.5 * 0.5 * 0.023g + 0.5 * 0.5 * 0.014g + 0.5 * 0.5 * 0.016g **= 0.018 ± 0.003g**

MDE (Return Period 475 years) =
0.5 * 0.5 * 0.039g + 0.5 * 0.5 * 0.059g + 0.5 * 0.5 * 0.025g + 0.5 * 0.5 * 0.034g **= 0.039 ± 0.012g**

MCE (Return Period 10,000 years) =
0.5 * 0.5 * 0.178g + 0.5 * 0.5 * 0.220g + 0.5 * 0.5 * 0.112g + 0.5 * 0.5 * 0.125g **= 0.159 ± 0.043g**

According to the applied guidelines, the site of the future dam is rated as **low risk**.

D.6 CONCLUSIONS

The PSHA was performed using the conventional, Cornell-McGuire procedure (Cornell, 1968; McGuire, 1976, 1978). The earthquake recurrence parameters *b*-value, λ, and m_{max} were calculated by the procedure of Kijko and Sellevoll (1989, 1992) and Kijko (2004).

In general, a PSHA procedure requires knowledge of regional geology, tectonics, paleo, historic and instrumentally recorded seismicity. Unfortunately, at this stage of the investigation, not all of the required information was available. The incompleteness of information (in our case information about the seismotectonic model of the area) contributes to the uncertainties of the PSHA assessment.

All calculations are repeated two times, each for a different ground motion prediction equation.

The uncertainties in the GMPE have been taken into account through logic tree formalism. The logic tree allows inclusions of alternative scenarios and interpretations that are weighted according to their probability of being correct.

Following the international guidance, (ICOLD, 1989; *Engineering and Design*, ER 1110, 1995), three designed levels of PGA were considered, Operating Basis Earthquake, OBE, (return period 144 years); Maximum Design Earthquake, MDE, (return period 475 years) and Maximum Credible Earthquake, MCE (return period 10,000 years).

The uniform acceleration response spectra and the 5% damping Newmark-Hall elastic design spectra are also provided.

According to the applied guidelines, the site of the future dam is rated as **low risk**.

The lack of a reliable regional ground motion prediction equation, tectonics, paleo, historic and instrumentally recorded seismicity, information about seismogenic zones and seismic capability of tectonic faults in the vicinity of the dam site are the major sources of uncertainty in this PSHA assessment.

Substantial uncertainties exist regarding seismic potential (seismic capability) of tectonic faults in vicinity of the dame site. Incorporation of such information can significantly affect the provided hazard assessments. The uncertainty in hazard assessment can be significantly reduced by incorporation results of the seismotectonic and geological investigations on the site.

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Annex A

Year/Month/Day	Latitude	Longitude	Magnitude		Year/Month/Day	Latitude	Longitude	Magnitude

Seismicity of Area Surrounding the Mzimvubu Dam Site

year	month	day	lat	long	magnitude
1850	5	21	-33.30	26.60	5.00
1854	8	20	-29.70	31.00	3.70
1860	6	15	-29.90	31.00	3.70
1860	9	21	-29.60	30.40	3.70
1862	6	16	-29.90	31.00	3.70
1867	10	15	-32.90	27.40	3.70
1870	8	3	-28.30	29.10	5.00
1871	4	15	-32.10	28.30	3.70
1883	9	26	-29.80	27.40	3.00
1895	5	9	-33.30	26.60	3.70
1898	8	11	-29.70	31.10	3.00
1905	11	28	-30.50	29.40	3.70
1905	12	1	-30.50	29.40	3.70
1907	3	20	-29.90	30.30	3.00
1909	4	15	-30.70	30.00	3.70
1913	9	17	-30.50	29.40	3.70
1919	6	24	-30.50	29.40	3.00
1920	5	8	-30.50	29.40	3.00
1920	9	10	-30.50	29.40	3.70
1920	10	15	-30.50	29.40	3.00
1921	1	22	-30.50	29.40	4.30
1921	8	13	-30.50	29.40	4.30
1922	3	20	-30.50	29.40	4.30
1922	9	18	-30.50	29.40	3.70
1923	3	1	-30.50	25.50	3.70
1923	8	7	-30.50	29.40	3.00
1924	3	6	-30.50	29.40	3.70
1924	10	28	-30.50	29.40	3.00
1925	9	3	-30.50	29.40	3.70
1927	9	22	-33.00	27.90	3.70
1928	7	10	-30.40	27.70	3.00
1929	12	28	-30.50	29.40	3.70
1930	4	24	-30.50	29.40	3.70
1930	7	20	-30.20	30.00	4.30
1932	5	25	-29.30	30.00	3.00
1932	6	30	-30.50	29.40	3.70
1932	8	9	-33.30	26.50	5.00
1933	2	25	-33.30	26.50	3.00
1937	2	25	-30.40	29.00	3.00
1938	1	21	-30.50	29.40	3.70
1938	9	4	-32.40	28.70	3.00
1940	2	29	-28.60	28.20	4.30
1940	8	28	-30.00	30.50	3.00
1940	9	29	-30.80	30.20	3.70
1940	10	24	-30.00	30.50	3.00
1940	11	10	-33.30	26.70	3.00
1942	11	1	-31.10	30.50	5.50
1942	12	15	-31.10	30.20	3.00
1944	11	12	-29.00	27.70	4.30
1948	2	3	-29.10	30.60	4.30
1948	9	25	-30.30	29.90	4.30
1950	2	5	-31.20	29.80	3.70
1952	3	25	-30.00	28.30	3.50
1952	6	11	-30.10	29.80	4.20

1952	8	30	-30.00	27.50	3.40
1952	9	7	-29.00	28.00	3.80
1952	9	23	-30.00	29.00	3.20
1952	10	14	-29.80	27.00	4.40
1953	1	3	-30.50	27.50	3.40
1953	1	3	-30.50	27.50	3.40
1953	1	6	-30.50	27.50	3.60
1953	1	6	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	4.70
1953	1	15	-30.50	27.50	3.30
1953	1	15	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	3.50
1953	1	15	-30.50	27.50	4.00
1953	1	16	-30.50	27.50	3.80
1953	1	16	-30.50	27.50	3.20
1953	1	16	-30.50	27.50	3.60
1953	1	20	-33.30	26.50	3.00
1953	1	21	-30.50	27.50	3.90
1953	1	24	-30.50	27.50	3.60
1953	1	24	-30.50	27.50	4.20
1953	1	24	-30.50	27.50	3.50
1953	1	28	-30.50	27.50	3.40
1953	1	30	-30.50	27.50	4.40
1953	2	5	-30.50	27.00	3.40
1953	3	25	-30.30	28.50	3.50
1953	6	17	-30.00	28.50	3.90
1953	7	29	-30.50	28.00	3.60
1953	8	15	-30.50	28.50	3.00
1953	8	31	-30.00	26.50	3.00
1954	1	6	-30.00	26.50	4.20
1956	6	26	-30.00	26.00	3.50
1956	7	13	-30.30	29.70	4.20
1957	4	13	-30.50	27.20	5.50
1957	4	23	-30.30	27.20	4.70
1958	2	10	-29.30	28.20	3.80
1958	2	11	-29.30	28.20	3.80
1966	2	22	-29.00	28.00	3.80
1966	6	18	-29.30	29.30	5.00
1966	7	31	-32.50	29.80	4.10
1967	4	13	-29.70	29.00	4.20
1967	6	16	-30.20	27.60	3.60
1967	8	23	-29.70	30.00	3.80
1968	1	9	-29.80	28.30	3.30
1968	1	11	-30.30	28.50	3.90
1968	2	13	-29.40	27.10	3.10
1968	3	19	-29.90	28.30	3.20
1968	8	31	-29.60	25.90	4.40
1968	12	5	-29.00	26.50	3.30
1969	1	29	-30.40	27.60	3.20
1969	6	5	-29.90	30.30	3.40
1970	1	20	-29.90	29.90	3.20
1971	2	5	-29.60	28.10	5.41
1971	7	29	-31.70	25.80	4.88
1972	2	13	-29.30	27.20	3.60
1972	7	19	-31.70	25.80	4.10
1973	4	22	-30.60	27.40	3.50
1974	9	4	-29.80	29.50	3.80
1975	1	8	-29.60	30.40	3.50
1975	8	10	-30.30	27.70	4.10
1976	5	3	-29.70	28.10	3.60
1976	7	20	-30.70	26.10	3.70
1978	12	27	-28.40	28.60	4.00
1980	12	18	-29.30	29.10	5.09
1981	4	7	-30.90	30.20	3.40
1981	11	5	-29.90	27.30	4.00
1982	5	9	-29.60	27.00	3.30
1982	11	18	-29.40	27.50	3.60
1983	2	22	-29.16	27.79	4.38
1983	6	21	-32.38	29.58	3.83
1983	11	2	-30.06	25.79	3.25
1983	12	30	-29.82	27.27	3.89
1984	8	5	-30.21	26.13	3.12
1985	8	31	-30.10	27.13	3.06
1985	12	11	-29.77	28.02	3.56
1986	7	29	-29.63	27.50	3.22

1986	7	30	-30.87	28.29	3.00
1986	10	5	-30.24	28.15	5.15
1986	10	6	-30.03	28.61	3.17
1986	10	13	-30.26	27.69	3.62
1986	12	29	-29.98	27.61	3.09
1987	5	31	-30.40	30.40	5.04
1987	5	31	-30.40	30.40	4.83
1987	6	8	-30.01	27.13	3.36
1987	8	1	-30.35	28.34	4.22
1987	8	1	-30.60	28.13	3.73
1987	10	24	-30.63	29.01	4.33
1988	2	12	-30.28	28.57	4.30
1988	2	12	-30.15	28.37	4.05
1988	8	20	-29.42	30.10	3.67
1988	9	16	-29.52	27.57	3.26
1988	9	21	-31.03	28.70	3.04
1988	9	22	-30.61	28.89	3.16
1989	2	28	-30.82	28.23	3.43
1989	3	14	-30.07	28.67	3.04
1989	3	15	-30.03	29.04	3.06
1989	4	30	-30.56	29.01	3.37
1989	5	15	-31.51	28.49	3.51
1989	6	17	-29.74	27.14	3.89
1989	6	19	-29.89	27.18	3.18
1989	8	21	-29.48	30.83	3.91
1989	9	4	-29.10	27.58	3.37
1989	9	29	-30.64	28.43	5.00
1989	9	29	-30.79	28.99	3.18
1989	10	2	-29.98	28.05	3.76
1990	5	1	-29.82	27.70	3.90
1990	8	21	-30.25	28.87	3.10
1991	6	29	-30.69	28.51	3.70
1991	7	26	-30.01	29.19	3.60
1991	9	17	-29.92	26.18	3.00
1993	7	31	-29.60	27.71	3.80
1994	1	9	-29.50	30.20	3.70
1994	1	27	-30.82	28.86	3.60
1994	4	8	-30.60	30.89	3.40
1994	6	10	-30.06	29.61	3.20
1994	9	13	-30.39	29.12	3.20
1995	2	8	-29.73	27.55	3.70
1995	2	11	-30.46	30.27	3.30
1996	1	3	-29.23	28.50	3.00
1996	5	24	-30.08	27.37	3.10
1996	10	10	-29.20	30.63	3.40
1996	10	22	-30.50	29.06	3.50
1996	12	27	-31.01	30.30	3.80
1997	7	25	-29.38	27.79	3.20
1998	7	5	-29.73	26.26	3.00
1998	7	12	-30.68	27.31	3.90
1998	9	6	-30.51	26.59	3.40
1999	2	14	-30.22	29.37	4.10
1999	11	15	-30.59	26.47	3.00
2000	6	11	-31.36	29.85	4.10
2000	6	25	-29.33	27.31	3.20
2000	7	21	-29.69	27.27	3.10
2000	10	3	-30.26	28.24	3.20
2000	11	24	-28.54	28.50	3.30
2001	8	20	-30.40	29.58	3.10
2002	1	27	-29.81	27.64	4.90
2002	1	27	-29.58	27.49	4.70
2002	4	11	-32.82	28.12	4.10
2002	6	25	-29.91	27.04	3.50
2003	7	2	-29.81	27.13	3.00
2003	7	4	-30.00	27.10	3.30
2003	7	4	-30.00	27.04	3.00
2003	7	15	-28.52	28.58	3.40
2003	8	30	-28.28	28.27	3.50
2003	10	3	-29.77	27.45	3.60
2003	11	1	-30.40	28.15	3.00
2003	11	12	-30.56	27.70	3.00
2003	12	10	-30.32	27.67	3.70
2004	5	7	-32.08	30.36	3.70
2004	6	10	-30.11	28.10	3.40
2004	6	11	-30.19	27.94	3.00

2004	6	19	-29.99	27.19	3.20
2004	6	20	-31.01	25.97	3.40
2004	10	30	-31.90	29.48	3.40
2004	10	31	-33.17	28.52	3.10
2004	11	18	-32.92	29.05	3.20
2005	1	7	-29.96	27.30	4.20
2005	4	16	-29.75	27.33	3.20
2005	5	18	-29.73	27.85	3.30
2005	5	18	-29.45	28.23	3.60
2005	6	23	-30.25	29.73	3.20
2005	7	9	-29.74	26.38	3.50
2005	8	23	-33.09	26.53	3.10
2006	2	26	-29.95	26.64	3.10
2006	4	11	-30.77	25.88	3.60
2006	12	10	-31.79	28.79	3.30
2007	1	21	-30.22	28.16	3.10
2007	3	2	-29.57	28.44	3.30
2007	3	6	-30.23	28.17	3.20
2007	4	9	-29.82	26.79	4.00
2007	6	3	-30.19	28.57	3.70
2007	12	26	-29.96	29.50	3.70
2009	1	27	-30.22	29.28	3.70
2009	3	28	-30.61	26.64	4.90
2009	4	28	-31.84	30.07	5.50
2009	5	20	-29.65	27.68	3.60
2009	5	21	-28.64	28.98	3.50
2009	5	21	-28.63	28.99	3.70
2009	7	5	-30.93	29.29	3.10
2010	2	16	-28.86	26.84	3.10
2010	3	3	-30.49	31.00	3.40
2010	3	11	-30.36	26.00	3.60
2010	5	28	-31.50	27.25	4.90
2010	6	29	-31.04	30.20	5.60
2010	7	9	-30.76	27.82	4.80
2010	7	13	-32.27	26.62	5.10
2010	10	16	-28.51	29.68	3.90
2010	10	18	-30.09	27.30	4.30
2011	4	28	-30.27	30.81	3.00
2011	11	16	-30.17	29.03	3.10
2012	10	24	-28.54	27.32	3.70

Seismic Events within Selected Seismogenic Zones

Zone #1

Year/Month/Day	Latitude	Longitude	Magnitude	Year/Month/Day	Latitude	Longitude	Magnitude
1850-05-21	-33.30	26.60	5.00	1953-01-20	-33.30	26.50	3.00
1985-05-09	-33.30	26.60	3.70	2005-01-31	-33.17	28.52	3.10
1927-09-22	-33.00	27.90	3.70	2005-08-23	-33.09	26.53	3.10
1932-08-09	-33.30	26.50	5.00	2005-12-06	-33.21	26.03	3.50
1933-02-25	-33.30	26.50	3.00	2009-09-19	-33.00	26.10	5.60
1940-10-11	-33.30	26.70	3.00	2011-05-14	-34.19	28.31	4.00

```
year month day lat    long  magnitude
====================================================
```

Zone #2

```
year month day lat    long  magnitude
====================================================
1867  10  15  -32.90   27.40   3.70
1871   4  15  -32.10   28.30   3.70
1938   9   4  -32.40   28.70   3.00
1942  11   1  -31.10   30.50   5.50
1942  12  15  -31.10   30.20   3.00
1950   2   5  -31.20   29.80   3.70
1966   7  31  -32.50   29.80   4.10
1981   4   7  -30.90   30.20   3.40
1983   6  21  -32.38   29.58   3.83
1987  10  24  -30.63   29.01   4.33
1988   9  21  -31.03   28.70   3.04
1988   9  22  -30.61   28.89   3.16
1989   5  15  -31.51   28.49   3.51
1989   9  29  -30.79   28.99   3.18
1994   1  27  -30.82   28.86   3.60
1996  12  27  -31.01   30.30   3.80
2000   6  11  -31.36   29.85   4.10
2002   4  11  -32.82   28.12   4.10
2004   5   7  -32.08   30.36   3.70
2004  10  30  -31.90   29.48   3.40
2006  12  10  -31.79   28.79   3.30
2009   4  28  -31.84   30.07   5.50
2009   7   5  -30.93   29.29   3.10
2010   6  29  -31.04   30.20   5.60
```

Zone #3

```
year month day lat    long  magnitude
====================================================
1854   8  20  -29.70   31.00   3.70
1860   6  15  -29.90   31.00   3.70
1860   9  21  -29.60   30.40   3.70
1862   6  16  -29.90   31.00   3.70
```

1862	6	23	-29.10	26.10	3.70
1870	8	3	-28.30	29.10	5.00
1883	9	26	-29.80	27.40	3.00
1898	8	11	-29.70	31.10	3.00
1905	11	28	-30.50	29.40	3.70
1905	12	1	-30.50	29.40	3.70
1907	3	20	-29.90	30.30	3.00
1908	8	18	-29.00	26.00	4.00
1908	9	26	-29.00	26.00	5.00
1909	4	15	-30.70	30.00	3.70
1913	9	17	-30.50	29.40	3.70
1914	2	6	-29.00	31.70	3.00
1914	2	16	-29.00	31.70	4.30
1914	3	31	-28.70	31.90	3.70
1914	6	14	-29.30	31.30	3.00
1916	3	24	-28.90	31.70	3.00
1917	4	11	-28.90	31.70	3.70
1917	4	25	-28.00	31.00	3.70
1917	9	9	-28.00	31.00	3.70
1917	9	20	-28.00	31.00	3.00
1919	5	14	-28.00	31.00	3.00
1919	5	15	-28.00	31.00	3.70
1919	6	24	-30.50	29.40	3.00
1919	11	7	-28.00	31.00	3.70
1920	1	31	-29.30	31.30	3.00
1920	3	7	-28.00	31.00	3.00
1920	4	3	-28.00	31.00	3.70
1920	4	12	-28.00	31.00	3.00
1920	5	8	-30.50	29.40	3.00
1920	9	10	-30.50	29.40	3.70
1920	10	15	-30.50	29.40	3.00
1921	1	22	-30.50	29.40	4.30
1921	8	13	-30.50	29.40	4.30
1922	3	20	-30.50	29.40	4.30
1922	3	21	-28.00	31.00	3.70
1922	5	8	-28.00	31.00	3.00
1922	9	18	-30.50	29.40	3.70
1923	3	29	-28.00	31.00	4.00
1923	8	7	-30.50	29.40	3.00
1924	3	6	-30.50	29.40	3.70
1924	10	28	-30.50	29.40	3.00
1925	9	3	-30.50	29.40	3.70
1927	3	10	-28.40	32.30	3.70
1928	7	10	-30.40	27.70	3.00
1928	11	15	-28.90	31.50	3.70
1929	6	24	-28.90	31.70	3.70
1929	12	28	-30.50	29.40	3.70
1930	4	24	-30.50	29.40	3.70
1930	5	14	-28.90	31.70	3.00
1930	7	20	-30.20	30.00	4.30
1932	5	25	-29.30	30.00	3.00
1932	6	30	-30.50	29.40	3.70
1932	12	31	-28.30	32.50	6.30
1935	2	20	-28.70	31.90	3.00
1936	9	18	-28.40	32.30	3.00
1937	2	25	-30.40	29.00	3.00
1938	1	21	-30.50	29.40	3.70
1938	10	25	-28.20	28.70	3.70
1940	2	29	-28.60	28.20	4.30
1940	8	28	-30.00	30.50	3.00
1940	9	19	-28.60	31.40	3.00
1940	9	29	-30.80	30.20	3.70
1940	10	24	-30.00	30.50	3.00
1944	11	12	-29.00	27.70	4.30
1947	5	8	-28.60	32.10	3.70
1948	2	3	-29.10	30.60	4.30
1948	9	25	-30.30	29.90	4.30
1952	3	25	-30.00	28.30	3.50
1952	6	11	-30.10	29.80	4.20
1952	8	30	-30.00	27.50	3.40
1952	9	7	-29.00	28.00	3.80
1952	9	23	-30.00	29.00	3.20
1952	10	14	-29.80	27.00	4.40
1953	1	3	-30.50	27.50	3.40
1953	1	3	-30.50	27.50	3.40

1953	1	6	-30.50	27.50	3.60
1953	1	6	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	4.70
1953	1	15	-30.50	27.50	3.30
1953	1	15	-30.50	27.50	3.40
1953	1	15	-30.50	27.50	3.50
1953	1	15	-30.50	27.50	4.00
1953	1	16	-30.50	27.50	3.80
1953	1	16	-30.50	27.50	3.20
1953	1	16	-30.50	27.50	3.60
1953	1	21	-30.50	27.50	3.90
1953	1	24	-30.50	27.50	3.60
1953	1	24	-30.50	27.50	4.20
1953	1	24	-30.50	27.50	3.50
1953	1	28	-30.50	27.50	3.40
1953	1	30	-30.50	27.50	4.40
1953	2	5	-30.50	27.00	3.40
1953	3	25	-30.30	28.50	3.50
1953	6	17	-30.00	28.50	3.90
1953	7	29	-30.50	28.00	3.60
1953	8	15	-30.50	28.50	3.00
1953	8	31	-30.00	26.50	3.00
1954	1	6	-30.00	26.50	4.20
1954	11	18	-28.20	27.20	4.30
1956	6	26	-30.00	26.00	3.50
1956	6	29	-28.30	31.30	3.00
1956	7	13	-30.30	29.70	4.20
1957	4	13	-30.50	27.20	5.50
1957	4	23	-30.30	27.20	4.70
1958	2	10	-29.30	28.20	3.80
1958	2	11	-29.30	28.20	3.80
1966	2	22	-29.00	28.00	3.80
1966	6	18	-29.30	29.30	5.00
1966	6	20	-28.30	31.00	4.00
1967	4	13	-29.70	29.00	4.20
1967	6	16	-30.20	27.60	3.60
1967	8	23	-29.70	30.00	3.80
1968	1	9	-29.80	28.30	3.30
1968	1	11	-30.30	28.50	3.90
1968	2	13	-29.40	27.10	3.10
1968	3	19	-29.90	28.30	3.20
1968	8	31	-29.60	25.90	4.40
1968	12	5	-29.00	26.50	3.30
1969	1	29	-30.40	27.60	3.20
1969	6	5	-29.90	30.30	3.40
1970	1	20	-29.90	29.90	3.20
1970	3	21	-28.30	27.70	3.30
1971	1	4	-28.10	25.90	3.40
1971	2	5	-29.60	28.10	5.41
1971	6	8	-28.10	26.80	3.60
1971	12	8	-28.00	26.70	3.90
1972	2	13	-29.30	27.20	3.60
1972	2	23	-28.10	26.90	3.80
1972	2	23	-28.00	26.70	3.80
1972	4	22	-28.10	26.80	3.70
1972	7	4	-28.00	26.60	4.50
1972	7	22	-28.10	26.90	4.00
1972	12	29	-28.20	27.20	4.20
1973	3	9	-28.00	26.80	4.30
1973	4	11	-28.10	26.80	3.50
1973	4	15	-28.00	26.70	3.10
1973	4	22	-30.60	27.40	3.50
1973	5	23	-28.00	26.50	3.10
1973	7	24	-28.00	26.80	3.20
1973	8	31	-28.50	26.40	3.20
1973	9	11	-28.00	26.70	3.10
1973	9	20	-28.10	26.80	4.00
1973	9	29	-28.20	27.20	3.20
1973	10	6	-28.00	26.80	3.00
1973	11	29	-28.00	26.80	3.30
1974	2	21	-28.00	26.70	3.10
1974	9	2	-28.00	26.70	3.70
1974	9	4	-29.80	29.50	3.80
1974	9	18	-28.10	26.80	3.30
1974	10	1	-28.20	26.90	3.30

1974	10	13	-28.00	26.70	3.70
1974	10	28	-28.00	26.70	3.70
1975	1	8	-29.60	30.40	3.50
1975	3	12	-28.00	26.70	3.00
1975	5	14	-28.80	25.80	3.70
1975	5	23	-28.10	26.80	3.20
1975	6	2	-28.10	26.80	3.60
1975	6	26	-28.00	26.80	3.50
1975	7	3	-28.00	26.80	3.40
1975	8	10	-30.30	27.70	4.10
1975	8	25	-28.00	26.70	3.90
1975	9	15	-28.00	26.70	3.50
1975	10	28	-28.00	26.90	3.20
1975	11	14	-28.00	26.70	3.00
1975	11	22	-28.10	26.90	3.80
1976	1	26	-28.20	26.80	3.50
1976	3	9	-28.00	26.40	3.90
1976	3	18	-28.00	26.80	3.40
1976	5	3	-29.70	28.10	3.60
1976	6	22	-28.10	26.90	3.10
1976	6	25	-28.10	26.90	3.30
1976	7	1	-28.00	26.80	3.50
1976	7	20	-30.70	26.10	3.70
1976	8	29	-28.00	26.80	3.30
1976	9	11	-28.10	26.80	3.40
1976	10	28	-28.00	26.40	3.00
1976	11	20	-28.00	26.80	3.50
1976	11	30	-28.00	26.70	3.30
1976	12	8	-28.00	26.80	5.10
1976	12	8	-28.00	26.70	3.50
1976	12	8	-28.10	26.90	3.10
1977	1	8	-28.00	26.80	3.00
1977	3	14	-28.00	26.90	3.60
1977	4	29	-28.00	26.70	3.30
1977	4	30	-28.10	26.90	3.20
1977	5	12	-28.00	26.70	3.20
1977	6	15	-28.00	26.90	3.60
1977	7	30	-28.10	26.90	3.10
1977	8	4	-28.10	26.80	3.10
1977	8	17	-28.20	26.90	3.00
1977	8	22	-28.10	26.80	3.10
1977	8	31	-28.50	26.60	3.20
1977	9	30	-28.00	26.80	3.00
1977	10	11	-28.00	26.80	3.00
1977	10	15	-28.10	26.90	3.10
1977	11	22	-28.18	28.84	3.10
1977	12	20	-28.00	26.80	3.20
1978	2	1	-28.00	26.90	3.20
1978	2	11	-28.10	26.80	3.10
1978	2	21	-28.10	26.90	3.20
1978	2	23	-28.10	26.90	3.40
1978	3	15	-28.00	26.70	3.10
1978	3	31	-28.10	26.90	3.30
1978	4	7	-28.00	26.80	3.10
1978	4	12	-28.10	26.90	3.00
1978	5	1	-28.10	26.80	3.50
1978	5	23	-28.00	26.90	3.50
1978	6	18	-28.00	27.00	3.00
1978	7	21	-28.10	27.00	3.70
1978	7	27	-29.40	31.40	3.30
1978	8	9	-28.10	26.90	3.00
1978	8	24	-28.00	26.40	3.50
1978	9	15	-28.10	26.90	3.30
1978	10	8	-28.00	26.80	3.50
1978	11	1	-28.00	26.90	3.20
1978	11	15	-28.00	26.90	3.30
1978	12	27	-28.40	28.60	4.00
1979	1	10	-28.20	26.60	3.60
1979	1	28	-28.10	26.80	3.80
1979	2	7	-28.00	26.70	3.50
1979	2	7	-28.00	26.70	3.40
1979	2	23	-28.10	26.80	3.50
1979	3	15	-28.00	26.70	3.40
1979	5	11	-28.00	26.70	3.30
1979	5	22	-28.00	26.70	3.60

1979	6	4	-28.00	26.70	3.00
1979	6	20	-28.00	26.70	3.10
1979	9	14	-28.10	26.90	3.00
1979	11	14	-28.30	26.80	3.10
1979	11	19	-28.10	26.80	4.00
1979	11	28	-28.00	26.80	3.00
1979	12	15	-28.00	26.60	4.83
1980	2	2	-28.00	26.80	3.10
1980	2	5	-28.00	26.90	3.80
1980	2	9	-28.10	26.90	4.88
1980	2	15	-28.00	26.80	3.20
1980	2	17	-28.00	26.80	5.04
1980	2	18	-28.00	26.80	3.30
1980	4	28	-28.00	26.90	3.40
1980	5	15	-28.10	27.00	4.72
1980	6	11	-28.10	26.80	3.70
1980	6	28	-28.10	26.90	3.20
1980	7	9	-28.00	26.90	3.30
1980	7	19	-28.10	27.80	3.00
1980	7	21	-28.00	26.90	3.00
1980	8	1	-28.00	26.80	3.20
1980	8	11	-28.10	26.90	3.30
1980	8	24	-28.20	26.70	3.10
1980	8	25	-28.70	32.70	5.15
1980	9	1	-28.10	26.90	3.10
1980	9	2	-28.00	26.90	3.10
1980	9	19	-28.00	26.80	3.00
1980	9	22	-28.00	26.90	3.00
1980	10	13	-28.00	26.80	3.00
1980	10	27	-28.10	26.90	3.00
1980	10	30	-28.00	26.90	3.40
1980	10	31	-28.10	26.90	3.90
1980	11	5	-28.00	26.70	3.10
1980	11	8	-28.00	26.70	3.10
1980	12	18	-29.30	29.10	5.09
1980	12	23	-28.00	26.80	3.10
1981	1	10	-28.10	27.00	3.50
1981	4	6	-28.00	26.80	3.40
1981	4	8	-28.10	26.80	3.30
1981	4	17	-28.00	26.80	4.10
1981	4	27	-28.00	26.80	3.40
1981	6	23	-28.00	26.80	3.20
1981	7	8	-28.00	26.90	3.30
1981	7	9	-28.00	26.80	3.20
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1981	8	13	-28.20	27.00	3.50
1981	9	14	-28.00	26.90	3.00
1981	9	23	-28.00	26.70	3.10
1981	11	5	-29.90	27.30	4.00
1981	11	18	-28.20	31.80	4.10
1981	11	21	-28.00	26.80	3.30
1982	5	5	-28.10	26.90	3.20
1982	5	9	-29.60	27.00	3.30
1982	6	1	-28.00	26.70	3.10
1982	6	15	-28.00	26.70	3.10
1982	8	4	-28.00	26.70	3.00
1982	8	19	-28.00	26.80	3.40
1982	11	18	-29.40	27.50	3.60
1983	1	23	-28.09	26.90	3.18
1983	1	27	-28.13	26.90	3.02
1983	2	21	-27.97	31.39	3.01
1983	2	22	-29.16	27.79	4.38
1983	3	11	-28.01	26.70	3.02
1983	3	14	-28.01	26.82	3.44
1983	4	14	-28.01	26.87	3.92
1983	5	10	-28.01	26.85	3.05
1983	5	24	-27.99	26.81	3.24
1983	6	15	-28.01	26.71	3.04
1983	7	1	-28.11	26.80	3.28
1983	7	1	-28.09	26.76	3.02
1983	7	20	-27.98	26.83	3.68
1983	8	16	-28.06	27.21	3.00
1983	8	21	-28.10	26.97	3.51
1983	10	9	-28.03	26.89	3.73
1983	11	2	-28.50	26.20	4.46

1983	11	2	-30.06	25.79	3.25
1983	12	30	-29.82	27.27	3.89
1984	1	4	-28.03	26.85	3.30
1984	1	30	-28.00	26.85	3.29
1984	4	4	-28.06	26.83	3.42
1984	4	7	-28.02	26.86	3.53
1984	4	10	-28.01	26.85	3.39
1984	4	11	-28.04	26.79	3.02
1984	4	18	-28.04	26.93	4.50
1984	5	11	-27.99	26.76	3.60
1984	5	11	-28.03	26.78	3.55
1984	6	20	-28.09	26.87	3.90
1984	7	11	-28.05	26.89	3.31
1984	8	5	-30.21	26.13	3.12
1984	8	17	-28.01	26.82	3.35
1984	9	25	-27.98	26.67	3.22
1984	10	31	-28.07	26.83	3.49
1984	11	1	-28.03	26.79	3.73
1984	11	3	-28.03	26.81	3.10
1984	11	27	-28.00	26.87	3.52
1985	2	21	-28.03	26.80	3.36
1985	5	16	-28.00	26.82	3.43
1985	5	17	-28.00	26.70	4.00
1985	5	26	-28.00	26.78	3.25
1985	5	29	-28.00	26.80	3.30
1985	6	29	-28.03	26.81	3.92
1985	7	10	-28.03	26.79	3.41
1985	7	22	-28.00	26.84	3.20
1985	8	31	-30.10	27.13	3.06
1985	10	2	-28.07	26.73	3.42
1985	10	5	-28.05	26.73	3.12
1985	10	24	-28.00	26.82	3.03
1985	10	24	-27.98	26.77	3.35
1985	11	2	-28.07	26.85	3.05
1985	11	30	-28.06	26.82	3.00
1985	12	3	-28.07	26.83	3.56
1985	12	9	-27.98	26.79	3.72
1985	12	11	-29.77	28.02	3.56
1985	12	29	-27.99	26.79	3.04
1986	1	25	-28.04	26.87	3.05
1986	2	8	-28.03	26.91	3.16
1986	2	10	-28.02	26.68	3.54
1986	2	10	-28.02	26.69	3.34
1986	3	12	-28.02	26.85	3.24
1986	3	22	-28.06	26.84	3.09
1986	5	4	-28.01	26.79	3.19
1986	5	17	-28.06	26.83	3.46
1986	5	27	-28.01	26.70	3.09
1986	7	10	-28.02	26.80	3.11
1986	7	15	-28.00	26.83	3.37
1986	7	18	-28.03	26.78	3.05
1986	7	29	-29.63	27.50	3.22
1986	7	30	-30.87	28.29	3.00
1986	8	2	-28.03	26.88	3.65
1986	8	5	-28.20	28.10	3.00
1986	9	15	-28.00	26.83	3.47
1986	10	5	-30.24	28.15	5.15
1986	10	6	-30.03	28.61	3.17
1986	10	13	-30.26	27.69	3.62
1986	11	3	-28.06	26.84	3.52
1986	11	8	-28.10	26.87	3.16
1986	11	13	-28.05	26.81	3.18
1986	11	24	-28.06	26.79	3.29
1986	12	2	-27.98	26.77	3.13
1986	12	29	-29.98	27.61	3.09
1987	1	23	-28.02	26.89	3.53
1987	2	11	-28.04	26.82	3.10
1987	4	16	-28.08	26.85	3.39
1987	4	24	-28.00	26.79	3.09
1987	5	4	-27.99	26.68	3.33
1987	5	31	-30.40	30.40	5.04
1987	5	31	-30.40	30.40	4.83
1987	6	8	-30.01	27.13	3.36
1987	6	18	-27.99	26.78	3.08
1987	6	30	-28.03	26.76	3.14

1987	7	3	-28.04	26.89	3.02
1987	7	9	-28.00	26.73	3.21
1987	7	27	-28.06	26.85	3.38
1987	7	29	-28.07	26.87	3.33
1987	7	29	-28.07	26.87	3.33
1987	8	1	-30.35	28.34	4.22
1987	8	1	-30.60	28.13	3.73
1987	8	31	-28.06	26.77	3.46
1987	9	4	-27.98	26.84	3.35
1987	9	26	-28.01	26.80	3.09
1987	10	8	-28.03	26.71	3.13
1987	10	12	-28.01	26.85	3.38
1988	2	12	-30.28	28.57	4.30
1988	2	12	-30.15	28.37	4.05
1988	3	4	-28.06	26.80	3.69
1988	7	5	-28.01	26.69	3.50
1988	7	27	-28.13	26.88	3.08
1988	8	10	-28.04	26.80	3.26
1988	8	16	-28.04	26.75	3.81
1988	8	20	-29.42	30.10	3.67
1988	8	27	-27.98	26.83	3.25
1988	8	27	-27.99	26.70	3.11
1988	9	16	-29.52	27.57	3.26
1988	11	5	-27.98	26.81	3.87
1988	12	1	-28.02	26.83	3.17
1989	1	25	-28.01	26.75	3.19
1989	1	25	-28.00	26.78	3.03
1989	2	5	-27.99	26.68	3.03
1989	2	23	-28.08	26.02	3.52
1989	2	28	-30.82	28.23	3.43
1989	3	14	-30.07	28.67	3.04
1989	3	15	-30.03	29.04	3.06
1989	4	1	-28.01	26.70	3.54
1989	4	1	-28.07	26.65	3.39
1989	4	11	-27.99	26.75	3.67
1989	4	30	-30.56	29.01	3.37
1989	6	9	-28.03	26.78	3.27
1989	6	13	-27.99	26.69	3.13
1989	6	15	-28.03	26.78	3.24
1989	6	17	-29.74	27.14	3.89
1989	6	19	-29.89	27.18	3.18
1989	6	28	-27.98	26.75	3.18
1989	7	29	-28.07	26.82	3.04
1989	8	12	-28.00	26.81	3.17
1989	8	21	-29.48	30.83	3.91
1989	9	4	-29.10	27.58	3.37
1989	9	29	-30.64	28.43	5.00
1989	9	30	-28.03	26.88	3.05
1989	10	2	-29.98	28.05	3.76
1989	11	27	-28.03	26.88	3.80
1989	12	9	-28.08	26.83	3.00
1990	1	13	-28.01	26.73	3.00
1990	1	17	-28.10	26.87	3.00
1990	1	31	-28.03	26.88	3.20
1990	3	22	-28.06	30.56	3.70
1990	3	27	-27.98	26.77	3.00
1990	3	29	-28.13	26.85	3.10
1990	5	1	-29.82	27.70	3.90
1990	5	15	-27.99	26.81	3.30
1990	5	15	-28.00	26.68	3.10
1990	7	9	-28.06	26.92	3.30
1990	7	14	-28.03	26.66	3.10
1990	8	1	-28.03	26.73	3.20
1990	8	8	-28.09	26.89	3.10
1990	8	21	-30.25	28.87	3.10
1990	9	26	-28.10	26.91	4.80
1990	9	27	-28.07	26.85	3.60
1990	9	28	-28.04	26.91	3.20
1990	9	28	-28.02	26.76	3.80
1990	9	30	-28.16	26.86	3.00
1990	10	9	-28.08	26.88	3.00
1990	10	20	-28.07	26.90	3.40
1990	10	24	-28.04	26.90	3.60
1990	11	1	-28.00	26.83	3.10
1990	11	14	-28.12	26.90	4.00

1990	12	31	-28.08	26.82	3.30
1991	2	5	-28.10	26.90	3.30
1991	4	28	-28.00	26.80	3.10
1991	5	26	-28.05	26.80	3.30
1991	6	23	-28.05	26.79	3.10
1991	6	29	-30.69	28.51	3.70
1991	7	26	-30.01	29.19	3.60
1991	8	5	-28.09	26.83	3.60
1991	8	22	-27.99	26.69	3.70
1991	9	17	-29.92	26.18	3.00
1991	10	18	-28.05	26.83	3.20
1991	10	31	-28.10	26.91	3.00
1991	11	16	-28.04	26.70	3.30
1991	12	18	-28.03	26.78	3.50
1991	12	31	-28.00	26.78	3.10
1992	1	4	-28.00	26.84	3.00
1992	1	4	-28.09	26.89	3.10
1992	1	10	-27.98	26.70	3.30
1992	2	7	-28.14	26.87	3.50
1992	2	10	-28.02	26.74	3.40
1992	2	10	-28.03	26.73	3.60
1992	4	11	-28.02	26.71	3.30
1992	4	13	-28.00	26.73	3.10
1992	4	14	-28.03	26.73	3.40
1992	4	30	-28.06	26.87	3.40
1992	5	5	-28.03	26.79	3.40
1992	5	5	-28.04	26.79	4.00
1992	5	6	-28.05	26.79	3.10
1992	6	10	-28.04	26.80	3.20
1992	6	14	-28.01	26.69	3.10
1992	6	29	-28.02	26.68	3.20
1992	7	17	-28.06	26.84	3.50
1992	11	21	-28.04	26.78	3.10
1992	12	20	-28.03	26.85	3.20
1992	12	30	-28.07	26.87	3.20
1993	1	8	-28.02	26.72	3.20
1993	1	8	-27.98	26.73	3.00
1993	3	4	-27.99	26.75	3.50
1993	3	11	-28.04	26.79	3.10
1993	3	21	-28.06	26.88	3.00
1993	4	18	-28.07	26.85	3.70
1993	5	1	-28.05	26.77	3.10
1993	5	6	-28.03	26.74	3.10
1993	5	22	-27.98	26.77	3.10
1993	6	2	-28.05	26.80	3.10
1993	6	26	-28.00	26.84	3.70
1993	7	7	-28.08	26.85	3.30
1993	7	31	-29.60	27.71	3.80
1993	8	15	-28.04	26.86	3.40
1993	9	7	-28.13	26.90	3.70
1993	9	20	-28.07	26.84	3.60
1993	10	11	-28.48	30.67	3.30
1993	10	26	-28.00	26.77	3.10
1993	11	7	-27.99	26.70	3.00
1993	11	15	-28.00	26.78	3.00
1993	11	16	-28.03	26.73	3.30
1993	11	29	-28.04	26.77	3.10
1993	12	3	-28.04	26.82	3.00
1994	1	2	-28.09	26.91	3.40
1994	1	9	-29.50	30.20	3.70
1994	1	25	-28.01	26.86	3.20
1994	4	7	-28.03	26.76	3.10
1994	4	8	-30.60	30.89	3.40
1994	4	18	-28.15	28.90	3.10
1994	5	9	-28.04	26.78	3.60
1994	5	29	-28.05	26.82	3.40
1994	6	3	-28.02	26.72	3.10
1994	6	10	-30.06	29.61	3.20
1994	6	27	-27.99	26.75	4.10
1994	7	4	-28.05	26.80	3.10
1994	7	8	-28.04	26.80	3.10
1994	7	18	-28.05	26.78	3.20
1994	9	13	-30.39	29.12	3.20
1994	10	9	-28.03	26.77	3.20
1994	10	10	-28.02	26.74	3.10

1994	10	26	-28.06	26.87	3.10
1994	10	30	-28.02	26.77	5.10
1994	11	1	-28.02	26.76	4.20
1994	11	11	-28.02	26.73	3.10
1994	12	1	-28.03	26.81	3.00
1994	12	12	-28.10	26.85	3.20
1995	1	19	-27.99	26.74	3.10
1995	2	8	-29.73	27.55	3.70
1995	2	11	-30.46	30.27	3.30
1995	4	6	-28.01	26.73	3.00
1995	5	19	-28.03	26.72	3.90
1995	5	20	-27.98	26.70	3.00
1995	6	22	-28.01	26.70	3.00
1995	9	12	-28.02	26.76	3.10
1995	10	14	-28.10	26.85	3.50
1995	12	7	-28.06	26.85	3.00
1995	12	17	-27.99	26.69	4.20
1995	12	26	-27.98	26.76	3.00
1996	1	3	-29.23	28.50	3.00
1996	1	12	-28.03	26.73	3.20
1996	1	21	-28.01	26.78	3.30
1996	2	16	-28.03	26.74	3.00
1996	2	21	-28.00	26.71	3.00
1996	2	21	-28.11	26.90	3.60
1996	2	24	-28.04	26.80	3.10
1996	4	5	-27.98	26.78	3.00
1996	5	24	-30.08	27.37	3.10
1996	6	30	-28.18	29.84	3.20
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1996	9	28	-28.08	26.91	3.60
1996	10	10	-29.20	30.63	3.40
1996	10	22	-28.00	26.65	3.20
1996	10	22	-30.50	29.06	3.50
1996	12	11	-28.01	26.77	4.20
1996	12	20	-28.08	26.90	3.20
1997	1	23	-28.03	26.89	3.10
1997	5	5	-27.99	26.63	3.10
1997	6	17	-27.99	26.68	3.10
1997	7	25	-29.38	27.79	3.20
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1997	8	3	-28.02	26.70	3.60
1997	8	7	-28.12	26.89	3.40
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1997	8	11	-28.00	26.77	3.40
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1997	9	24	-28.02	26.79	3.40
1997	10	19	-28.36	31.83	3.50
1998	1	5	-27.99	26.80	3.30
1998	2	3	-28.08	26.85	3.70
1998	3	26	-28.04	26.80	3.40
1998	3	28	-28.00	26.70	3.40
1998	4	4	-28.03	26.70	3.10
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1998	5	25	-28.08	26.82	3.10
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1998	7	2	-28.00	26.69	3.60
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1998	7	26	-27.98	26.73	3.60
1998	7	29	-28.03	26.82	3.40
1998	8	27	-28.06	26.81	3.00
1998	8	30	-28.07	26.85	3.20
1998	9	1	-28.00	26.76	3.30
1998	9	6	-30.51	26.59	3.40
1998	9	18	-27.98	26.74	3.30
1998	11	3	-28.05	26.84	3.60
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1998	12	6	-28.05	26.73	3.50
1999	1	8	-28.07	26.86	3.50
1999	2	14	-30.22	29.37	4.10
1999	5	1	-28.00	26.73	3.40
1999	5	2	-28.10	26.85	3.40
1999	6	4	-27.98	26.71	3.60

1999	6	24	-28.02	26.86	4.10
1999	6	30	-28.06	26.89	3.60
1999	7	18	-28.04	26.80	3.40
1999	7	20	-28.12	26.90	3.30
1999	8	17	-28.02	26.81	3.50
1999	8	18	-28.00	26.80	3.40
1999	9	5	-28.02	26.79	3.60
1999	10	13	-28.02	26.86	3.70
1999	10	17	-28.05	26.81	3.00
1999	11	15	-30.59	26.47	3.00
2000	1	13	-28.01	26.90	3.00
2000	2	12	-28.18	26.60	3.00
2000	3	16	-28.02	26.68	3.20
2000	5	11	-27.98	26.87	3.00
2000	6	6	-27.99	26.75	3.10
2000	6	25	-29.33	27.31	3.20
2000	7	5	-28.01	26.86	3.10
2000	7	21	-29.69	27.27	3.10
2000	8	21	-27.99	26.89	3.30
2000	9	17	-27.99	26.70	3.00
2000	9	25	-27.98	26.74	3.20
2000	10	3	-30.26	28.24	3.20
2000	11	24	-28.54	28.50	3.30
2001	2	16	-28.00	26.67	3.00
2001	6	10	-28.04	26.69	3.00
2001	7	24	-28.01	26.75	3.80
2001	8	20	-30.40	29.58	3.10
2001	9	20	-28.02	26.77	3.20
2002	1	27	-29.81	27.64	4.90
2002	1	27	-29.58	27.49	4.70
2002	2	28	-27.98	26.71	4.80
2002	6	25	-29.91	27.04	3.50
2002	6	28	-28.14	31.35	3.70
2002	8	1	-28.04	26.63	3.90
2002	10	6	-28.08	26.76	3.00
2003	2	4	-28.06	26.76	3.20
2003	2	7	-28.06	26.86	3.50
2003	2	13	-28.07	26.79	3.00
2003	5	12	-29.38	25.73	3.50
2003	7	2	-29.81	27.13	3.00
2003	7	4	-30.00	27.10	3.30
2003	7	4	-30.00	27.04	3.00
2003	7	15	-28.52	28.58	3.40
2003	8	2	-28.07	26.94	3.50
2003	8	18	-28.06	26.88	3.70
2003	8	19	-28.11	26.74	3.30
2003	8	30	-28.28	28.27	3.50
2003	9	3	-28.04	28.48	3.50
2003	9	7	-28.26	26.71	3.20
2003	10	3	-29.77	27.45	3.60
2003	10	11	-28.09	26.84	4.30
2003	11	1	-30.40	28.15	3.00
2003	11	12	-30.56	27.70	3.00
2003	12	6	-28.56	26.35	3.00
2003	12	10	-30.32	27.67	3.70
2003	12	13	-27.98	26.88	3.30
2004	2	3	-28.02	26.87	3.50
2004	3	5	-28.10	26.86	3.00
2004	3	26	-28.25	26.71	3.40
2004	3	29	-28.06	26.86	3.40
2004	4	8	-28.11	26.77	3.60
2004	4	10	-28.02	26.79	3.20
2004	4	16	-28.06	26.84	3.40
2004	4	29	-28.14	26.86	3.10
2004	5	7	-28.12	26.83	3.60
2004	6	2	-28.13	26.80	3.40
2004	6	10	-30.11	28.10	3.40
2004	6	11	-30.19	27.94	3.00
2004	6	18	-28.18	26.70	3.20
2004	6	19	-29.99	27.19	3.20
2004	6	20	-31.01	25.97	3.40
2004	7	4	-28.30	26.77	3.00
2004	7	25	-28.00	26.85	3.20
2004	8	3	-28.06	26.89	3.50
2004	8	3	-28.05	26.80	3.70

2004	8	12	-28.06	26.87	3.00
2004	9	8	-28.06	26.68	3.30
2004	10	4	-28.13	26.77	3.70
2004	11	3	-28.07	26.84	3.30
2004	11	18	-28.22	26.86	3.20
2004	11	24	-28.07	26.86	3.50
2004	12	14	-28.23	26.87	3.40
2004	12	15	-28.23	26.75	3.50
2004	12	16	-28.07	26.86	3.80
2004	12	22	-28.28	26.85	3.10
2005	1	7	-29.96	27.30	4.20
2005	1	8	-28.04	26.77	4.30
2005	1	16	-28.00	29.54	3.50
2005	1	31	-28.00	26.74	3.20
2005	2	1	-28.02	26.67	3.30
2005	2	4	-28.02	26.74	3.20
2005	4	11	-28.21	26.74	3.50
2005	4	12	-28.27	26.75	3.50
2005	4	16	-29.75	27.33	3.20
2005	5	13	-28.11	26.79	3.10
2005	5	18	-29.73	27.85	3.30
2005	5	18	-29.45	28.23	3.60
2005	6	11	-28.09	26.76	3.00
2005	6	23	-30.25	29.73	3.20
2005	7	9	-29.74	26.38	3.50
2005	7	27	-28.16	26.73	3.00
2005	7	27	-28.00	26.81	3.10
2005	8	18	-28.09	26.69	3.10
2005	8	21	-28.18	26.69	3.30
2005	8	23	-28.00	26.75	3.60
2005	9	4	-28.08	26.75	3.20
2005	9	22	-28.07	26.73	3.30
2005	9	24	-28.22	26.73	3.10
2005	10	10	-28.08	26.78	3.30
2005	10	13	-28.06	26.89	3.00
2005	10	26	-28.02	26.78	3.00
2005	11	7	-28.11	26.75	3.00
2005	11	7	-28.09	26.69	3.10
2005	11	12	-28.10	26.77	3.80
2006	1	6	-27.99	26.71	3.10
2006	1	6	-27.98	26.72	3.00
2006	1	24	-28.04	26.73	3.00
2006	1	26	-28.28	26.80	3.10
2006	1	28	-28.20	26.84	3.00
2006	2	26	-29.95	26.64	3.10
2006	3	4	-28.03	26.85	3.30
2006	3	19	-28.06	26.84	4.00
2006	4	11	-30.77	25.88	3.60
2006	4	23	-28.10	26.91	3.30
2006	5	8	-28.09	26.72	3.10
2006	5	20	-28.05	26.79	3.60
2006	5	29	-28.04	31.27	3.70
2006	6	4	-28.19	26.73	3.00
2006	12	25	-28.05	26.76	3.70
2007	1	21	-30.22	28.16	3.10
2007	2	27	-28.06	26.73	3.10
2007	3	2	-29.57	28.44	3.30
2007	3	6	-30.23	28.17	3.20
2007	3	17	-27.98	26.70	3.40
2007	4	9	-29.82	26.79	4.00
2007	5	5	-28.03	26.68	3.20
2007	6	3	-30.19	28.57	3.70
2007	9	9	-28.05	26.73	3.10
2007	9	25	-28.08	26.84	3.00
2007	11	2	-28.06	26.87	3.10
2007	11	23	-28.16	26.91	3.00
2007	11	25	-28.05	26.73	3.20
2007	12	26	-29.96	29.50	3.70
2008	2	23	-28.06	26.67	3.00
2008	2	28	-28.73	30.90	3.60
2008	6	3	-28.08	26.78	3.00
2008	7	3	-27.98	26.73	3.20
2008	7	24	-28.00	26.77	3.00
2008	8	17	-28.10	26.84	3.10
2008	11	6	-28.08	26.79	3.00

2008	12	20	-28.74	32.82	3.60
2008	12	21	-28.09	26.76	3.80
2008	12	21	-28.07	26.80	3.00
2009	1	8	-28.72	32.66	4.10
2009	1	27	-30.22	29.28	3.70
2009	3	7	-28.33	32.35	4.70
2009	3	21	-28.15	32.70	5.00
2009	3	28	-30.61	26.64	4.90
2009	5	20	-29.65	27.68	3.60
2009	5	21	-28.64	28.98	3.50
2009	5	21	-28.63	28.99	3.70
2009	8	26	-28.14	26.85	3.70
2009	9	25	-28.00	26.70	3.00
2010	2	16	-28.86	26.84	3.10
2010	3	3	-30.49	31.00	3.40
2010	3	11	-30.36	26.00	3.60
2010	3	14	-28.14	29.11	4.00
2010	3	21	-28.08	27.90	4.00
2010	6	30	-28.93	32.05	4.70
2010	7	2	-27.98	26.73	3.00
2010	7	9	-30.76	27.82	4.80
2010	7	12	-28.15	28.88	4.30
2010	8	20	-28.04	26.76	3.30
2010	10	16	-28.51	29.68	3.90
2010	10	18	-30.09	27.30	4.30
2010	12	16	-28.05	26.77	3.30
2011	1	21	-28.65	30.55	3.40
2011	4	28	-30.27	30.81	3.00
2011	5	16	-28.11	31.28	3.60
2011	6	25	-28.00	26.69	3.00
2011	8	12	-28.20	28.37	3.20
2011	10	5	-28.06	26.72	4.60
2011	11	16	-30.17	29.03	3.10
2012	9	25	-28.47	27.23	3.10
2012	10	24	-28.54	27.32	3.70
2012	11	17	-28.12	26.95	4.00
2012	11	23	-28.08	32.18	3.90
2012	12	21	-28.37	27.16	4.00

ANNEX B

Applied Methodology for Probabilistic Seismic Hazard Analysis

1. Introduction

The essence of the Probabilistic Seismic Hazard Analysis (PSHA) is the calculation of the probability of exceedance of a specified ground motion level at a specified site (Cornell, 1968; Reiter, 1990). In principle, PSHA can address a very broad range of natural hazards associated with earthquakes, including ground shaking and ground rupture, landslide, liquefaction or tsunami. However, in most cases, the interest of designers is in the estimation of likelihood of a specified level of ground shaking, since it causes the greatest economic losses.

The typical output of the PSHA is **seismic hazard curve** (often, a set of seismic curves), i.e. plots of the estimated probability, per unit time, of the ground motion variable, e.g. peak ground acceleration (PGA) being equal to or exceeding the level as a function of PGA (Budnitz *et al*., 1997). The essence of the PSHA is that its product – the seismic hazard curve, quantifies the hazard at the site from all possible earthquakes of all possible magnitudes at all significant distances from the site of interest, by taking into account their frequency of occurrences. In addition to hazard curve, the output of PSHA includes results of the so called deaggregation procedure. The procedure provides information on earthquake magnitudes and distances that contribute to the hazard at a specified return period, and at a structural period of engineering interest (Budnitz *et al*., 1997).

In general, the standard PSHA procedure is based on two sources of information: (1) observed seismicity, recapitulated by seismic event catalogue, and (2) area-specific, geological data. After the combination of a selected model of earthquake occurrence with the information on the regional seismic wave attenuation or ground motion prediction equation (GMPE), a regional seismotectonic model of the area is formulated. In addition, the PSHA takes into account the site specific soil properties.

Complete PSHA can be performed only when information on the regional seismotectonic model and the site-specific soil properties are known.

Clearly, all above information, required by a complete PSHA is subjective and often, highly uncertain especially in stable continental areas where the earthquake activity is very low. According to convention established in the fundamental document by Budnitz *et al*. (1997), there are two types of uncertainties, associated with PSHA: these are **aleatory** and **epistemic** uncertainties. According to Budnitz *et al*. (1997), the uncertainties that are part of the applied model used in the analysis, are called aleatory uncertainties. The other names for the aleatory uncertainty are ‘stochastic’ or ‘random’ uncertainties. Even when the model is perfectly correct, and the numerical values of its parameters are known without any errors, aleatory uncertainties (for a given model) are still present (Budnitz *et al*. 1997).

The uncertainties which come from incomplete knowledge of the models, i.e. when wrong models are applied or/and the numerical values of their parameters are not known, are called epistemic uncertainties. As relevant information is collected, the epistemic uncertainties can be reduced (Budnitz *et al.*, 1997).

By definition of the PSHA procedure, the aleatory uncertainty is included in the process of PSHA calculations by means of applied models (statistical distributions) and by mathematical integration. Epistemic uncertainty can be incorporated in the PSHA by consideration of an alternative hypothesis (e.g. alternative boundaries of the seismic sources and their recurrence parameters), and alternative models (e.g. alternative earthquake distributions or/and application of alternative PGA attenuation equations). Incorporation of this type of uncertainties into the PSHA is performed by application of the logic tree formalism.

A complete PSHA includes an account of aleatory as well as epistemic uncertainties. Any PSHA without the incorporation of the above uncertainties is considered to be incomplete.

This Annex concentrates on two major mathematical aspects of the PSHA:

(1) The procedure for assessment of the seismic source characteristic, recurrence parameters when the data are incomplete and uncertain. Use is made of the most common assumptions in engineering seismology i.e. those earthquake occurrences in time follow a Poisson process and that earthquake magnitudes are distributed according to a Gutenberg-Richter doubly-truncated distribution. Following the above assumptions, seismic source recurrence parameters: the mean seismic activity rate, λ (which is a parameter of the Poisson distribution); the level of completeness of the earthquake catalogue m_{min}, the maximum regional earthquake magnitude m_{max}, and the Gutenberg-Richter parameter b. To assess the above parameters, a seismic event catalogue containing origin times, size of seismic events and spatial locations is needed. The maximum seismic source characteristic earthquake magnitude m_{max} is of paramount importance in this approach; therefore a statistical technique that can be used for evaluating this important parameter is presented.

(2) PSHA methodology i.e. calculating the probability of exceedance of a specified ground motion level at a specified site. Often, the presented approach is known as the Cornell-McGuire procedure.

2. Estimation of the Seismic Source Recurrence Parameters – Bayesian Approach

This section gives an outline of the procedure used to determine the seismic source recurrence parameters: the mean seismic activity rate λ, the Gutenberg-Richter parameter *b,* and the maximum regional earthquake magnitude m_{max}.

2.1 Nature of input data

The lack, or incompleteness, of data in earthquake catalogues is a frequent issue in a statistical analysis of seismic hazard. Contributing factors include the historical and socio–economic context, demographic variations and alterations in the seismic network. Generally, the degree of completeness is a monotonically increasing function of time, i.e. the more recent portion of the catalogue has a lower level of completeness. The methodology makes provision for the earthquake catalogue to contain three types of data: (1) very strong prehistoric seismic events (paleo-earthquakes), which usually occurred over the last thousands of years; (2) the macro-seismic observations of some of the strongest seismic events that occurred over a period of the last few hundred years; and (3) complete recent data for a relatively short period of time. The complete part of the catalogue can be divided into several sub-catalogues, each of which is complete for events above a given threshold magnitude $m_{min}^{(i)}$, and occurring in a certain period of time T_i where $i = 1,\ldots,s$ and s is the number of complete sub-catalogues. The approach permits 'gaps' (T_g) when records were missing or the seismic networks were out of operation. Uncertainty in earthquake magnitude is also taken into account in that an assumption is made that the observed magnitude is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation. Figure 2.1 depicts the typical scenario confronted when conducting seismic hazard assessments.

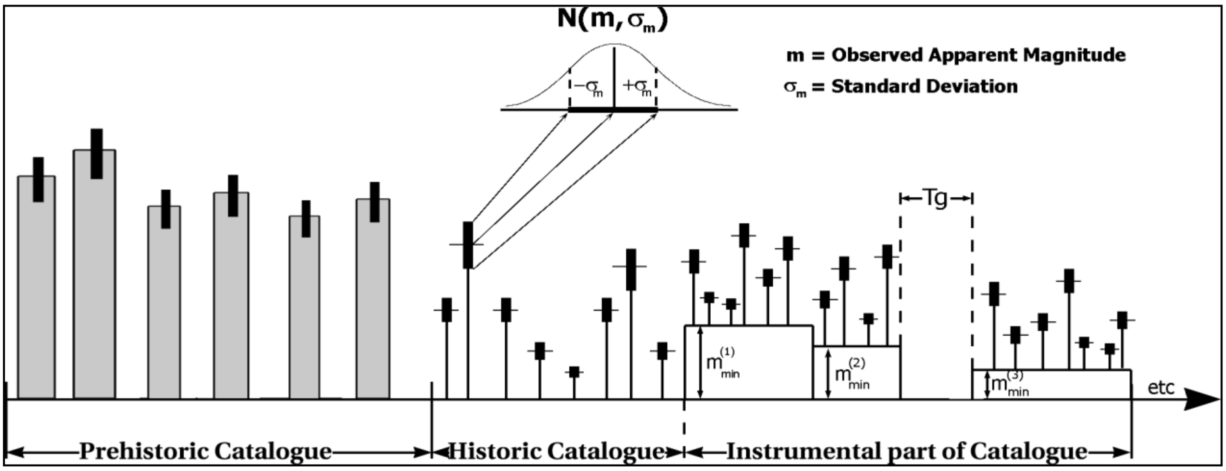

Figure 2.1: Illustration of data which can be used to obtain reccurence parameters for the specified seismic source. The approach permits the combination of the largest earthquakes (prehistoric/paleo- and historic) data and complete (instrumental) data having variable threshold magnitudes. It accepts 'gaps' (Tg) when records were missing or the seismic networks were out of operation. The procedure is capable of accounting for uncertainties of occurrence time of prehistoric earthquakes. Uncertainty in earthquake magnitude is also taken into account, in that an assumption is made that the observed magnitude, is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation. (Modified after Kijko and Sellevoll, 1992)

2.2 Statistical preliminaries

Basic statistical distributions and quantities utilized in the development of the methodology are briefly described in what follows.

The Poisson distribution is used to model the number of occurrences of a given earthquake magnitude or a given amplitude of a selected ground motion parameter being exceeded within a specified time interval.

$$p(n|\lambda,t) = P(N = n|\lambda,t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad n = 0,1,2,... \tag{1}$$

Note that λ here refers to the mean of the distribution, and describes the mean activity rate (mean number of occurrences).

The gamma distribution, given its flexibility, is used to model the distribution of various parameters in our approach, and is given by

$$f(x) = (x)^{q-1} \frac{p^q}{\Gamma(q)} e^{-px}, \qquad x > 0 \ , \tag{2}$$

where $\Gamma(q)$ is the gamma function defined as

$$\Gamma(q) = \int_0^\infty y^{q-1} e^{-y} dy, \quad q > 0 \,, \tag{3}$$

The parameters p and q are related to the mean μ, and variance σ^2, of the distribution according to

$$\mu_x = \frac{q}{p} , \tag{4}$$

$$\sigma_x{}^2 = \frac{q}{p^2} , \tag{5}$$

The coefficient of variation expresses the uncertainty related to a given parameter, and is given by

$$COV_x = \frac{\sigma_x}{\mu_x} , \tag{6}$$

thus describing the variation of a parameter relative to its mean value, with a higher value indicating a greater dispersion of the parameter.

2.3 Estimation of the seismic source recurrence parameters

The standard assumption adopted is that the distribution of earthquakes, with respect to their size, obeys the classic Gutenberg-Richter relation

$$\log N(m) = a - b \cdot (m - m_{\min}) , \tag{7}$$

where $N(m)$ is the number of earthquakes of $m \geq m_{\min}$, occurring within a specified period of time, and a and b are parameters.

Aki (1965) found that equation (7) implied a singly truncated exponential distribution of the form

$$\begin{aligned} F_M(m) &= P(M \leq m) \\ &= 1 - e^{-\beta(m - m_{\min})} , \end{aligned} \tag{8}$$

where $\beta = b \ln(10)$.

The earthquake occurrences over time in the given area are assumed to satisfy a Poisson process (1) having an unknown mean seismic activity rate λ.

The disregard of temporal and spatial variations of the parameters λ and b can lead to biased estimates of seismic hazard. An explicit assumption behind most hazard assessment procedures is that parameters λ and b and remain constant in time. However, examination of most earthquake catalogues indicates that there are temporal changes of the mean seismic activity rate λ as well as of the parameter b. For some seismic areas, the b-value has been reported to change (decrease/increase) its value before large earthquakes. Usually, such changes are explained by the state of stress; the higher the stress, the lower the b-value. Other theories connect the b-value with the homogeneity of the rock: the more heterogeneous the rock, the higher the b-value. Finally, some scientists connect the fluctuation of the b-value with the seismicity pattern and believe that the b-value is controlled by the buckling of the stratum. Whatever the mechanism, the phenomenon of space-time b-value fluctuation is indubitable and well-known. A wide range of international opinions concerning changes of patterns in seismicity, together with an extensive reference list, are found in a monograph by

Simpson and Richards (1981) and in two special issues of *Pure and Applied Geophysics*, (Seismicity Patterns …, 1999; Microscopic and Macroscopic …, 2000). Treating both parameters λ and b as random variables modelled by respective gamma distributions, allows for appropriately accounting for the statistical uncertainty in these important parameters. In practice, the adoption of the gamma distribution does not really introduce much limitation, since the gamma distribution can fit a large variety of shapes. Combining the Poisson distribution (1) together with the gamma distribution (2) with parameters p_λ and q_λ, the probability related to a certain number of earthquakes, n, per unit time t, for randomly varying seismicity is obtained

$$P(n|t) = \int_0^\infty p(n|\lambda_A, t) f(\lambda_A) d\lambda_A = \frac{\Gamma(n+q_\lambda)}{n!\Gamma(q_\lambda)} \left(\frac{p_\lambda}{t+p_\lambda}\right)^{q_\lambda} \left(\frac{t}{t+p_\lambda}\right)^n, \quad (9)$$

where $p_\lambda = \bar{\lambda} / \sigma_\lambda^2$, $q_\lambda = \bar{\lambda}^2 / \sigma_\lambda^2$ and $\Gamma(\cdot)$ is the Gamma function (3). Parameter $\bar{\lambda}$ denotes the mean value of activity rate λ.

Similarly, combining the exponential distribution (8) with the gamma distribution for β with parameters p_β and q_β, and normalizing (e.g. Campbell, 1982) upon introducing an upper limit $m_{\max}$ for the distribution of earthquake magnitudes, the CDF of earthquake magnitudes is obtained

$$F_M(m|m_{\min}) = C_\beta \left[1 - \left(\frac{p_\beta}{p_\beta + m - m_{\min}}\right)^{q_\beta}\right], \quad (10)$$

where $p_\beta = \bar{\beta} / \sigma_\beta^2$ and $q_\beta = \bar{\beta}^2 / \sigma_\beta^2$. The symbol $\bar{\beta}$ denotes the mean value of parameter β, σ_β denotes the standard deviation of β and the normalizing coefficient C_β is given by

$$C_\beta = \left[1 - \left(\frac{p_\beta}{p_\beta + m_{\max} - m_{\min}}\right)^{q_\beta}\right]^{-1}, \quad (11)$$

Noting that $q_\lambda = \bar{\lambda} \cdot p_\lambda$ and $q_\beta = \bar{\beta} \cdot p_\beta$, equations (9) and (10) may alternatively be written respectively as

$$P(n|t) = \frac{\Gamma(n+q_\lambda)}{n!\Gamma(q_\lambda)} \left(\frac{q_\lambda}{\bar{\lambda}_A t + q_\lambda}\right)^{q_\lambda} \left(\frac{\bar{\lambda}_A t}{\bar{\lambda}_A t + q_\lambda}\right)^n, \quad (12)$$

and

$$F_M(m|m_{\min}) = C_\beta \left[1 - \left(\frac{q_\beta}{q_\beta + \bar{\beta}(m - m_{\min})}\right)^{q_\beta}\right], \quad (13)$$

with

$$C_\beta = \left[1 - \left(\frac{q_\beta}{q_\beta + \bar{\beta}(m - m_{\min})}\right)^{q_\beta}\right]^{-1}, \tag{14}$$

Note that $q_\beta = \left(COV_\beta^{-1}\right)^2$ and $q_\lambda = \left(COV_\lambda^{-1}\right)^2$. Upon specification of the COV, the parameters $\bar{\lambda}$ and $\bar{\beta}$, referred to as hyper-parameters of the respective distributions are estimated on the basis of observed data by applying the maximum likelihood procedure.

2.3.1 Extreme magnitude distribution as applied to prehistoric (paleo) and historic events

The likelihood function of desired seismicity parameters $\boldsymbol{\theta}$ = ($\bar{\lambda}$, $\bar{\beta}$) is built based on the prehistoric (paleo) and historic parts of the catalogue containing the strongest events only. In this section the details of the likelihood function based on historic earthquakes will be discussed, since except for a few details, the likelihood function based on prehistoric events is built in a similar manner.

By the Theorem of the Total Probability (e.g. Cramér, 1961), the probability that in time interval t either no earthquake occurs, or all occurring earthquakes have magnitude not exceeding m, may be expressed as (Epstein and Lomnitz, 1966; Gan and Tung, 1983; Gibowicz and Kijko, 1994)

$$F_M^{\max}(m \mid m_0, t) = \sum_{i=0}^{\infty} P(i|t)\left[F_M(m \mid m_0)\right]^i, \tag{15}$$

Relation (15) can be expressed in a much more simpler form (e.g. Campbell, 1982), which may be written as

$$F_M^{\max}(m \mid m_0, t) = \left[\frac{q_\lambda}{q_\lambda + \bar{\lambda}_0 t\left[1 - F_M(m \mid m_0)\right]}\right]^{q_\lambda}, \tag{16}$$

In relations (15) and (16), m_0 is the threshold magnitude for the prehistoric or historic part of the catalogue ($m_0 \geq m_{\min}$). Magnitude $m_{\min}$ is the 'total' threshold magnitude and has a rather formal character. The only restriction on the choice of its value is that $m_{\min}$ may not exceed the threshold magnitude of any part - prehistoric, historic or complete - of the catalogue.

It follows from relation (16) that the probability density function (PDF) of the largest earthquake magnitudes m within a period t is

$$f_M^{\max}(m \mid m_0, t) = \frac{\bar{\lambda}_0 t q_\lambda f_M(m \mid m_0) F_M^{\max}(m \mid m_0, t)}{q_\lambda + \bar{\lambda}_0 t[1 - F_M(m \mid m_0)]}, \tag{17}$$

$\bar{\lambda}_0$ represents the mean of the distribution of the mean activity rate for earthquakes with magnitudes not less than m_0, and is given by

$$\bar{\lambda}_0 = \bar{\lambda}_A\left[1 - F_M(m \mid m_0)\right], \tag{18}$$

where $\bar{\lambda}_A$, as defined above, is the mean of the distribution of the mean activity rate corresponding to magnitude value $m_{\min}$. Function $f_M(m|m_0)$ denotes the PDF of earthquake magnitude. Based on (13) and the definition of the probability density function, it takes the following form:

$$f_M(m) = C_\beta \, \bar{\beta} \left(\frac{q_\beta}{q_\beta + \bar{\beta}(m - m_0)} \right)^{q_\beta + 1}, \tag{19}$$

After introducing the PDF (17) of the largest earthquake magnitude m within a period t, the likelihood function of unknown parameters $\boldsymbol{\theta}$ becomes:

$$L_0(\boldsymbol{\theta} \,|\, \boldsymbol{m}_0, \boldsymbol{t}_0, \boldsymbol{cov}) = \prod_{i=1}^{n_0} f_M^{\max}(m_{0i} \,|\, m_0, t_i) \,, \tag{20}$$

In order to build the likelihood function (20), three kinds of input data are required: $\boldsymbol{m}_0$, $\boldsymbol{t}$, and $\boldsymbol{cov}$, where $\boldsymbol{m}_0$ is vector of the largest magnitudes, $\boldsymbol{t}$ denotes vector of the time intervals within which the largest events occurred, and vector, $\boldsymbol{cov} = (cov_\lambda, cov_\beta)$ consists of the coefficients of variation (amount of dispersion (uncertainty relative to the mean) of the unknown parameters $\boldsymbol{\theta}$ = ($\bar{\lambda}$, $\bar{\beta}$).

2.3.2 Combination of extreme and complete seismic catalogues with different levels of completeness

If it is assumed that the third, complete part of the catalogue can be divided into s sub-catalogues (Kijko and Sellevoll, 1992), each of them has a span T_i and is complete starting from the known magnitude $m_{\min}^{(i)}$. For each sub-catalogue i, $\boldsymbol{m}_i$ is used to denote n_i earthquake magnitudes m_{ij}, where $m_{ij} \geq m_{\min}^{(i)}$, $i = 1, \ldots, s$ and $j = 1, \ldots, n_i$. Let $L_i(\boldsymbol{\theta}|\boldsymbol{m}_i)$ denote the likelihood function of the unknown $\boldsymbol{\theta}$ = ($\bar{\lambda}$, $\bar{\beta}$), based on the i-th complete sub-catalogue. If the size of seismic events is independent of their number, the likelihood function $L_i(\boldsymbol{\theta}|\boldsymbol{m}_i)$ is the product of two functions, $L_i(\bar{\lambda}|\mathbf{m}_i)$ and $L_i(\bar{\beta}|\boldsymbol{m}_i)$.

The assumption that the number of earthquakes per unit time is distributed according to (12) means that $L_i(\bar{\lambda}|\mathbf{m}_i)$ has the following form:

$$L_i(\bar{\lambda}|\mathbf{m}_i) = const \cdot \left(\bar{\lambda}^{(i)} t + q_\lambda\right)^{-q_\lambda} \left(\frac{\bar{\lambda}^{(i)} t}{\bar{\lambda}^{(i)} t + q_\lambda} \right)^{n_i}, \tag{21}$$

where $const$ does not depend on $\bar{\lambda}$ and $\bar{\lambda}^{(i)}$ is the mean activity rate corresponding to the threshold magnitude $m_{\min}^{(i)}$ and is given by,

$$\bar{\lambda}^i = \bar{\lambda} \left[1 - F_M\left(m_{\min}^{(i)} \,|\, m_{\min}\right)\right], \tag{22}$$

Following the definition of the likelihood function based on a set of independent observations, and (19), $L_i(\beta|\boldsymbol{m}_i)$ takes the form

$$L_i\left(\bar{\beta}|\boldsymbol{m}_i\right)=\left[C_\beta\ \bar{\beta}\right]^{n_i}\prod_{j=1}^{n_i}\left[1+\frac{\bar{\beta}}{q_\beta}\left(m_{ij}-m_{\min}^{(i)}\right)\right]^{-(q_\beta+1)}, \qquad (23)$$

Relations (21) and (23) define the likelihood function of the unknown parameters $\boldsymbol{\theta}=(\bar{\lambda},\bar{\beta})$ for each complete sub-catalogue.

Finally, $L(\boldsymbol{\theta})$, the joint likelihood function based on all data, i.e. the likelihood function based on the whole catalogue, is calculated as the product of the likelihood functions based on prehistoric, historic and complete data.

The maximum likelihood estimates of the required hazard parameters $\boldsymbol{\theta}$ = ($\bar{\lambda}$, $\bar{\beta}$), are given by the value of $\boldsymbol{\theta}$ which, for a given maximum regional magnitude $m_{\max}$, maximizes the likelihood function $L(\boldsymbol{\theta})$. The maximum of the likelihood function is obtained by solving the system of two equations $\frac{\partial \ell}{\partial \bar{\lambda}_A}=0$ and $\frac{\partial \ell}{\partial \bar{\beta}}=0$, where $\ell=\ln[L(\boldsymbol{\theta})]$.

A variance-covariance matrix $D(\boldsymbol{\theta})$, of the estimated hazard parameters, $\hat{\bar{\lambda}}$ and $\hat{\bar{\beta}}$, is calculated according to the formula (Edwards, 1972):

$$\mathrm{D}(\theta)=-\begin{bmatrix}\frac{\partial^2\ell}{\partial\bar{\lambda}^2} & \frac{\partial^2\ell}{\partial\bar{\lambda}\,\partial\bar{\beta}}\\ \frac{\partial^2\ell}{\partial\bar{\beta}\partial\bar{\lambda}} & \frac{\partial^2\ell}{\partial\bar{\beta}^2}\end{bmatrix}^{-1}, \qquad (24)$$

where derivatives are calculated at the point $\bar{\lambda}=\hat{\bar{\lambda}}$ and $\bar{\beta}=\hat{\bar{\beta}}$.

2.4 Estimation of the maximum regional earthquake magnitude $m_{\max}$

Suppose that in the area of concern, within a specified time interval T , there are n main seismic events with magnitudes $m_1,\ldots,m_n$. Each magnitude $m_i \geq m_{\min}$ ($i=1,\ldots,n$), where $m_{\min}$ is a known threshold of completeness (i.e. all events having magnitude greater than or equal to $m_{\min}$ are recorded). It is further assumed that the seismic event magnitudes are independent, identically distributed, random variables with CDF described by equation (13).

From the condition that compares the largest observed magnitude $m_{\max}^{obs}$ and the maximum expected magnitude during a specified time interval T , the maximum regional magnitude $m_{\max}$ is obtained (Kijko and Graham, 1998; Kijko, 2004)

$$m_{\max}=m_{\max}^{obs}+\frac{\delta^{1/q}\exp\left[nr^q/\left(1-r^q\right)\right]}{\bar{\beta}}\left[\Gamma\left(-1/q,\delta r^q\right)-\Gamma\left(-1/q,\delta\right)\right], \qquad (25)$$

where $\delta = nC_\beta$ and $\Gamma(\cdot,\cdot)$ is the complementary incomplete gamma function. The approximate variance of the above estimator is equal to (Kijko, 2004)

$$\sigma^2_{m_{\max}} \cong \sigma^2_M + \left\{ \frac{\delta^{1/q} \exp\left[nr^q / \left(1 - r^q\right)\right]}{\bar{\beta}} \left[\Gamma\left(-1/q, \delta r^q\right) - \Gamma\left(-1/q, \delta\right)\right] \right\}^2 , \quad (26)$$

where σ_M is the standard error in determination of the largest observed magnitude $m^{obs}_{\max}$.

1. The Cornell-McGuire PSHA Methodology

The essence of the PSHA is the calculation of the probability of exceedance of a specified ground motion level at a specified site. The so called, Cornell-McGuire solution of this problem consists of four steps: (e.g. Budnitz *et al*., 1997; Reiter, 1990):

1. Determination of the possible seismic sources around the site. The sources are typically identified faults, point sources, or area sources, in which it is assumed that the occurrence of earthquakes is spatially uniform. In the territory of Eastern and Southern Africa, like the central and eastern United States or Australia, the main contribution to the seismic hazard comes from the area sources. The seismicity of the area not always correlates well with geological structures recognizable at the surface therefore identification of the geological structures that are responsible for earthquakes are difficult.

2. Determination and assessment of the recurrence parameters for each seismic source. This is typically expressed in terms of three parameters: the mean seismic activity rate λ , b-value of the Gutenberg – Richter frequency magnitude relation and the upper-bound of earthquake magnitude $m_{\max}$.

Selection of the ground motion prediction equation (GMPE), which is most suitable for the region, is crucial. For Eastern and Southern Africa areas, the strong motion records are very limited therefore theoretical models of the ground motion attenuation are used. Since the ground motion attenuation relationship is a major source of uncertainty in the computed PSHA, some codes and recommendations require use of a number of alternative GMPE's (Bernreuter *et al*., 1989).

3. Computation of the hazard curves. These curves are usually expressed in terms of the mean annual frequency of events with site ground motion level a or more, $\lambda(a)$ or probability of exceedance, Pr[A>a in time t], vs. a ground motion parameter a, like PGA or a spectral acceleration. By the Theorem of the Total Probability, (Cramér, 1961), the frequency $\lambda(a)$, is defined as (Budnitz, 1997)

$$\lambda(a) = \sum_{i=1}^{n_s} \lambda_i \int_{m_{\min}}^{m_{\max}} \int_{R|M} \Pr[A \ge a \mid M, R]\, f_M(m)\, f_{R|M}(r \mid m)\, dr\, dm \quad (27)$$

in which the subscripts *i*, (*i*=1,…n_S), denoting seismic source number are deleted for simplicity. In equation (27), λ is the mean activity rate (per time unit and per seismic area unit) of earthquakes on seismic source i, having magnitudes between m_{min} and m_{max}; m_{min} is the minimum magnitude of engineering significance; m_{max} is the maximum earthquake magnitude assumed to occur on the seismic source; $\Pr[A \ge a|M,R]$ denotes the conditional probability that the chosen ground motion level is exceeded for a given magnitude and distance. Standard choice for $\Pr[A \ge a|M,R]$ is Gaussian complementary cumulative distribution function, which is based on the assumption that the ground motion parameter *a* is a lognormal random (aleatory) variable. In equation (27), $f_M(m)$

denotes the PDF of earthquake magnitude. In most engineering applications it is assumed that earthquake magnitudes follow the Gutenberg-Richter relation, which implies that $f_M(m)$ is negative, exponential distribution, with magnitudes between m_{min} and m_{max}. If uncertainty of the earthquake magnitude distribution is taken into account, $f_M(m)$ takes the familiar (Bayesian) form of equation (19). Finally, PDF $f_{R|M}(r\,|\,m)$ describes the spatial distribution of earthquake occurrence, or, more precisely, the PDF of distance from the earthquake source to the site of interest. In general cases, spatial distribution of the earthquake occurrence can be different for different earthquake magnitudes.

Under the condition that earthquake occurrence in every seismic source is Poisson event, i.e. independent in time and space, the ground motion $A \geq a$ at a site is also a Poisson event. Hence the probability, that *a*, a specified level of ground motion at a given site, will be exceeded at least once in any time interval *t* is

Pr[*A*>*a* in time *t*] =

$$1-\exp\left[-\sum_{i=1}^{n_s}\lambda_i\int_{m_{\min}}^{m_{\max}}\int_{R|M}\Pr[A\geq a\,|\,M,R]\,f_M(m)\,f_{R|M}(r\,|\,m)\,dr\,dm\right]. \qquad (28)$$

The equation (28) is fundamental in PSHA. The plot of this equation vs. ground motion parameter *a*, is the hazard curve – the ultimate product of the PSHA assessment.

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Annex C

Seismic Sources and their Recurrence Parameters

SS	Lat	Long	Depth	m_min	Lambda	b	m_max
Diff	-31.742	25.298	10.0	4.0	1.067006e-003	0.92	6.39
Diff	-31.492	25.298	10.0	4.0	1.150647e-003	0.92	6.39
Diff	-31.242	25.298	10.0	4.0	1.182564e-003	0.93	6.39
Diff	-30.992	25.298	10.0	4.0	1.236915e-003	0.92	6.39
Diff	-30.742	25.298	10.0	4.0	1.243571e-003	0.95	6.39
Diff	-30.492	25.298	10.0	4.0	2.372983e-003	1.16	6.29
Diff	-32.242	25.548	10.0	4.0	8.338849e-004	0.93	6.39
Diff	-31.992	25.548	10.0	4.0	9.935946e-004	0.92	6.39
Diff	-31.742	25.548	10.0	4.0	1.153251e-003	0.92	6.39
Diff	-31.492	25.548	10.0	4.0	1.178256e-003	0.93	6.39
Diff	-31.242	25.548	10.0	4.0	1.257173e-003	0.93	6.39
Diff	-30.992	25.548	10.0	4.0	1.277150e-003	0.92	6.29
Diff	-30.742	25.548	10.0	4.0	1.370742e-003	1.00	6.29
Diff	-30.492	25.548	10.0	4.0	2.655825e-003	1.18	6.29
Diff	-30.242	25.548	10.0	4.0	2.745619e-003	1.18	6.29
Diff	-29.992	25.548	10.0	4.0	2.783991e-003	1.17	6.29
Diff	-32.742	25.798	10.0	4.0	4.858467e-004	0.94	6.40
Diff	-32.492	25.798	10.0	4.0	6.407324e-004	0.95	6.39
Diff	-32.242	25.798	10.0	4.0	8.640027e-004	0.93	6.39
Diff	-31.992	25.798	10.0	4.0	1.034358e-003	0.94	6.39
Diff	-31.742	25.798	10.0	4.0	1.184021e-003	0.94	6.39
Diff	-31.492	25.798	10.0	4.0	1.221857e-003	0.94	6.29
Diff	-31.242	25.798	10.0	4.0	1.279422e-003	0.94	6.29
SZ	-30.992	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	25.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-32.992	26.048	10.0	4.0	2.967743e-004	0.94	6.41
Diff	-32.742	26.048	10.0	4.0	5.279067e-004	0.95	6.40
Diff	-32.492	26.048	10.0	4.0	5.804518e-004	0.96	6.39
Diff	-32.242	26.048	10.0	4.0	8.494998e-004	0.96	6.30
Diff	-31.992	26.048	10.0	4.0	1.101232e-003	0.95	6.30
Diff	-31.742	26.048	10.0	4.0	1.192373e-003	0.94	6.30
Diff	-31.492	26.048	10.0	4.0	1.268049e-003	0.95	6.29
Diff	-31.242	26.048	10.0	4.0	1.286917e-003	0.95	6.29
SZ	-30.992	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	26.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.242	26.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	26.298	10.0	4.0	2.967743e-004	0.94	6.41
Diff	-32.742	26.298	10.0	4.0	5.051986e-004	0.96	6.30
Diff	-32.492	26.298	10.0	4.0	6.793677e-004	0.98	6.30
Diff	-32.242	26.298	10.0	4.0	8.454000e-004	1.00	6.30
Diff	-31.992	26.298	10.0	4.0	1.122035e-003	0.96	6.30
Diff	-31.742	26.298	10.0	4.0	1.190108e-003	0.96	6.30
Diff	-31.492	26.298	10.0	4.0	1.253572e-003	0.95	6.29
Diff	-31.242	26.298	10.0	4.0	1.312872e-003	0.96	6.29
SZ	-30.992	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	26.298	10.0	4.0	3.728210e-003	1.31	6.39

SZ	-28.992	26.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.492	26.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	26.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	26.548	10.0	4.0	2.967743e-004	0.94	6.41
Diff	-32.742	26.548	10.0	4.0	5.557833e-004	0.96	6.30
Diff	-32.492	26.548	10.0	4.0	7.223453e-004	1.00	6.30
Diff	-32.242	26.548	10.0	4.0	8.380018e-004	1.01	6.30
Diff	-31.992	26.548	10.0	4.0	1.046964e-003	0.97	6.30
Diff	-31.742	26.548	10.0	4.0	1.211817e-003	0.97	6.29
Diff	-31.492	26.548	10.0	4.0	1.275483e-003	0.98	6.29
Diff	-31.242	26.548	10.0	4.0	1.335744e-003	0.96	6.29
SZ	-30.992	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	26.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.492	26.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	26.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	26.798	10.0	4.0	2.967743e-004	0.94	6.41
Diff	-32.742	26.798	10.0	4.0	5.357843e-004	0.97	6.30
Diff	-32.492	26.798	10.0	4.0	7.293507e-004	1.01	6.30
Diff	-32.242	26.798	10.0	4.0	8.395973e-004	0.99	6.30
Diff	-31.992	26.798	10.0	4.0	1.033668e-003	0.99	6.30
Diff	-31.742	26.798	10.0	4.0	1.220024e-003	0.96	6.29
Diff	-31.492	26.798	10.0	4.0	1.260447e-003	0.96	6.29
Diff	-31.242	26.798	10.0	4.0	1.315531e-003	0.97	6.29
SZ	-30.992	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	26.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.742	27.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	27.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	27.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	27.048	10.0	4.0	2.967743e-004	0.94	6.41
Diff	-32.742	27.048	10.0	4.0	5.721622e-004	0.98	6.30
Diff	-32.492	27.048	10.0	4.0	7.366271e-004	1.01	6.30
Diff	-32.242	27.048	10.0	4.0	8.409698e-004	1.00	6.30
Diff	-31.992	27.048	10.0	4.0	9.036017e-004	1.01	6.30
Diff	-31.742	27.048	10.0	4.0	1.138635e-003	0.97	6.29
Diff	-31.492	27.048	10.0	4.0	1.274922e-003	0.96	6.39
Diff	-31.242	27.048	10.0	4.0	1.311360e-003	0.96	6.39
SZ	-30.992	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	27.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.742	27.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	27.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	27.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	27.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	27.298	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-32.492	27.298	10.0	4.0	7.105437e-004	1.01	6.30
Diff	-32.242	27.298	10.0	4.0	8.297272e-004	1.00	6.30
Diff	-31.992	27.298	10.0	4.0	9.371306e-004	1.00	6.30
Diff	-31.742	27.298	10.0	4.0	1.046136e-003	0.98	6.39
Diff	-31.492	27.298	10.0	4.0	1.250815e-003	0.95	6.39
Diff	-31.242	27.298	10.0	4.0	1.326215e-003	0.95	6.37
SZ	-30.992	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	27.298	10.0	4.0	3.728210e-003	1.31	6.39

SZ	-30.492	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	27.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.742	27.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	27.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	27.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	27.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	27.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	27.548	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-32.242	27.548	10.0	4.0	8.308396e-004	1.01	6.30
Diff	-31.992	27.548	10.0	4.0	8.684250e-004	1.01	6.40
Diff	-31.742	27.548	10.0	4.0	1.025587e-003	0.98	6.39
Diff	-31.492	27.548	10.0	4.0	1.162399e-003	0.97	6.37
Diff	-31.242	27.548	10.0	4.0	1.262887e-003	0.95	6.37
SZ	-30.992	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	27.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	27.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	27.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	27.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	27.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	27.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	27.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	27.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	27.798	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-31.992	27.798	10.0	4.0	8.889552e-004	1.00	6.40
Diff	-31.742	27.798	10.0	4.0	9.258553e-004	0.99	6.39
Diff	-31.492	27.798	10.0	4.0	9.900418e-004	0.99	6.37
Diff	-31.242	27.798	10.0	4.0	1.193980e-003	0.99	6.37
SZ	-30.992	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	27.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	28.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	28.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	28.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	28.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	28.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	28.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	28.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	28.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	28.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	28.048	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-31.492	28.048	10.0	4.0	9.550681e-004	0.99	6.37
Diff	-31.242	28.048	10.0	4.0	1.013707e-003	1.00	6.37
SZ	-30.992	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	28.048	10.0	4.0	3.728210e-003	1.31	6.39

SZ	-28.992	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	28.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	28.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	28.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	28.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	28.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	28.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	28.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	28.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	28.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	28.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	28.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	28.298	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-31.242	28.298	10.0	4.0	9.458338e-004	1.05	6.37
SZ	-30.992	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	28.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	28.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	28.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	28.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	28.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	28.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	28.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	28.548	10.0	4.0	7.016127e-004	1.00	6.41
Diff	-30.992	28.548	10.0	4.0	9.513691e-004	1.04	6.37
SZ	-30.742	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	28.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	28.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	28.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	28.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	28.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	28.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	28.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.492	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	28.798	10.0	4.0	3.728210e-003	1.31	6.39

SZ	-28.242	28.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	29.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	29.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	29.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	29.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	29.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	29.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.492	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	29.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	29.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	29.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	29.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	29.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	29.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	29.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.492	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	29.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-33.992	29.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.742	29.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.492	29.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	29.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	29.548	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	29.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.492	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	29.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	29.548	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.992	29.798	10.0	4.0	1.358189e-004	0.96	5.63
Diff	-33.742	29.798	10.0	4.0	1.765650e-004	0.94	6.15

SZ	-33.492	29.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-33.242	29.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	29.798	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	29.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.492	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	29.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.242	29.798	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.742	30.048	10.0	4.0	1.775832e-004	0.93	5.63
Diff	-33.492	30.048	10.0	4.0	1.796329e-004	0.96	6.44
SZ	-33.242	30.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.992	30.048	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	30.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	30.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	30.048	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.742	30.298	10.0	4.0	1.797803e-004	0.93	5.63
Diff	-33.492	30.298	10.0	4.0	1.663484e-004	0.95	6.47
Diff	-33.242	30.298	10.0	4.0	2.547050e-004	0.95	6.44
SZ	-32.992	30.298	10.0	4.0	2.967743e-004	0.94	6.41
SZ	-32.742	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	30.298	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	30.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.492	30.298	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.492	30.548	10.0	4.0	1.663484e-004	0.95	6.47
Diff	-33.242	30.548	10.0	4.0	2.356007e-004	0.95	6.47
Diff	-32.992	30.548	10.0	4.0	2.841740e-004	0.97	6.44
SZ	-32.742	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.492	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-32.242	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.992	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	30.548	10.0	4.0	7.016127e-004	1.00	6.41

SZ	-31.242	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	30.548	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	30.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	30.548	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.492	30.798	10.0	4.0	1.663484e-004	0.95	6.47
Diff	-33.242	30.798	10.0	4.0	2.210415e-004	0.94	6.47
Diff	-32.992	30.798	10.0	4.0	2.549933e-004	0.95	6.47
Diff	-32.742	30.798	10.0	4.0	3.144533e-004	0.97	6.44
Diff	-32.492	30.798	10.0	4.0	3.654858e-004	0.98	6.40
Diff	-32.242	30.798	10.0	4.0	4.505011e-004	0.99	6.38
SZ	-31.992	30.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.742	30.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.492	30.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	30.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	30.798	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	30.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.742	30.798	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-33.242	31.048	10.0	4.0	1.814077e-004	0.96	6.47
Diff	-32.992	31.048	10.0	4.0	2.362724e-004	0.95	6.47
Diff	-32.742	31.048	10.0	4.0	2.702369e-004	0.96	6.47
Diff	-32.492	31.048	10.0	4.0	3.514514e-004	0.97	6.42
Diff	-32.242	31.048	10.0	4.0	4.172777e-004	0.99	6.40
Diff	-31.992	31.048	10.0	4.0	4.517371e-004	0.99	6.38
Diff	-31.742	31.048	10.0	4.0	5.142018e-004	0.99	6.38
SZ	-31.492	31.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-31.242	31.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.992	31.048	10.0	4.0	7.016127e-004	1.00	6.41
SZ	-30.742	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	31.048	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-28.992	31.048	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-32.992	31.298	10.0	4.0	2.216717e-004	0.94	6.47
Diff	-32.742	31.298	10.0	4.0	2.564317e-004	0.95	6.42
Diff	-32.492	31.298	10.0	4.0	3.015685e-004	0.97	6.42
Diff	-32.242	31.298	10.0	4.0	3.618306e-004	0.99	6.42
Diff	-31.992	31.298	10.0	4.0	4.179953e-004	0.99	6.42
Diff	-31.742	31.298	10.0	4.0	4.668344e-004	0.99	6.40
Diff	-31.492	31.298	10.0	4.0	4.770974e-004	0.98	6.38
Diff	-31.242	31.298	10.0	4.0	5.426160e-004	0.97	6.38
SZ	-30.992	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.742	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.492	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-30.242	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	31.298	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.242	31.298	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-32.742	31.548	10.0	4.0	2.228366e-004	0.94	6.42
Diff	-32.492	31.548	10.0	4.0	2.571489e-004	0.95	6.42
Diff	-32.242	31.548	10.0	4.0	3.190580e-004	0.98	6.42
Diff	-31.992	31.548	10.0	4.0	3.755951e-004	1.00	6.42
Diff	-31.742	31.548	10.0	4.0	4.171651e-004	0.98	6.42
Diff	-31.492	31.548	10.0	4.0	4.837682e-004	0.98	6.42
Diff	-31.242	31.548	10.0	4.0	5.060296e-004	0.98	6.40
Diff	-30.992	31.548	10.0	4.0	7.329340e-004	0.91	6.40
Diff	-30.742	31.548	10.0	4.0	7.812375e-004	0.90	6.38
SZ	-30.492	31.548	10.0	4.0	3.728210e-003	1.31	6.39

SZ	-30.242	31.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	31.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	31.548	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.492	31.548	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-32.492	31.798	10.0	4.0	2.071273e-004	0.94	6.42
Diff	-32.242	31.798	10.0	4.0	2.578613e-004	0.95	6.42
Diff	-31.992	31.798	10.0	4.0	3.488934e-004	0.99	6.42
Diff	-31.742	31.798	10.0	4.0	3.998008e-004	0.98	6.42
Diff	-31.492	31.798	10.0	4.0	4.140806e-004	0.98	6.42
Diff	-31.242	31.798	10.0	4.0	4.234605e-004	0.99	6.42
Diff	-30.992	31.798	10.0	4.0	6.803598e-004	0.90	6.42
Diff	-30.742	31.798	10.0	4.0	7.445805e-004	0.90	6.42
Diff	-30.492	31.798	10.0	4.0	7.608028e-004	0.90	6.39
SZ	-30.242	31.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.992	31.798	10.0	4.0	3.728210e-003	1.31	6.39
SZ	-29.742	31.798	10.0	4.0	3.728210e-003	1.31	6.39
Diff	-31.992	32.048	10.0	4.0	2.582247e-004	0.95	6.43
Diff	-31.742	32.048	10.0	4.0	3.862472e-004	0.97	6.43
Diff	-31.492	32.048	10.0	4.0	3.933879e-004	0.98	6.42
Diff	-31.242	32.048	10.0	4.0	4.056722e-004	0.98	6.42
Diff	-30.992	32.048	10.0	4.0	5.864194e-004	0.90	6.42
Diff	-30.742	32.048	10.0	4.0	6.206808e-004	0.90	6.42
Diff	-30.492	32.048	10.0	4.0	6.755289e-004	0.90	6.42
Diff	-30.242	32.048	10.0	4.0	6.968541e-004	0.89	6.41

Coordinates of the Seismogenic Zones and Their Parameters

Zone #1

Long [DEG]	Lat [DEG]
25.06	-32.93
30.48	-32.96
29.12	-34.49
26.93	-34.82

COMPUTED HAZARD PARAMETERS OF SEISMOGENIC ZONE #1

MEAN SEISMIC ACTIVITY RATE lambda = 0.020 [EVENTS/YEAR]
b-VALUE OF THE GUTENBERG-RICHTER = 0.94
MINIMUM VALUE OF EQ-e MAGNITUDE = 4.0
MAXIMUM VALUE OF EQ-e MAGNITUDE = 6.4
AVERAGE DEPTH OF EQ-s WITHIN ZONE = 10.0 [KM]

Zone #2

Long [DEG]	Lat [DEG]
27.10	-32.96
28.92	-30.56
31.36	-31.04
30.50	-32.87

COMPUTED HAZARD PARAMETERS OF SEISMOGENIC ZONE #2

MEAN SEISMIC ACTIVITY RATE lambda = 0.071 [EVENTS/YEAR]
b-VALUE OF THE GUTENBERG-RICHTER = 1.00
MINIMUM VALUE OF EQ-e MAGNITUDE = 4.0
MAXIMUM VALUE OF EQ-e MAGNITUDE = 6.4
AVERAGE DEPTH OF EQ-s WITHIN ZONE = 10.0 [KM]

Zone #3

Long [DEG]	Lat [DEG]
25.74	-31.07
25.62	-27.98
33.43	-27.95
31.34	-31.01
28.87	-30.56
28.46	-31.01

COMPUTED HAZARD PARAMETERS OF SEISMOGENIC ZONE #3

MEAN SEISMIC ACTIVITY RATE lambda = 0.876 [EVENTS/YEAR]
b-VALUE OF THE GUTENBERG-RICHTER = 1.31
MINIMUM VALUE OF EQ-e MAGNITUDE = 4.0
MAXIMUM VALUE OF EQ-e MAGNITUDE = 6.4
AVERAGE DEPTH OF EQ-s WITHIN ZONE = 10.0 [KM]

ANNEX D

Ground Motion Prediction Equation #1

AB2006: ATKINSON-BOORE (BSSA, vol.96, pp.2181-2205, 2006)

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ln[a(f)] = c1 + c2*mag + c3*mag^2 + (c4 + c5*mag)*f1 + (c6 + c7*mag)*f2 + (c8 + c9*mag)*f0 + c10*r + p*SD

WHERE:

a = MEDIAN VALUE, HARD ROCK, AVERAGE HORIZONTAL COMPONENT PGA/ARS [g]
f = GROUND MOTION FREQUENCY. IF a = PGA, f = 99.9 [Hz]
mag = EARTHQUAKE MAGNITUDE Mw
r = HYPOCENTRAL DISTANCE (CLOSEST DISTANCE TO THE FAULT) [KM]
f0 = MAX[log10(r0/r),0], r0 = 10 KM
f1 = MIN[log10(r/r1], r1 = 70 KM
f2 = MAX[log10(r/r2),0], r2 = 140 KM
p = 0. IF p = 1, ln(a) = MEAN[ln(a)] + SD[ln(a)]
c1,...,c10 = COEFFICIENTS; SD OF PREDICTED ln(a) = 0.69

ATTENUATION COEFFICIENTS

==============================

Freq.(Hz)	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10
0.2	-5.41	1.710	-0.0901	-2.54	0.227	-1.270	0.116	0.979	-0.1770	-0.0002
0.3	-5.79	1.920	-0.1070	-2.44	0.211	-1.160	0.102	1.010	-0.1820	-0.0002
0.4	-6.17	2.210	-0.1350	-2.30	0.190	-0.986	0.079	0.968	-0.1770	-0.0003
0.5	-6.18	2.300	-0.1440	-2.22	0.177	-0.937	0.071	0.952	-0.1770	-0.0003
0.8	-5.72	2.320	-0.1510	-2.10	0.157	-0.820	0.052	0.856	-0.1660	-0.0004
1.0	-5.27	2.260	-0.1480	-2.07	0.150	-0.813	0.047	0.826	-0.1620	-0.0005
2.0	-3.22	1.830	-0.1200	-2.02	0.134	-0.813	0.044	0.884	-0.1750	-0.0008
2.5	-2.44	1.650	-0.1080	-2.05	0.136	-0.843	0.045	0.739	-0.1560	-0.0009
4.0	-1.12	1.340	-0.0872	-2.08	0.135	-0.971	0.056	0.614	0.1430	-0.0011
5.0	-0.61	1.230	-0.0789	-2.09	0.131	-1.120	0.068	0.606	-0.1460	-0.0011
8.0	0.21	1.050	-0.0666	-2.15	0.130	-1.610	0.105	0.427	-0.1300	-0.0012
10.0	0.48	1.020	-0.0640	-2.20	0.127	-2.010	0.133	0.337	-0.1270	-0.0010
20.0	1.11	0.972	-0.0620	-2.47	0.128	-3.390	0.214	-0.139	-0.0984	-0.0003
25.2	1.26	0.968	-0.0623	-2.58	0.132	-3.640	0.228	-0.351	-0.0813	-0.0001
40.0	1.52	0.960	-0.0635	-2.81	0.146	-3.650	0.236	-0.654	-0.0550	-0.0000
PGA	0.91	0.983	-0.0660	-2.70	0.159	-2.800	0.212	-0.301	-0.0653	-0.0004

Ground Motion Prediction Equation #2

BA2008: BOORE-ATKINSON NGA (Earthquake Spectra, vol.24, pp.99-138, 2008)
==

ln[a(f)] = F_M(mag) + F_D(r_JB) + p*SD

WHERE:

F_M, and F_D are mag scaling and distance function
f = GROUND MOTION FREQUENCY. IF a = PGA, f = 99.9 [Hz]
mag = EARTHQUAKE MAGNITUDE Mw
r_JB = JB DISTANCE (CLOSEST DISTANCE TO THE FAULT) [KM]
p = 0. IF p = 1, ln(a) = MEAN[ln(a)] + SD[ln(a)]

For details see: Boore D.M. and G.M. Atkinson (2008). "Ground motion prediction equationfor the average horizontal component of PGA, PGV, and periods between 0.01s and 10.0s.", Earthquake Spectra, vol.24, pp.99-138

ANNEX E

Results of PSHA. Tabulated values of mean activity rate, return periods and probability of exceedance in 1, 144, 475 and 10,000 years for specified values of PGA

GMPE: AB06. Scenario #1: Faults are not active

File : info_Mzimvubu_AB06_faults_no_active.txt
Created on : 11-Jan-2014 17:59:45

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
BY THE CORNELL-McGUIRE PROCEDURE
==

THE APPLIED METHODOLOGY IS DESCRIBED IN THE DOCUMENT:

"Recommendation for Probabilistic Seismic Hazard Analysis:
Guidance on Uncertainty and Use of Experts",

Prepared by:

Senior Seismic Hazard Analysis Committee (SSHAC),
R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff,
K.J. Coppersmith, C.A. Cornell, and P.A. Morris.

Lawrence Livermore National Laboratory.

Prepared for:

U.S. Nuclear Regulatory Commission, U.S. Department of Energy and
Electric Power Research Institute.

NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997

THE CODE REQUIRES TWO INPUT FILES:

FILE CONTAINING SITE-SPECIFIC INFORMATION:
--

- Site coordinates, LATITUDE & LONGITUDE [DEG]

- MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
PSHA calculations are to be performed. Suggested values:
for nuclear facilities, between 10^(-6) and 10^(-4),
for large water reservoirs/dams between 10^(-4) and 10^(-3).

- 3 TIME INTERVALS for which PSHA will be performed.
Suggested values: 50, 100 and 1000 years.

- Parameter controlling the ACCURACY of numerical integration.
If its value = 1, the accuracy of integration is LOW,
but computation time is SHORT.
If its value = 2, accuracy of integration is MODERATE,
but computation time is LONGER. If its value is 3,
accuracy of integration is HIGHEST, but computations require
SIGNIFICANTLY more time.

- Parameter providing provision for increase/decrease
of future seismicity.

- Two parameters controlling UNCERTAINTY of the assumed seismicity model.

First parameter controls uncertainty of b-value in the FREQUENCY-MAGNITUDE, Gutenberg-Richter relation. Second parameter controls uncertainty of the level of seismicity described by the mean activity rate LAMBDA.

- Parameter controlling predicted value of Ground Motion. If its value is = 1, in all calculations the MEAN value of ln(Ground Motion) is used. If its value is = 2, the predicted, mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION

FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE
--

Each seismic source is described by 7 parameters:

(1) latitude [DEG]
(2) longitude [DEG]
(3) depth [KM] of seismic source,
(4) minimum earthquake magnitude Mmin
(5) Mean seismic activity rate LAMBDA
(6) b-value of the frequency-magnitude Gutenberg-Richter relation
(7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.

==

PROGRAM NAME : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

WRITTEN : 15 SEP 2007 by A.K.
REVISED : 27 SEP 2007 by A.K.
: 30 SEP 2007 by A.K.
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: 15 SEP 2009 by A.K.
: 28 OCT 2010 by A.K.
: 19 AUG 2011 by A.K.
: 14 OCT 2011 by A.K.
: 01 OCT 2012 by A.K.

REVISION : 1.15

==

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E-mail : andrzej.kijko@up.ac.za
: andrzej.kijko@gmail.com

PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
===

The applied approach takes into account ground motion variability by integrating across the scatter in the attenuation equation

NAME OF THE SITE: Mzimvubu DAM (GMPE=AB06. No active faults)

ATTENUATION MODEL #3: ATKINSON & BOORE (2006)

SITE COORDINATES (LATITUDE) = -30.117 [DEG]
SITE COORDINATES (LONGITUDE) = 28.673 [DEG]

MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE = 1.000e-005 [DEG]

PSHA IS CALCULATED FOR TIME INTERVALS = 50 100 and 1000 YEARS

ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
MAGNITUDE INTEGRATION INTERVAL = 0.25

PROVISION FOR INDUCED SEISMICITY: REQUIRED
MULTIPLICATIVE FACTOR OF LAMBDA = 1

MODEL UNCERTAINTY OF THE b-VALUE = 25 [per cent]
MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25 [per cent]

ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss_circle.txt

Max EXPECTED PGA AT THE SITE = 0.183 [g] (FROM SEISMIC SOURCE #257)

SEISMIC HAZARD
==

PGA[g]	Lambda[EQ/Y]	RP[Y]	<RP-SD	RP+SD>	Pr(T = 1	50	100	1000 [Y])
0.010	2.75e-002	3.64e+001	<9.75e-002	7.27e+001>	0.0271	0.7469	0.9359	1.0000
0.020	9.42e-003	1.06e+002	<7.16e-001	2.12e+002>	0.0094	0.3757	0.6103	0.9999
0.030	4.77e-003	2.10e+002	<1.84e+000	4.17e+002>	0.0048	0.2122	0.3793	0.9915
0.040	2.82e-003	3.54e+002	<3.42e+000	7.05e+002>	0.0028	0.1317	0.2461	0.9407
0.050	1.83e-003	5.46e+002	<5.49e+000	1.09e+003>	0.0018	0.0876	0.1675	0.8401
0.060	1.27e-003	7.90e+002	<8.18e+000	1.57e+003>	0.0013	0.0614	0.1190	0.7182
0.070	9.17e-004	1.09e+003	<1.16e+001	2.17e+003>	0.0009	0.0448	0.0876	0.6001
0.080	6.87e-004	1.46e+003	<1.58e+001	2.89e+003>	0.0007	0.0338	0.0664	0.4970
0.090	5.30e-004	1.89e+003	<2.11e+001	3.75e+003>	0.0005	0.0261	0.0516	0.4113
0.100	4.18e-004	2.39e+003	<2.74e+001	4.76e+003>	0.0004	0.0207	0.0409	0.3417
0.110	3.36e-004	2.98e+003	<3.50e+001	5.92e+003>	0.0003	0.0167	0.0330	0.2854
0.120	2.74e-004	3.64e+003	<4.40e+001	7.24e+003>	0.0003	0.0136	0.0271	0.2400
0.130	2.27e-004	4.40e+003	<5.45e+001	8.75e+003>	0.0002	0.0113	0.0225	0.2032
0.140	1.90e-004	5.26e+003	<6.69e+001	1.05e+004>	0.0002	0.0095	0.0188	0.1731
0.150	1.61e-004	6.22e+003	<8.11e+001	1.24e+004>	0.0002	0.0080	0.0159	0.1485
0.160	1.37e-004	7.30e+003	<9.76e+001	1.45e+004>	0.0001	0.0068	0.0136	0.1281
0.170	1.18e-004	8.49e+003	<1.16e+002	1.69e+004>	0.0001	0.0059	0.0117	0.1111
0.180	1.02e-004	9.82e+003	<1.38e+002	1.95e+004>	0.0001	0.0051	0.0101	0.0968
0.190	8.86e-005	1.13e+004	<1.62e+002	2.24e+004>	0.0001	0.0044	0.0088	0.0848
0.200	7.75e-005	1.29e+004	<1.90e+002	2.56e+004>	0.0001	0.0039	0.0077	0.0746
0.210	6.82e-005	1.47e+004	<2.21e+002	2.91e+004>	0.0001	0.0034	0.0068	0.0659
0.220	6.02e-005	1.66e+004	<2.55e+002	3.30e+004>	0.0001	0.0030	0.0060	0.0584
0.230	5.34e-005	1.87e+004	<2.94e+002	3.72e+004>	0.0001	0.0027	0.0053	0.0520
0.240	4.75e-005	2.11e+004	<3.38e+002	4.18e+004>	0.0000	0.0024	0.0047	0.0464
0.250	4.24e-005	2.36e+004	<3.86e+002	4.68e+004>	0.0000	0.0021	0.0042	0.0415
0.260	3.80e-005	2.63e+004	<4.40e+002	5.22e+004>	0.0000	0.0019	0.0038	0.0373
0.270	3.41e-005	2.93e+004	<4.99e+002	5.81e+004>	0.0000	0.0017	0.0034	0.0335
0.280	3.07e-005	3.25e+004	<5.65e+002	6.45e+004>	0.0000	0.0015	0.0031	0.0303
0.290	2.77e-005	3.60e+004	<6.37e+002	7.14e+004>	0.0000	0.0014	0.0028	0.0274
0.300	2.51e-005	3.98e+004	<7.16e+002	7.89e+004>	0.0000	0.0013	0.0025	0.0248
0.310	2.28e-005	4.39e+004	<8.03e+002	8.70e+004>	0.0000	0.0011	0.0023	0.0225
0.320	2.07e-005	4.83e+004	<8.99e+002	9.57e+004>	0.0000	0.0010	0.0021	0.0205
0.330	1.89e-005	5.30e+004	<1.00e+003	1.05e+005>	0.0000	0.0009	0.0019	0.0187
0.340	1.72e-005	5.81e+004	<1.12e+003	1.15e+005>	0.0000	0.0009	0.0017	0.0171
0.350	1.57e-005	6.35e+004	<1.24e+003	1.26e+005>	0.0000	0.0008	0.0016	0.0156
0.360	1.44e-005	6.94e+004	<1.38e+003	1.37e+005>	0.0000	0.0007	0.0014	0.0143
0.370	1.32e-005	7.56e+004	<1.52e+003	1.50e+005>	0.0000	0.0007	0.0013	0.0131
0.380	1.21e-005	8.24e+004	<1.68e+003	1.63e+005>	0.0000	0.0006	0.0012	0.0121
0.390	1.12e-005	8.95e+004	<1.86e+003	1.77e+005>	0.0000	0.0006	0.0011	0.0111
0.400	1.03e-005	9.72e+004	<2.04e+003	1.92e+005>	0.0000	0.0005	0.0010	0.0102
0.410	9.49e-006	1.05e+005	<2.25e+003	2.08e+005>	0.0000	0.0005	0.0009	0.0094

UNIFORM ACCELERATION RERSPONSE SPECTRA
==

Return Period = 144 [Y]

Period [SEC] Freq [Hz] UARS [g]

0.50	2.00	0.011
0.40	2.50	0.013
0.25	4.00	0.018
0.20	5.00	0.024
0.13	8.00	0.034
0.10	10.00	0.045
0.05	20.00	0.054
0.04	25.20	0.052
0.03	40.00	0.043
	PGA	0.017

Return Period = 200 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.012
0.40	2.50	0.014
0.25	4.00	0.022
0.20	5.00	0.030
0.13	8.00	0.044
0.10	10.00	0.060
0.05	20.00	0.065
0.04	25.20	0.064
0.03	40.00	0.058
	PGA	0.021

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.50	2.00	0.017
0.40	2.50	0.022
0.25	4.00	0.040
0.20	5.00	0.060
0.13	8.00	0.072
0.10	10.00	0.087
0.05	20.00	0.106
0.04	25.20	0.105
0.03	40.00	0.093
	PGA	0.039

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.25	0.80	0.010
1.00	1.00	0.011
0.50	2.00	0.025
0.40	2.50	0.038
0.25	4.00	0.064
0.20	5.00	0.077
0.13	8.00	0.105
0.10	10.00	0.126
0.05	20.00	0.151
0.04	25.20	0.151
0.03	40.00	0.139
	PGA	0.065

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.00	0.50	0.010
1.25	0.80	0.014
1.00	1.00	0.024
0.50	2.00	0.086

0.40	2.50	0.114
0.25	4.00	0.165
0.20	5.00	0.208
0.13	8.00	0.269
0.10	10.00	0.331
0.05	20.00	0.404
0.04	25.20	0.409
0.03	40.00	0.386
	PGA	0.178

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.50	0.40	0.010
2.00	0.50	0.013
1.25	0.80	0.050
1.00	1.00	0.075
0.50	2.00	0.201
0.40	2.50	0.258
0.25	4.00	0.369
0.20	5.00	0.464
0.13	8.00	0.595
0.10	10.00	0.735
0.05	20.00	0.890
0.04	25.20	0.902
0.03	40.00	0.857
	PGA	0.403

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
4.00	0.25	0.010
2.50	0.40	0.015
2.00	0.50	0.044
1.25	0.80	0.107
1.00	1.00	0.161
0.50	2.00	0.392
0.40	2.50	0.497
0.25	4.00	0.706
0.20	5.00	0.881
0.13	8.00	1.119
0.10	10.00	1.382
0.05	20.00	1.663
0.04	25.20	1.684
0.03	40.00	1.599
	PGA	0.755

GMPE: AB06. Scenario #2: Faults are active

File : info_Mzimvubu_AB06_WITH_active_faults.txt
Created on : 11-Jan-2014 18:19:25

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
BY THE CORNELL-McGUIRE PROCEDURE
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Prepared for:

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NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997

THE CODE REQUIRES TWO INPUT FILES:

FILE CONTAINING SITE-SPECIFIC INFORMATION:

- Site coordinates, LATITUDE & LONGITUDE [DEG]

**- MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
PSHA calculations are to be performed. Suggested values:
for nuclear facilities, between 10^(-6) and 10^(-4),
for large water reservoirs/dams between 10^(-4) and 10^(-3).**

**- 3 TIME INTERVALS for which PSHA will be performed.
Suggested values: 50, 100 and 1000 years.**

**- Parameter controlling the ACCURACY of numerical integration.
If its value = 1, the accuracy of integration is LOW,
but computation time is SHORT.
If its value = 2, accuracy of integration is MODERATE,
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SIGNIFICANTLY more time.**

**- Parameter providing provision for increase/decrease
of future seismicity.**

**- Two parameters controlling UNCERTAINTY of the assumed seismicity model.
First parameter controls uncertainty of b-value in the
FREQUENCY-MAGNITUDE, Gutenberg-Richter relation.
Second parameter controls uncertainty of the level of seismicity
described by the mean activity rate LAMBDA.**

**- Parameter controlling predicted value of Ground Motion.
If its value is = 1, in all calculations the MEAN value of
ln(Ground Motion) is used. If its value is = 2, the predicted,
mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION**

FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE
--

Each seismic source is described by 7 parameters:

**(1) latitude [DEG]
(2) longitude [DEG]
(3) depth [KM] of seismic source,
(4) minimum earthquake magnitude Mmin
(5) Mean seismic activity rate LAMBDA
(6) b-value of the frequency-magnitude Gutenberg-Richter relation
(7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.**

==

PROGRAM NAME : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

**WRITTEN : 15 SEP 2007 by A.K.
REVISED : 27 SEP 2007 by A.K.
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: 01 OCT 2012 by A.K.

REVISION : 1.15

==

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PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
==

The applied approach takes into account ground motion variability
by integrating across the scatter in the attenuation equation

NAME OF THE SITE: Mzimvubu Dam (GMPE=AB06. With faults)

ATTENUATION MODEL #3: ATKINSON & BOORE (2006)

SITE COORDINATES (LATITUDE) = -30.117 [DEG]
SITE COORDINATES (LONGITUDE) = 28.673 [DEG]

MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE = 1.000e-005 [DEG]

PSHA IS CALCULATED FOR TIME INTERVALS = 50 100 and 1000 YEARS

ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
MAGNITUDE INTEGRATION INTERVAL = 0.25

PROVISION FOR INDUCED SEISMICITY: REQUIRED
MULTIPLICATIVE FACTOR OF LAMBDA = 1

MODEL UNCERTAINTY OF THE b-VALUE = 25 [per cent]
MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25 [per cent]

ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss_circle_and_faults.txt

Max EXPECTED PGA AT THE SITE = 0.183 [g] (FROM SEISMIC SOURCE #257)

SEISMIC HAZARD
==

PGA[g]	Lambda[EQ/Y]	RP[Y]	<RP-SD RP+SD>	Pr(T = 1	50	100	1000 [Y])
0.010	3.62e-002	2.76e+001	<6.88e-002 5.52e+001>	0.0355	0.8363	0.9732	1.0000
0.020	1.36e-002	7.33e+001	<3.89e-001 1.46e+002>	0.0136	0.4946	0.7446	1.0000
0.030	7.25e-003	1.38e+002	<8.67e-001 2.75e+002>	0.0072	0.3042	0.5158	0.9993
0.040	4.42e-003	2.26e+002	<1.48e+000 4.51e+002>	0.0044	0.1984	0.3574	0.9880
0.050	2.93e-003	3.42e+002	<2.24e+000 6.81e+002>	0.0029	0.1362	0.2538	0.9465
0.060	2.05e-003	4.87e+002	<3.21e+000 9.72e+002>	0.0020	0.0975	0.1855	0.8715
0.070	1.50e-003	6.67e+002	<4.41e+000 1.33e+003>	0.0015	0.0723	0.1393	0.7769
0.080	1.13e-003	8.82e+002	<5.89e+000 1.76e+003>	0.0011	0.0551	0.1072	0.6782
0.090	8.80e-004	1.14e+003	<7.69e+000 2.26e+003>	0.0009	0.0431	0.0842	0.5853
0.100	6.98e-004	1.43e+003	<9.86e+000 2.86e+003>	0.0007	0.0343	0.0674	0.5024
0.110	5.63e-004	1.77e+003	<1.24e+001 3.54e+003>	0.0006	0.0278	0.0548	0.4308

0.120	4.62e-004	2.17e+003	<1.55e+001 4.32e+003>	0.0005	0.0228	0.0451	0.3698
0.130	3.83e-004	2.61e+003	<1.91e+001 5.20e+003>	0.0004	0.0190	0.0376	0.3183
0.140	3.22e-004	3.11e+003	<2.32e+001 6.20e+003>	0.0003	0.0159	0.0316	0.2750
0.150	2.72e-004	3.67e+003	<2.80e+001 7.31e+003>	0.0003	0.0135	0.0269	0.2384
0.160	2.33e-004	4.30e+003	<3.35e+001 8.56e+003>	0.0002	0.0116	0.0230	0.2076
0.170	2.00e-004	5.00e+003	<3.98e+001 9.95e+003>	0.0002	0.0100	0.0198	0.1814
0.180	1.73e-004	5.77e+003	<4.70e+001 1.15e+004>	0.0002	0.0086	0.0172	0.1592
0.190	1.51e-004	6.62e+003	<5.51e+001 1.32e+004>	0.0002	0.0075	0.0150	0.1402
0.200	1.32e-004	7.56e+003	<6.43e+001 1.51e+004>	0.0001	0.0066	0.0131	0.1239
0.210	1.16e-004	8.59e+003	<7.46e+001 1.71e+004>	0.0001	0.0058	0.0116	0.1099
0.220	1.03e-004	9.72e+003	<8.62e+001 1.94e+004>	0.0001	0.0051	0.0102	0.0977
0.230	9.12e-005	1.10e+004	<9.92e+001 2.18e+004>	0.0001	0.0046	0.0091	0.0872
0.240	8.12e-005	1.23e+004	<1.14e+002 2.45e+004>	0.0001	0.0041	0.0081	0.0780
0.250	7.26e-005	1.38e+004	<1.30e+002 2.74e+004>	0.0001	0.0036	0.0072	0.0700
0.260	6.50e-005	1.54e+004	<1.48e+002 3.06e+004>	0.0001	0.0032	0.0065	0.0630
0.270	5.84e-005	1.71e+004	<1.67e+002 3.41e+004>	0.0001	0.0029	0.0058	0.0568
0.280	5.27e-005	1.90e+004	<1.89e+002 3.78e+004>	0.0001	0.0026	0.0053	0.0513
0.290	4.76e-005	2.10e+004	<2.13e+002 4.18e+004>	0.0000	0.0024	0.0047	0.0465
0.300	4.31e-005	2.32e+004	<2.39e+002 4.62e+004>	0.0000	0.0022	0.0043	0.0422
0.310	3.91e-005	2.56e+004	<2.68e+002 5.09e+004>	0.0000	0.0020	0.0039	0.0383
0.320	3.56e-005	2.81e+004	<3.00e+002 5.60e+004>	0.0000	0.0018	0.0035	0.0349
0.330	3.24e-005	3.09e+004	<3.34e+002 6.14e+004>	0.0000	0.0016	0.0032	0.0319
0.340	2.96e-005	3.38e+004	<3.72e+002 6.73e+004>	0.0000	0.0015	0.0030	0.0291
0.350	2.70e-005	3.70e+004	<4.13e+002 7.36e+004>	0.0000	0.0014	0.0027	0.0267
0.360	2.48e-005	4.04e+004	<4.58e+002 8.03e+004>	0.0000	0.0012	0.0025	0.0245
0.370	2.27e-005	4.40e+004	<5.07e+002 8.75e+004>	0.0000	0.0011	0.0023	0.0225
0.380	2.09e-005	4.79e+004	<5.60e+002 9.53e+004>	0.0000	0.0010	0.0021	0.0207
0.390	1.92e-005	5.21e+004	<6.17e+002 1.04e+005>	0.0000	0.0010	0.0019	0.0190
0.400	1.77e-005	5.65e+004	<6.79e+002 1.12e+005>	0.0000	0.0009	0.0018	0.0175
0.410	1.63e-005	6.13e+004	<7.46e+002 1.22e+005>	0.0000	0.0008	0.0016	0.0162
0.420	1.51e-005	6.63e+004	<8.18e+002 1.32e+005>	0.0000	0.0008	0.0015	0.0150
0.430	1.39e-005	7.17e+004	<8.96e+002 1.43e+005>	0.0000	0.0007	0.0014	0.0138
0.440	1.29e-005	7.75e+004	<9.80e+002 1.54e+005>	0.0000	0.0006	0.0013	0.0128
0.450	1.20e-005	8.36e+004	<1.07e+003 1.66e+005>	0.0000	0.0006	0.0012	0.0119
0.460	1.11e-005	9.01e+004	<1.17e+003 1.79e+005>	0.0000	0.0006	0.0011	0.0110
0.470	1.03e-005	9.70e+004	<1.27e+003 1.93e+005>	0.0000	0.0005	0.0010	0.0103
0.480	9.59e-006	1.04e+005	<1.38e+003 2.07e+005>	0.0000	0.0005	0.0010	0.0095

UNIFORM ACCELERATION RERSPONSE SPECTRA
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Return Period = 144 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.012
0.40	2.50	0.014
0.25	4.00	0.022
0.20	5.00	0.030
0.13	8.00	0.046
0.10	10.00	0.061
0.05	20.00	0.068
0.04	25.20	0.068
0.03	40.00	0.062
	PGA	0.023

Return Period = 200 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
0.50	2.00	0.013
0.40	2.50	0.017
0.25	4.00	0.027
0.20	5.00	0.039
0.13	8.00	0.060
0.10	10.00	0.070
0.05	20.00	0.082
0.04	25.20	0.081
0.03	40.00	0.074

PGA 0.029

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.50	2.00	0.020
0.40	2.50	0.028
0.25	4.00	0.053
0.20	5.00	0.067
0.13	8.00	0.088
0.10	10.00	0.112
0.05	20.00	0.132
0.04	25.20	0.132
0.03	40.00	0.123
	PGA	0.059

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.25	0.80	0.010
1.00	1.00	0.012
0.50	2.00	0.032
0.40	2.50	0.049
0.25	4.00	0.073
0.20	5.00	0.094
0.13	8.00	0.126
0.10	10.00	0.157
0.05	20.00	0.190
0.04	25.20	0.191
0.03	40.00	0.179
	PGA	0.080

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.00	0.50	0.010
1.25	0.80	0.016
1.00	1.00	0.031
0.50	2.00	0.106
0.40	2.50	0.133
0.25	4.00	0.197
0.20	5.00	0.250
0.13	8.00	0.326
0.10	10.00	0.404
0.05	20.00	0.493
0.04	25.20	0.500
0.03	40.00	0.474
	PGA	0.220

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.50	0.40	0.011
2.00	0.50	0.016
1.25	0.80	0.062
1.00	1.00	0.090
0.50	2.00	0.235
0.40	2.50	0.302
0.25	4.00	0.434
0.20	5.00	0.545
0.13	8.00	0.699
0.10	10.00	0.864

0.05	20.00	1.045
0.04	25.20	1.060
0.03	40.00	1.006
	PGA	0.473

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
4.00	0.25	0.010
2.50	0.40	0.018
2.00	0.50	0.061
1.25	0.80	0.118
1.00	1.00	0.179
0.50	2.00	0.450
0.40	2.50	0.569
0.25	4.00	0.806
0.20	5.00	1.006
0.13	8.00	1.274
0.10	10.00	1.575
0.05	20.00	1.892
0.04	25.20	1.917
0.03	40.00	1.819
	PGA	0.860

GMPE: BA08. Scenario #1: Faults are not active

File : info_Mzimvubu_BA08_NO_active_faults.txt
Created on : 11-Jan-2014 18:35:38

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
BY THE CORNELL-McGUIRE PROCEDURE
==

THE APPLIED METHODOLOGY IS DESCRIBED IN THE DOCUMENT:

"Recommendation for Probabilistic Seismic Hazard Analysis:
Guidance on Uncertainty and Use of Experts",

Prepared by:

Senior Seismic Hazard Analysis Committee (SSHAC),
R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff,
K.J. Coppersmith, C.A. Cornell, and P.A. Morris.

Lawrence Livermore National Laboratory.

Prepared for:

U.S. Nuclear Regulatory Commission, U.S. Department of Energy and
Electric Power Research Institute.

NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997

THE CODE REQUIRES TWO INPUT FILES:

FILE CONTAINING SITE-SPECIFIC INFORMATION:

- Site coordinates, LATITUDE & LONGITUDE [DEG]

- MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
PSHA calculations are to be performed. Suggested values:
for nuclear facilities, between 10^(-6) and 10^(-4),
for large water reservoirs/dams between 10^(-4) and 10^(-3).

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    - 3 TIME INTERVALS for which PSHA will be performed.
      Suggested values: 50, 100 and 1000 years.

    - Parameter controlling the ACCURACY of numerical integration.
      If its value = 1, the accuracy of integration is LOW,
      but computation time is SHORT.
      If its value = 2, accuracy of integration is MODERATE,
       but computation time is LONGER. If its value is 3,
       accuracy of integration is HIGHEST, but computations require
       SIGNIFICANTLY more time.

    - Parameter providing provision for increase/decrease
      of future seismicity.

    - Two parameters controlling UNCERTAINTY of the assumed seismicity model.
      First parameter controls uncertainty of b-value in the
      FREQUENCY-MAGNITUDE, Gutenberg-Richter relation.
      Second parameter controls uncertainty of the level of seismicity
      described by the mean activity rate LAMBDA.

    - Parameter controlling predicted value of Ground Motion.
      If its value is = 1, in all calculations the MEAN value of
      ln(Ground Motion) is used. If its value is = 2, the predicted,
      mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION


  FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE
  ------------------------------------------------------------------------

    Each seismic source is described by 7 parameters:

    (1) latitude [DEG]
    (2) longitude [DEG]
    (3) depth [KM] of seismic source,
    (4) minimum earthquake magnitude Mmin
    (5) Mean seismic activity rate LAMBDA
    (6) b-value of the frequency-magnitude Gutenberg-Richter relation
    (7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.


=============================================================================

 PROGRAM NAME     : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

 WRITTEN          : 15 SEP 2007 by A.K.
 REVISED          : 27 SEP 2007 by A.K.
               : 30 SEP 2007 by A.K.
               : 01 OCT 2007 by A.K.
               : 20 FEB 2008 by A.K.
               : 12 MAY 2008 by A.K.
               : 21 JUN 2008 by A.K.
               : 15 SEP 2009 by A.K.
               : 28 OCT 2010 by A.K.
               : 19 AUG 2011 by A.K.
               : 14 OCT 2011 by A.K.
               : 01 OCT 2012 by A.K.

 REVISION         : 1.15

=============================================================================

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  PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
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The applied approach takes into account ground motion variability by integrating across the scatter in the attenuation equation

NAME OF THE SITE: Mzimvubu Dam (GMPE=BA08. No active faults)

ATTENUATION MODEL #12: NGA for Active Tectonic Regions (Boore & Atkinson, 2008)

SITE COORDINATES (LATITUDE) = -30.117 [DEG]
SITE COORDINATES (LONGITUDE) = 28.673 [DEG]

MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE = 1.000e-005 [DEG]

PSHA IS CALCULATED FOR TIME INTERVALS = 50 100 and 1000 YEARS

ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
MAGNITUDE INTEGRATION INTERVAL = 0.25

PROVISION FOR INDUCED SEISMICITY: REQUIRED
MULTIPLICATIVE FACTOR OF LAMBDA = 1

MODEL UNCERTAINTY OF THE b-VALUE = 25 [per cent]
MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25 [per cent]

ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss_circle.txt

Max EXPECTED PGA AT THE SITE = 0.109 [g] (FROM SEISMIC SOURCE #257)

SEISMIC HAZARD

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PGA[g]	Lambda[EQ/Y]	RP[Y]	<RP-SD RP+SD>	Pr(T = 1 50 100 1000 [Y])			
0.010	2.68e-002	3.74e+001	<1.37e-001 7.46e+001>	0.0264	0.7376	0.9311	1.0000
0.020	8.50e-003	1.18e+002	<6.74e-001 2.35e+002>	0.0085	0.3463	0.5727	0.9998
0.030	3.74e-003	2.68e+002	<1.62e+000 5.34e+002>	0.0037	0.1704	0.3118	0.9762
0.040	1.93e-003	5.19e+002	<3.13e+000 1.04e+003>	0.0019	0.0918	0.1751	0.8541
0.050	1.10e-003	9.10e+002	<5.58e+000 1.81e+003>	0.0011	0.0535	0.1041	0.6669
0.060	6.76e-004	1.48e+003	<9.45e+000 2.95e+003>	0.0007	0.0332	0.0653	0.4911
0.070	4.38e-004	2.28e+003	<1.54e+001 4.55e+003>	0.0004	0.0217	0.0429	0.3549
0.080	2.97e-004	3.37e+003	<2.44e+001 6.72e+003>	0.0003	0.0147	0.0292	0.2568
0.090	2.08e-004	4.82e+003	<3.75e+001 9.59e+003>	0.0002	0.0103	0.0206	0.1875
0.100	1.49e-004	6.70e+003	<5.63e+001 1.33e+004>	0.0001	0.0074	0.0148	0.1387
0.110	1.10e-004	9.12e+003	<8.25e+001 1.82e+004>	0.0001	0.0055	0.0109	0.1039
0.120	8.21e-005	1.22e+004	<1.19e+002 2.42e+004>	0.0001	0.0041	0.0082	0.0788
0.130	6.24e-005	1.60e+004	<1.68e+002 3.19e+004>	0.0001	0.0031	0.0062	0.0605
0.140	4.81e-005	2.08e+004	<2.33e+002 4.13e+004>	0.0000	0.0024	0.0048	0.0470
0.150	3.75e-005	2.66e+004	<3.19e+002 5.30e+004>	0.0000	0.0019	0.0037	0.0368
0.160	2.96e-005	3.38e+004	<4.31e+002 6.72e+004>	0.0000	0.0015	0.0030	0.0291
0.170	2.35e-005	4.25e+004	<5.75e+002 8.45e+004>	0.0000	0.0012	0.0023	0.0232
0.180	1.89e-005	5.30e+004	<7.59e+002 1.05e+005>	0.0000	0.0009	0.0019	0.0187
0.190	1.52e-005	6.56e+004	<9.91e+002 1.30e+005>	0.0000	0.0008	0.0015	0.0151
0.200	1.24e-005	8.07e+004	<1.28e+003 1.60e+005>	0.0000	0.0006	0.0012	0.0123
0.210	1.01e-005	9.86e+004	<1.65e+003 1.95e+005>	0.0000	0.0005	0.0010	0.0101
0.220	8.35e-006	1.20e+005	<2.09e+003 2.37e+005>	0.0000	0.0004	0.0008	0.0083

UNIFORM ACCELERATION RERSPONSE SPECTRA

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Return Period = 144 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.75	1.33	0.011
0.50	2.00	0.016

0.40	2.50	0.021
0.30	3.33	0.032
0.25	4.00	0.036
0.20	5.00	0.047
0.15	6.67	0.052
0.10	10.00	0.044
0.07	13.33	0.032
0.05	20.00	0.019
0.03	33.33	0.015
0.02	50.00	0.014
	PGA	0.014

Return Period = 200 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.75	1.33	0.012
0.50	2.00	0.018
0.40	2.50	0.027
0.30	3.33	0.041
0.25	4.00	0.047
0.20	5.00	0.061
0.15	6.67	0.063
0.10	10.00	0.059
0.07	13.33	0.041
0.05	20.00	0.024
0.03	33.33	0.018
0.02	50.00	0.016
	PGA	0.016

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.50	0.67	0.010
1.00	1.00	0.012
0.75	1.33	0.016
0.50	2.00	0.032
0.40	2.50	0.051
0.30	3.33	0.068
0.25	4.00	0.072
0.20	5.00	0.084
0.15	6.67	0.091
0.10	10.00	0.082
0.07	13.33	0.068
0.05	20.00	0.046
0.03	33.33	0.031
0.02	50.00	0.027
	PGA	0.025

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.00	0.50	0.010
1.50	0.67	0.011
1.00	1.00	0.015
0.75	1.33	0.024
0.50	2.00	0.057
0.40	2.50	0.070
0.30	3.33	0.092
0.25	4.00	0.102
0.20	5.00	0.118
0.15	6.67	0.126
0.10	10.00	0.117
0.07	13.33	0.094
0.05	20.00	0.066
0.03	33.33	0.056

0.02	50.00	0.048
	PGA	0.043

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
3.00	0.33	0.010
2.00	0.50	0.015
1.50	0.67	0.027
1.00	1.00	0.062
0.75	1.33	0.081
0.50	2.00	0.130
0.40	2.50	0.168
0.30	3.33	0.219
0.25	4.00	0.232
0.20	5.00	0.268
0.15	6.67	0.281
0.10	10.00	0.257
0.07	13.33	0.215
0.05	20.00	0.154
0.03	33.33	0.122
0.02	50.00	0.115
	PGA	0.112

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
5.00	0.20	0.010
4.00	0.25	0.010
3.00	0.33	0.015
2.00	0.50	0.059
1.50	0.67	0.078
1.00	1.00	0.126
0.75	1.33	0.176
0.50	2.00	0.266
0.40	2.50	0.330
0.30	3.33	0.426
0.25	4.00	0.450
0.20	5.00	0.515
0.15	6.67	0.525
0.10	10.00	0.474
0.07	13.33	0.401
0.05	20.00	0.287
0.03	33.33	0.234
0.02	50.00	0.217
	PGA	0.210

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
7.50	0.13	0.010
5.00	0.20	0.011
4.00	0.25	0.015
3.00	0.33	0.057
2.00	0.50	0.110
1.50	0.67	0.160
1.00	1.00	0.234
0.75	1.33	0.319
0.50	2.00	0.465
0.40	2.50	0.572
0.30	3.33	0.729
0.25	4.00	0.763
0.20	5.00	0.868
0.15	6.67	0.871
0.10	10.00	0.784
0.07	13.33	0.665

0.05	**20.00**	**0.478**
0.03	**33.33**	**0.391**
0.02	**50.00**	**0.362**
	PGA	**0.344**

GMPE: BA08. Scenario #2: Faults are active

File : info_Mzimvubu_BA08_WITH_active_faults.txt
Created on : 11-Jan-2014 18:50:59

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR A SELECTED SITE
BY THE CORNELL-McGUIRE PROCEDURE
==

THE APPLIED METHODOLOGY IS DESCRIBED IN THE DOCUMENT:

"Recommendation for Probabilistic Seismic Hazard Analysis:
Guidance on Uncertainty and Use of Experts",

Prepared by:

Senior Seismic Hazard Analysis Committee (SSHAC),
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Prepared for:

U.S. Nuclear Regulatory Commission, U.S. Department of Energy and
Electric Power Research Institute.

NUREG/CR-6372, UCRL-ID-122160, vol.1, April 1997

THE CODE REQUIRES TWO INPUT FILES:

FILE CONTAINING SITE-SPECIFIC INFORMATION:

- Site coordinates, LATITUDE & LONGITUDE [DEG]

- MINIMUM VALUE OF ANNUAL PROBABILITY OF EXCEEDANCE of PGA for which
PSHA calculations are to be performed. Suggested values:
for nuclear facilities, between 10^(-6) and 10^(-4),
for large water reservoirs/dams between 10^(-4) and 10^(-3).

- 3 TIME INTERVALS for which PSHA will be performed.
Suggested values: 50, 100 and 1000 years.

- Parameter controlling the ACCURACY of numerical integration.
If its value = 1, the accuracy of integration is LOW,
but computation time is SHORT.
If its value = 2, accuracy of integration is MODERATE,
but computation time is LONGER. If its value is 3,
accuracy of integration is HIGHEST, but computations require
SIGNIFICANTLY more time.

- Parameter providing provision for increase/decrease
of future seismicity.

- Two parameters controlling UNCERTAINTY of the assumed seismicity model.
First parameter controls uncertainty of b-value in the
FREQUENCY-MAGNITUDE, Gutenberg-Richter relation.
Second parameter controls uncertainty of the level of seismicity
described by the mean activity rate LAMBDA.

- Parameter controlling predicted value of Ground Motion.
  If its value is = 1, in all calculations the MEAN value of
  ln(Ground Motion) is used. If its value is = 2, the predicted,
  mean value of ln(Ground Motion) is increased by its STANDARD DEVIATION

FILE CONTAINING INFORMATION ON SEISMIC SOURCES IN THE VICINITY OF THE SITE

Each seismic source is described by 7 parameters:

(1) latitude [DEG]
(2) longitude [DEG]
(3) depth [KM] of seismic source,
(4) minimum earthquake magnitude Mmin
(5) Mean seismic activity rate LAMBDA
(6) b-value of the frequency-magnitude Gutenberg-Richter relation
(7) MAXIMUM, seismic source-characteristic EQ-e magnitude Mmax.

===

PROGRAM NAME : HS_C_McG (H = Hazard; S = Site; C = Cornell; McG = McGuire)

WRITTEN : 15 SEP 2007 by A.K.
REVISED : 27 SEP 2007 by A.K.
: 30 SEP 2007 by A.K.
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: 12 MAY 2008 by A.K.
: 21 JUN 2008 by A.K.
: 15 SEP 2009 by A.K.
: 28 OCT 2010 by A.K.
: 19 AUG 2011 by A.K.
: 14 OCT 2011 by A.K.
: 01 OCT 2012 by A.K.

REVISION : 1.15

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PROBABILISTIC SEISMIC HAZARD ASSESSMENT BY CORNELL-McGUIRE PROCEDURE
==

The applied approach takes into account ground motion variability
by integrating across the scatter in the attenuation equation

NAME OF THE SITE: Mzimvubu Dam (GMPE=BA08. With faults)

ATTENUATION MODEL #12: NGA for Active Tectonic Regions (Boore & Atkinson, 2008)

SITE COORDINATES (LATITUDE) = -30.117 [DEG]
SITE COORDINATES (LONGITUDE) = 28.673 [DEG]

MINIMUM ANNUAL PROBABILITY OF EXCEEDANCE = 1.000e-005 [DEG]

PSHA IS CALCULATED FOR TIME INTERVALS = 50 100 and 1000 YEARS

ACCURACY OF NUMERICAL INTEGRATION: MEDIUM
MAGNITUDE INTEGRATION INTERVAL = 0.25

PROVISION FOR INDUCED SEISMICITY: REQUIRED

MULTIPLICATIVE FACTOR OF LAMBDA = 1

MODEL UNCERTAINTY OF THE b-VALUE = 25 [per cent]
MODEL UNCERTAINTY OF THE SITE-SPECIFIC LAMBDA = 25 [per cent]

ALL CALCULATIONS ARE PERFORMED FOR MEAN VALUE OF ln[PGA/ARS]

NAME OF INPUT FILE WITH PARAMETERS OF SEISMIC SOURCES: ss_circle_and_faults.txt

Max EXPECTED PGA AT THE SITE = 0.109 [g] (FROM SEISMIC SOURCE #257)

SEISMIC HAZARD
==

PGA[g]	Lambda[EQ/Y]	RP[Y]	<RP-SD RP+SD>	Pr(T = 1 50 100 1000 [Y])
0.010	3.59e-002	2.78e+001	<8.78e-002 5.56e+001>	0.0353 0.8342 0.9725 1.0000
0.020	1.24e-002	8.07e+001	<3.53e-001 1.61e+002>	0.0123 0.4619 0.7105 1.0000
0.030	5.63e-003	1.78e+002	<7.75e-001 3.54e+002>	0.0056 0.2453 0.4305 0.9964
0.040	2.96e-003	3.38e+002	<1.42e+000 6.75e+002>	0.0030 0.1374 0.2559 0.9480
0.050	1.71e-003	5.85e+002	<2.44e+000 1.17e+003>	0.0017 0.0820 0.1572 0.8193
0.060	1.06e-003	9.41e+002	<4.01e+000 1.88e+003>	0.0011 0.0518 0.1008 0.6545
0.070	6.96e-004	1.44e+003	<6.39e+000 2.87e+003>	0.0007 0.0342 0.0672 0.5015
0.080	4.75e-004	2.11e+003	<9.89e+000 4.20e+003>	0.0005 0.0235 0.0464 0.3781
0.090	3.35e-004	2.99e+003	<1.49e+001 5.96e+003>	0.0003 0.0166 0.0329 0.2844
0.100	2.42e-004	4.13e+003	<2.20e+001 8.24e+003>	0.0002 0.0120 0.0239 0.2149
0.110	1.79e-004	5.59e+003	<3.18e+001 1.12e+004>	0.0002 0.0089 0.0177 0.1637
0.120	1.34e-004	7.44e+003	<4.52e+001 1.48e+004>	0.0001 0.0067 0.0134 0.1258
0.130	1.03e-004	9.74e+003	<6.31e+001 1.94e+004>	0.0001 0.0051 0.0102 0.0976
0.140	7.94e-005	1.26e+004	<8.69e+001 2.51e+004>	0.0001 0.0040 0.0079 0.0764
0.150	6.22e-005	1.61e+004	<1.18e+002 3.21e+004>	0.0001 0.0031 0.0062 0.0603
0.160	4.91e-005	2.04e+004	<1.58e+002 4.06e+004>	0.0000 0.0025 0.0049 0.0479
0.170	3.92e-005	2.55e+004	<2.09e+002 5.08e+004>	0.0000 0.0020 0.0039 0.0384
0.180	3.15e-005	3.18e+004	<2.74e+002 6.32e+004>	0.0000 0.0016 0.0031 0.0310
0.190	2.55e-005	3.92e+004	<3.56e+002 7.81e+004>	0.0000 0.0013 0.0025 0.0252
0.200	2.08e-005	4.81e+004	<4.59e+002 9.58e+004>	0.0000 0.0010 0.0021 0.0206
0.210	1.70e-005	5.87e+004	<5.85e+002 1.17e+005>	0.0000 0.0009 0.0017 0.0169
0.220	1.40e-005	7.12e+004	<7.42e+002 1.42e+005>	0.0000 0.0007 0.0014 0.0139
0.230	1.16e-005	8.59e+004	<9.33e+002 1.71e+005>	0.0000 0.0006 0.0012 0.0116
0.240	9.69e-006	1.03e+005	<1.16e+003 2.05e+005>	0.0000 0.0005 0.0010 0.0096

UNIFORM ACCELERATION RERSPONSE SPECTRA
===

Return Period = 144 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.00	1.00	0.010
0.75	1.33	0.012
0.50	2.00	0.018
0.40	2.50	0.027
0.30	3.33	0.041
0.25	4.00	0.047
0.20	5.00	0.061
0.15	6.67	0.065
0.10	10.00	0.061
0.07	13.33	0.045
0.05	20.00	0.025
0.03	33.33	0.019
0.02	50.00	0.017
	PGA	0.016

Return Period = 200 [Y]

Period [SEC] Freq [Hz] UARS [g]

1.00	1.00	0.011
0.75	1.33	0.013
0.50	2.00	0.022
0.40	2.50	0.034
0.30	3.33	0.053
0.25	4.00	0.061
0.20	5.00	0.068
0.15	6.67	0.074
0.10	10.00	0.069
0.07	13.33	0.060
0.05	20.00	0.032
0.03	33.33	0.023
0.02	50.00	0.021
	PGA	0.019

Return Period = 475 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
1.50	0.67	0.011
1.00	1.00	0.013
0.75	1.33	0.019
0.50	2.00	0.041
0.40	2.50	0.062
0.30	3.33	0.077
0.25	4.00	0.084
0.20	5.00	0.104
0.15	6.67	0.114
0.10	10.00	0.105
0.07	13.33	0.082
0.05	20.00	0.062
0.03	33.33	0.044
0.02	50.00	0.038
	PGA	0.034

Return Period = 1000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
2.00	0.50	0.010
1.50	0.67	0.012
1.00	1.00	0.018
0.75	1.33	0.030
0.50	2.00	0.064
0.40	2.50	0.080
0.30	3.33	0.111
0.25	4.00	0.119
0.20	5.00	0.138
0.15	6.67	0.153
0.10	10.00	0.138
0.07	13.33	0.115
0.05	20.00	0.077
0.03	33.33	0.065
0.02	50.00	0.062
	PGA	0.061

Return Period = 10000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
4.00	0.25	0.010
3.00	0.33	0.011
2.00	0.50	0.017
1.50	0.67	0.035
1.00	1.00	0.068
0.75	1.33	0.097
0.50	2.00	0.154
0.40	2.50	0.193
0.30	3.33	0.253

0.25	4.00	0.270
0.20	5.00	0.312
0.15	6.67	0.326
0.10	10.00	0.297
0.07	13.33	0.249
0.05	20.00	0.177
0.03	33.33	0.144
0.02	50.00	0.131
	PGA	0.125

Return Period = 100000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
5.00	0.20	0.010
4.00	0.25	0.011
3.00	0.33	0.017
2.00	0.50	0.063
1.50	0.67	0.092
1.00	1.00	0.147
0.75	1.33	0.203
0.50	2.00	0.303
0.40	2.50	0.376
0.30	3.33	0.483
0.25	4.00	0.512
0.20	5.00	0.583
0.15	6.67	0.595
0.10	10.00	0.536
0.07	13.33	0.454
0.05	20.00	0.326
0.03	33.33	0.268
0.02	50.00	0.245
	PGA	0.233

Return Period = 1000000 [Y]

Period [SEC]	Freq [Hz]	UARS [g]
7.50	0.13	0.010
5.00	0.20	0.012
4.00	0.25	0.019
3.00	0.33	0.062
2.00	0.50	0.118
1.50	0.67	0.174
1.00	1.00	0.265
0.75	1.33	0.360
0.50	2.00	0.519
0.40	2.50	0.638
0.30	3.33	0.813
0.25	4.00	0.849
0.20	5.00	0.966
0.15	6.67	0.967
0.10	10.00	0.870
0.07	13.33	0.737
0.05	20.00	0.531
0.03	33.33	0.434
0.02	50.00	0.400
	PGA	0.381

ANNEX F

Plots of hazard curves and return periods, including their confidence intervals

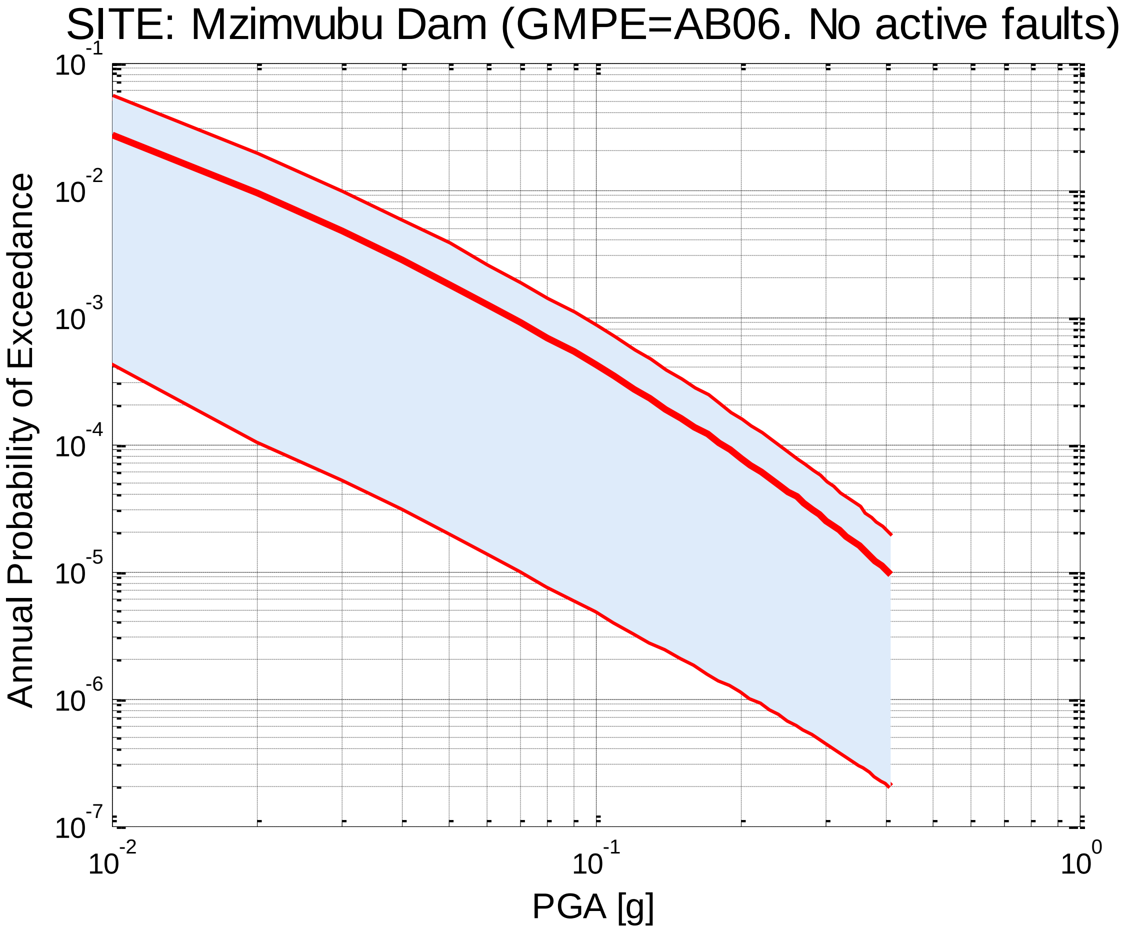


Figure 1(a): Annual probability of exceedance and its confidence intervals of the median value of horizontal PGA at the dam site calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006). Scenario #1: all known faults in vicinity of the dam site are not active.

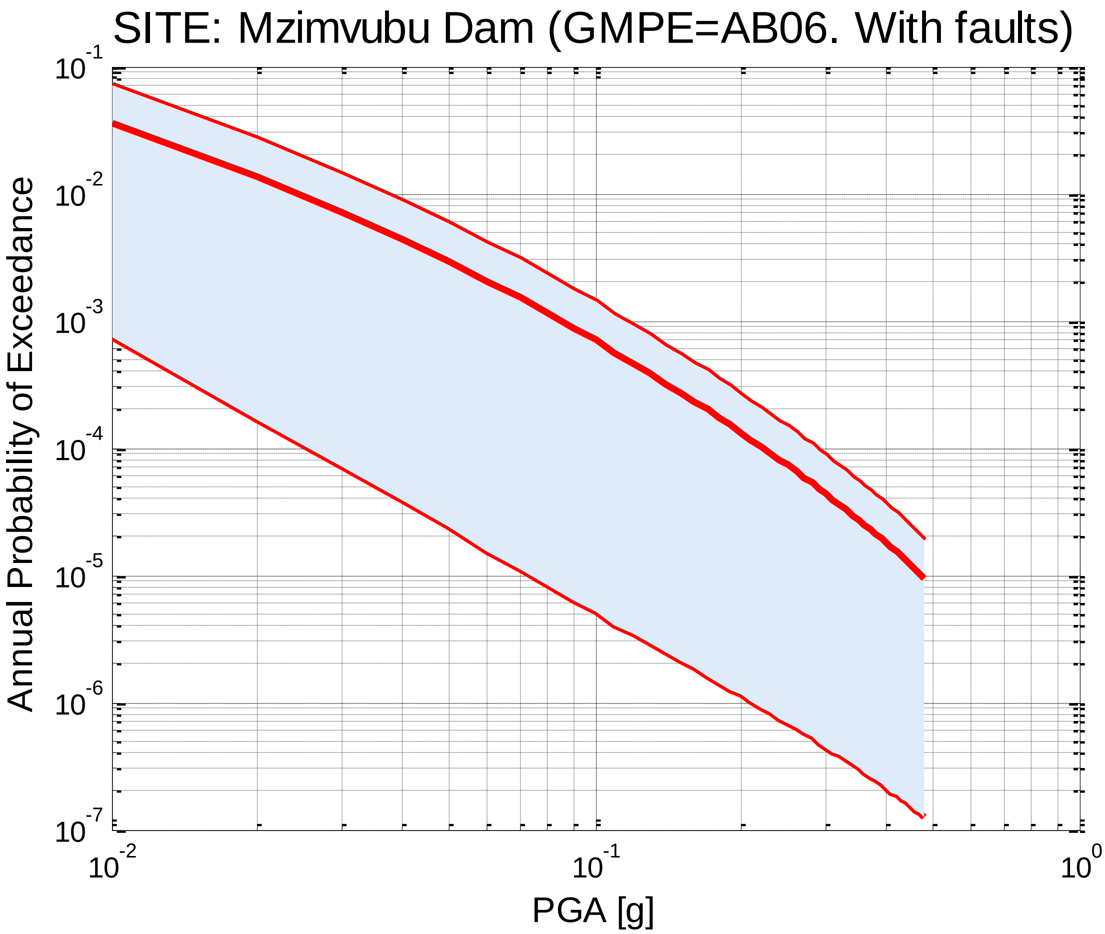


Figure 1(b): Annual probability of exceedance and its confidence intervals of the median value of horizontal PGA at the dam site calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006). Scenario #2: all known faults in vicinity of the dam site are active.

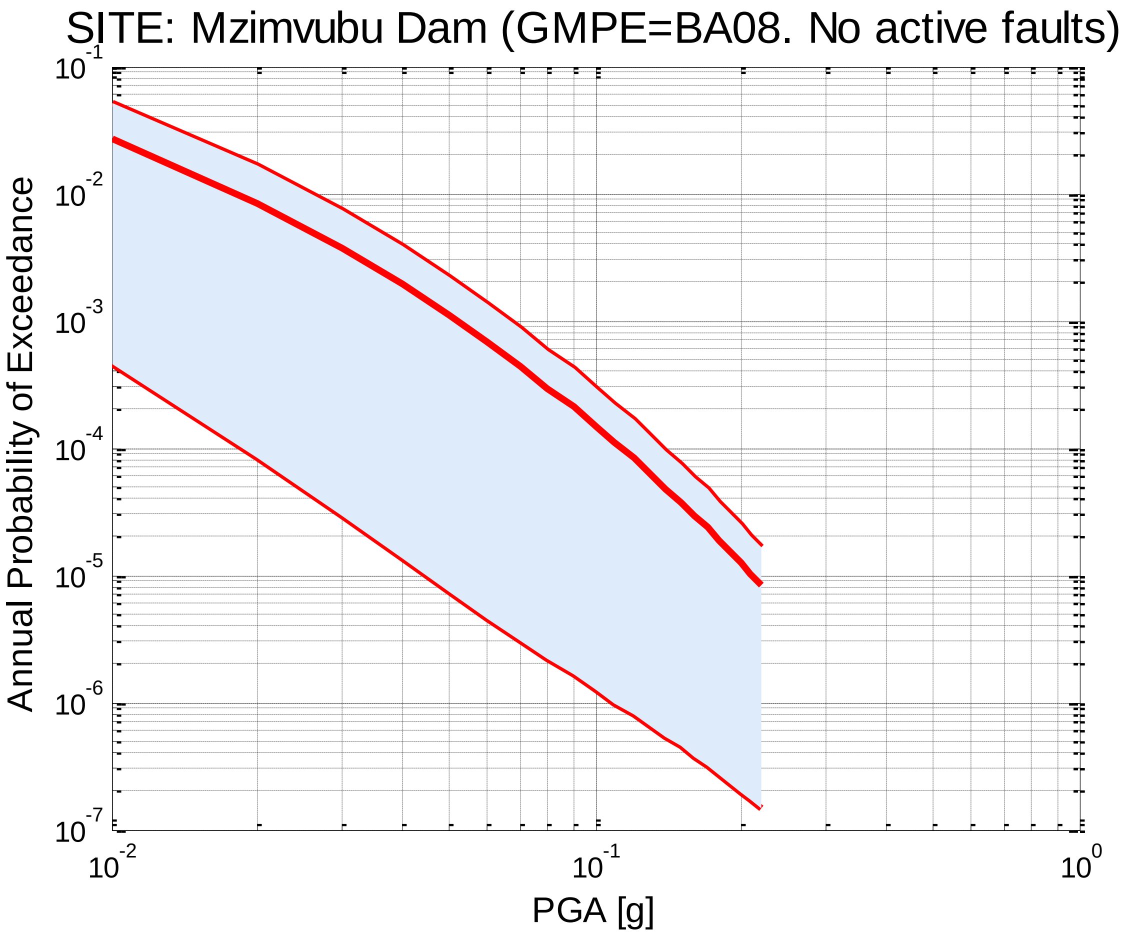


Figure 1(c): Annual probability of exceedance and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008). Scenario #1: all known faults in vicinity of the dam site are not active.

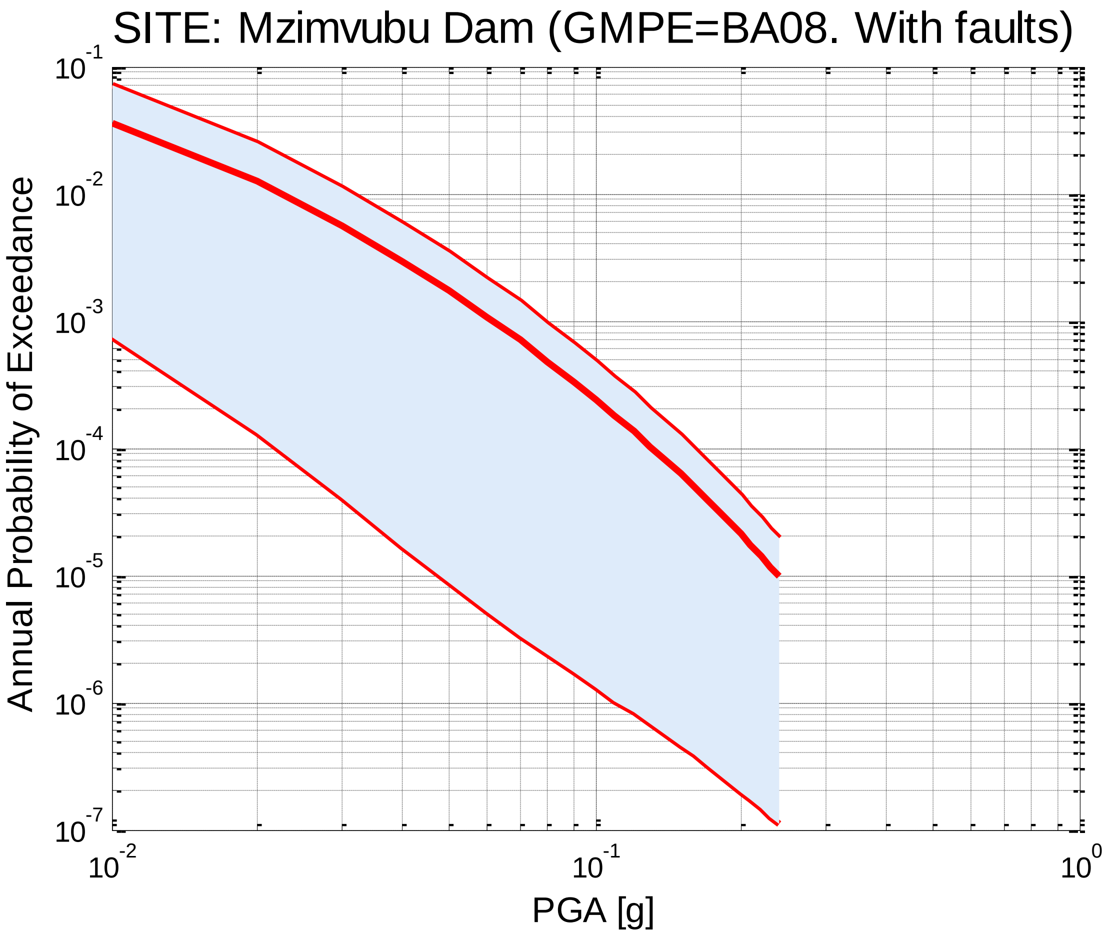


Figure 1(d): Annual probability of exceedance and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008). #2: all known faults in vicinity of the dam site are active.

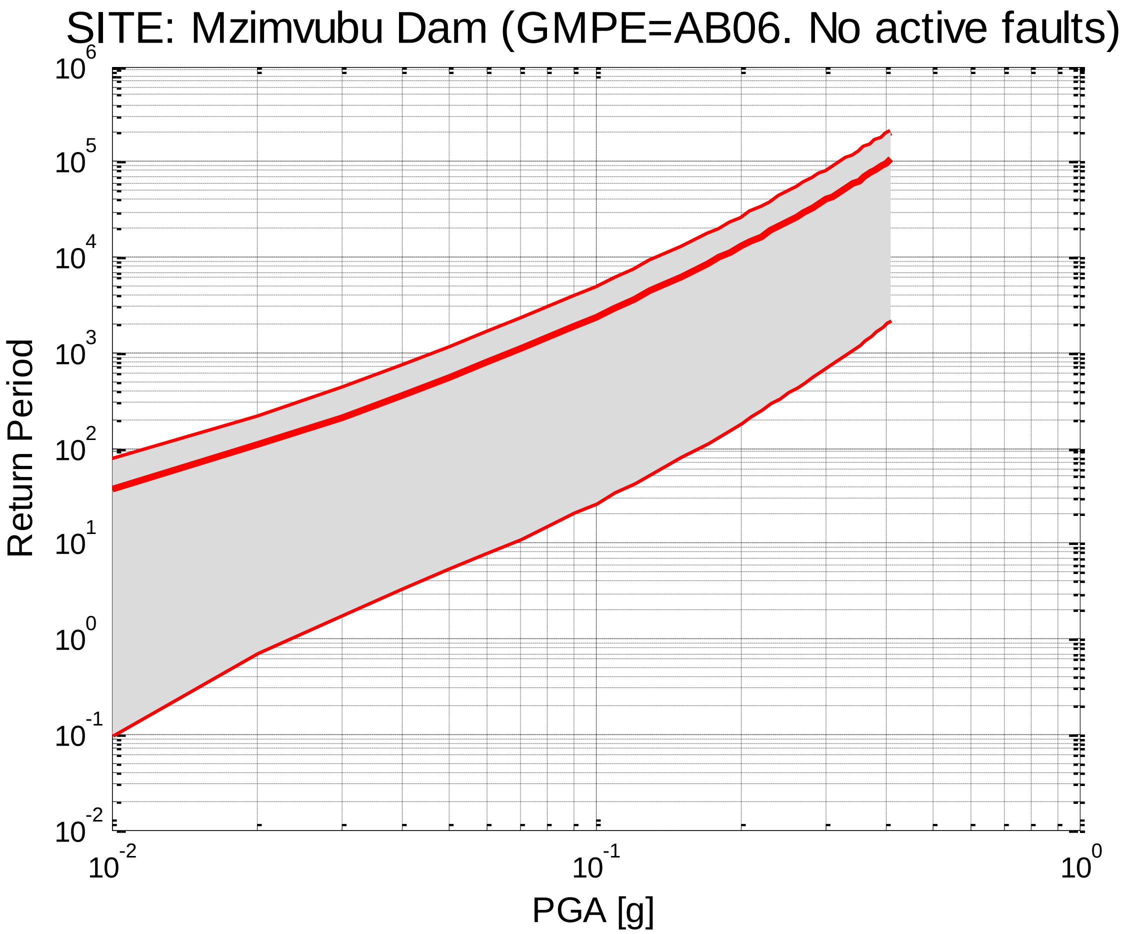


Figure 2(a): Mean return period and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006). Scenario #1: all known faults in vicinity of the dam site are not active.

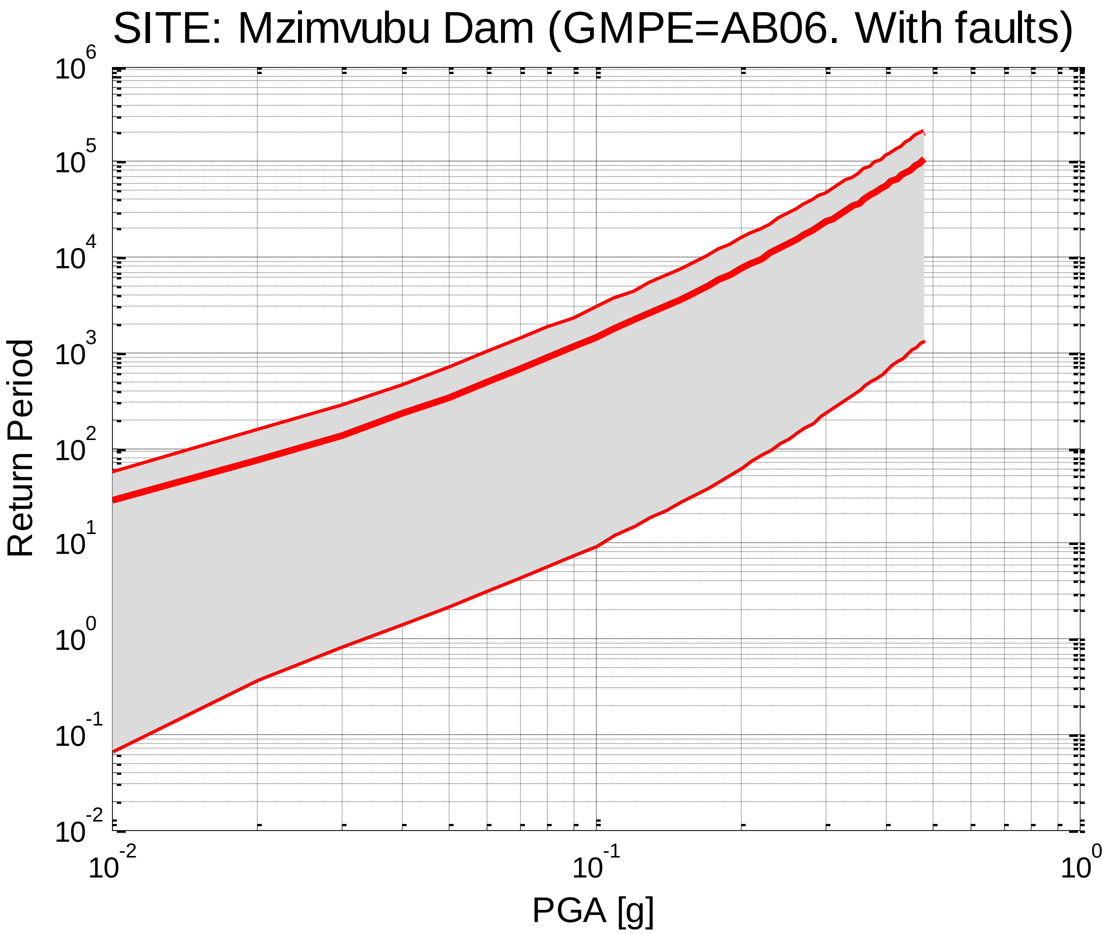


Figure 2(b): Mean return period and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation AB06 (Atkinson and Boore, 2006). Scenario #2: all known faults in vicinity of the dam site are active.

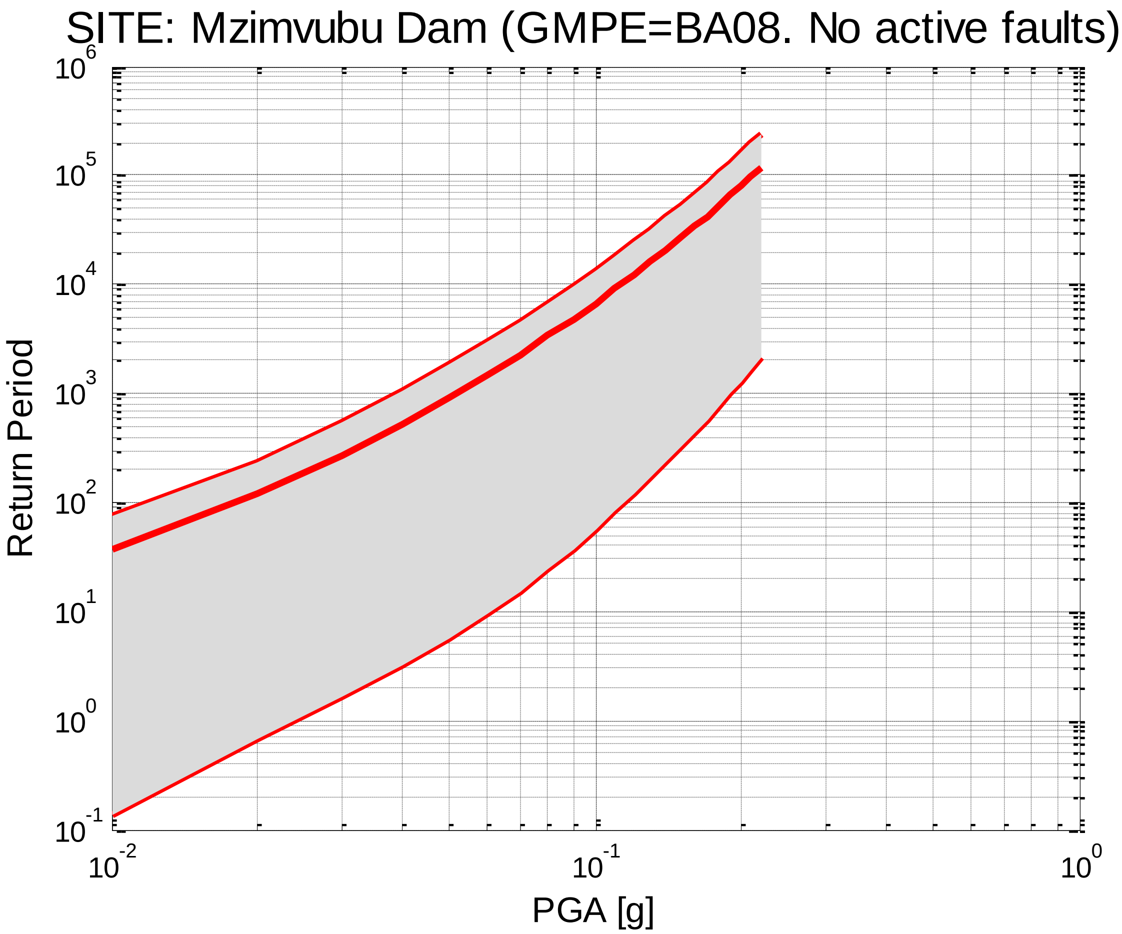


Figure 2(c): Mean return period and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008). Scenario #1: all known faults in vicinity of the dam site are not active.

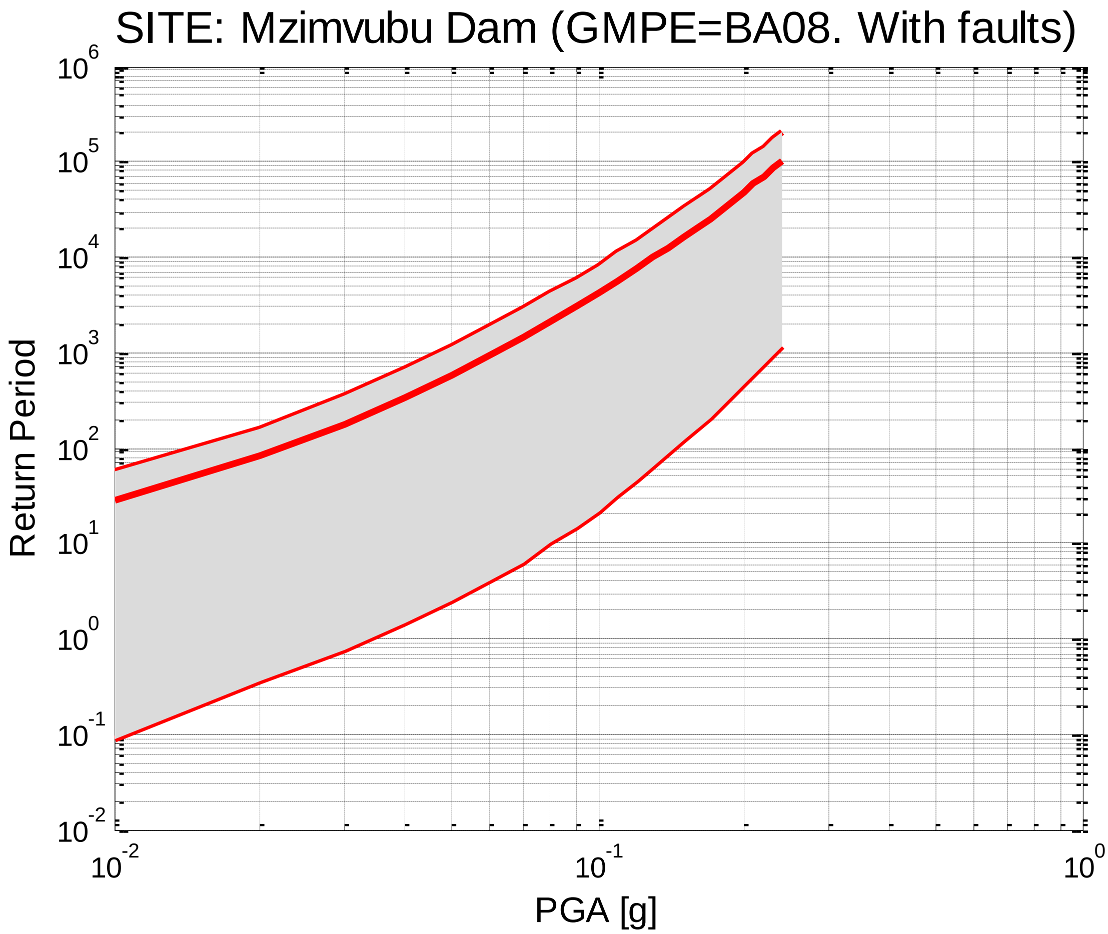


Figure 2(d): Mean return period and its confidence intervals of median value of horizontal PGA at the dam site, calculated for the ground motion prediction equation BA08 (Boore and Atkinson, 2008). Scenario #2: all known faults in vicinity of the dam site are active.

ANNEX G

Attenuation of Vertical Peak Acceleration

N. A. ABRAHAMSON and J. J. LITEHISER
BECHTEL CIVIL, INC., P.O. BOX 3965, SAN FRANCISCO, CALIFORNIA 94119

Peak vertical accelerations from a suite of 585 strong ground motion records from 76 worldwide earthquakes are fit to an attenuation model that has a magnitude dependent shape. The regression uses a two-step procedure that is a hybrid of the Joyner and Boore (1981) and Campbell (1981) regression methods. The resulting vertical attenuation relation is

$$log_{10} a_v(g) = -1.15 + 0.245M - 1.096 log_{10}(r + e^{0.256M}) + 0.096F - 0.0011Er, \quad (1)$$

where M is magnitude, r is the distance in kilometers to the closest approach of the zone of energy release, F is a dummy variable that is 1 for reverse or reverse oblique events and 0 otherwise, and E is a dummy variable that is 1 for interplate events and 0 for intraplate events. The standard error of $\log_{10} a_v$ is 0.296.

Because the vertical to horizontal acceleration ratio is also sought, the attenuation of the horizontal peaks from the same suite of records is also obtained using the same regression procedure. The resulting horizontal attenuation relation is

$$log_{10} a_H(g) = -0.62 + 0.177M - 0.982 log_{10}(r + e^{0.284M}) + 0.132F - 0.0008Er, \quad (2)$$

where a_H is the peak acceleration of the larger of the two horizontal components. The standard error of $\log_{10} a_H$ is 0.277.

The expected ratio of peak vertical to peak horizontal strong ground motion predicted by these equations (Figure 1) is enveloped by the widely used rule-of-thumb value of two-thirds for earthquakes with magnitudes less than 7.0 and distances greater than 20 km. The expected ratio exceeds 1.0 for earthquakes with magnitudes greater than 8.0 at very short distances. The standard error of $\log_{10}(V/H)$ is 0.20, which is less than the standard error of either the vertical or horizontal acceleration. Therefore, the peak vertical and horizontal accelerations for a given record are strongly correlated and we can have more confidence in the predicted ratio than in either the predicted vertical or horizontal peaks.

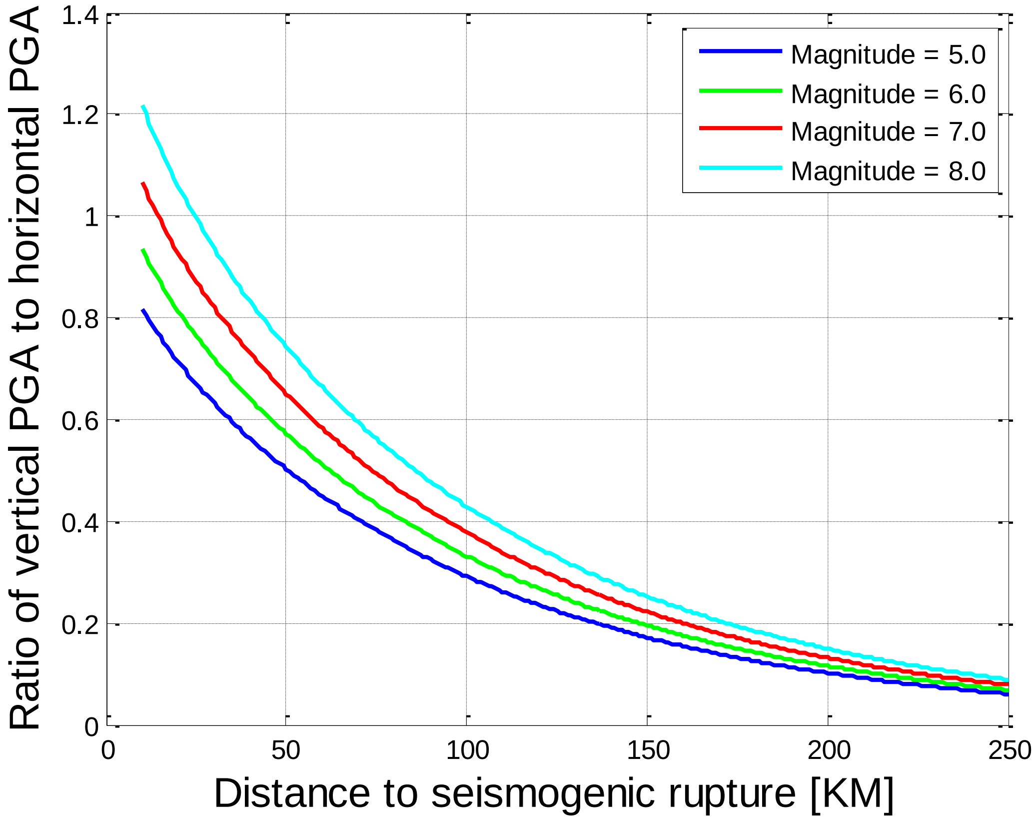


Figure 1: The expected ratio of peak vertical to peak horizontal ground acceleration predicted by equation (1) and (2).

ANNEX H

Account of Site Effect in Terms of PGA

Any ground motion prediction equation (GMPE) is specific to a soil or rock type on which the PSHA is to be made. These ground types are known as the site classes (International Building Code, 2000; *NEHRP Provisions*, 2001, Table 1), and are classify as hard rock, soft rock, firm soil and soft soil. The site classes are defended by their shear velocities (see table below). The knowledge of the site class is important, since soil have a tendency to amplify long period ground motion vibration and de-amplify short period ground motion.

Table 1*. NEHRP Site Classes. Site class definitions are published in 2000 International Building Code, International Code Council, Inc. on page 350, Table 1615 1.1 Site Class Definitions.*

Site Class	**Soil Profile Name**	**Average Properties in Top 100 feet (as per 2000 IBC section 1615.1.5) Soil Shear Wave Velocity, V_s**	
		Feet/second	Meters/second
A	Hard Rock	$V_{s30} > 5000$	$V_{s30} > 1524$
B	Rock	$2500 < V_s \leq 5000$	$762 < V_s \leq 1524$
C	Very dense soil and soft rock	$1200 < V_s \leq 2500$	$366 < V_s \leq 762$
D	Stiff soil profile	$600 < V_s \leq 1200$	$183 < V_s \leq 366$
E	Soft soil profile	$V_s < 600$	$V_s < 183$
F	Soil requiring site specific evaluations • Soils vulnerable to potential failure or collapse under seismic loading, e.g. liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. • Peats and/or		

highly organic clays.
- Very high plasticity clays.
- Very thick soft/medium stiff clays – 36 m or thicker layer

Following Atkinson and Boore (2006), the site correction of $\log_{10}$(PGA), denoted as $\Delta\log_{10}(\mathrm{PGA})$, has two components, linear and nonlinear. For PGA ≤ 60 cm/sec^2

$$\Delta\log_{10}(\mathrm{PGA}) = \log_{10}\{\exp[b_{\mathrm{LIN}}\cdot\ln\left(\frac{V_{s0}}{V_{\mathrm{REF}}}\right) + b_{\mathrm{NL}}\cdot\ln\left(\frac{60}{100}\right)]\}. \quad (1)$$

For PGA > 60 cm/sec^2, the same correction is of the form

$$\Delta\log_{10}(\mathrm{PGA}) = \log_{10}\{\exp[b_{\mathrm{LIN}}\cdot\ln\left(\frac{V_{S30}}{V_{\mathrm{REF}}}\right) + b_{\mathrm{NL}}\cdot\ln\left(\frac{\mathrm{PGA}}{100}\right)]\}. \quad (1)$$

In equation (1) and (2) the PGA is expressed in units of cm/sec^2 and denotes PGA predicted for V_{S30} = 760 m/sec, or equivalently relative to the reference condition of NEHRP B/C boundary, with V_{REF} = 760 m/sec. The nonlinear component of the PGA site correction is controlled by parameter b_{NL} and is defined by the following relation

$$b_{\mathrm{NL}} = b_1, \qquad \text{for } V_{S30} \le V_1$$

$$b_{\mathrm{NL}} = (b_1 - b_2)\frac{\ln\left(\frac{V_{s30}}{V_2}\right)}{\ln\left(\frac{V_1}{V_2}\right)}, \qquad \text{for } V_1 < V_{S30} \le V_2$$

$$b_{\mathrm{NL}} = \frac{b_2\ln\left(\frac{V_{S30}}{V_{\mathrm{REF}}}\right)}{\ln\left(\frac{V_2}{V_{\mathrm{REF}}}\right)}, \qquad \text{for } V_2 < V_{S30} \le V_{\mathrm{REF}}$$

$$b_{\mathrm{NL}} = 0.0, \qquad \text{for } V_{S30} > V_{\mathrm{REF}}.$$

where b_{LIN} = -0.361, V_1 = -0.641 and V_2 = -0.144.

The geological materials associated with different values of Vs_{30} are given in Table 2.

Table 2. *Modified NEHRP site classes, associated Vs_{30} values and general groupings of geologic units associated with each class (Wills et al., 2000).*

Site Class Vs30 (m/s) Geological Materials

==

B	> 760	Plutonic/metamorphic rocks incl. most volcanic; pre Tertiary sedimentary units
BC	555-1000	Cretaceous fine - grained sediments ; serpentine ;sheared/weathered crystalline rocks
C	360-760	Oligocene – Cretaceous sedimentary rocks; coarse-grained younger material
CD	270-555	Miocene fine-grained sediments; Plio-Pleistocene alluvium; coarse younger alluvium
D	180-360	Holocene alluvium
DE	90-270	Fine-grained alluvial/estuarine deposits
E	< 180	Inter-tidal mud

==

References

Atkinson, G.M. and D.M. Boore (2006). Earthquake ground-motion prediction equations for Eastern North America. *Bull. Seism. Soc. Am*. **96**, 2181-2205.

Building Seismic Safety Council (BSSC), 2001. *2000 Edition, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA-368*, Part 1 (Provisions): Developed for the Federal Emergency Management Agency, Washington, D.C.

Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G. and Treiman, J. (2000). A site-condition map for California based on geology and shear-wave velocity. *Bull. Seism. Soc. Am.* **90** (6B), S187-S208.

Some Additional References and Relevant Building Codes

Building Seismic Safety Council, 2001, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2000 edition, Part 1: Provisions (FEMA 368). Developed for the Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council, 2001, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, 2000 edition, Part 2: Commentary (FEMA 369). Developed for the Federal Emergency Management Agency, Washington, D.C.

Boore, D.M. Joyner, W.B. and Fumal, T.E. (1997). Equations for estimating horizontal response spectra and peak acceleration for Western North American Earthquakes: A summary of recent work. *Seismol. Res. Lett*, **68**, 128-153.

Boore, D.M. (2005). Erratum. Equations for estimating horizontal response spectra and peak acceleration for Western North American Earthquakes: A summary of recent work. *Seismol. Res. Lett*, **76**, 368-369.

<u>Amplification factor for acceleration response spectra</u>

The National Earthquake Hazards Reduction Program (NEHRP) classified the ground to six site classes from A to F. The amplification factor of acceleration response spectrum for each site classes are provided as Table 4.5.1 and Table 4.5.2 (NEHRP Provisions, 2001). The site class B is the rock and the amplification of other site classes were defined comparing to the site class B. The

S_s and S_1 in Table 5.5.1 and Table 5.5.2 means the spectral response acceleration value in (g) at 0.2 sec and 1.0 sec of site class B respectively.

Table 4.5.1 Amplification factor for acceleration response spectra at 0.2 sec

Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at Short Periods				
	$S_S \leq 0.25$	S_S=0.50	S_S=0.75	S_S=1.00	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_S.
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

Table 4.5.2 Amplification factor for acceleration response spectra at 1.0

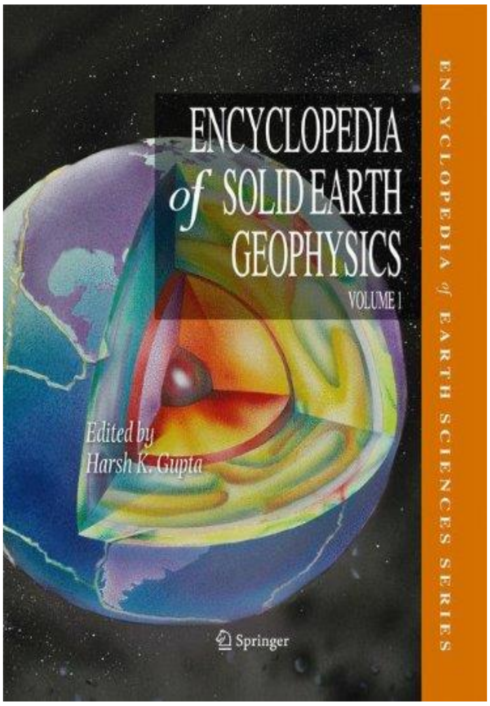
Site Class	Mapped Maximum Considered Earthquake Spectral Response Acceleration at 1 Second Periods				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_1.
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed.

ANNEX I

"*Introduction to Probabilistic Seismic Hazard Analysis*"

Extended version of contribution by A. Kijko to *Encyclopedia of Solid Earth Geophysics*, Harsh Gupta (Ed.), Springer, 2011.



Seismic Hazard

Encyclopedia of Solid Earth Geophysics
Harsh Gupta (Ed.)
Springer

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SEISMIC HAZARD

Definition

Seismic hazard. Any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land, man-made structure and socio-economic systems that have the potential to produce a loss. It is also used without regard to a loss to indicate the probable level of ground shaking occurring at a given point within a certain period of time.

Seismic hazard analysis. Quantification of the ground-motion expected at a particular site.

Deterministic seismic hazard analysis. Quantification of a single or relatively small number of individual earthquake scenarios.

Probabilistic seismic hazard analysis. Quantification of the probability that a specified level of ground motion will be exceeded at least once at a site or in a region during a specified exposure time.

Ground motion prediction equation. A mathematical equation which indicates the relative decline of the ground motion parameter as the distance from the earthquake increases.

1. Introduction

The estimation of the expected ground motion which can occur at a particular site is vital to the design of important structures such as nuclear power plants, bridges and dams. The process of evaluating the design parameters of earthquake ground motion is called seismic hazard assessment or seismic hazard analysis. Seismologists and earthquake engineers distinguish between seismic hazard and seismic risk assessments in spite of the fact that in everyday usage these two phrases have the same meaning. Seismic hazard is used to characterize the severity of ground motion at a site regardless of the consequences, while the risk refers exclusively to the consequences to human life and property loss resulting from the occurred hazard. Thus, even a strong earthquake can have little risk potential if it is far from human development and infrastructure, while a small seismic event in an unfortunate location may cause extensive damage and losses.

Seismic hazard analysis can be performed *deterministically*, when a particular earthquake scenario is considered, or *probabilistically*, when likelihood or frequency of specified earthquake size and location are evaluated.

The process of *deterministic* seismic hazard analysis (DSHA) involves the initial assessment of the maximum possible earthquake magnitude for each of the various seismic sources such as active faults or seismic source zones (SSHAC, 1997). An area of up to 450 km radius around the site of interest can be investigated. Assuming that each of these earthquakes will occur at the minimum possible distance from the site, the ground motion is calculated using appropriate attenuation equations. Unfortunately this straightforward and intuitive procedure is overshadowed by the complexity and uncertainty in selecting the appropriate earthquake scenario, creating the need for an alternative, *probabilistic* methodology, which is free from discrete selection of scenario earthquakes. Probabilistic seismic hazard analysis (PSHA) quantifies as a probability whatever hazard may result from all earthquakes of all possible magnitudes and at all significant distances from the site of interest. It does this by taking into account their frequency of occurrence (Gupta, 2002; Thenhaus and Campbell, 2003; McGuire, 2004). Deterministic earthquake scenarios, therefore, are a special case of the probabilistic approach. Depending on the scope of the project, DSHA and PSHA can complement one another to provide additional insights to the seismic hazard (McGuire, 2004). This study will concentrate on a discussion of PSHA.

In principle, any natural hazard caused by seismic activity can be described and quantified by the formalism of the PSHA. Since the damages caused by ground shaking very often result in the largest economic losses, our presentation of the basic concepts of PSHA is illustrated by the quantification of the likelihood of ground-shaking generated by earthquakes. Modification of the presented formalism to quantify any other natural hazard is straightforward.

The classic (Cornell, 1968; Cornell, 1971; Merz and Cornell, 1973; McGuire, 1976) procedure known as Cornell-McGuire procedure for the PSHA includes four steps (Reiter, 1990; Kramer, 1996), (Figure 1).

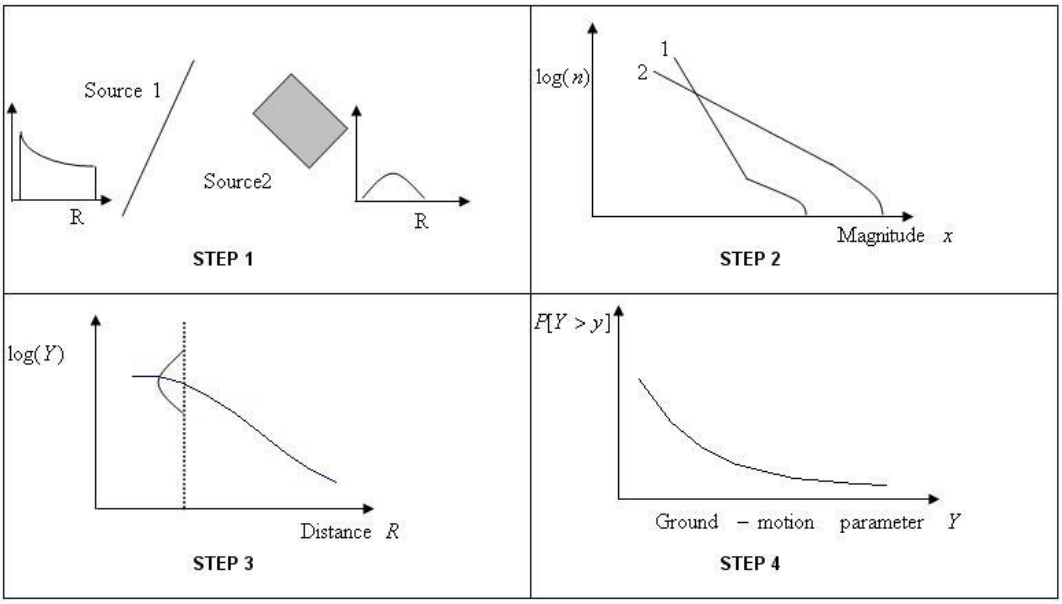

Figure 1: Four steps of a PSHA (modified from Reiter, 1990).

1. The first step of PSHA consists of the identification and parameterization of the *seismic sources* (known also as *source zones*, *earthquake sources* or *seismic zones*) that may affect the site of interest. These may be represented as area, fault, or point sources. Area sources are often used when one cannot identify a specific fault. In classic PSHA, a uniform distribution of seismicity is assigned to each earthquake source, implying that earthquakes are equally likely to occur at any point within the source zone. The combination of earthquake occurrence distributions with the source geometry, results in space, time and magnitude distributions of earthquake occurrences. Seismic source models can be interpreted as a list of potential scenarios, each with an associated magnitude, location and seismic activity rate (Field, 1995).

2. The next step consists of the specification of temporal and magnitude distributions of seismicity for each source. The classic, Cornell-McGuire approach, assumes that earthquake occurrence in time is random and follows the Poisson process. This implies that earthquakes occurrences in time are statistically independent and that they occur at a constant rate. Statistical independence means that occurrence of future earthquakes does not depend on the occurrence of the past earthquake. The most often used model of earthquake magnitude recurrence is the frequency-magnitude Gutenberg-Richter relationship (Gutenberg and Richter, 1944)

$$\log(n) = a - bm, \quad (1)$$

where *n* is the number of earthquakes with a magnitude of *m* and *a* and *b* are parameters. It is assumed that earthquake magnitude *m* belongs to the domain <m_{min}, m_{max}>, where m_{min} is the level of completeness of earthquake catalogue and magnitude m_{max} is the upper limit of earthquake magnitude for a given seismic source. The parameter *a,* is the measure of the level of seismicity, while *b* describes the ratio between the number of small and large events. The Gutenberg-Richter relationship may be interpreted either as being a cumulative relationship, if *n* is the number of events with magnitude equal or larger than *m*, or as being a density law, stating that *n* is the number of earthquakes in a specific, small magnitude interval around *m*. Under the above assumptions, the seismicity of each seismic source is described by four parameters: the (annual) rate of seismicity λ, which is equal to the parameter of the Poisson distribution, the lower and upper limits of earthquake magnitude m_{min} and m_{max} and the *b*-value of the Gutenberg-Richter relationship.

3. Calculation of ground motion prediction equations and their uncertainty. Ground motion prediction equations are used to predict ground motion at the site itself. The parameters of interest include peak ground acceleration, peak ground velocity, peak ground displacement, spectral acceleration, intensity, strong ground motion duration, etc. Most ground motion prediction equations available today are empirical and depend on the earthquake magnitude, source-to-site distance, type of faulting and local site conditions (Thenhaus and Campbell, 2003; Campbell, 2003; Douglas, 2003; 2004). The choice of an appropriate ground motion prediction equation is crucial since, very often, it is a major contributor to uncertainty in the estimated PSHA.

4. Integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction equation into probability that the ground motion parameter of interest will be exceeded at the specified site during the specified time interval. The ultimate result of a PSHA is a *seismic hazard curve*: the annual probability of exceeding a specified ground motion parameter at least once. An alternative definition of the hazard curve is the frequency of exceedance *vs* ground motion amplitude (McGuire, 2004).

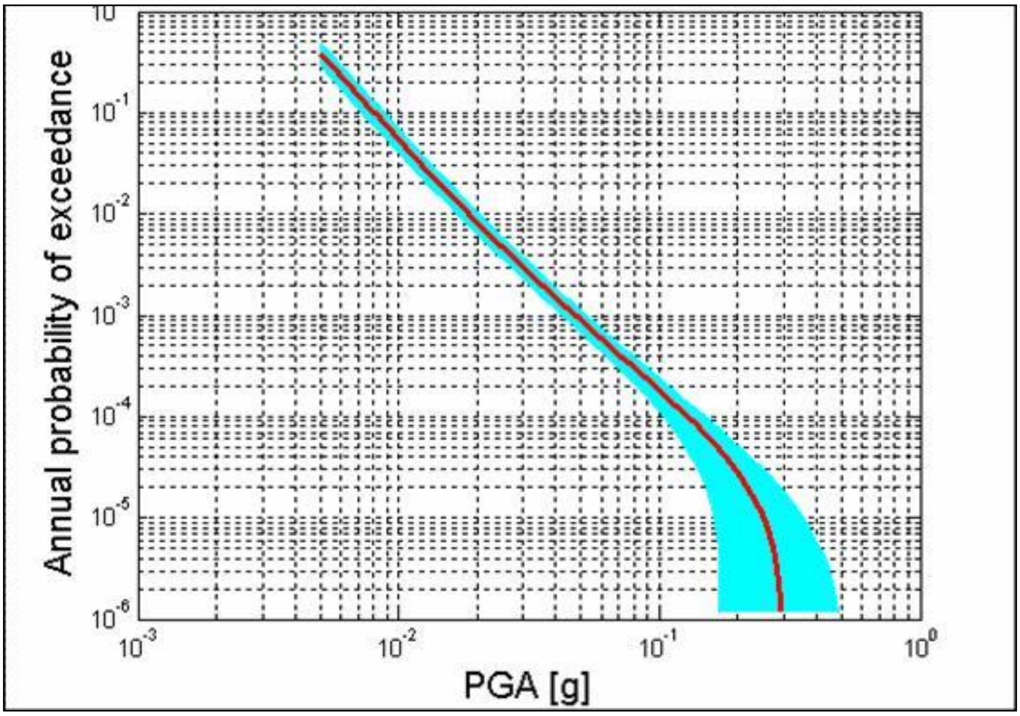

Figure 2: Example of a peak ground acceleration (PGA) seismic hazard curve and its confidence intervals

The following section provides the mathematical framework of the classic PSHA procedure, including its deaggregation. The most common modifications of the procedure will be discussed in the Section 3.

2. The Cornell-McGuire PSHA Methodology

Conceptually, the computation of a seismic hazard curve is fairly simple (Kramer, 1996). Let us assume that seismic hazard is characterized by ground motion parameter *Y*. The probability of exceeding a specified value *y*, $P[Y \geq y]$, is calculated for an earthquake of particular magnitude located at a possible source, and then multiplied by the probability that that particular earthquake will occur. The computations are repeated and summed for the whole range of possible magnitudes and earthquake locations. The resulting probability $P[Y \geq y]$ is calculated by utilizing the Total Probability Theorem (Benjamin and Cornell, 1970) which is:

$$P[Y \geq y] = \sum P[Y \geq y \mid E_i] \cdot P[E_i], \tag{2}$$

where

$$P[Y \geq y \mid E_i] = \int \cdots \int P[Y \geq y \mid x_1, x_2, x_3 ...] \cdot f_i(x_1) \cdot f_i(x_2 \mid x_1) \cdot f_i(x_3 \mid x_1, x_2) \; ... \; dx_3 \, dx_2 \, dx_1. \tag{3}$$

$P[Y \geq y \mid E_i]$ denotes the probability of ground motion parameter $Y \geq y,$ at the site of interest, when an earthquake occurs within the seismic source *i*. Variables $x_i \; (i = 1, 2, ...)$ are uncertainty parameters that influence *Y*. In the classic approach, as developed by Cornell (1968), and later extended to accommodate ground motion uncertainty (Cornell, 1971), the parameters of ground motion are earthquake magnitude *M* and earthquake distance *R*. Functions $f(\cdot)$ are probability density functions (PDF) of parameters x_i. Assuming that indeed $x_1 \equiv M$ and $x_2 \equiv R$, $x_2 \equiv R$, the probability of exceedance (3) takes the form:

$$P[Y \geq y \mid E] = \int_{m_{\min}}^{m_{\max}} \int_{R|M} P[Y \geq y \mid m, r] \, f_M(m) \, f_{R|M}(r \mid m) \, dr \, dm \,, \tag{4}$$

where $P[Y \geq y \mid m, r]$ denotes the conditional probability that the chosen ground motion level *y* is exceeded for a given magnitude and distance; $f_M(m)$ is the probability density function (PDF) of earthquake magnitude, and $f_{R|M}(r \mid m)$ is the conditional PDF of the distance from the earthquake for a given magnitude. The conditional PDF of the distance $f_{R|M}(r \mid m)$ arises in specific instances, such as those where a seismic source is represented by a fault rupture. Since the earthquake magnitude depends on the length of fault rupture, the distance to the rupture and resulting magnitude are correlated.

If, in the vicinity of the site of interest, one can distinguish n_S seismic sources, each with annual average rate of earthquake magnitudes λ_i, then the total average annual rate of events with a site ground motion level *y* or more, takes the form:

$$\lambda(y) = \sum_{i=1}^{n_S} \lambda \int_{m_{\min}}^{m_{\max}} \int_{R|M} P[Y \geq y \mid M, R]\, f_M(m)\, f_{R|M}(r \mid m)\, dr\, dm, \tag{5}$$

In equation (5) the subscripts denoting seismic source number are deleted for simplicity, $P[Y \geq y \mid m, r]$ denotes the conditional probability that the chosen ground motion level *y*, is exceeded for a given magnitude *m* and distance *r*. The standard choice for the probability $P[Y \geq y \mid m, r]$ is a normal, complementary cumulative distribution function (CDF), which is based on the assumption that the ground motion parameter *y* is a log-normal random variable, $\ln(y) = g(m, r) + \varepsilon$, where ε is random error. The mean value of $\ln(y)$ and its standard deviation are known and are defined as $\overline{\ln(y)}$ and $\sigma_{\ln(y)}$ respectively. The function $f_M(m)$ denotes the PDF of earthquake magnitude. In most engineering applications of PSHA, it is assumed that earthquake magnitudes follow the Gutenberg-Richter relation (1), which implies that $f_M(m)$ is a negative, exponential distribution, shifted from zero to $m_{\min}$ and truncated from the top by $m_{\max}$, (Page, 1968)

$$f_M(m) = \frac{\beta \exp[(-(m - m_{\min})]}{1 - \exp[(-\beta(m_{\max} - m_{\min})]}, \tag{6}$$

In equation (6), $\beta = b \ln 10$, where *b* is the parameter of the frequency-magnitude Gutenberg-Richter relation (1).

After assuming that in every seismic source, earthquake occurrences in time follow a Poissonian distribution, the probability that *y*, a specified level of ground motion at a given site, will be exceeded at least once within any time interval *t* is

$$P[Y > y;\, t] = 1 - \exp[-\lambda(y) \cdot t]. \tag{7}$$

The equation (7) is fundamental to PSHA. For *t*=1 year, its plot *vs.* ground motion parameter *y*, is the *hazard curve* – the ultimate product of the PSHA, (Figure 2). For small probabilities, less than 0.05,

$$P[Y > y;\, t = 1] = 1 - \exp(-\lambda) \cong 1 - (1 - \lambda + \frac{1}{2}\lambda^2 - \ldots) \cong \lambda\,, \tag{8}$$

which means that the probability (7) is approximately equal to $\lambda(y)$.

This proves that PSHA can be characterised interchangeably by the annual probability (7) or by the rate of seismicity (5).

In the classic Cornell-McGuire procedure for PSHA it is assumed that the earthquakes in the catalogue are independent events. The presence of clusters of seismicity, multiple events occurring in a short period of time or presence of foreshocks and aftershocks violates this assumption. Therefore, before computation of PSHA, these dependent events must be removed from the catalogue. Most of the procedures used for removal of dependent events are based on empirical, space-time-magnitude distributions (see, e.g., Molchan and Dmitrieva, 1992).

2.1. Estimation of seismic source parameters

Following the classic Cornell-McGuire PSHA procedure, each seismic source is characterised by four parameters:

- level of completeness of the seismic data, m_{min}
- annual rate of seismic activity λ, corresponding to magnitude m_{min}
- *b*-value of the frequency-magnitude Gutenberg-Richter relation (1)
- upper limit of earthquake magnitude m_{max}

Estimation of m_{min}. The level of completeness of the seismic event catalogue, m_{min}, can be estimated in at least two different ways (Schorlemmer and Woessner, 2008).

The first approach is based on information provided by the seismic event catalogue itself, where m_{min} is defined as the deviation point from an empirical or assumed earthquake magnitude distribution model. In most cases the model is based on the Gutenberg-Richter relation (1). Probably the first procedure belonging to this category was proposed by Stepp (1973). More recent procedures of the same category are developed e.g. by Weimer and Wyss (2000) and Amorese (2007). Occasionally, m_{min} is estimated from comparison of the day-to-night ratio of events (Rydelek and Sacks, 1989). Despite the fact that the evaluation of m_{min} based on information provided entirely by seismic event catalogue is widely used, it has several weak points. By definition, the estimated levels of m_{min} represent only the average values over space and time. However, most procedures in this category require assumptions on a model of earthquake occurrence, such as a Poissonian distribution in time and frequency-magnitude Gutenberg-Richter relation.

The second approach used for the estimation of m_{min} level is based on a different principle: it utilizes information on the detection capabilities and signal-to-noise ratio of the seismic stations recording the seismic events. The most recently developed techniques that belong to this category have been proposed by Albarello *et al.,* (2001) and Schorlemmer and Woessner (2008). These procedures release users from the assumptions of stationarity and statistical independence of event occurrence. The choice of the most appropriate procedure for m_{min} estimation depends on several factors, such as the knowledge of the history of the development of the seismic network, data collection and processing.

Estimation of rate of seismic activity λ and *b*-value of Gutenberg-Richter. The accepted approach to estimating seismic source recurrence parameters λ and *b* is the maximum likelihood procedure (Weichert, 1980; Kijko and Sellevoll, 1989; McGuire 2004). If successive earthquakes are independent in time, the number of earthquakes with magnitude equal to or exceeding a level of completeness, $m_{min,}$ follows the Poisson distribution with the parameter equal to the annual rate of seismic activity λ. The maximum likelihood estimator of λ is then equal to *n/t*, where *n* is number of events that occurred within time interval *t* (Benjamin and Cornell, 1970).

For given m_{max}, the maximum likelihood estimator of the *b*-value of the Gutenberg-Richter equation can be obtained from the recursive solution of the following:

$$1/\beta = \overline{m} - m_{min} + \frac{(m_{max} - m_{min}) \cdot \exp[-\beta(m_{max} - m_{min})]}{1 - \exp[-\beta(m_{max} - m_{min})]} . \quad (9)$$

Where $\beta = b \ln 10$, and $\overline{m}$ is the sample mean of earthquake magnitude (Page, 1968). If the range of earthquake magnitudes $< m_{max}, m_{min} >$ exceeds 2 magnitude units, the solution of equation (9) can be approximated by the well known Aki-Utsu estimator (Aki, 1965; Utsu, 1965)

$$\beta = 1 / (\overline{m} - m_{min}). \quad (10)$$

In most real cases, estimation of parameters λ and the *b*-value by the above simple formulas cannot be performed due to the incompleteness of seismic event catalogues. The typical seismic event catalogue can be divided into two parts. The first part contains only the largest historic events which occurred over a period of a few hundred years while the second part contains instrumental data for a relatively short period of time (in most cases ca. the last 50 years), with varying periods of completeness (Figure 3).

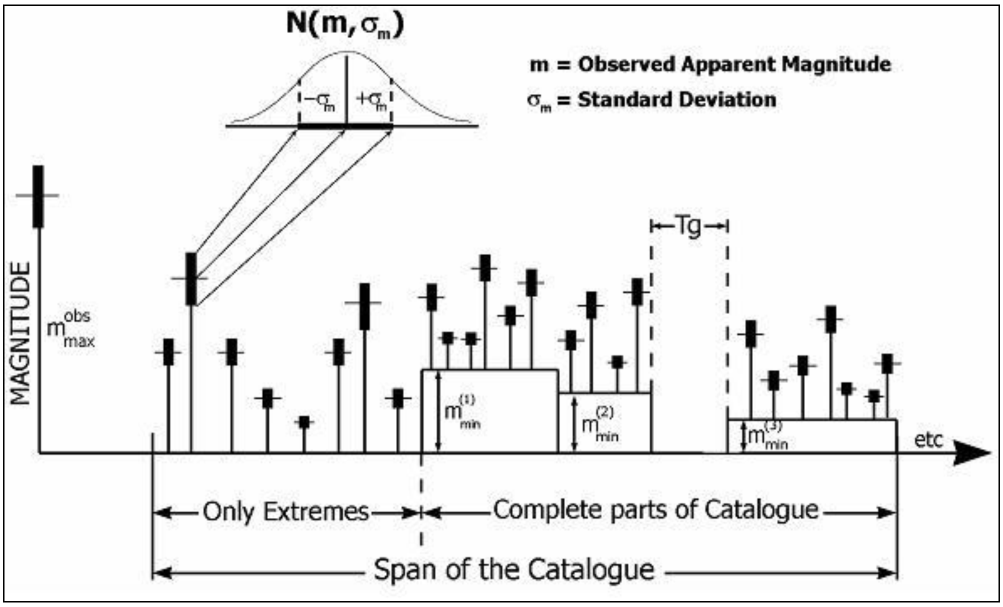

Figure 3: Illustration of data which can be used to obtain maximum likelihood estimators of recurrence oparameters by the procedure developed by Kijko and Sellevoll (1992). The approach permits the combination of largest earthquake data and complete data having variable periods of completeness. It allows the use of the largest known historical earthquake magnitude (m_{max}^{obs}) which occurred before the catalogue began. It also accepts "gaps" (Tg) when records were missing or the seismic networks were out of operation. Uncertainty in earthquake magnitude is taken into account in that an assumption is made that the observed magnitude is true magnitude subjected to a random error that follows a Gaussian distribution having zero mean and a known standard deviation.

The best procedure to utilize all the information contained in the catalogue will combine the macroseismic part of the catalogue (strong events only) with variable periods of completeness. Such a procedure has been developed by Kijko and Sellevoll (1989; 1992). This methodology follows from the similar approach developed by Weichert (1980) which did not accommodate the presence of the macroseismic part of the catalogue, and did not assess the maximum possible earthquake magnitude m_{max}. Comparison of both approaches for catalogues of variable periods of completeness shows that for values of m_{max} large enough, the two procedures are equivalent (Weichert and Kijko, 1989).

Estimation of m_{max}. The maximum magnitude, m_{max}, is defined as the upper limit of magnitude for a given seismic source. Also, synonymous with the upper limit of earthquake magnitude, is the magnitude of the largest possible earthquake or maximum credible earthquake. This definition of maximum magnitude is also used by earthquake engineers (EERI Committee, 1984), and complies with the meaning of this parameter as used by e.g. the Working Group on California Earthquake Probabilities (WGCEP, 1995; 2008), Stein and Hanks (1998), and Field *et al*. (1999).

This terminology assumes a sharp cut-off magnitude at a maximum magnitude m_{max}. Cognisance should be taken of the fact that an alternative, "soft" cut-off maximum earthquake magnitude is also being used (Main and Burton, 1984; Kagan, 1991). The later formalism is based on the assumption that seismic moments of seismic events follow the Gamma distribution. One of the distribution parameters is called the maximum seismic moment and the corresponding value of earthquake magnitude is called the “soft” maximum magnitude. Beyond the value of this maximum magnitude, the distribution decays much faster than the classical Gutenberg-Richter relation. However, this means that earthquakes with magnitudes larger than such a “soft” maximum magnitude are not excluded. Although this model has been used by Kagan (1994, 1997), Main (1996), Main *et al.* (1999), Sornette and Sornette (1999), the classic PSHA only considers models having a sharp cut-off of earthquake magnitude.

As a rule, m_{max} plays an important role in PSHA, especially in assessment of long return periods. At present, there is no generally accepted method for estimating m_{max}. It is estimated by the combination of several factors, which are based on two kinds of information (Wheeler, 2009): seismicity of the area, and geological, geophysical and structural information of the seismic source. The utilization of the seismological information focuses on the maximum observed earthquake magnitude within a seismic source and statistical analysis of the available seismic event catalogue. The geological information is used to identify distinctive tectonic features, which control the value of m_{max}.

The current evaluations of m_{max} are divided between deterministic and probabilistic procedures, based on the nature of the tools applied (e.g. Gupta, 2002).

<u>Deterministic procedures.</u> The deterministic procedure most often applied is based on the empirical relationships between magnitude and various tectonic and fault parameters, such as fault length or rupture dimension. The relationships are different for different seismic areas and different types of faults (Wells and Coppersmith, 1994; Anderson *et al.,* 1996; 2000 and references therein). Despite the fact that empirical relationships between magnitudes and fault parameters are extensively used in PSHA (especially for the assessment of maximum possible magnitude generated by the fault-type seismic sources), the weak point of the approach is its requirement to specify the highly uncertain length of the future rupture. An alternative approach to the determination of earthquake recurrence on singular faults with a segment specific slip rate is provided by the so-called cascade model, where segment rupture is defined by the individual cascade-characteristic rupture dimension (Cramer *et al*., 2000).

Another deterministic procedure which has a strong, intuitive appeal is based on records of the largest historic or paleo-earthquakes (McCalpin, 1996). This approach is especially applicable in the areas of low seismicity, where large events have long return periods. In the absence of any additional tectono-geological indications, it is assumed that the maximum possible earthquake magnitude is equal to the largest magnitude observed, m_{max}^{obs}, or the largest observed plus an increment. Typically, the increment varies from ¼ to 1 magnitude unit. The procedure is often used for the areas with several, small seismic sources, each having its own m_{max}^{obs} (Wheeler, 2009).

Another commonly used deterministic procedure for m_{max} evaluation, especially for area-type seismic sources, is based on the extrapolation of the frequency-magnitude Gutenberg-Richter relation. The best known extrapolation procedures are probably those by Frohlich (1998) and the “probabilistic” extrapolation procedure applied by Nuttli (1981), in which the frequency-magnitude curve is truncated at the specified value of annual probability of exceedance (e.g. 0.001).

An alternative procedure for the estimation of m_{max} was developed by Jin and Aki (1988), where a remarkably linear relationship was established between the logarithm of coda Q_0 and the largest observed magnitude for earthquakes in China. The authors postulate that if the largest magnitude observed during the last 400 years is the maximum possible magnitude m_{max}, the established relation will give a spatial mapping of m_{max}.

Ward (1997) developed a procedure for the estimation of m_{max} by simulation of the earthquake rupture process. Ward's computer simulations are impressive; nevertheless, one must realize that all the quantitative assessments are based on the particular rupture model, postulated parameters of the strength and assumed configuration of the faults.

The value of m_{max} can also be estimated from the tectono-geological features like strain rate or the rate of seismic-moment release (Papastamatiou, 1980; Anderson and Luco, 1983; WGCEP, 1995, 2008; Stein and Hanks, 1998; Field *et al.,* 1999). Similar approaches have also been applied in evaluating the maximum possible magnitude of seismic events induced by mining (e.g. McGarr, 1984). However, in most cases, the uncertainty of m_{max}as determined by any deterministic procedure is large, often reaching a value of the order of one unit on the Richter scale.

Probabilistic procedures. The first probabilistic procedure for maximum regional magnitude was developed in the late sixties, and is based on the formalism of the extreme values of random variables. A major breakthrough in the seismological applications of extreme-value statistics was made by Epstein and Lomnitz (1966), who proved that the Gumbel I distribution of extremes can be derived directly from the assumptions that seismic events are generated by a Poisson process and that they follow the frequency-magnitude Gutenberg-Richter relation. Statistical tools required for the estimation of the end-point of distribution functions (as e.g. Tate, 1959; Robson and Whitlock, 1964; Cooke, 1979) have only recently been used in the estimation of maximum earthquake magnitude (Dargahi-Noubary, 1983; Gupta and Trifunac, 1988; Gupta and Deshpande 1994; Pisarenko *et al*., 1996; Kijko, 2004 and references therein).

The statistical tools available for the estimation of m_{max} vary significantly. The selection of the most suitable procedure depends on the assumptions of the statistical distribution model and/or the information available on past seismicity. Some of the procedures can be applied in the extreme cases when no information about the nature of the earthquake magnitude distribution is available. Some of the procedures can also be used when the earthquake catalogue is incomplete, i.e. when only a limited number of the largest magnitudes are known. Two estimators are presented here. Broadly speaking, the first estimator is straightforward and simple in application, while the second one requires more computational effort but provides more accurate results (Kijko and Graham, 1998). It is assumed that both the analytical form and the parameters of the distribution functions of earthquake magnitude are known. This knowledge can be very approximate, but must be available.

Based on the distribution of the largest among *n* observations (Benjamin and Cornell, 1970), and on the condition that the largest observed magnitude $m_{\max}^{obs}$ is equal to the largest magnitude to be expected, the "simple" estimate of m_{max} is of the form (Pisarenko *et al.*, 1996)

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{1}{n\, f_M(m_{\max}^{obs})}\,, \tag{11}$$

where $f_M(m_{\max}^{obs})$ is PDF of the earthquake magnitude distribution. If applied to the Gutenberg-Richter recurrence relation with PDF (6), it takes the simple form

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{1-\exp[-\beta(m_{\max}^{obs} - m_{\min})]}{n\beta \exp[-\beta(m_{\max}^{obs} - m_{\min})]}\,. \tag{12}$$

The approximate variance of the estimator (12) is of the form

$$VAR(\hat{m}_{\max}) = \sigma_M^2 + \frac{1}{n^2}\left[\frac{1-\exp[-\beta(m_{\max}^{obs} - m_{\min})]}{\beta\exp[-\beta(m_{\max}^{obs} - m_{\min})]}\right]^2, \tag{13}$$

where σ_M stands for epistemic uncertainty and denotes the standard error in the determination of the largest observed magnitude $m_{\max}^{obs}$. The second part of the variance represents the aleatory uncertainty of $m_{\max}$.

The second ("advanced") procedure often used for assessment of $m_{\max}$ is based on the formalism derived by Cooke (1979)

$$\hat{m}_{\max} = m_{\max}^{obs} + \int_{m_{\min}}^{m_{\max}^{obs}} \left[F_M(m)\right]^n \mathrm{d}m\,, \tag{14}$$

where $F_M(m)$ denotes the CDF of random variable m. If applied to the frequency-magnitude Gutenberg-Richter relation (1), the respective CDF is (Page, 1968)

$$F_M(m) = \begin{cases} 0, & \text{for } m < m_{\min}, \\ \dfrac{1-\exp[-\beta(m-m_{\min})]}{1-\exp[-\beta(m_{\max}-m_{\min})]}, & \text{for } m_{min} \le m \le m_{\max}, \\ 1, & \text{for } m > m_{\max}, \end{cases} \tag{15}$$

and the $m_{\max}$ estimator (14) takes the form

$$\hat{m}_{\max} = m_{\max}^{obs} + \frac{E_1(n_2) - E_1(n_1)}{\beta\exp(-n_2)} + m_{\min}\exp(-n), \tag{16}$$

where $n_1 = n/\{1-\exp[-\beta(m_{\max}^{obs} - m_{\min})]\}$, $n_2 = n_1\exp[-\beta(m_{\max}^{obs} - m_{\min})]$, and $E_1(\cdot)$ denotes an exponential integral function. The variance of estimator (16) has two components, epistemic and aleatory, and is of the form

$$VAR(\hat{m}_{\max}) = \sigma_M^2 + \left[\frac{E_1(n_2) - E_1(n_1)}{\beta\exp(-n_2)} + m_{\min}\exp(-n)\right]^2, \tag{17}$$

where σ_M denotes standard error in the determination of the largest observed magnitude $m_{\max}^{obs}$.

Both above estimators of $m_{\max}$, by their nature, are very general and have several attractive properties. They are applicable for a very broad range of magnitude distributions. They may also be used when the exact number of earthquakes, n, is not known. In this case, the number of earthquakes can be replaced by λt. Such a replacement is equivalent to the assumption that the number of earthquakes occurring in unit time conforms to a Poisson distribution with parameter λ, where t is the span of the seismic event catalogue. It is also important to note that both estimators provide a value of $\hat{m}_{\max}$, which is never less than the largest magnitude already observed.

Alternative procedures are discussed by Kijko (2004), which are appropriate for the case when the empirical magnitude distribution deviates from the Gutenberg-Richter relation. These procedures assume no specific form of the magnitude distribution or that only a few of the largest magnitudes are known.

Despite the fact, that statistical procedures based the mathematical formalism of extreme values provide powerful tools for the evaluation of m_{max}, they have one weak point: often available seismic event catalogues are too short and insufficient to provide reliable estimations of m_{max}. Therefore the Bayesian extension of statistical procedures (Cornell, 1994), allowing the inclusion of alternative and independent information such as local geological conditions, tectonic environment, geophysical data, paleo-seismicity, similarity with another seismic area, etc., are able to provide more reliable assessments of m_{max}.

2.2. Numerical computation of PSHA

With the exception of a few special cases (Bender, 1984), the hazard curve (7) cannot be computed analytically. For the most realistic distributions, the integrations can only be evaluated numerically (i.e. Frankel, *et al*., 1996; Kramer, 1996; Wesson and Perkins, 2001). The common practice is to divide the possible ranges of magnitude and distance into n_M and n_R intervals respectively. The average annual rate (4) is then estimated as

$$\lambda(Y > y) \cong \sum_{i=1}^{n_S}\sum_{j=1}^{n_M}\sum_{k=1}^{n_R} \lambda_i P[Y > y \mid m_j, r_k]\, f_{M_j}(m_j)\, f_{R_k}(r_k)\,\Delta m \Delta r\,, \qquad (18)$$

where $m_j = m_{min} + (j - 0.5)\cdot(m_{max} - m_{min})/n_M$, $r_k = r_{min} + (k - 0.5)\cdot(r_{max} - r_{min})/n_R$, $\Delta m = (m_{max} - m_{min})/n_M$, and $\Delta r = (r_{max} - r_{min})/n_R$.

If the procedure is applied to a grid of points, it will result in a map of PSHA, in which the contours of the expected ground motion parameter during the specified time interval can be drawn.

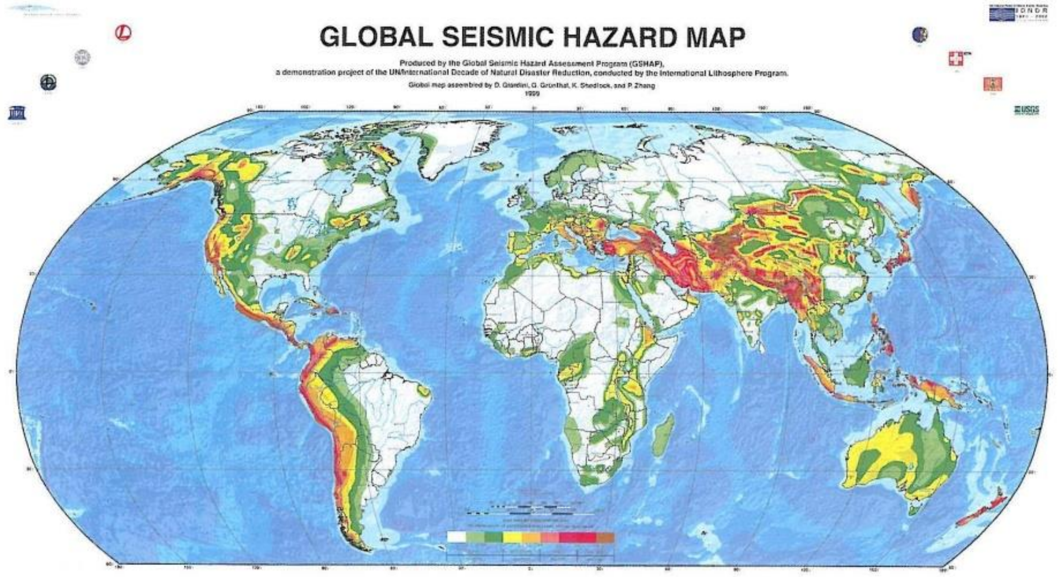

Figure 4: Example of product of PSHA. Map of seismic hazard of the world. Peak ground acceleration expected at 10% probability of exceedance at least once in 50 years. (From Giardini, 1999, http://www.gfz-potsdam.de/pb5/pb53/projects/gshap).

2.3. Deaggregation of Seismic Hazard

By definition, the PSHA aggregates ground motion contributions from earthquake magnitudes and distances of significance to a site of engineering interest. One has to note that the PSHA results are not representative of a single earthquake. However, an integral part of the design procedure of any critical structure is the analysis of the most relevant earthquake acceleration time series, which are generated by earthquakes, at specific magnitudes and distances. Such earthquakes are called "controlling earthquakes" and they are used to determine the shapes of the response spectral acceleration or PGA at the site.

Controlling earthquakes are characterised by mean magnitudes and distances derived from so called deaggregation analysis (e.g. McGuire, 1995; 2004). During the deaggregation procedure, the results of PSHA are separated to determine the dominant magnitudes and the distances that contribute to the hazard curve at a specified (reference) probability. Controlling earthquakes are calculated for different structural frequency vibrations, typically for the fundamental frequency of a structure. In the process of deaggregation, the hazard for a reference probability of exceedance of specified ground motion is portioned into magnitude and distance bins. The relative contribution to the hazard for each bin is calculated. The bins with the largest relative contribution identify those earthquakes that contribute the most to the total seismic hazard.

3. Some Modifications of Cornell-McGuire PSHA Procedure and Alternative Models.

3.1. Source-free PSHA procedures.

The concept of seismic sources is the core element of the Cornell-McGuire PSHA procedure. Unfortunately, seismic sources or specific faults can often not be identified and mapped and the causes of seismicity are not understood. In these cases, the delineation of seismic sources is highly subjective and is a matter of expert opinion. In addition, often, seismicity within the seismic sources is not distributed uniformly, as it is required by the classic Cornell-McGuire procedure. The difficulties experienced in dealing with seismic sources have stimulated the development of an alternative technique to PSHA, which is free from delineation of seismic sources.

One of the first attempts to develop an alternative to the Cornell-McGuire procedure was made by Veneziano *et al*. (1984). Indeed, the procedure does not require the specification of seismic sources, is non-parametric and as input, requires only information about past seismicity. The empirical distribution of the specified seismic hazard parameter is calculated by using the observed earthquake magnitudes, epicentral distances and assumed ground motion prediction equation. By normalizing this distribution for the duration of the seismic event catalogue, one obtains an annual rate of the exceedance for the required hazard parameter.

Another non-parametric PSHA procedure has been developed by Woo (1996). The procedure is also source-free, where seismicity distributions are approximated by data-based kernel functions. Molina *at al*. (2001) compared the Cornell-McGuire and kernel based procedures and found that the former yields a lower hazard. The kernel based approach has also been used by Jackson and Kagan, (1999) where non-parametric earthquake forecasting is achieved by the computation of the annual rate of seismic activity. Again, the procedure is based exclusively on the seismic event catalogue.

By their nature, the non-parametric procedures work well in areas with a frequent occurrence of strong seismic events and where the record of past seismicity is considerably complete. At the same time, the non-parametric approach has significant weak points. Its primary disadvantage is a poor reliability in estimating small probabilities for areas of low seismicity. The procedure is not recommended for an area where the seismic event catalogues are highly incomplete. In addition, in its present form, the procedure is not capable of making use of any additional geophysical or geological information to supplement the pure seismological data. Therefore, a procedure that accommodates the incompleteness of the seismic event catalogues and, at the same time, does not require the specification of seismic sources, would be an ideal tool for analysing and assessing seismic hazard.

Such a procedure, which can be classified as a *parametric-historic* procedure for PSHA (McGuire, 1993), has been successfully used in several parts of the world. Shepherd *et al.* (1993) used it for mapping the seismic hazard in El Salvador. The procedure has been applied in selected parts of the world by the Global Seismic Hazard Assessment Program (GSHAP, Giardini, 1999), while Frankel *et al.* (1996; 2002) applied it for mapping the seismic hazard in the United States. In a series of papers, Frankel and his colleagues modified and substantially extended the original procedure. Their final approach is parametric and based on the assumption that earthquakes within a specified grid size are Poissonian in time, and that the earthquake magnitudes follow the Gutenberg-Richter relation truncated from the top by maximum possible earthquake magnitude m_{max}.

In some cases, the frequency-magnitude Gutenberg-Richter relation is extended by characteristic events. The procedure accepts the contribution of seismicity from active faults and compensates for incompleteness of seismic event catalogues. The final maps of seismic hazard are smoothed by a Gaussian type kernel function. Frankel's conceptually simple and intuitive parametric-historic approach combines the best of the deductive and non-parametric historic procedures and, in many cases, is free from the disadvantages characteristic of each of the procedures. The rigorous mathematical foundations of the parametric-historic PSHA formalism has been given by Kijko and Graham (1998; 1999) and Kijko (2004).

3.2. Alternative earthquake recurrence models.

Time dependent models. In addition to the classic assumption, that earthquake occurrence in time follows a Poisson process, alternative approaches are occasionally used. These procedures attempt to assess temporal, or temporal and spatial dependence of seismicity. Time dependent earthquake occurrence models specify a distribution of the time to the next earthquake, where this distribution depends on the magnitude of the most recent earthquake. In order to incorporate the memory of past events, the non-Poissonian distributions or Markov chains are applied. In this approach, the seismogenic zones that recently produced strong earthquakes become less hazardous than those that did not rupture in recent history.

Clearly such models may result in a more realistic PSHA, but most of them are still only research tools and have not yet reached the level of development required by routine engineering applications. An excellent review of such procedures is given by Anagnos and Kiremidjian (1988), Cornell and Winterstein (1988), and by Cornell and Toro (1992). Other more recent treatises of the subject are reviewed e.g. by Muir-Wood (1993) and Boschi *et al*. (1996).

Time dependent occurrence of large earthquakes on segments of active faults is extensively discussed by Rhoades *et al.* (1994), Ogata (1999), and recently by Faenza *et al.* (2007). Also, a comprehensive review of all aspects of non-Poissonian models is provided by Kramer (1996). There are several time-dependent models which play an important role in PSHA. The best known models, which have both firm physical and empirical bases, are probably the two models by Shimazaki and Nakata (1980). Based on the correlation of seismic activity with earthquake related coastal uplift in Japan, Shimazaki and Nakata (1980) proposed two models of earthquake occurrence: a *time-predictable* and a *slip-predictable* model.

The time predictable model states that earthquakes occur when accumulated stress on a fault reaches a critical level, however the stress drop and magnitudes of the subsequent earthquakes vary among seismic cycles. Thus, assuming a constant fault-slip rate, the time to the next earthquake can be estimated from the slip of the previous earthquake. The second, the slip-predictable model, is based on the assumption that, irrespective of the initial stress on the fault, an earthquake occurrence always causes a reduction in stress to the same level. Thus, the fault-slip in the next earthquake can be estimated from the time since the previous earthquake (Shimazaki and Nakata, 1980; Scholz, 1990; Thenhaus and Campbell, 2003).

The second group of time-dependent models are less tightly based on the physical considerations of earthquake occurrence, and attempt to describe intervals between the consecutive events by specified statistical distributions. Ogata (1999), after Utsu (1984), considers five models: log-normal, gamma, Weibull, doubly exponential and exponential, which result in the stationary Poisson process. After application of these models to several paleo-earthquake data sets, he concluded that no one of the distributions is consistently the best fit; the quality of the fit strongly depends on the data. From several attempts to describe earthquake time intervals between consecutive events using statistical distributions, at least two play a significant role in the current practice of PSHA: the log-normal model of earthquake occurrence by Nishenko and Buland (1987) and the Brownian passage time (BPT) renewal model by Matthewes *et al*. (2002).

The use of a log-normal model is justified by the discovery that normalized intervals between the consecutive large earthquakes in the circum-Pacific region follow a log-normal distribution with an almost constant standard deviation (Nishenko and Buland, 1987). The finite value for the intrinsic standard deviation is important because it controls the degree of aperiodicity in the occurrence of *characteristic earthquakes,* making accurate earthquake prediction impossible (Scholz, 1990).

Since this discovery, the log-normal model has become a key component of most time-dependant PSHA procedures, and is routinely used by the Working Group on California Earthquake Probabilities (WGCEP, 1995).

A time-dependent earthquake occurrence model which is applied more often is the Brownian passage time (BPT) distribution, also known as the inverse Gaussian distribution (Matthewes *et al*., 2002). The model is described by two parameters: μ and σ, which respectively represent the mean time interval between the consecutive earthquakes and the standard deviation. The aperiodicity of earthquake occurrence, as described by the BPT model, is controlled by the variation coefficient $\alpha = \sigma / \mu$. For a small α, the aperiodicity of earthquake occurrence is small and the shape of distribution is almost symmetrical. For a large α, the shape of distribution is similar to log-normal model, i.e. skewed to the right and peaked at a smaller value than the mean. The straightforward control of aperiodicity of earthquake occurrence, by parameter α, makes the BPT model very attractive. It has been used to model earthquake occurrence in many parts of the world and has been applied by the Working Group on California Earthquake Probabilities (1995).

Several comparisons of time-dependent with time-independent earthquake occurrence models (Cornell and Winterstein, 1986, Kramer, 1996; Peruzza *et al.,* 2008) have shown that the time-independent (Poissonian) model can be used for most engineering computations of PSHA. The exception to this rule is when the seismic hazard is dominated by a single seismic source, with a significant component of characteristic occurrence when the time interval from the last earthquake exceeds the mean time interval between consecutive events. Note that, in most cases, the information on strong seismic events provided by current databases is insufficient to distinguish between different models. The use of non-Poissonian models will therefore only be justified if more data will be available.

Alternative frequency-magnitude models. In the classic Cornell-McGuire procedure for PSHA assessment, it is assumed that earthquake magnitudes follows the Gutenberg-Richter relation truncated from the top by a seismic source characteristic, the maximum possible earthquake magnitude m_{max}. The PDF of this distribution is given by equation (5).

Despite the fact that in many cases the Gutenberg-Richter relation describes magnitude distributions within seismic source zones sufficiently well, there are some instances where it does not apply and the relationship (5) must be modified. In many places, especially for areas of seismic belts and large faults, the Gutenberg-Richter relation underestimates the occurrence of large magnitudes. The continuity of the distribution (5) breaks down. The distribution is adequate only for small events up to magnitude 6.0-7.0. Larger events tend to occur within a relatively narrow range of magnitudes (7.5-8.0) but with a frequency higher than that predicted by the Gutenberg-Richter relation (5). These events are known as *characteristic earthquakes* (Youngs and Coppersmith, 1985, Figure 5). Often it is assumed that characteristic events follow a truncated Gaussian magnitude distribution (WGCEP, 1995).

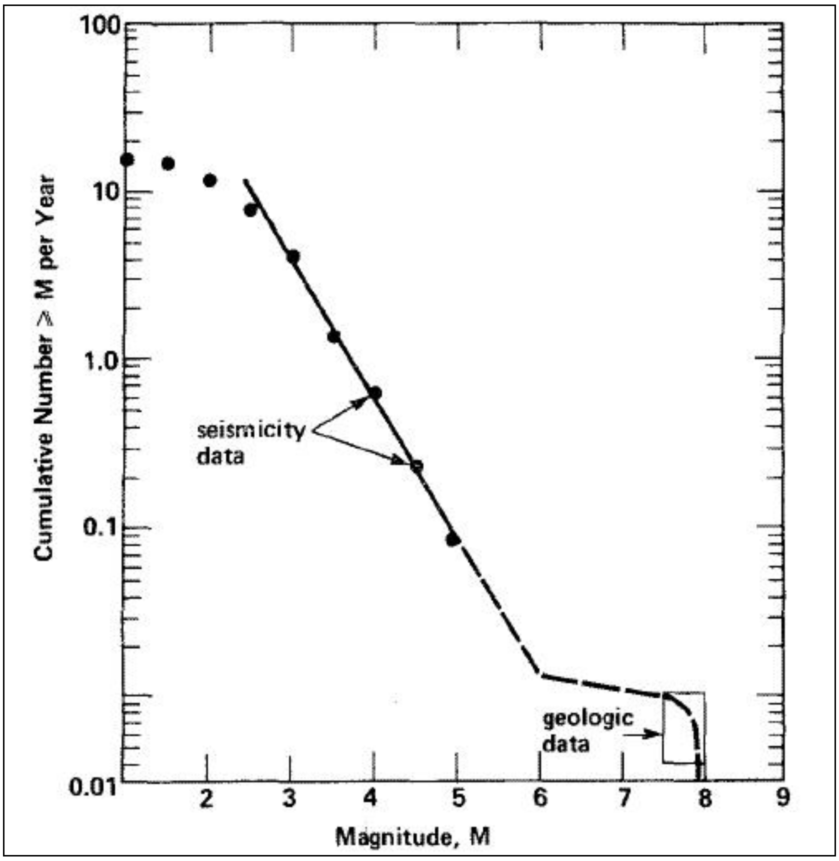

Figure 5: Gutenberg-Richter characteristic earthquake magnitude distribution. The model combines frequency-magnitude Gutenberg-Richter relation a with a uniform distribution of characteristic earthquakes. The model predicts higher rates of exceedance at magnitudes near the characteristic earthquake magnitude. (After Youngs and Coppersmith, 1985).

There are several alternative frequency-magnitude relations, which are used in PSHA. The best known is probably the relation by Merz and Cornell (1973), which accounts for a possible curvature in the log-frequency-magnitude relation (1) by the inclusion of a quadratic term of magnitude. Departure from linearity of the distribution (1) is built into the model by Lomnitz-Adler and Lomnitz (1979). The model is based on simple physical considerations of strain accumulation and release at plate boundaries. Despite the fact that m_{max} is not present in the model, it provides estimates of the occurrence of large events which are more realistic than those predicted by the Gutenberg-Richter relation (1). When seismic hazard is caused by induced seismicity, an alternative distribution to the Gutenberg-Richter model (1) is always required. For example, the magnitude distributions of tremors generated by mining activity are multimodal and change their shape in time (Gibowicz and Kijko, 1994). Often the only possible method that can lead to a successfully PSHA for mining areas is the replacement of the analytical, parametric frequency-magnitude distribution by its model-free, nonparametric counterpart (Kijko *et. al.*, 2001).

Two more modifications of the recurrence models are regularly introduced: one when earthquake magnitudes are uncertain and the other when the seismic occurrence process is composed of temporal trends, cycles, short-term oscillations and pure random fluctuations. The effect of error in earthquake magnitude determination (especially significant for historic events) can be minimized by the simple procedure of correction of the earthquake magnitudes in a catalogue (e.g. Rhoades, 1996). The modelling of random fluctuations in earthquake occurrence is often done by introducing compound distributions in which parameters of earthquake recurrence models are treated as random variables (Campbell, 1982).

4. Ground Motion Prediction Equations

The assessment of seismic hazard at a site requires knowledge of the prediction equation of the particular strong motion parameter, as a function of distance, earthquake magnitude, faulting mechanism and often the local site condition below the site. The most simple and most commonly used form of a prediction equation is

$$\ln(y) = c_1 - c_2 m - c_3 \ln(r) - c_4 r + c_5 F + c_6 S + \varepsilon \,, \quad (19)$$

where *y* is the amplitude of the ground motion parameter (PGA, MM intensity, seismic record duration, spectral acceleration, etc.); *m* is the earthquake magnitude, *r* is the shortest earthquake distance from the site to the earthquake source, *F* is responsible for the faulting mechanism; *S* is a term describing the site effect; and ε is the random error with zero mean and standard deviation $\sigma_{\ln(y)}$, which has two components: epistemic and aleatory.

The coefficients $c_1,...,c_6$ are estimated by the least squares or maximum likelihood procedure, using strong motion data. It has been found that the coefficients depend on the tectonic settings of the site. They are different for sites within stable continental regions, active tectonic regions or subduction zone environments (Thenhaus and Campbell, 2003; Campbell, 2003). Assuming that ln(*y*) has a normal distribution, regression of (19) provides the mean value of ln(*y*), the exponent of which corresponds to the median value of *y*, $\breve{y}$, (Benjamin and Cornell, 1970). Since the log-normal distribution is positively skewed, the mean value of *y*, $\bar{y}$, exceeds the median value $\breve{y}$ by a factor of $\exp(-0.5\sigma^2_{\ln(y)})$. This indicates that the seismic hazard for a particular site is higher when expressed in terms of $\bar{y}$, than the hazard for the same site expressed in terms of $\breve{y}$. It has been shown that the ground motion prediction equation remains a particularly important component of PSHA, since its uncertainty is a major contributor to uncertainty of the PSHA results (Bender, 1984; SSHAC, 1997).

5. Uncertainties in PSHA

Contemporary PSHA distinguishes between two types of uncertainties, aleatory and epistemic.

The *aleatory uncertainty* is due to randomness in nature; it is the probabilistic uncertainty inherent in any random phenomenon. It represents unique details of any earthquake as its source, path, and site and cannot be quantified before the earthquake occurrence and cannot be reduced by current theories, acquiring addition data or information. It is sometimes referred as “randomness”, “stochastic uncertainty” or “inherent variability” (SSHAC, 1997) and is denoted as U_R (McGuire, 2004). The typical examples of aleatory uncertainties are: the number of future earthquakes in a specified area; parameters of future earthquakes such as origin times, epicenter coordinates, depths and their magnitudes; size of the fault rupture; associated stress drop and ground motion parameters like PGA, displacement or seismic record duration at the given site. The aleatory uncertainties are characteristic to the current model and cannot be reduced by the incorporation of addition data. It can only be reduced by the conceptualization of a better model.

The *epistemic uncertainty*, denoted as U_K is the uncertainty due to insufficient knowledge about the model or its parameters. The model (in the broad sense of its meaning; as, e.g., a particular statistical distribution etc.) may be approximate and inexact, and therefore predicts values that differ from the observed values by a fixed, but unknown, amount. If uncertainties are associated with numerical values of the parameters, they are also epistemic by nature. Epistemic uncertainty can be reduced by incorporating additional information or data. Epistemic distributions of a model's parameters can be updated using the Bayes' theorem. When new information about parameters is significant and accurate, these epistemic distributions of parameters become delta functions about the exact numerical values of the parameters. In such a case, no epistemic uncertainty about the numerical values of the parameters exists and the only remaining uncertainty in the problem is aleatory uncertainty.

In the past, epistemic uncertainty has been known as statistical or professional uncertainty (McGuire, 2004). The examples of the epistemic uncertainties are: boundaries of seismic sources, distributions of seismic sources parameters (e.g. annual rate of seismic activity λ, *b*-value and m_{max}), or median value of the ground motion parameter given the source properties.

Aleatory uncertainties are included in the PSHA by means of integration over these uncertainties (see eq. 5) and they are represented by the hazard curve. In contrast, epistemic uncertainties are included through the use of an alternative hypothesis - different sets of parameters with different numerical values, different models or through a *logic tree*. Therefore, by default, if in the process of PSHA, the logic tree formalism is applied, the resulting uncertainties of the hazard curve are of epistemic nature.

The major benefit of the separation of uncertainties into aleatory and epistemic is potential guidance in the preparation of input for PSHA and the interpretation of the results. Unfortunately, the division of uncertainties into aleatory and epistemic is model dependent and to a large extent arbitrary, indefinite and confusing (*Panel of Seismic hazard Evaluation* …, 1997; Toro *et al*., 1997; Anderson *et al*., 2000).

6. Logic Tree

The mathematical formalism of PSHA computation, (equation 7 and 9), integrates over all random (aleatory) uncertainties of a particular seismic hazard model. In many cases, however, because of our lack of understanding of the mechanism that controls earthquake generation and wave propagation processes, the best choices for elements of the seismic hazard model is not clear. The uncertainty may originate from the choice of alternative seismic sources, competitive earthquake recurrence models and their parameters as well as from the choice of the most appropriate ground motion. The standard approach for the explicit treatment of alternative hypotheses, models and parameters is the use of a *logic tree* (Coppersmith and Youngs, 1986). The logic tree formalism provides a convenient tool for quantitative treatment of any alternatives. Each node of the logic tree (Figure 3) represents uncertain assumptions, models or parameters and the branches extending from each node are the discrete uncertainty alternatives (McGuire, 2004).

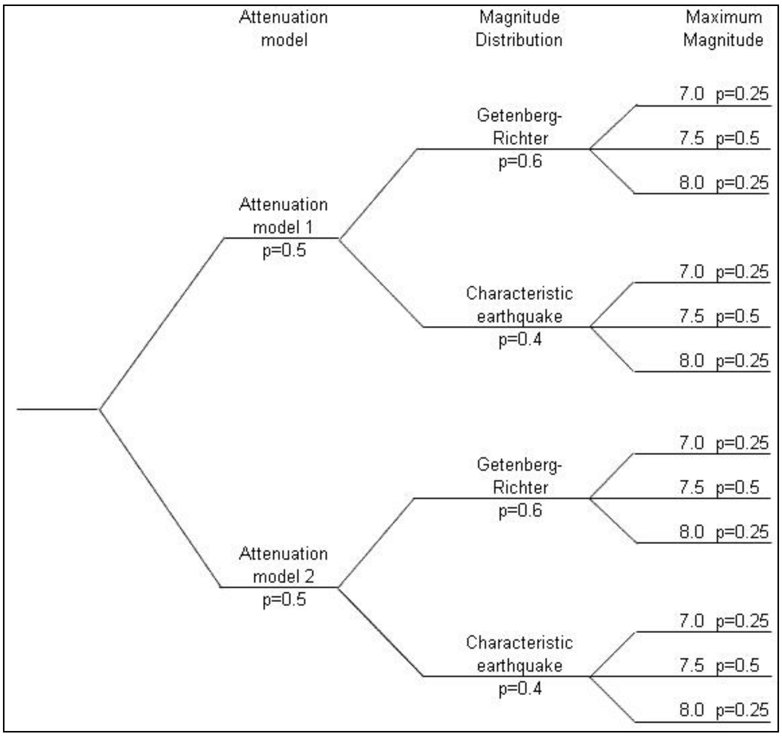

Figure. 6. An example of a simple logic tree. The alternative hypothesis accounts for uncertainty in ground motion attenuation relation, magnitude distribution model and the assigned maximum magnitude m_{max}.

In the logic tree analysis, each branch is weighted according to its probability of being correct. As a result, each end branch represents a hazard curve with an assigned weight, where the sum of weights of all the hazard curves is equal to 1. The derived hazard curves are thus used to compute the final (e.g. mean) hazard curve and their confidence intervals. An example of a logic tree is shown in Figure 3 (Kramer, 1996). The alternative hypotheses account for uncertainty in the ground motion attenuation model, the magnitude distribution model and the assigned maximum magnitude $m_{\max}$.

7. Controversy

Despite the fact that the PSHA procedure, as we know it in its current form, was formulated almost half of century ago, it is not without controversy. The controversy surrounds questions such as: (1) the absence of the upper limit of ground motion parameters, (2) division of uncertainties between aleatory and epistemic, and (3) methodology itself, especially the application of the logic tree formalism.

In most currently used Cornell-McGuire based PSHA procedures, the ground motion parameter used to describe the seismic hazard is distributed log-normally. Since the log-normal distribution is unlimited from the top, it results in a nonzero probability of unrealistically high values for the ground motion parameter, e.g., PGA $\approx$ 20g, obtained originally from a PSHA for a nuclear-waste repository at Yucca Mountain in the USA (Corradini, 2003). The lack of the upper bound of earthquake-generated ground motion in current hazard assessment procedures has been identified as the "missing piece" of the PSHA procedure (Bommer *et al.,* 2004).

Another criticism of the current PSHA procedure concerns portioning of uncertainties into aleatory and epistemic. As noted in Section 5 above, the division between aleatory and epistemic uncertainty remains an open issue.

A different criticism comes from the ergodic assumptions which underlie the formalism of the PSHA procedure. The ergodic process is a random process in which the distribution of a random variable in space is the same as distribution of that variable at a single point, when sampled as a function of time (Anderson and Brune, 1999). It has been shown that the major contribution to PSHA uncertainty comes from uncertainty of the ground motion prediction equation. The uncertainty of the ground motion parameter *y,* is characterised by its standard deviation, $\sigma_{\ln(y)}$, which is calculated as the misfit between the observed and predicted ground motions at several seismic stations for a small number of recorded earthquakes.

Thus, $\sigma_{\ln(y)}$ mainly characterises the spatial and not the temporal uncertainty of ground motion at a single point. This violates the ergodic assumption of the PSHA procedure. According to Anderson and Brune (1999), such violation leads to overestimation of seismic hazard, especially when exposure times are longer than earthquake return times. In addition, Anderson (2000) shows that high-frequency PGA-s observed at short distances do not increase as fast as predicted by most ground motion relations. Therefore the use of the current ground motion prediction equations, especially relating to seismicity recorded at short distances, results in overestimation of the seismic hazard.

A similar view has been expressed by Wang and Zhou (2007) and Wang (2009). *Inter alia* they argue that in the Cornell-McGuire based PSHA procedure, the ground motion variability is not treated correctly. By definition, the ground motion variability is implicitly or explicitly dependent on earthquake magnitude and distance, however, the current PSHA procedure treats it as an independent random variable. The incorrect treatment of ground motion variability results in variability in earthquake magnitudes and distance being counted twice. They conclude that the current PSHA is not consistent with modern earthquake science, is mathematically invalid, can lead to unrealistic hazard estimates and causes confusion. Similar reservations have been expressed in a series of papers by Klügel (see e.g. Klügel, 2007 and references therein)

Equally strong criticism of the currently PSHA procedure has been expressed by Castanos and Lomnitz (2002). The main target of their criticism is the logic tree, the key component of the PSHA. They describe the application of the logic tree formalism as a misunderstanding in probability and statistics, since it is fundamentally wrong to admit "expert opinion as evidence on the same level as hard earthquake data".

The science of seismic hazard assessment is thus subject to much debate, especially in the realms where instrumental records of strong earthquakes are missing. At this time, PSHA represents a best-effort approach by our species to quantify an issue where not enough is known to provide definitive results, and by many estimations a great deal more time and measurement will be needed before these issues can be resolved.

Further reading: There are several excellent studies that describe all aspects of the modern PSHA. Bommer and Abrahamson (2006) and McGuire (2008) trace the intriguing historical development of PSHA. Hanks and Cornell (1999), and Field (1996) present an entertaining and unconventional summary of the issues related to PSHA, including its misinterpretation. Reiter (1990) comprehensively describes both the deterministic as well as probabilistic seismic hazard procedures from several points of view, including a regulatory perspective. Seismic hazard from the geologist's perspective is described in the book by Yeats *et al*., (1997). Kramer (1996) provides an elegant, coherent and understandable description of the mathematical aspects of both, DSHA and PSHA. Anderson *et al*. (2000), Gupta (2002), and Thenhaus and Campbell (2003), present excellent overviews covering theoretical, methodological as well as procedural issues of modern PSHA. Finally, the most comprehensive treatment to date of all aspects of PSHA, including treatment of *aleatory* and *epistemic* uncertainties, is provided by the SSHAC (1997) report and in book form by McGuire (2004). The presentations here benefited from all quoted above sources, especially the excellent book by Kramer (1996).

8. Summary

Seismic hazard is a term referring to any physical phenomena associated with an earthquake (e.g., ground motion, ground failure, liquefaction, and tsunami) and their effects on land, man-made structures and socio-economic systems that have the potential to produce a loss. The term is also used, without regard to a loss, to indicate the probable level of ground shaking occurring at a given point within a certain period of time. Seismic hazard analysis is an expression referring to quantification of the expected ground-motion at the particular site. Seismic hazard analysis can be performed deterministically, when a particular earthquake scenario is considered, or probabilistically, when the likelihood or frequency of a specified level of ground motion at a site during a specified exposure time is evaluated. In principle, any natural hazard caused by seismic activity can be described and quantified in terms of the probabilistic methodology. Classic probabilistic seismic hazard analysis (PSHA) includes four steps: (1) identification and parameterization of the seismic sources, (2) specification of temporal and magnitude distributions of earthquake occurrence, (3) calculation of ground motion prediction equations and their uncertainty, and (4) integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction equations into the hazard curve.

An integral part of PSHA is the assessment of uncertainties. Contemporary PSHA distinguishes between two types of uncertainties, aleatory and epistemic. The aleatory uncertainty is due to randomness in nature; it is the probabilistic uncertainty inherent in any random phenomenon. The aleatory uncertainties are characteristic to the current model and cannot be reduced by the incorporation of addition data. The epistemic uncertainty is the uncertainty due to insufficient knowledge about the model or its parameters. Epistemic uncertainty can be reduced by incorporating additional information or data. Aleatory uncertainties are included in the probabilistic seismic hazard analysis due to the integration over these uncertainties and they are represented by the hazard curve. In contrast, epistemic uncertainties are included through the use of alternative models, different sets of parameters with different numerical values or through a logic tree.

Unfortunately, the PSHA procedure, as we know it in its current form, is not without controversy. The controversy arises from questions such as: (1) the absence of the upper limit of ground motion parameter, (2) division of uncertainties between aleatory and epistemic, and (3) methodology itself, especially the application of the logic tree formalism

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APPENDIX E

MONTHLY ENVIRONMENTAL FLOW RELEASE REQUIREMENTS AT NTABELANGA DAM

Table E-1: Monthly Environmental Flow Release Requirements at Ntabelanga Dam

MONTHLY ENVIRONMENTAL FLOW RELEASE REQUIREMENTS AT NTABELANGA DAM

Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Average
1920	1.57	1.014	1.59	1.625	10.946	8.601	3.049	1.89	0.952	0.516	0.452	1.051	2.72
1921	1.311	2.592	2.476	2.21	4.024	1.688	0.936	1.913	1.423	1.207	1.124	1.665	1.87
1922	1.577	2.605	2.39	3.079	22.054	9.529	2.411	0.777	0.983	1.207	1.124	1.333	3.98
1923	0.601	0.82	1.662	2.017	9.623	6.127	2.407	0.86	0.875	0.715	0.769	1.532	2.29
1924	1.056	1.772	2.501	3.099	3.186	12.22	3.079	1.926	1.195	0.59	0.474	1.445	2.72
1925	0.809	1.116	0.788	1.494	6.238	9.74	2.969	1.798	1.419	1.191	0.686	1.647	2.47
1926	1.684	1.695	2.131	1.589	5.625	12.22	3.079	1.224	0.577	0.545	0.844	1.066	2.68
1927	1.8	1.871	2.496	3.142	12.933	2.015	1.2	0.853	0.825	0.594	1.079	1.318	2.45
1928	0.802	1.308	2.445	2.782	10.007	11.451	3.052	1.638	1.423	1.207	1.111	1.658	3.21
1929	1.851	2.556	2.49	3.123	9.807	6.742	2.956	1.768	0.982	0.977	1.111	1.612	2.96
1930	1.548	0.871	2.232	3.106	21.294	11.47	3.051	1.541	0.623	1.207	1.124	1.403	4.02
1931	1.002	1.286	2.377	2.448	19.605	7.208	1.671	1.054	1.075	1.11	0.796	1.67	3.34
1932	1.834	2.599	2.482	1.564	2.35	2.662	2.269	1.426	0.584	0.525	0.538	0.652	1.62
1933	0.626	2.605	2.501	3.142	17.865	8.902	2.904	0.938	0.768	1.207	1.111	0.79	3.53
1934	1.591	2.425	2.479	2.419	3.969	5.167	2.981	1.919	1.421	1.169	1.111	1.577	2.34
1935	0.637	0.754	0.601	1.042	17.244	8.09	1.86	1.911	1.423	1.154	0.934	0.945	2.96
1936	1.714	2.605	2.45	2.571	22.614	10.695	2.331	0.746	0.574	0.497	0.459	0.878	3.90
1937	0.858	0.79	1.181	2.946	18.703	5.129	2.989	1.924	1.301	1.191	1.098	1.386	3.19
1938	1.109	1.184	2.471	3.101	22.614	7.48	1.201	1.16	1.199	1.178	1.036	1.667	3.67
1939	1.816	2.281	1.417	1.114	17.087	8.096	2.092	1.922	1.421	0.917	0.518	1.456	3.26
1940	1.324	1.483	1.839	1.835	7.122	2.411	1.859	1.388	0.631	0.966	0.867	0.649	1.83
1941	0.725	0.8	0.616	1.462	16.329	10.556	2.91	1.813	1.021	0.495	1.086	1.601	3.21
1942	1.837	2.583	2.501	2.859	2.681	6.795	3.067	1.926	1.411	1.123	1.124	1.67	2.47
1943	1.844	2.595	2.501	2.945	7.697	4.568	2.068	0.737	1.364	1.119	0.647	1.67	2.45
1944	1.835	0.864	0.633	1.067	12.837	8.536	2.442	0.805	0.604	0.494	0.452	0.5	2.53
1945	1.796	1.37	0.76	3.075	10.504	3.189	2.224	1.866	1.366	0.771	0.59	0.562	2.29
1946	0.649	1.74	1.561	2.956	17.551	9.31	2.819	1.617	1.408	1.194	0.778	1.403	3.50
1947	1.326	2.605	2.501	3.081	20.51	9.228	2.705	1.793	0.976	0.556	0.46	0.552	3.76
1948	1.29	0.87	0.74	1.178	7.274	2.778	1.636	1.029	0.681	0.698	0.633	0.917	1.61
1949	0.6	0.824	1.417	1.719	15.91	11.518	3.04	1.915	1.417	1.085	1.124	1.657	3.45
1950	1.757	1.318	2.491	3.003	10.877	3.321	1.385	0.858	0.812	0.562	1.06	1.629	2.37
1951	1.841	1.869	0.735	1.236	17.378	5.68	1.604	1.338	1.159	1.097	0.831	1.542	2.93
1952	1.137	2.545	2.379	2.679	17.292	5.477	2.62	1.87	0.607	0.487	0.775	1.652	3.20
1953	1.784	2.236	2.184	2.432	9.494	8.235	2.813	1.922	1.423	1.191	0.62	1.091	2.91
1954	1.373	1.902	1.513	3.142	22.614	9.555	2.611	1.782	1.356	1.083	0.541	0.869	3.91
1955	1.095	2.166	2.232	1.281	13.336	10.637	2.811	1.174	1.351	1.027	0.503	1.332	3.18
1956	0.948	2.58	2.501	3.1	11.748	11.956	3.079	1.866	1.002	0.938	1.11	1.67	3.50
1957	1.839	1.479	1.143	3.1	11.612	1.891	2.395	1.884	1.214	0.682	0.497	0.717	2.31
1958	0.604	2.605	2.5	2.337	8.863	4.238	2.832	1.926	1.423	1.179	1.079	1.175	2.52
1959	0.878	1.91	1.896	2.54	9.442	2.082	1.431	1.368	0.871	0.675	0.93	1.625	2.09
1960	1.378	2.441	2.463	2.645	3.04	4.368	3.054	1.926	1.262	0.57	0.673	0.716	2.04
1961	0.571	2.524	2.306	2.43	16.2	10.553	2.971	1.807	0.719	0.504	0.637	0.625	3.41
1962	0.804	2.482	2.363	3.142	21.85	12.22	3.079	1.755	0.734	1.189	1.038	0.563	4.16
1963	1.844	2.605	2.376	1.753	3.14	6.051	3.006	1.858	1.423	1.207	1.018	1.538	2.31
1964	1.833	1.568	2.024	1.797	18.408	5.417	1.396	1.444	1.423	1.207	1.116	1.612	3.18
1965	1.585	2.405	1.337	3.07	16.318	2.178	1.127	1.829	1.375	0.676	1.078	1.533	2.79
1966	0.749	0.957	1.999	2.884	17.056	11.184	3.079	1.926	1.402	1.195	1.025	0.555	3.59
1967	0.917	1.671	0.92	1.065	2.495	1.832	1.334	0.83	0.537	0.493	0.94	1.327	1.19
1968	0.735	1.136	1.033	1.085	2.963	10.611	3.046	1.65	1.197	0.864	0.592	0.665	2.13
1969	1.791	1.514	1.882	1.218	5.671	1.845	1.121	0.765	1.323	1.057	1.124	1.67	1.72
1970	1.854	2.277	0.914	2.74	9.408	2.043	1.49	1.907	1.419	1.196	1.124	1.661	2.29
1971	1.854	2.515	2	3.013	22.614	12.22	2.889	0.949	0.765	0.561	0.461	0.533	4.09
1972	0.687	2.56	1.964	1.121	15.635	11.375	3.041	1.709	0.786	0.855	0.902	1.289	3.42
1973	1.091	2.103	1.502	3.142	22.614	12.22	3.079	1.871	1.372	1.039	0.667	0.529	4.16
1974	0.555	2.521	2.336	1.63	2.644	3.923	2.304	0.799	0.576	0.553	0.47	1.67	1.66
1975	1.71	1.802	2.501	3.142	20.378	12.22	3.079	1.926	1.423	1.097	0.735	1.612	4.21
1976	1.854	2.57	0.734	1.277	10.408	5.23	2.462	1.776	0.651	1.091	1.004	1.653	2.51
1977	1.746	2.36	2.198	2.102	3.833	2.874	3.079	1.926	1.371	0.661	0.911	1.628	2.04
1978	1.835	1.864	2.414	2.322	7.928	2.786	1.533	0.974	0.658	1.207	1.111	1.391	2.13
1979	1.329	0.955	1.03	1.213	5.116	3.41	1.821	0.717	0.557	0.491	0.452	1.661	1.54
1980	1.674	1.354	1.956	2.889	20.806	5.758	1.217	1.537	1.368	0.99	1.104	1.536	3.41
1981	0.633	0.978	1.212	1.864	4.764	7.092	2.902	1.527	1.272	1.192	1.014	1.346	2.14
1982	1.734	2.428	1.317	0.714	1.089	1.721	1.476	1.332	0.805	1.069	0.728	0.717	1.26
1983	1.525	2.554	2.454	2.925	9.186	9.19	3.031	1.844	1.358	1.176	1.015	0.816	3.06
1984	1.756	2.204	0.991	2.923	22.614	7.064	1.18	0.722	0.57	0.495	0.444	0.759	3.36
1985	1.854	2.588	2.496	3.082	8.669	2.018	1.416	0.728	0.578	0.755	1.1	1.632	2.20
1986	1.854	2.585	2.189	1.246	5.152	2.793	1.883	0.872	1.114	0.782	1.097	1.67	1.91
1987	1.854	2.453	1.935	2.042	22.614	12.22	2.916	1.865	1.312	1.084	0.991	1.51	4.29
1988	1.47	2.397	2.501	3.022	20.736	8.304	3.058	1.926	1.15	1.16	0.977	0.556	3.84
1989	1.631	2.605	2.489	2.656	3.829	7.907	3.004	1.712	1.121	0.868	1.11	1.556	2.54
1990	1.568	0.98	0.964	2.028	8.011	1.888	1.146	0.67	0.589	0.49	0.443	1.352	1.64
1991	1.854	2.555	2.438	2.255	4.622	1.832	1.209	0.778	0.552	0.469	0.472	1.161	1.66
1992	0.761	0.847	0.682	1.092	3.482	4.61	2.583	1.293	0.562	0.474	0.599	1.612	1.54
1993	1.854	2.494	2.351	3.015	16.322	12.22	3.062	0.88	0.779	1.164	1.073	0.795	3.76
1994	0.628	0.775	1.927	2.396	2.982	9.56	3.059	1.867	1.234	0.971	0.492	0.959	2.24
1995	1.376	1.348	2.501	3.142	22.572	4.359	1.466	1.224	0.833	1.049	0.651	0.644	3.31
1996	0.805	2.605	2.491	3.001	7.465	4.285	2.653	1.5	1.423	1.207	1.11	1.188	2.45
1997	1.744	2.296	1.618	2.971	22.614	10.982	2.846	1.87	1.307	0.961	1.004	1.145	4.17
1998	0.812	2.579	2.481	2.822	18.076	5.853	1.36	0.731	0.643	0.654	0.461	0.51	2.99
1999	1.806	2.182	2.406	3.142	22.614	12.22	3.079	1.926	1.406	1.001	0.512	1.445	4.37
2000	1.38	1.989	1.736	2.808	9.592	4.118	2.104	0.951	0.576	0.563	0.527	1.394	2.27
2001	1.702	2.605	2.497	2.925	7.147	3.024	2.007	1.651	1.37	1.201	1.124	1.664	2.38
2002	1.067	0.829	2.205	2.409	5.297	2.096	1.72	1.736	1.293	0.707	0.853	1.636	1.80
2003	1.216	0.979	0.747	3.036	14.299	10.402	3.019	1.602	0.908	1.199	1.094	1.67	3.28
2004	1.796	2.52	2.271	3.142	14.87	3.397	2.166	1.37	0.784	0.52	0.855	0.694	2.79
2005	0.818	2.111	1.028	3.03	15.791	4.151	2.835	1.913	1.367	0.933	1.124	1.67	2.98
2006	1.854	2.584	2.279	2.314	5.44	1.822	1.811	1.591	0.986	0.724	0.557	0.571	1.86
2007	1.81	2.278	1.785	2.685	13.25	8.43	3.054	1.897	1.405	1.172	0.976	0.945	3.25
2008	0.579	1.044	2.43	2.764	13.251	3.018	1.119	0.989	1.282	0.826	1.037	1.401	2.41
2009	1.841	2.191	0.807	3.048	10.733	1.912	1.414	1.129	0.797	0.648	0.466	0.504	2.07
Average	1.358	1.91	1.881	2.387	12.161	6.622	2.34	1.467	1.054	0.895	0.837	1.23	2.79

APPENDIX F

SIMULATED MONTHLY WATER LEVELS AT NTABELANGA DAM

Table F-1: Monthly Water Levels at Ntabelanga Dam

MONTHLY WATER LEVELS AT NTABELANGA DAM													
Year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Average
1920	946.96	946.44	946.59	946.95	946.66	947.3	947.3	947	946.09	945.92	945.7	943.66	946.38
1921	943.44	946.28	947.3	947.27	946.53	946.43	946.12	946.29	946.92	947.3	947.3	947.3	946.54
1922	946.61	947.3	947.3	947.3	947.3	947.3	947.3	947.11	946.88	947.3	947.3	947.12	947.18
1923	946.85	946.07	944.79	945.12	944.92	946.62	947.18	946.43	946.08	945.68	944.61	943.55	945.66
1924	942.72	941.93	947.3	947.3	947.27	947.3	947.3	947.3	947.18	947.02	946.17	944.77	946.13
1925	944	943.53	943.02	942.12	940.83	943.4	944.07	944.15	944.5	944.24	944.05	942.42	943.38
1926	942.52	942.45	941.73	942.03	941.21	947.3	947.3	947.2	947.03	946.33	945.2	943	944.46
1927	942.76	943	946.67	947.3	947.3	947.07	946.22	946.08	945.91	945.17	944.22	942.98	945.39
1928	942.22	941.59	944.18	944.89	945.17	947.3	947.3	946.43	946.98	947.3	946.87	947.3	945.63
1929	947.3	947.3	947.3	947.3	947.3	947.3	947.3	946.59	945.72	945.59	945.78	945.82	946.71
1930	945.73	945.58	944.43	947.3	947.3	947.3	947.3	947.24	947.09	947.3	947.3	947.13	946.75
1931	947.01	946.85	946.41	947.27	947.3	947.3	946.64	945.74	945.51	945.42	945.08	945.45	946.33
1932	946.11	947.3	947.3	946.62	945.44	946.29	946.85	946.37	946.21	945.4	944.29	943.04	945.94
1933	941.94	946.77	947.3	947.3	947.3	947.3	947.3	947.15	947.02	947.07	946.69	944.95	946.5
1934	944.65	945.35	947.3	947.3	947.24	947.3	947.3	947.3	947.3	946.65	946.3	946.26	946.68
1935	946.05	945.24	943.87	942.47	944.55	946.71	946.99	947.28	947.26	946.47	945.52	945.36	945.65
1936	945.16	947.3	947.3	947.3	947.3	947.3	946.98	946.08	945.92	945.75	944.84	943.44	946.22
1937	942.67	941.55	940.76	942.97	945.07	946.3	947.3	947.3	947.28	947.3	946.73	945.25	945.04
1938	945	945.09	947.3	947.3	947.3	947.3	947.18	946.95	946.75	946.13	945.35	946.22	946.49
1939	946.92	947.23	946.59	946.51	947.3	947.3	947.3	947.3	947.3	947.16	946.95	945.01	946.91
1940	944.96	944.87	944.2	944.47	943.98	944.44	943.73	943.2	942.19	940.01	939.89	938.63	942.88
1941	938.02	937.37	935.93	934.75	936.49	939.54	938.72	935.06	928.42	918.15	918.15	918.15	931.54
1942	922.55	928.89	935.61	937.41	937.21	939.29	941.66	942.54	942.8	942.45	943.94	944.89	938.26
1943	946.14	947.3	947.3	947.3	947.3	947.3	947.3	947.09	946.84	946.74	945.65	947.3	946.96
1944	947.3	947.15	946.81	946.03	946.14	947.3	947.3	946.47	946.31	946.14	945.21	943.7	946.33
1945	943.61	943.43	942.33	945.68	946.81	947.3	947.3	947.12	946.49	946.36	946.17	944.01	945.54
1946	943.75	943.53	942.94	942.98	945	947.3	947.3	947.25	947.3	946.77	946.59	944.56	945.44
1947	944.49	947.3	947.3	947.3	947.3	947.3	947.3	946.41	945.48	945.33	945.12	942.97	946.13
1948	942.61	942.46	941.33	940.64	940.04	940.61	940.64	939.51	938.37	937.52	936.36	935.01	939.59
1949	933.56	932.42	931	930.45	933.47	938.33	940.04	940.67	940.96	940.44	941.08	940.96	936.96
1950	941.14	940.81	944.47	947.08	947.3	947.3	946.62	945.67	945.52	945.36	944.6	943.53	944.94
1951	944.14	944.13	942.99	941.98	944.08	945.11	945.32	945.04	944.65	943.56	942.52	941.44	943.74
1952	941.29	940.45	941.73	941.18	942.93	942.94	943.66	943.14	942.98	941.87	940.74	940.04	941.91
1953	940.57	941.11	941.22	942.09	941.43	943.64	943.62	943.67	943.4	941.56	938.9	938.62	941.65
1954	938.27	938.02	937.5	944.16	947.3	947.3	947.3	947.3	946.62	945.64	945.44	944.37	944.08
1955	944.2	943.78	943.45	943.12	943	945.95	946.99	946.91	946.81	946.15	945.02	943.86	944.95
1956	943.21	944.37	947.3	947.3	947.3	947.3	947.3	946.98	946.03	945.9	945.95	945.64	946.21
1957	946.45	946.05	946.25	947.3	947.3	947	946.84	946.4	946.3	946.16	945.28	943.8	946.26
1958	942.95	945.89	947.3	947.26	947.06	947.3	947.3	947.3	947.3	947.3	947.27	946.97	946.76
1959	946.78	946.44	946.5	947.07	946.41	946.67	946.81	946.7	946.24	945.19	944.09	943.27	946.01
1960	942.79	942.72	945.12	945.28	945.23	946.42	947.3	947.3	947.22	947.06	946.48	944.74	945.64
1961	944.13	944.05	945.36	945.02	946.86	947.3	947.3	946.55	945.65	945.48	945.26	943.16	945.5
1962	942.86	944.24	945.2	947.3	947.3	947.3	947.3	946.59	945.68	945.59	945.51	944.15	945.74
1963	945.37	947.3	947.3	947.28	946.72	947.3	947.3	946.73	947.3	947.3	947.2	946.38	946.96
1964	946.86	947.01	946.88	947.3	947.3	947.3	946.59	945.63	947.3	947.3	947.3	946.5	946.94
1965	946.63	947.3	947.07	947.3	947.3	947.3	947.03	946.72	946.77	946.61	945.82	944.63	946.71
1966	944.06	943.08	941.73	942.64	944.71	947.3	947.3	947.3	946.93	946.63	946.54	945.51	945.31
1967	945.23	944.98	944.42	943.18	942.02	941.57	941.24	940.21	939.11	936.72	936.44	935.48	940.88
1968	935.11	933.65	932.11	930.68	929.17	934.26	936.29	936.33	936.25	934.6	932.61	930.41	933.48
1969	931.08	930.73	928.91	928.29	927.36	922.82	921.64	918.15	918.15	918.15	926.5	930.05	925.14
1970	933.36	934.49	933.59	935.38	936.02	935.69	935.86	935.75	936.13	935.53	936.65	937.26	935.47
1971	940.34	941.43	941.79	944.28	947.3	947.3	947.3	947.18	947.01	946.37	945.24	943.95	944.94
1972	942.99	943.34	943.97	943.23	945.02	947.3	947.3	947.28	947.13	946.44	945.43	944.17	945.3
1973	943.46	943.27	943.48	947.3	947.3	947.3	947.3	947.05	946.57	946.46	946.28	944	945.81
1974	943.72	943.84	944.32	943.87	943.26	942.8	943.35	942.48	941.9	940.82	939.64	939.65	942.47
1975	939.76	939.58	946.5	947.3	947.3	947.3	947.3	947.3	947.3	947.23	947.06	945.25	945.76
1976	947.3	947.3	947.21	947.15	946.44	947.3	947.05	946.14	946.01	945.69	945.09	943.95	946.39
1977	944.08	943.43	943.58	943.81	943.25	942.97	947.3	947.3	946.43	945.47	945.18	944.91	944.81
1978	945.53	945.56	947.3	947.3	947.3	947.3	946.65	945.73	945.59	945.72	945.9	945.21	946.26
1979	945.1	944.81	943.7	943.16	942.32	942.85	942.14	941.71	940.63	939.48	938.42	938.98	941.94
1980	938.87	939.06	938.24	940.02	942.76	944.25	944.2	943.92	943.96	943.74	943.28	941.87	942.01
1981	941.38	940.39	939.8	940.33	939.89	941.89	943.14	943.1	943.06	942.86	942.18	940.61	941.56
1982	940.09	940.8	940.37	939.72	938.37	936.09	936.18	935.19	934.39	932.72	931.05	928.42	936.11
1983	926.57	930.61	934.61	936.42	937	939.54	941.19	940.33	940.35	940.29	940.13	937.9	937.07
1984	937.86	938.24	938	940.16	944.48	946.33	946.22	946	945.39	944.32	943.16	941.95	942.66
1985	945.33	947.3	947.3	947.3	947.3	947.3	946.77	945.77	945.6	945.37	944.93	943.91	946.18
1986	945.61	947.3	947.3	946.61	946.61	947.3	947.29	947.13	946.4	945.37	944.47	947.3	946.55
1987	947.3	947.3	947.28	947.3	947.3	947.3	947.3	946.75	945.92	945.84	945.76	943.85	946.6
1988	943.83	944.25	947.3	947.3	947.3	947.3	947.3	947.3	947.18	947.2	946.62	944.72	946.47
1989	944.34	947.3	947.3	947.3	947.2	947.3	947.3	947.28	947.18	946.41	945.75	944.6	946.6
1990	944.31	943.5	942.68	941.78	941.4	941.57	940.39	939.27	938.01	936.98	935.75	934.39	940
1991	937.1	939.07	941.57	942.3	942.3	942.12	942.09	941.03	939.82	938.85	937.59	935.17	939.91
1992	934.99	933.24	931.27	928.64	926.29	925.2	927.11	921.22	918.28	918.15	918.15	918.15	925.06
1993	925.88	929.19	932.47	936.17	938.24	943.22	945.31	945.17	945.03	944.44	943.8	942.14	939.25
1994	941.52	940.35	939.09	939.66	939.54	942	944.06	944.25	944.16	943.92	942.8	941.64	941.93
1995	940.79	940.23	946.17	947.3	947.3	947.3	946.63	945.68	945.54	945.24	944.69	942.81	944.97
1996	942.56	946.31	947.3	947.3	947.3	947.3	947.3	947.25	947.3	947.3	947.1	946.94	946.77
1997	946.69	947.02	946.51	947.23	947.3	947.3	947.3	946.87	945.97	945.85	945.75	943.64	946.45
1998	943.44	945.36	947.3	947.3	947.3	947.3	946.81	945.83	945.64	945.45	944.72	943.05	945.79
1999	943.12	943.45	944.1	947.3	947.3	947.3	947.3	947.3	946.69	945.68	945.47	944.54	945.79
2000	944.51	944.44	944.26	945.22	945.83	946.62	947	946.53	946.3	945.23	944.04	941.9	945.15
2001	941.88	946.63	947.3	947.3	947.06	947.3	947.02	946.29	946.31	946.58	947.3	947.3	946.52
2002	947.14	946.96	945.97	946.84	946.21	945.76	945.93	945.65	944.92	943.85	942.74	941.95	945.32
2003	941.18	940.33	938.32	940.87	941.59	944.48	946.07	946.03	945.9	945.42	945.02	946.01	943.44
2004	946.42	946.44	947.05	947.3	947.3	947.3	947.02	946.17	946.02	945.85	944.99	943.54	946.28
2005	942.91	942.53	942.7	943.93	945.68	946.32	947.3	947.3	947.29	947.17	947.15	947.3	945.63
2006	947.3	947.3	947.3	947.24	946.79	946.95	946.76	946.7	946.16	945.08	943.9	942.72	946.18
2007	942.81	943.27	943.56	943.03	943.91	944.55	946.18	945.27	944.55	944.59	944.24	942.26	944.02
2008	941.93	940.92	940.96	942.07	942.48	943.27	942.2	941.66	940.61	939.64	938.49	936.13	940.86
2009	937.32	937.2	936.75	939.05	940.13	939.02	939.11	938.72	938.01	936.82	935.62	933.86	937.62
Average	942.53	942.98	943.42	943.92	944.19	944.9	945.09	944.6	944.21	943.62	943.17	942.23	943.74