Molse Nete river :
Basic characteristics and evaluation of restoration options

Restoration Strategies for radioactively contaminated
Sites and their Close Surroundings
RESTRAT - WP1.3

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RESTRAT-TD 11

Issue 1

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1. Terms of reference

This report is submitted as Technical Deliverable No. 11 (TD 11) against the requirements of the RESTRAT (Restoration Strategies for radioactively contaminated sites and their Close Surroundings) Project.

The RESTRAT project is co-funded by the European Commission under the fourth framework of the Nuclear Fission Safety Programme. Its overall objective concerns the development of a methodology for ranking restoration techniques as a function of contamination and site characteristics.

It is based on an analysis of existing remediation methodologies and contaminated sites and is structured in the following steps:
1. characterisation of relevant contaminated sites;
2. identification and characterisation of relevant restoration techniques;
3. assessment of the radiological impact;
4. development and application of a methodology for the ranking and selection of restoration options;
5. formulation of general conclusions and development of a manual.

This report concerns the characterisation of the site of the Molse Nete river (Belgium) which has been contaminated by low-level liquid effluents from a nuclear waste treatment facility at the Mol site. The radiological and non-radiological characteristics of the site are described. Potentially relevant restoration techniques for the site are identified and their characteristics quantified.

The radiological impact assessment with and without remediation measures has been carried out in another working package of the project (Stiglund and Nordlinder, 1999) as has been the development and application of the ranking methodology of the restoration options (Hedemann Jensen, 1999). In this report the results for the Molse Nete river site are summarised and conclusions drawn.

2. Introduction

Since August 1956, controlled releases of low-level radioactive effluents, following legal authorisation, are made in the river Molse Nete, a branch of the river Grote Nete (Figure 1). In the early years, only the liquid waste of the nuclear research centre SCK•CEN, located at 4 km to the north of the river, was discharged via the underground pipeline of 0.2 m diameter and 9 km length. Since the seventies, the effluents of neighbouring nuclear installations are also discharged into the Molse Nete. The annual limit has never been attained. The highest releases corresponded to about 60% of the authorised limit and these were reached during the period 1970 - 1974. Meanwhile, some nuclear installations were shut down, leading to a significant decline of the releases. Nowadays, only a few percent of the authorised limit is released into the Molse Nete. This mainly comes from the test reactor BR2, the radioactive laboratories of SCK and the waste treatment operations of Belgoprocess.

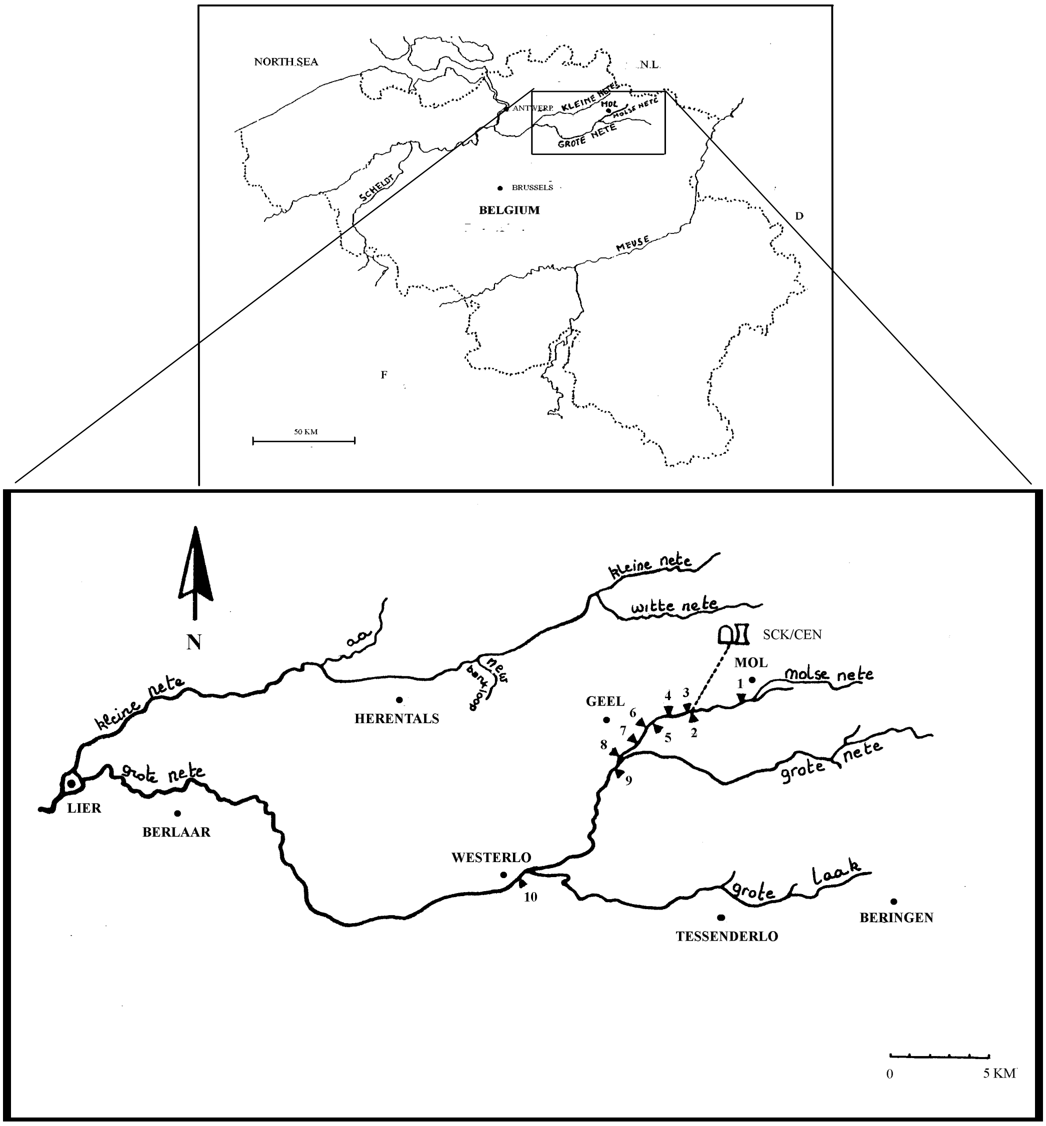

__Figure 1:__ Localisation of the river Molse Nete

SCK•CEN carried out extensive monitoring campaigns at the Molse Nete for almost every year until 1989; the year in which the licence to release low-level liquid radioactive waste into the river was transferred to Belgoprocess.

3. General site characterisation

3.1 Description of the area.

3.1.1 Geography and topography

The section between the discharge point and the confluence with the Grote Nete, 6.8 km further downstream is, from radiological viewpoint, the most important part of the Molse Nete. At this site, the Molse Nete is about 7 to 10 m wide (5 m averaged over depth). The sampling points on the Molse Nete are given (Table 1 and Figure 1), where samples of river water, water-suspended matter and sediment were regularly taken.

Table 1: *Localisation of the sampling points*

Sampling point	*Distance to the discharge point (km)*	*Localisation*
		Molse Nete
1	- 2.2	first bend downstream bridge
2	0	discharge point
3	+ 0.05	first bend downstream discharge point
4	+ 0.9	first bend downstream bridge
5	+ 2.5	first bend downstream bridge
6	+ 3.7	depositing zone upstream watermill
7	+ 5.3	first bend downstream bridge
8	+ 6.4	bend upstream confluence with Grote Nete
	+ 6.8	**Grote Nete**
9	+ 7.0	first bend downstream confluence
10	+ 18.5	500 m downstream confluence with Grote Laak (Westerlo)

The Molse Nete is located in the northern part of Belgium, approximately 50 km to the east of Antwerp and 75 km to the north-east of Brussels. It is a small river flowing from north-east to south-west through the Campines, a region that is characterised by a predominantly sandy soil layer. The topography of the site is flat, having an evelation between 20 to 25 m above sea level. During the Quarternary, the marine transgressions were far more limited than during the Tertiary. Generally speaking, it can be said that since the Holocene (about 10 500 years ago), the present relief of the site, and its situation in relation to the sea, have not changed.

The average slope of the Molse Nete is about $0.4^{0}/_{00}$. The profile of the slope in the sampling area is given in Figure 2. There are no locks in the Molse Nete, but there is a water mill at 3.7 km downstream the discharge point, causing some discontinuity in the water movement. At 1 km downstream the water mill, the slope of the river is zero. However, the water will not stagnate in this zone due to the water fall caused by the water mill.

Land-use in the Nete basin is as follows: 75% is arable land, with large parts not used any longer, 15% is urban area and 10% is woodland. The area upstream the water mill is mainly pasture on the south bank with a few ponds on the north bank. Downstream the water mill, the ground is covered with undergrowth, less pasture and more wetlands are found.

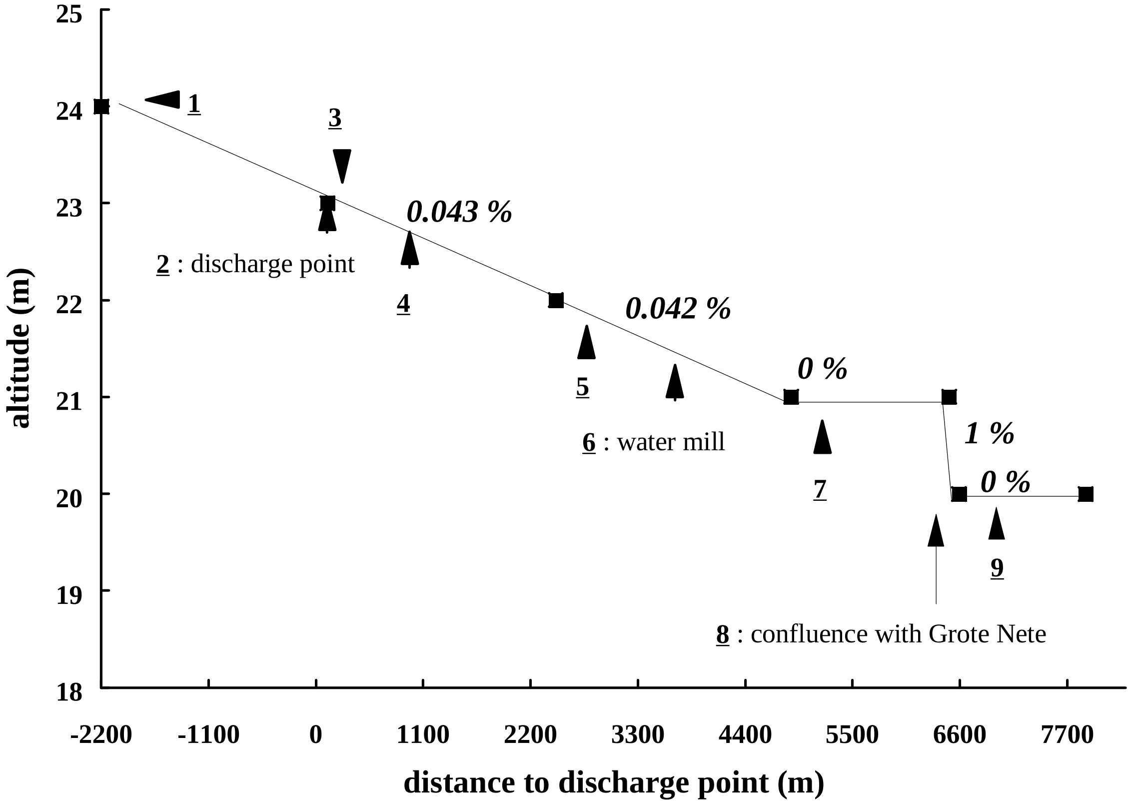

Figure 2: *Profile of the slope of the Molse Nete river in sampling area (Metayer-Piret et al., '78)*

3.1.2 Geology and hydrogeology

In Figure 3, the geological profile nearby the Molse Nete is given. The upper sand layer (Quarternary, Pleistocene) consist of mainly fine to medium fine, locally coarse sands with clay lenses forming sometimes a clay layer and has a variable thickness (range : 2 to 10 m). Below the Quarternary deposit, there is the Kasterlee formation (Tertiary, Mio-Pliocene), which is normally a homogeneous fine sand (mode: 150 µm) layer, micaceous and slightly glauconiferous, with lenses of micaceous clay. At the base, small flint pebbles can be locally found. Between the discharge point and the confluence with the Grote Nete, the Kasterlee formation is 10 to 15 m thick.

The Kasterlee formation is lying upon the Diest formation (Tertiary, Miocene), which is approximately 120 m thick at the Molse Nete site. It consists of locally clayey, glauconiferous, mostly heterogeneous coarse-grained sands. Locally, thin layers of vivianite, siderite and limonite appear. Often, sandstone layers are present. At its base, the Diest formation includes the Dessel sands. These sands are a very homogeneous facies, consisting of calcareous fine sands, micaceous and glauconiferous and are nearly 20 m thick.

The Berchem formation (Tertiary, Miocene) underlying the Diest formation is a blackish, fine-to-medium, often slightly clayey, very glauconiferous sand. It is rich in shells and has, at the site, a thickness of about 25 m. Directly under the Berchem formation lies the Voort formation, a 10 m thick dark, green glauconiferous, fossiliferous fine and rather clayey sand layer.

The most important clay formation is the Boom Clay, which reaches a thickness of about 100 m at a depth of 170 m below ground level in Mol. It is a detrital, fully marine deposit. It contains illite (20 - 30%), smectite (10 - 20%), illite-smectite random interlayers (5 - 10 %), kaolinite (20 - 30%) and some minor chlorite or degraded chlorite (5 - 10%). Quartz and feldspar mainly represent the sand-sized grain. Authigenic glauconite occurs especially in the most silty beds. Pyrite, and occasionally marcasite, occurs in different forms. Typical carbonate concretions of calcite and siderite are concentrated in layers which evolve into septaria.

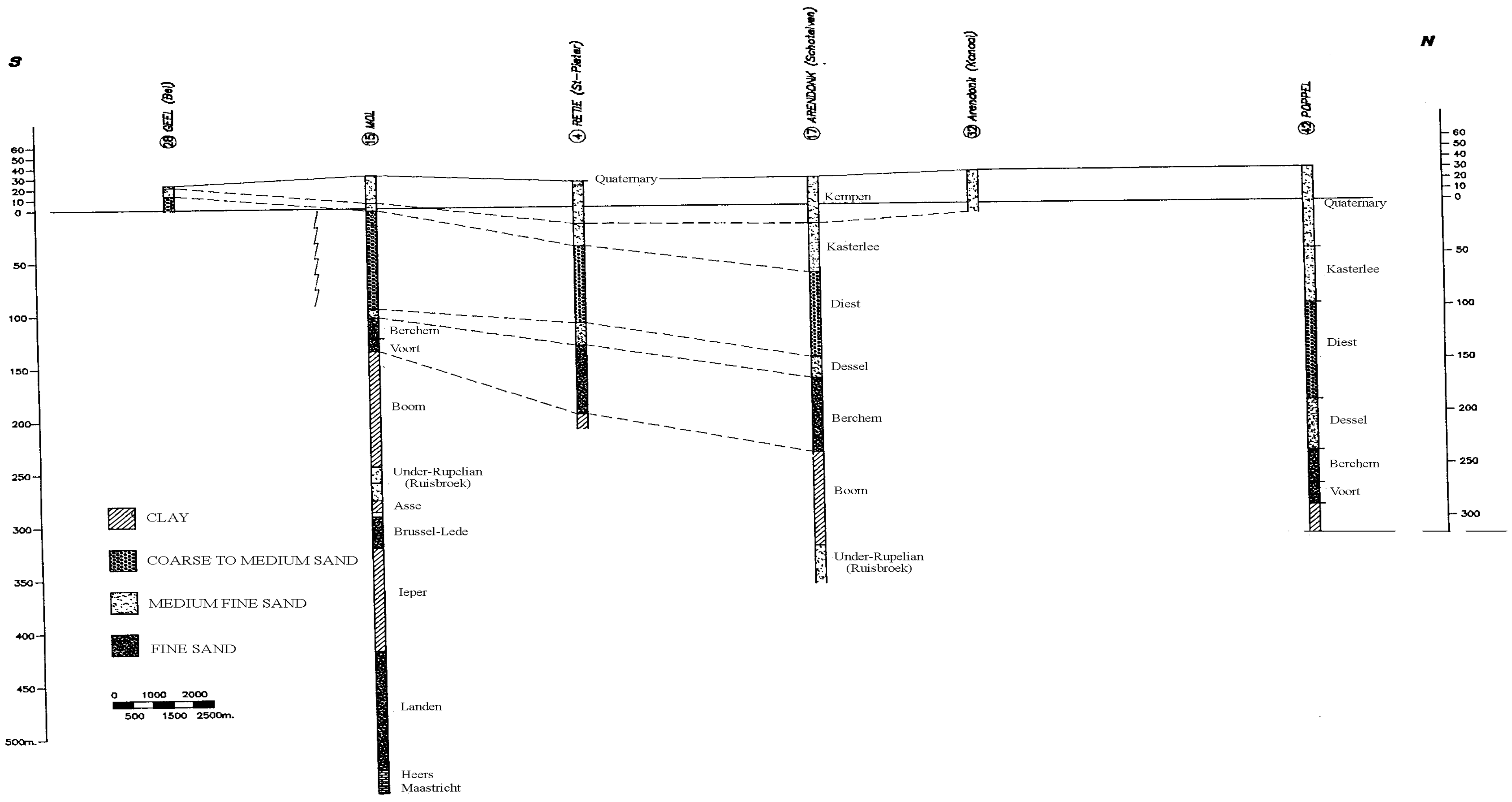

Figure 3: *S-N geological profile (C) from the borehole information of the SCK•CEN piezometer network (preliminary interpretation) (Wemaere et al., 1995)*

The regional hydrogeological pattern of the Antwerp-Campines region is shown in Figure 4. Three aquifers need to be considered: a near surface one located in the Quaternary deposits and isolated from the underlying formations by its clay lenses, a deeper one located in the Kasterlee formation and a third one located between the Kasterlee formation and the Boom Clay. The first aquifer lies one to two metres beneath ground level and is only extended in the northern part of the Campines. The second aquifer is delimited by the clay lenses or layer in the lower part of the Kasterlee formation. These two aquifers are not considered to be an important potential source for human water consumption. The water is generally not drinkable, the Kasterlee aquifer has too high a salt content and moreover, due to human and agricultural activities both aquifers are, at times, highly bacteriologically polluted. This water can only be used for watering cattle. The third aquifer gathers in the sand formations of Diest, Berchem and Voort, mainly represented by the sands of Diest and is therefore called the Miocene or Diestian aquifer. This aquifer is affected by an important water exploitation. In general, the iron contents of water from this aquifer is high and needs a deionization treatment before being suitable for human use. The permeability for the Kasterlee formation was found to be 1E-06 to 4E-08 m s^{-1} and, for the Diestian formation, 3.5E-05 m s^{-1}. The seasonal fluctuations of the water level of the Diestian aquifer rarely exceed one metre between the dry and the wet season of the year.

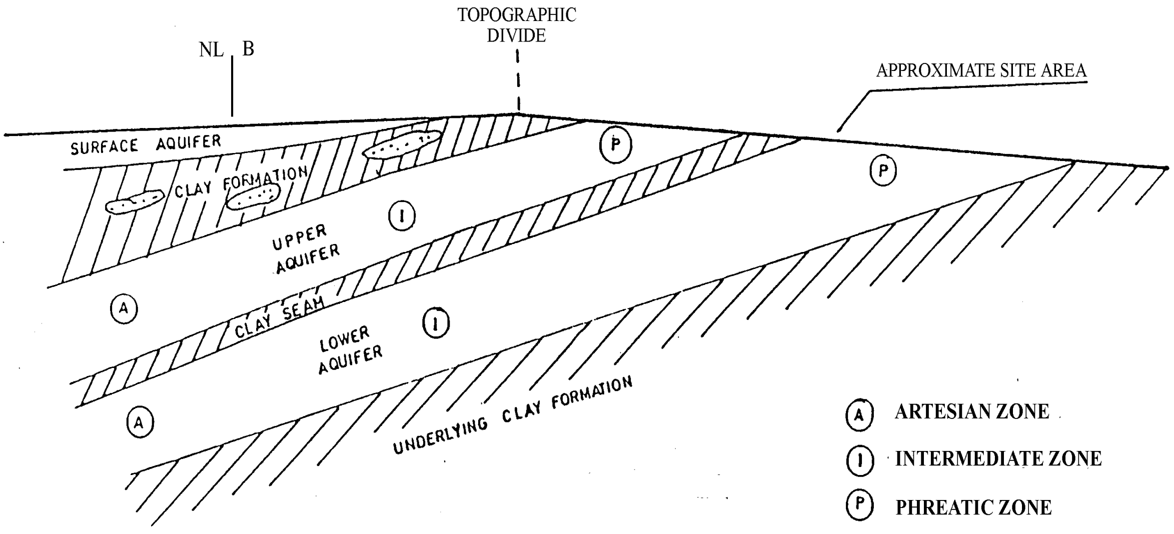

Figure 4: *Regional hydrogeological pattern of the Antwerp-Campines region*

3.1.3 Pedology

Three different types of mineral soils can be found in the area surrounding the Molse Nete, namely sand soils (Zcm, Zbm, Zdm, Zdg, Zdc, Zeg, Zcf, Zbg, Zbf, Zcg and Zep), loamy sand (Seg, Sfd and Sep) and light sandy loam soils (Pfp and Pep). The categorisation by texture is given in Table 2 and in Figure 5, the soil map of the area surrounding the Molse Nete is visualised.

The majority of the soils within a distance of 1 km from the Molse Nete are humid soils and have a peaty substrate starting at small or moderate depth. Also sandy soils with a iron B horizon are found. At the Molse Nete river study site (i.e. the area between the discharge point and the confluence with the Grote Nete) the following soil types occur :

- Moderately dry sandy soils with a 60 to 90 cm thick anthropogenic humic A horizon (Zcm). These soils are suitable for horticultural or agricultural purposes and as pasture.
- Humid soils on loamy sand (Sep). Water management is necessary to make these waterlogged soils suitable for horticultural or agricultural purposes and as pasture.
- Very humid soils on light loamy sand (vPfp) or on loamy sand (vSfp) with a peaty substrate starting at 20 to 125 cm depth. These soils are regularly flooded during winter. In summer, the water level drops to 40 - 80 cm beneath ground level. These soils , even drained, cannot be used for horticultural or agricultural purposes. They are only suitable as grazingland, meadowland or for growing certain types of tree such as poplars or willows.

***Table 2**: Texture classification*

Soil type	% sand (50 µm - 2 mm)	% loam (2-50 µm)	% clay (< 2 µm)
sand	83 - 100	≤ 17	≤ 8
loamy sand	68 - 91	≤ 32	≤ 17
light sandy loam	50 - 68	20 - 50	≤ 12

Legend

Sandy soils

Zbf	dry sandy soils with a slightly distinct B humic or/and iron horizon
Zdc	moderate humid sandy soils with a B horizon of crumbled texture
Zbg	dry sandy soils with a distinct B humic or/and iron horizon
Zcg	moderate sec sandy soils with a distinct B humic or/and iron horizon
Zdg	moderate humid sandy soils with a distinct B humic or/and iron horizon
Zeg	humid sandy soils with a distinct B humus or/and iron horizon
Zbm	dry sandy soils with a deep anthropogenic humic A horizon
Zcm	moderate dry sandy soils with a deep anthropogenic humic A horizon
Zdm	moderate humid sandy soils with a deep anthropogenic humic A horizon
Zep	humid soils on sand

Loamy sand soils

Sdc	moderate humid loamy sand soils with a B horizon of crumbled texture
Seg	humid loamy sand soils with a distinct humic and/or iron B horizon
Sep	humic soils on loamy sand

Light sandy loam soils

Pep	humic soils on light sandy loam
Pfp	very humic soils on light sandy loam

Substrates

VVV	peaty substrate starting at low or moderate depth

Not differentiate terrains

V	soils on peaty materials
〰	dunes

Phases and variants

⁺⁺	iron-rich surface ground
⁚	becomes more light or coarse with depth
●	thick humic surface ground

Artificial soils

▨	raised terrains
▩	lowered terrains
▤	grooves

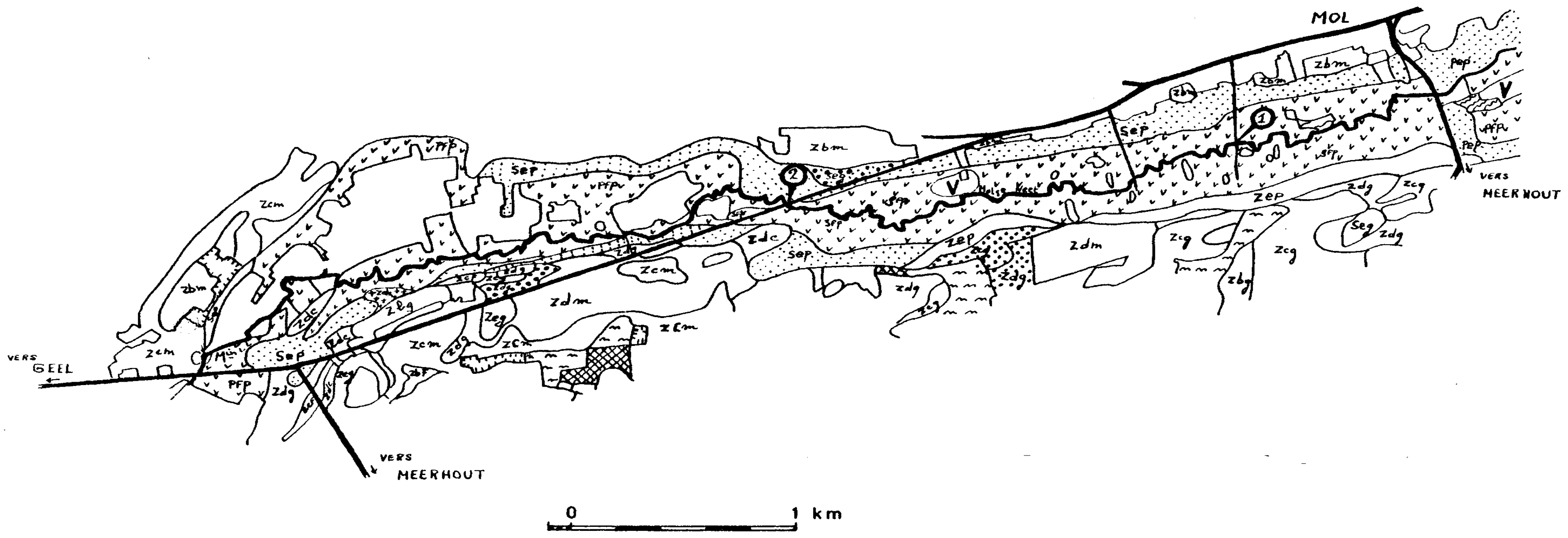

Figure 5: *Pedological map of the river Molse Nete (Bodemkaart van België, Meerhout 46W, 1969)*

3.1.4 Meteorology

The site climate is temperate with a slight maritime influence. The meteorological characteristics originate from the SCK•CEN and are summarised in following tables. For temperatures (Table 3) and relative humidity (Table 4), verified data over 28 consecutive years are available.

Concerning the wind (Table 5), the distribution of the wind speeds (u) is indicated over several categories (measured over 20 years at 24 m height):

u < 1.5 m.s^{-1} : 5.5 %
1.5 m.s^{-1} ≤ u < 3.5 m.s^{-1} : 53 %
3.5 m.s^{-1} ≤ u < 6.5 m.s^{-1} : 37 %
6.5 m.s^{-1} ≤ u < 11.5 m.s^{-1} : 3.9 %
11.5 m.s^{-1} ≤ u 0.02 %

Precipitation rates and duration over 16 years (Table 6) are also given.
It is shown that the mean annual temperature is 9.7°C and the monthly averages vary from 4.6 to 22 °C for the maximum and from -0.5 to 12.4°C for the minimum. Precipitation averages 757 mm annually and ranges between absolute extremes of 527 and 996 mm. Winds blow most frequently from 200° to 250°, corresponding with a wind direction from south-west to north-east. The average wind speed, at 24 m, is 3.93 m s^{-1} and the atmospheric pressure varies between 950 and 1050 mbar.

Table 3: *Mean, maximum and minimum day temperatures during the period 1956-1983*

Month	*Average values of day temperatures (°C)*			*Highest day*	*Lowest day*
	Mean	*maximum*	*minimum*	*maximum*	*minimum*
January	2.3	4.6	-0.1	13.8	-19.0
February	2.6	5.7	-0.5	18.4	-19.0
March	5.6	9.3	2.0	23.0	-15.1
April	8.4	12.8	3.9	28.5	-4.7
May	12.8	17.4	7.7	30.0	-2.2
June	15.8	20.6	10.5	33.5	-0.4
July	17.3	22.0	12.4	36.2	3.1
August	16.7	21.5	12.0	34.6	2.8
September	14.5	19.0	9.9	31.2	-0.3
October	10.4	14.4	6.7	27.0	-2.4
November	6.0	8.7	3.2	19.4	-6.8
December	3.1	5.3	0.7	15.5	-14.9
Year	9.7	13.5	5.8	36.2	-19.0

Table 4: *Relative humidity (%) during the period 1956-1983*

Relative humidity	*Frequency (%)*		
	Mean	*Minimum*	*Maximum*
> 90	44.2	26.3	57.0
80-89	21.9	13.3	38.1
70-79	13.6	10.1	18.7
60-69	9.3	7.3	12.8
50-59	6.1	4.3	8.2
40-49	3.3	1.5	5.9
30-39	1.2	0.3	3.4
20-29	0.4	<0.1	2.4
<20	<0.1	<0.1	0.4

Table 5: *Wind data at a level of 24 m, during period 1964-1983 (WR = wind direction (180° means coming from the west), N = number of (hour) measurements, $^{0}/_{00}$ = frequency per 1000, u = mean wind velocity (m/s) per wind direction area or independent))*

WR	*u<1.5*		*1.5<u<3.5*		*3.5<u<6.5*		*6.5<u<11.5*		*11.5≤u*		*sum wind velocities*		
	N	$^{0}/_{00}$	*N*	$^{0}/_{00}$	*N*	$^{0}/_{00}$	*N*	$^{0}/_{00}$	*N*	$^{0}/_{00}$	*N*	$^{0}/_{00}$	*u*
10	155	1.15	1544	11.42	452	3.34	5	0.04			2156	15.94	2.71
20	177	1.31	2023	14.96	733	5.42	13	0.10			2946	21.79	2.87
30	184	1.36	1990	14.72	892	6.60	16	0.12			3082	22.79	2.99
40	176	1.30	1421	10.51	819	6.06	26	0.19			2442	18.06	3.08
50	157	1.16	1291	9.55	880	6.51	34	0.25			2362	17.47	3.25
60	166	1.23	1782	13.18	1911	14.13	129	0.95			3988	29.50	3.60
70	142	1.05	1723	12.74	2290	16.94	166	1.23			4321	31.95	3.73
80	129	0.95	1305	9.65	1182	8.74	63	0.47			2679	19.81	3.46
90	156	1.15	1819	13.45	1545	11.43	87	0.64			3607	26.68	3.44
100	132	0.98	1578	11.67	1299	9.61	88	0.65			3097	22.91	3.53
110	172	1.27	1325	9.80	653	4.83	31	0.23			2181	16.13	3.00
120	175	1.29	1460	10.80	424	3.14	19	0.14			2078	15.37	2.76
130	180	1.33	1377	10.18	205	1.52	3	0.02			1765	13.05	2.50
140	178	1.32	1382	10.22	267	1.97	1	0.01			1828	13.52	2.52
150	193	1.43	1616	11.95	430	3.18	7	0.05			2246	16.61	2.69
160	171	1.26	2010	14.87	628	4.64	33	0.24			2842	21.02	2.90
170	153	1.13	2529	18.70	1106	8.18	64	0.47			3852	28.49	3.12
180	187	1.38	3119	23.07	1624	12.01	148	1.09			5078	37.56	3.30
190	176	1.30	2825	20.89	1999	14.78	222	1.64	1	0.01	5223	38.63	3.52
200	164	1.21	3024	22.37	2731	20.20	378	2.80	2	0.01	6299	46.59	3.73
210	190	1.41	3253	24.06	3219	23.81	528	3.91	4	0.03	7149	53.21	3.86
220	190	1.41	3272	24.20	3989	25.67	503	3.72	1	0.01	7437	55.00	3.86
230	172	1.27	3188	23.58	4236	29.50	551	4.08	6	0.04	7906	58.47	3.97
240	189	1.40	3195	23.63	2957	31.33	604	4.47	7	0.05	8231	60.88	4.00
250	166	1.23	2646	19.57	1742	21.87	495	3.66	7	0.05	6271	46.38	3.90
260	133	0.98	2137	15.81	1296	12.88	282	2.09	1	0.01	4295	31.76	3.63
270	185	1.37	1924	14.23	1151	9.59	232	1.72	3	0.02	3640	26.92	3.46
280	157	1.16	1905	14.09	1008	8.51	158	1.17			3371	24.93	3.36
290	186	1.38	1808	13.37	1010	7.46	114	0.84			3116	23.05	3.29
300	168	1.24	1653	12.23		7.47	97	0.72			2928	21.66	3.28
310	162	1.20	1413	10.45	971	7.18	77	0.57			2623	19.40	3.32
320	124	0.92	1305	9.65	818	6.05	49	0.36			2296	16.98	3.21
330	158	1.17	1196	8.85	693	5.13	41	0.30			2088	15.44	3.14
340	155	1.15	1330	9.084	609	4.50	50	0.37			2144	15.86	3.01
350	153	1.13	1391	10.29	638	4.72	17	0.13			2199	16.26	2.89
360	180	1.33	1616	11.95	569	4.21	6	0.04			2371	17.54	2.76
370	1395	10.32	1555	11.50	75	0.55	2	0.01			3027	22.39	1.61
total	7386	54.63	71930	532.0	50522	373.7	5339	39.49			135209	1000	3.40

Table 6: *Precipitation data during the period 1968-1983*

Month	*Precipitation amounts (mm)*			*Precipitation duration (h)*		
	Mean	*Minimum*	*Maximum*	*Mean*	*Minimum*	*Maximum*
January	60	24	116	32	13	49
February	51	13	113	28	11	58
March	67	23	129	35	11	64
April	47	8	99	21	2	43
May	64	21	129	25	11	68
June	73	17	125	26	5	60
July	71	24	160	21	4	49
August	60	14	136	18	4	40
September	56	8	130	20	2	69
October	62	7	153	26	3	62
November	78	36	171	36	16	63
December	68	16	143	32	5	65
Year	757	527	996	318	206	470

3.1.5 Hydrology

The river Molse Nete rises in Lommel, a city in the province of Limburg and has a mean water velocity between 0.24 and 0.47 m s^{-1}. The average depth of the Molse Nete amounts to 0.5 m, its average width is 5 m. In Table 7, the average annual flow rates measured at Mol (sampling point 1, Figure 1) are given. These values are the means of limnological measurements carried out in the period 1968 to 1981. Seasonal fluctuations of the water flow have been observed; during the wet season the flow rate can rise to 2.9 m^3 s^{-1}, while during the dry season a minimum of 0.28 m^3 s^{-1}has been measured.

The Grote Nete flows, through the intermediary of the river Rupel into the Scheldt upstream from Antwerp (Figure 1). The maximum amplitude of the spring-tides in Antwerp reaches 5.6 m. If strong tides happen to coincide with strong winds blowing from the sea inland, an additional 1 m difference can be recorded in Antwerp. Thus, a maximum amplitude of 6.6 m can be reached. In normal conditions, the influence of the tides is felt up to Lier, the city where the Kleine Nete flows into the Grote Nete. Under extreme conditions, they may reach the confluence with the Molse Nete.

The Molse Nete drains approximately 62 km², which is about 3% of the Nete hydrographic basin. The water balance elements of the river Grote Nete, into which the Molse Nete flows, have been estimated over 6 consecutive years by Bladt *et al.* (1977). The results are:

Total precipitation	P = 725 mm a^{-1}
Evapotranspiration	ET = 450 mm a^{-1}
Infiltration	I = 230 mm a^{-1}
Surface run-off	Qsr = 60 mm a^{-1}

Note that P- ET = I + Qsr and that the total discharge into the river consists of the surface run-off, Qsr and the groundwater discharge Qr, which amounts to 320 mm a^{-1}.
The mass balance yields an error of about 8%.

This water balance gives an indication of the water balance of the Molse Nete.

Table 7: *Average monthly flow rate of the Molse Nete (1968-1981). The standard errors are given in parentheses.*

Month	*Flow rate ($m^3 h^{-1}$)*
January	3525 (717)
February	3773 (961)
March	3591 (912)
April	3153 (682)
May	2850 (809)
June	2438 (1146)
July	1925 (695)
August	2213 (761)
September	2724 (976)
October	2700 (869)
November	3226 (743)
December	3654 (1091)

3.1.6 Population

3.1.6.1 Demography

The area along the Molse Nete site is not densely inhabited. At this time, there are only a few houses. The population density within a circle of 10 km around the discharge point is about 300 people km^{-2}. The nearest larger community downstream of the discharge point of the radioactive effluents is the centre of Geel, which has a few ten thousand inhabitants, at 1 km (shortest distance) from the river.

3.1.6.2 Habits and activities

Fishing or swimming in the Molse Nete are not common, although the occurrence of these and other recreational activities (e.g. go out boating) cannot be totally excluded. Fishing can take place in the ponds nearby, which receive their water mainly from the aquifer, and sometimes fishermen collect larvae from the river.

Periodic floods are observed in some parts of the Molse Nete. Therefore, between once every year and once every five years, the river is dredged. The sediment, deposited on the banks, is sometimes used to fertilise the pasture or vegetable gardens. A typical application rate for pasture or agricultural fields amounts to 8 and 16 kg m^{-2}, respectively, every five year. (see further section 3.3.2.3).

The Molse Nete is situated in an agricultural region. Also, its water can be used for agricultural purposes (irrigation, watering of the cattle). Typical irrigation rates are of the order of 1 L m^{-2} day^{-1} during 100 days a^{-1}, typical water intake rates by the cattle (per cow) 65 L day^{-1}.

The region is characterised by an important dairy farming and an extensive woodland.; about 35 % of the land is used for feed or food crops, 40% is pasture, 10% is woodland, less than 1% is horticulture and 12% are either ponds or lie fallow.

Concerning the average dietary habits of the population, the differences between the various regions are only minor. Consumption rates for Belgium are given in Table 8.

The contribution of the natural ecosystem to the diet of the population is negligible. Blackberries are native plants which may occur at the site and may be eaten occasionally. Some small game, mostly rabbits, may be hunted and eaten.

Concerning the intake by cattle (cows), following rates have been estimated:

pasture:	14 kg DW d^{-1}
soil:	4% pasture
water:	65 L d^{-1}

Table 8: *Consumption values (adults)*

drinking water	0.4 m^3 a^{-1}
freshwater fish	5 kg a^{-1}
grain	72 kg FW a^{-1}
leafy vegetables	56 kg FW a^{-1}
tubers (potatoes)	94 kg FW a^{-1}
root crops	70 kg FW a^{-1}
milk	120 L a^{-1}
meat	73 kg a^{-1}

3.2 Physico-chemical characteristics

3.2.1 The water column

Analysis of the water samples from several locations along the river Molse Nete did not reveal large changes. Therefore, the water can be regarded as homogeneous throughout the course of the river; at least inside the defined site area. This is certainly due to the continuous flow in the river, without larger basins or tributaries with a differing composition, leading to a good mixing of the water body.The temperature of the Molse Nete water will be naturally a few degrees higher during summer than during winter time. The seasonal variation of temperature and pH is shown in Figure 6.

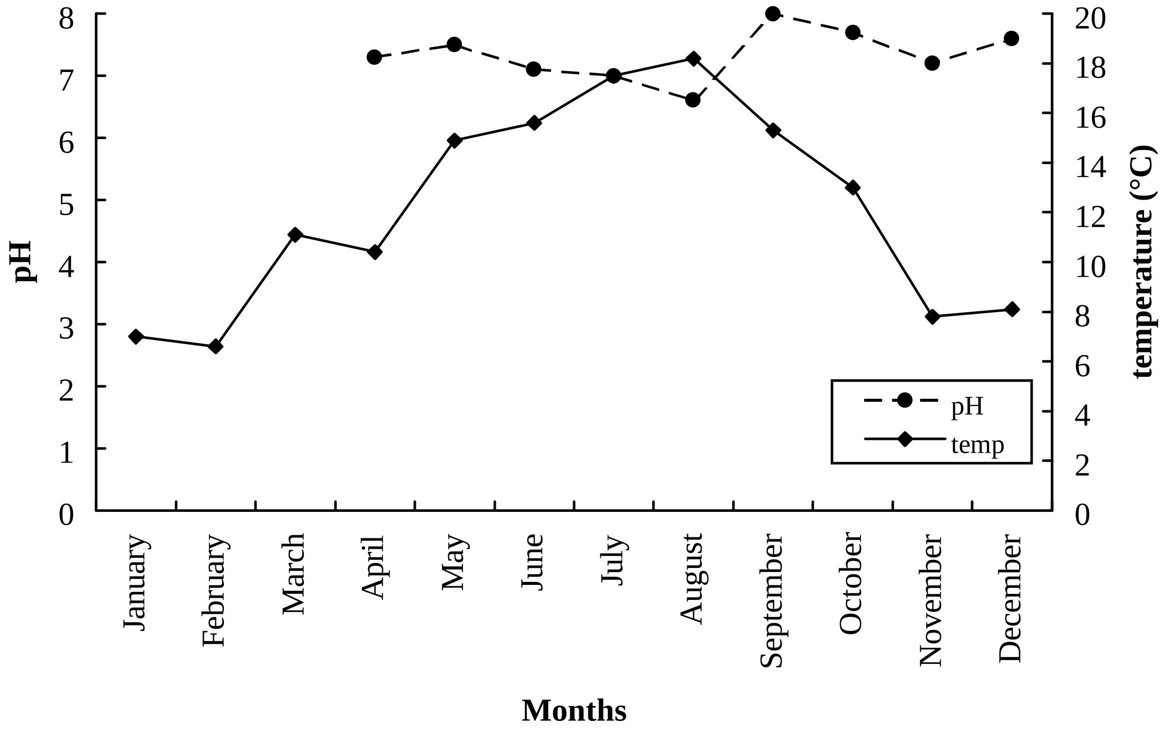

Figure 6: *Variation of pH and temperature measured at the discharge point during the year 1977.*

The results from various sampling campaigns in the past are summarized in Table 9. Different methods were used to sample and analyse the various ions. The zinc, potassium, sodium, calcium, magnesium, iron and aluminium concentrations were measured by atomic absorption spectrometry, PO_4 by spectrophotometry, Cl by titration. Except for the data of 1978(b), each parameter value is the mean of at least three independent measurements. In August 1996, additional measurements were performed as part of the RESTRAT project to close gaps in the previous investigations, and to verify the accuracy of those measurements. The new results are also listed in Table 9. Mean values and standard deviations were calculated giving equal weights to all listed values. Exceptions are zinc, aluminium and iron, where only the values from 1996 were taken into consideration, see below for an explanation.

***Table 9**: Summary of analysis of river water from the Molse Nete*

Year	1977 mol L^{-1}	1978 (a) mol L^{-1}	1978 (b) mol L^{-1}	1979 mol L^{-1}	1980 mol L^{-1}	1996* mol L^{-1}	1996** mol L^{-1}	Mean mol L^{-1}	Std.Dev. mol L^{-1}
PO43-	4.37E-06	5.69E-06		2.11E-06				4.05E-06	1.81E-06
NO3-	1.60E-04	1.50E-04	7.42E-05	2.31E-04		3.29E-04	3.79E-04	2.20E-04	1.16E-04
NO2-	3.70E-05	6.74E-06	2.61E-06	1.80E-06	2.61E-06			1.01E-05	1.51E-05
NH4+	2.38E-05	4.88E-06	1.55E-06	1.50E-06	1.11E-06			6.57E-06	9.77E-06
SO42-	9.47E-04	9.37E-04	9.06E-04	7.82E-04	7.60E-04	7.78E-04	9.90E-04	8.71E-04	9.53E-05
HCO3-	1.25E-03		1.29E-03			1.56E-03	1.61E-03	1.43E-03	1.82E-04
Cl-	1.54E-03	9.59E-04	1.13E-03	8.46E-04	1.02E-03	1.46E-03	1.49E-03	1.21E-03	2.86E-04
Si			5.84E-05			1.84E-04	1.87E-04	1.43E-04	7.36E-05
K+	2.35E-04	1.76E-04	2.48E-04	2.02E-04	1.46E-04	2.53E-04	3.02E-04	2.23E-04	5.24E-05
Na+	1.39E-03	1.35E-03	1.22E-03	9.13E-04	1.30E-03	1.77E-03	1.82E-03	1.40E-03	3.15E-04
Ca2+	1.41E-03	1.25E-03	1.05E-03	1.07E-03	1.05E-03	1.17E-03	1.27E-03	1.18E-03	1.36E-04
Mg2+	2.47E-04	2.26E-04	3.37E-04	2.10E-04	1.97E-04	2.80E-04	3.86E-04	2.69E-04	7.01E-05
Fe		1.70E-05	2.69E-06	2.95E-05		8.95E-07	8.95E-07	1.02E-05	1.27E-05
Al3+	1.59E-06	2.59E-06	9.64E-06	3.15E-06		8.75E-08	8.01E-08	2.86E-06	3.55E-06
Zn2+	6.35E-06	5.20E-06		3.90E-06		8.32E-07	3.30E-07	3.32E-06	2.65E-06
U						2.48E-09	6.26E-09	4.37E-09	2.67E-09
Pb2+	4.83E-09					2.41E-10	2.41E-10	1.77E-09	2.65E-09
Ni2+						1.46E-07	2.10E-07	1.78E-07	4.52E-08
Mn2+						2.26E-07	2.39E-06	1.31E-06	1.53E-06
As						4.55E-08	4.27E-08	4.41E-08	1.98E-09
Cd2+	1.25E-08							1.25E-08	
pH	6.6 - 8.0	7.2	6.7	7.0 - 7.2		7.2	6.9 - 7.2	7.11	
Conduct. (µS cm^{-1}	311 (25)	371 (7)	n.d.	371 (35)	385 (18)				

* 3.7 km downstream from discharge pipe (filtered samples)

** 0.7 km downstream from discharge pipe (filtered samples)

A more detailed overview about the investigations, performed in 1996 with samples from two different points, are given below. Samples were taken by SCK•CEN and shipped to FZ Rossendorf, were the analyses were done. *In-situ* determinations in the river yielded a temperature of 15 °C at both points, the pH was also determined in-situ. Table 10 summarizes the analytical results for the location S1, 3.7 km downstream from the discharge pipe, whereas Table 11 is related to the point S2, 0.7 km downstream from the discharge pipe. Sampling was performed on August 7, 1996. The samples were analysed twice, first without further treatment (columns A), and second after filtering (columns B, done in three steps for 450, 100, and 15 nm particle size). Columns labelled with MW give the molecular weight of the atoms or ionic units from column one, n.d. stands for “not determined”. Upper limit values denote, that the analytical value was below the respective detection limit. The methods given in the last column are: IC = ion chromatography, ICP-MS = inductively coupled plasma - mass spectrometry, F-AAS = flame - atom absorption spectrometry.

A critical review of the data based on Table 10 shows, that for most of the major anions and cations the analytical values are in good agreement over the whole time range from 1977 to 1996.

Table 10: *Analysis of river water from Molse Nete, 3.7 km downstream from discharge pipe*(1)

	A µg L^{-1}	B µg L^{-1}	MW g mol^{-1}	A mol L^{-1}	B mol L^{-1}	Method
F-	n.d.	n.d.	18.9984			
PO43-	< 2000	< 2000	94.971	< 2.105E-05	< 2.105E-05	IC
NO3-	21800	23500	62.005	3,516E-04	3,790E-04	IC
NO2-	< 1000	< 1000	46.0055	< 2.174E-05	< 2.174E-05	IC
NH4+	n.d.	n.d.	18.0383			
SO42-	75100	95100	96.058	7,818E-04	9,900E-04	IC
HCO3-	90700	98400	61.017	1,486E-03	1,613E-03	IC
Cl-	51800	52900	35.453	1,461E-03	1,492E-03	IC
Si	5240	5260	28.086	1,866E-04	1,873E-04	ICP-MS
K+	10200	11800	39.098	2,609E-04	3,018E-04	F-AAS
Na+	39600	41900	22.99	1,722E-03	1,823E-03	F-AAS
Ca2+	48300	50800	40.08	1,205E-03	1,267E-03	ICP-MS
Mg2+	6690	9390	24.305	2,753E-04	3,863E-04	F-AAS
Fe	260	50	55.847	4,656E-06	8,953E-07	F-AAS
Al3+	14.6	2.16	26.9815	5,411E-07	8,005E-08	ICP-MS
Zn2+	102	21.6	65.38	1,560E-06	3,304E-07	ICP-MS
U	0.3	1.49	238.03	1,260E-09	6,260E-09	ICP-MS
Pb2+	1.04	0.05	207.2	5,019E-09	2,413E-10	ICP-MS
Ni2+	n.d.	12.3	58.7		2,095E-07	ICP-MS
Mn2+	13.6	131.3	54.938	2,476E-07	2,390E-06	ICP-MS
Cd2+	n.d.	n.d.	112.41			ICP-MS
As	n.d.	3.2	74.922		4,271E-08	ICP-MS

(1) The pH value was determined to be 7.2 *in-situ*, 6.93 before filtration, and 7.65 after filtration. Suspended material was determined to be 15.94 mg g^{-1}. Radium and thorium were analysed with g - spectrometry, giving 0.22 Bq kg^{-1} Ra-226 (equals 2.66E-14 mol L^{-1}, with Ra-223 and Ra-224 being negligible) and 0.7 Bq kg^{-1} Th-232 (equals 7.06E-07 mol L^{-1}, determined from equilibrium with Ac-228, other Th-nuclides being negligible).

Remarkable exceptions are the content of zinc, iron and aluminium. Here the older measurements clearly gave much too high concentrations, indicating considerable oversaturation with respect to many minerals. Obviously those samples were not filtered, so the analytical values incorporated fine-disperse and colloidal material. Also, an slight increase of the water quality has occurred over the last decade. The values from filtered samples from 1996 show, that both iron and aluminium are only trace components, thereby not heavily influencing the contaminant speciation. There are no *in-situ* determinations of the redox state available, only some measurements of the oxygen content in the water where the method and measurement conditions were not specified. From these rather uncertain values (in the range between 2.5 and 11.2 mg L^{-1} O_2), and from computations based on concentrations for the redox pairs NO_3^-/NH_4^+ and NO_2^-/NH_4^+, a redox potential between 771 and 872 mV was obtained. This means oxidizing conditions, as to be expected from water of a river with free contact to atmosphere. Moreover, the observed ammonia and nitrate concentrations indicate that the water is slightly polluted. Also the sodium concentration is rather high. The concentration of most ions lies in the common range. The main components are chlorides and (hydrogen) carbonates of sodium and calcium, contributing to an ionic strength of about 6.5×10^{-5} mol L^{-1}. Moreover, the silica content seems to be determined by the dissolution of quartz, as could be concluded from speciation modelling. As can be seen in Table 11 the water maintains a neutral pH, varying between 6.7 and 7.5.

Table 11: *Analysis of river water from Molse Nete, 0.7 km downstream from discharge pipe*(2)

	A µg L^{-1}	B µg L^{-1}	MW g mol^{-1}	A mol / L	B mol / L	Method
F-	n.d.	n.d.	18,9984			
PO43-	< 2000	< 2000	94,971	< 2.105E-05	< 2.105E-05	IC
NO3-	20300	20400	62,005	3,274E-04	3,290E-04	IC
NO2-	< 1000	< 1000	46,0055	< 2.174E-05	< 2.174E-05	IC
NH4+	n.d.	n.d.	18,0383			
SO42-	74300	74700	96,058	7,735E-04	7,777E-04	IC
HCO3-	92900	95200	61,017	1,523E-03	1,560E-03	IC
Cl-	51200	51800	35,453	1,444E-03	1,461E-03	IC
Si	5210	5180	28,086	1,855E-04	1,844E-04	ICP-MS
K+	9710	9910	39,098	2,484E-04	2,535E-04	F-AAS
Na+	37200	40700	22,99	1,618E-03	1,770E-03	F-AAS
Ca2+	43700	47000	40,08	1,090E-03	1,173E-03	ICP-MS
Mg2+	6030	6810	24,305	2,481E-04	2,802E-04	F-AAS
Fe	200	50	55,847	3,581E-06	8,953E-07	F-AAS
Al3+	12,4	2,36	26,9815	4,596E-07	8,747E-08	ICP-MS
Zn2+	158	54,4	65,38	2,417E-06	8,321E-07	ICP-MS
U	0,3	0,59	238,03	1,260E-09	2,479E-09	ICP-MS
Pb2+	1,89	0,05	207,2	9,122E-09	2,413E-10	ICP-MS
Ni2+	n.d.	8,55	58,7		1,457E-07	ICP-MS
Mn2+	13,3	12,4	54,938	2,421E-07	2,257E-07	ICP-MS
Cd2+	n.d.	n.d.	112,41			ICP-MS
As	n.d.	3,41	74,922		4,551E-08	ICP-MS

(2) The pH value was determined to be 6.9 - 7.2 *in-situ*, 6.95 before filtration, and 8.05 after filtration. Suspended material was determined to be 1.68 mg g^{-1}. Radium and thorium were analysed with g-spectrometry, giving 1.18 Bq kg^{-1} Ra-226 (equals 1.43E-13 mol L^{-1}, with Ra-223 and Ra-224 being negligible) and 0.16 Bq kg^{-1} Th-232 (equals 1.61E-07 mol L^{-1}, determined from equilibrium with Ac-228, other Th-nuclides being negligible).

A seasonal variation is also observed for the solids in suspension; in the summer about 9 mg L^{-1} solids (April to September) are in suspension, in winter (October to March) on an average, 28 mg L^{-1} suspended matter is measured.

3.2.2 Solid phases

The characterization of the relevant solid phases, both in the river bed, and on the soil next to the river, where the dredges are piled, is not as satisfactory as compared to the aqueous phase. Bed sediment analyses were performed on several occasions. They delivered the elemental composition and the size distribution of the bed sediment. But this does, unfortunately, not tell anything about the mineralogy, which eventually is responsible for the interaction with dissolved and suspended matter in the river water. There are no mineralogical investigations for this site available, only rather general descriptions of the geological state. They indicate, that the river sediments mostly consist of quartz sands and clays based on mica, glauconite, and flint. This is in good agreement with our own observations based on X-ray diffraction measurements of samples from the river. These analyses are complicated by a considerable content of organic matter from various origins and in different states of degradation. The soil is based on glauconite, and iron-enriched sandstone.

The bed sediment of the Molse Nete has been sampled on several occasions. Bed sediment sampling campaigns have been performed in 1977, 1978, 1979, 1980, 1983, 1986 and 1991. To sample the bed sediment, a boat-operated coring tube (Kahlsico) was used. Each core had a diameter of 3.8 cm and a height of 40 cm. Physico-chemical characteristics and especially the radioactive contamination have been studied. The physico-chemical characteristics obtained from the campaign organised in 1978 are shown in Table 12.

The chemical composition of the bed sediment shows that it mainly consist of silicates. The cation exchange capacity of the bed sediment is 18 meq $(100\ g)^{-1}$ and can mainly be ascribed to humic sites, since the organic matter content is high (10.5%) and the clay content is rather low (lower than 2%).

The water soluble ions are mainly calcium and sulphates. The solubility of the metal ions clearly increases in acid media. The relatively high zinc, copper and manganese concentrations may be the result of industrial pollution. Under normal conditions, the pH of the sediment is about 5.7.

In 1978, also the granulometry of the sediment has been determined. Two different methods were used to measure the granulometry of the bed sediment (Table 13). The pipette method (method A) makes use of oxidants ($NaOCl + H_2O_2$) to breakdown and determine the granular structure. The particle diameter can also by determined by sieving (method B). The sediment consists mainly of fine sand. About 70% of the particles has a diameter between 50 and 400 µm. The fraction coarse sand (diam.> 1 mm) is very low. Also the fraction clay (<2 µm) is rather low; 0.1% to 2.1% depending on the method used.

Table 12: *Physico-chemical characteristics of the Molse Nete sediment (Van de Voorde, 1968; Metayer-piret et al., Janvier 1979)*

Composition (dw)	77% SiO_2,, 3.7% Fe_2O_3, 2.0% Al_2O_3, 4.3% ZnO, 0.46% MgO, 0.96% K_2O, 0.48% Na_2O, 1.1% CaO
Organic Matter (%)	10.5
Humidity 110°C (%)	3.18
CEC (meq $(100g)^{-1}$) at pH= 7.0	18.2
Base Saturation (%)	61.3
Density	1.8-2.2 *(bulk density estimated to amount to approx. 1.6)
% C	2.89 (+/- 1.82)
Net sedimentation rate	1.8 mg s^{-1} m^{-2}

Ion Concentration (mg $(100g)^{-1}$) (water soluble and as result of pH extraction)

	water soluble	*pH 3.0*	*pH 4.0*	*pH 5.0*	*pH 7.0*	*pH 8.5*
Na	3.7	17.5	13.0	7.0	4.5	4.0
K	3.2	21.2	16.8	16.0	11.0	9.0
Ca	40.0	470.0	402.5	295.0	185.0	110.0
Mg	4.5	22.8	22.8	19.8	17.0	13.8
Mn	0.4	11.3	10.5	5.1	1.8	0.8
Zn	0.6	98.5	79.0	60.0	9.8	5.3
Al	< 0.1	95.0	48.0	10.0	2.0	3.0
Fe	< 0.1	1687.0	1375.0	300.0	1.3	1.2
Cu	1.1	2.8	0.8	0.5	0.4	0.4
SiO_2	< 0.2	8.5	13.0	5.4	0.6	0.4
P	< 0.1	292.5	275.0	47.5	3.0	10.0
Cl	4.8	37.5	20.0	20.0	10.0	8.8
SO_4	95.0	332.5	237.5	222.5	220.5	217.5

Table 13: *Granulometry of the bed sediment obtained by NaOCl + H_2O_2 attack (A) and by sieving (B), measured in 1978 (Metayer-Piret et al., Janvier 1979).*

Size	*Method A*	*Size*	*Method B*
< 2 µm	2.3 %	< 5	0.1 - 0.7 %
2 - 20 µm	3.7 %	5 - 10	0.6 - 2.5 %
20 - 50 µm	3.9 %	10 - 30	2.4 - 6.8 %
50 - 100 µm	12.8%	30 - 75	11 - 21 %
100 - 200 µm	55.4 %	75 - 200	9 - 18 %
200 - 315 µm	10.6 %	200 - 400	56 - 66 %
315 - 630 µm	7.2 %	400 µm - 1 mm	0.1 - 2.0 %
630 µm - 1 mm	3.0 %	1 - 2 mm	0.0 - 0.3 %
> 1 mm	1.1 %	> 2 mm	0.0 %.

3.3 Radiological characteristics[1]

3.3.1 Source term and discharges/effluents

The limit on the discharges of radioactive effluents in the Molse Nete authorised by the license is set on 166 Gbq/month, calculated according to the following ponderation formula (Fieuw *et al.*, 1986):

$$5. (\text{total} - \alpha) + (\text{total} - \beta) + 30. ({}^{90}\text{Sr}) + 3. ({}^{131}\text{I}) + 300. ({}^{226}\text{Ra}) + 0.001. ({}^{3}\text{H})$$

Since July 1986, following the ICRP regulations, the impact of ^{90}Sr has been reduced due to its ponderation coefficient being decreased by a factor of 4.

In Table 14, the discharges of the main radionuclides in the liquid radioactive waste for the period 1955 - 1990 are summarised.

As stated earlier, the annual limit has never been attained. The highest discharges were reached during the period 1971 to 1976 as shown in Figure 7 and amount to 60%. The close-down of the reprocessing plant Eurochemic and the reactor BR3 of the SCK•CEN and the removal of the IRE (Institute for radioactive elements) has led to a significant decrease of subsequent releases.

Nowadays, only 1 to 2.5 % of the authorised limit is discharged, originating mainly from the test reactor BR2 and the radioactive laboratories of SCK and from the waste treatment operations of Belgoprocess. In the future, the amount of radioactive waste released will mainly depend on the waste treatment operations and dismantling activities. In Table 14, it is shown that the ^{3}H releases are at least two orders of magnitude higher than the releases of the other radionuclides. However, its radiotoxicity is low and there is no sign of bioaccumulation in the food chains.

It has been shown that the most important radionuclides discharged into the Molse Nete are ^{60}Co, ^{137}Cs, ^{239}Pu and ^{241}Am. During the period 1961 to 1990, on an average, 130 GBq ^{60}Co, 37 GBq ^{137}Cs, 1.3 GBq ^{239}Pu, 0.68 GBq ^{241}Am were released annually. The radionuclides ^{137}Cs, ^{60}Co, ^{241}Am and Pu, characterised by a high adsorption capacity, tend to accumulate in the soil and sediment and subsequently might lead on the long term to non-negligible doses.

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[1] The information concerning the discharges and contamination of the different environmental compartments (river water, sediment, plants, river banks) is incomplete after 1989. In that year, together with the licence to discharge liquid radioactive waste, also the responsibility for carrying out monitoring campaigns was transferred to Belgoprocess. Since then, almost no complementary data have been made available.

Table 14: *Radionuclide discharges to the river Molse Nete, 1955-1990 (MBq)*

Nuclide	*1955*	*1956*	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*	*1963*	*1964*	*1965*	*1966*
^{3}H	0.00E+00	5.63E+06	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07	2.25E+07
^{60}Co	0.00E+00	4.92E+01	1.98E+02	1.58E+03	1.23E+03	1.96E+03	2.71E+03	3.47E+03	5.83E+03	6.76E+03	1.61E+04	4.85E+04
^{90}Sr	0.00E+00	2.04E+01	8.20E+01	1.01E+02	2.88E+02	1.49E+02	2.03E+02	2.56E+02	4.67E+02	6.38E+02	4.38E+02	1.61E+03
^{131}I	0.00E+00	4.70E+00	1.87E+01	1.22E+02	1.05E+02	1.53E+02	2.12E+02	2.70E+02	4.56E+02	5.33E+02	1.22E+03	3.68E+03
^{134}Cs	0.00E+00	1.82E+00	7.32E+00	5.85E+01	4.55E+01	7.26E+01	1.00E+02	1.28E+02	2.16E+02	2.50E+02	5.96E+02	1.80E+03
^{137}Cs	0.00E+00	1.39E+01	5.59E+01	4.46E+02	3.48E+02	5.54E+02	7.67E+02	9.80E+02	1.65E+03	1.91E+03	4.55E+03	1.37E+04
^{239}Pu	0.00E+00	9.01E-01	3.59E+00	4.57E+00	7.31E-01	5.73E+00	1.64E+01	2.71E+01	1.74E+01	3.17E+01	5.99E+01	1.66E+02
^{241}Am	0.00E+00	4.98E-01	4.98E-01	2.53E+00	4.04E-01	3.17E+00	9.09E+00	1.50E+01	9.63E+00	1.75E+01	3.31E+01	9.21E+01
Nuclide	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*	*1976*	*1977*	*1978*
^{3}H	2.25E+07	5.32E+07	1.04E+08	8.40E+07	8.53E+07	1.21E+08	2.80E+08	9.30E+07	1.94E+07	2.06E+07	2.80E+07	2.76E+07
^{60}Co	7.41E+04	3.12E+04	2.28E+05	4.23E+05	3.46E+05	2.77E+05	3.45E+05	2.80E+05	2.91E+05	2.27E+05	1.84E+05	1.37E+05
^{90}Sr	5.33E+03	2.85E+03	1.03E+04	1.06E+04	9.87E+03	1.23E+04	7.10E+03	1.73E+04	6.90E+03	1.10E+04	3.45E+03	3.88E+03
^{131}I	5.76E+03	4.98E+04	8.33E+03	6.69E+04	4.23E+04	1.15E+04	4.48E+04	3.40E+04	3.79E+04	6.23E+03	1.73E+04	9.99E+03
^{134}Cs	2.74E+03	1.16E+03	8.42E+03	1.57E+04	1.28E+04	1.03E+04	1.28E+04	1.04E+04	1.08E+04	8.75E+03	4.69E+03	3.51E+03
^{137}Cs	2.09E+04	8.83E+03	6.43E+04	1.20E+05	9.77E+04	7.84E+04	9.74E+04	7.91E+04	8.22E+04	6.68E+04	3.10E+04	3.00E+04
^{239}Pu	1.79E+02	7.38E+01	2.80E+02	6.20E+02	3.95E+02	3.90E+02	2.29E+03	4.14E+03	6.76E+03	9.99E+03	6.65E+03	1.46E+03
^{241}Am	9.88E+01	4.08E+01	1.55E+02	3.43E+02	2.18E+02	2.16E+02	1.27E+03	2.29E+03	3.74E+03	5.52E+03	3.09E+03	7.56E+02
Nuclide	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*
^{3}H	1.70E+07	8.30E+06	1.38E+07	1.73E+07	1.27E+07	2.18E+07	1.14E+07	1.01E+07	1.70E+07	1.45E+07	1.23E+07	1.03E+07
^{60}Co	8.10E+04	1.32E+05	1.81E+05	1.76E+05	9.72E+04	4.99E+04	5.25E+04	7.96E+04	2.84E+04	9.52E+03	1.19E+04	9.15E+03
^{90}Sr	1.37E+04	7.53E+03	6.64E+03	6.92E+03	9.21E+03	4.35E+03	3.00E+03	4.30E+03	5.10E+03	7.54E+03	2.86E+03	3.93E+03
^{131}I	6.48E+03	1.77E+04	8.27E+03	8.45E+03	2.43E+04	1.28E+04	3.07E+03	1.46E+03	2.24E+03	1.25E+03	7.28E+02	5.16E+02
^{134}Cs	4.97E+03	2.37E+03	1.12E+04	7.29E+03	5.16E+03	2.05E+03	2.00E+03	7.57E+02	1.20E+03	6.35E+02	1.61E+03	1.24E+03
^{137}Cs	4.05E+04	1.87E+04	7.64E+04	6.08E+04	3.49E+04	8.03E+03	1.13E+04	5.89E+03	1.37E+04	7.63E+03	1.35E+04	1.04E+04
^{239}Pu	1.41E+03	8.57E+02	8.30E+02	7.09E+02	1.62E+02	1.41E+02	5.13E+02	2.73E+02	1.31E+02	1.14E+02	8.19E+01	2.81E+01
^{241}Am	8.22E+02	2.20E+02	1.66E+02	5.07E+02	8.64E+01	7.54E+01	2.74E+02	1.46E+02	7.01E+01	6.11E+01	4.37E+01	1.51E+01

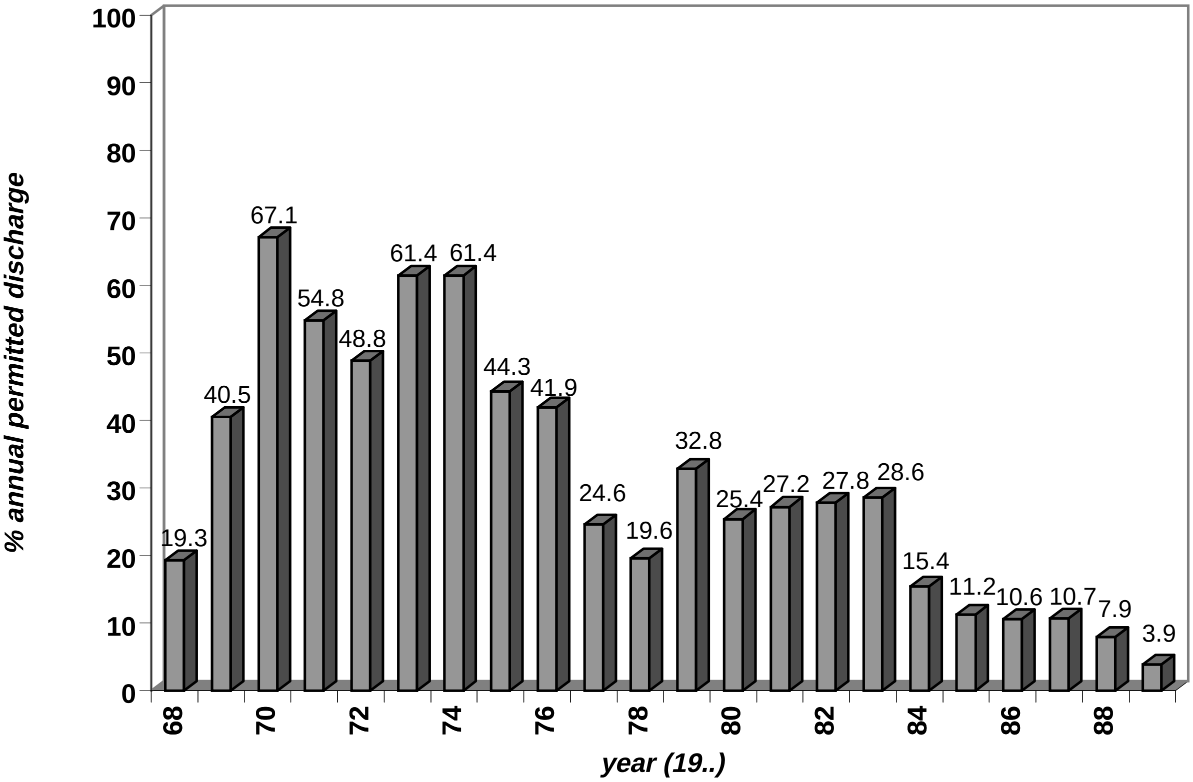

Figure 7: *Annual discharges into the river Molse Nete w.r.t. maximal permitted values (%) (Deworm et al., 1990)*

3.3.2 Contamination

3.3.2.1 Radiocontamination of the river water

The water in the Molse Nete and Grote Nete is sampled continuously at three different locations (sampling points 1, 6 and 10 on Figure 1). A 5 L bottle is filled over 14 days and replaced every two weeks. Of each sample, the concentrations of ^{3}H, ^{226}Ra, ^{90}Sr, the α- and β- emitting radionuclides are determined.

The annual averages of the total - α and total - β activities are shown in Figure 8 and Figure 9 respectively.

In the Molse Nete, the α activity varies between 0.008 and 0.063 Bq L^{-1} upstream the discharge point and between 0.04 and 0.42 Bq L^{-1} downstream the discharge point. The major source for the α radioactivity in the section upstream the discharge point is constituted by naturally occuring radionuclides (mainly ^{226}Ra and daughter products), in the section downstream the discharge point the releases of ^{239}Pu, ^{241}Am and, to a lesser extent, ^{226}Ra are the major source as shown in section 3.3.1. Much higher α levels are observed in the Grote Nete at Westerlo, downstream the influx of the Grote Laak river (sampling point 10, Figure 1). Here, the α activity ranges from 0.51 to 3.03 Bq L^{-1}. ^{226}Ra and its daughter products, coming from the phosphate industry of Tessenderlo and Kwaadmechelen, is mainly responsible for these higher α activities.

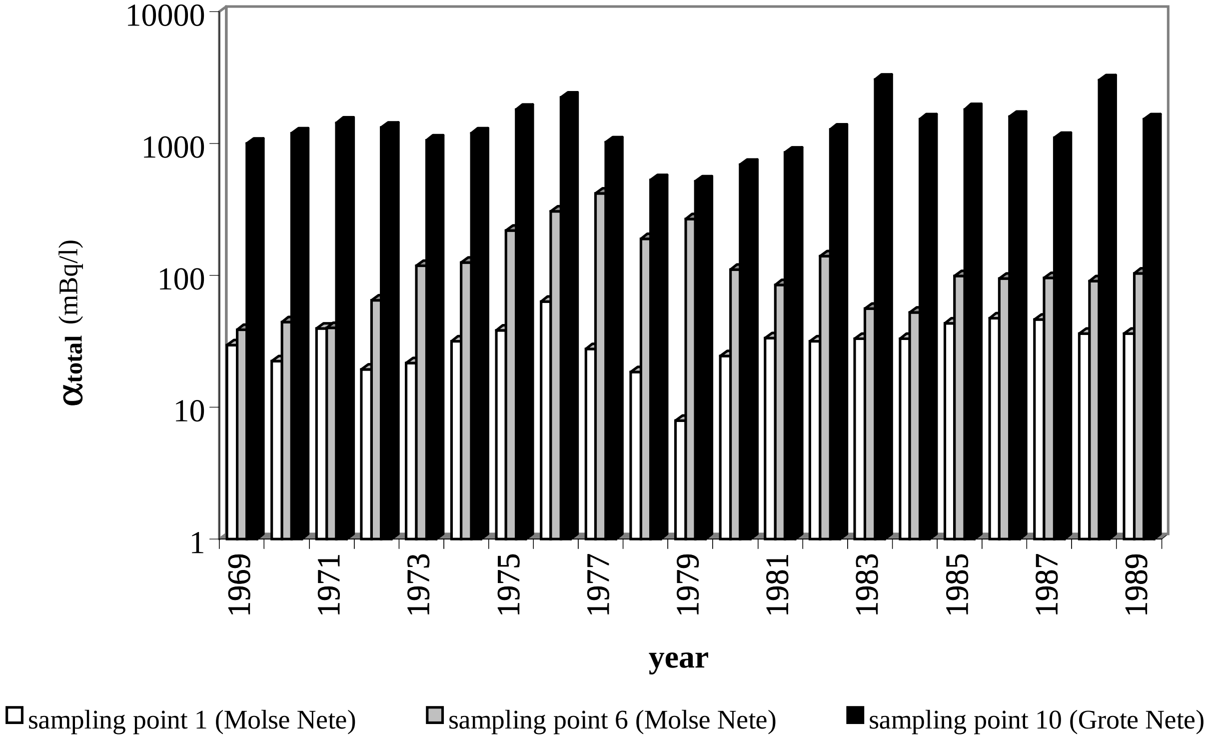

Figure 8: *Annual averages of the total α radioactivity (mBq L^{-1}) at three different locations during the period 1969 - 1989 (Deworm et al., 1990)*

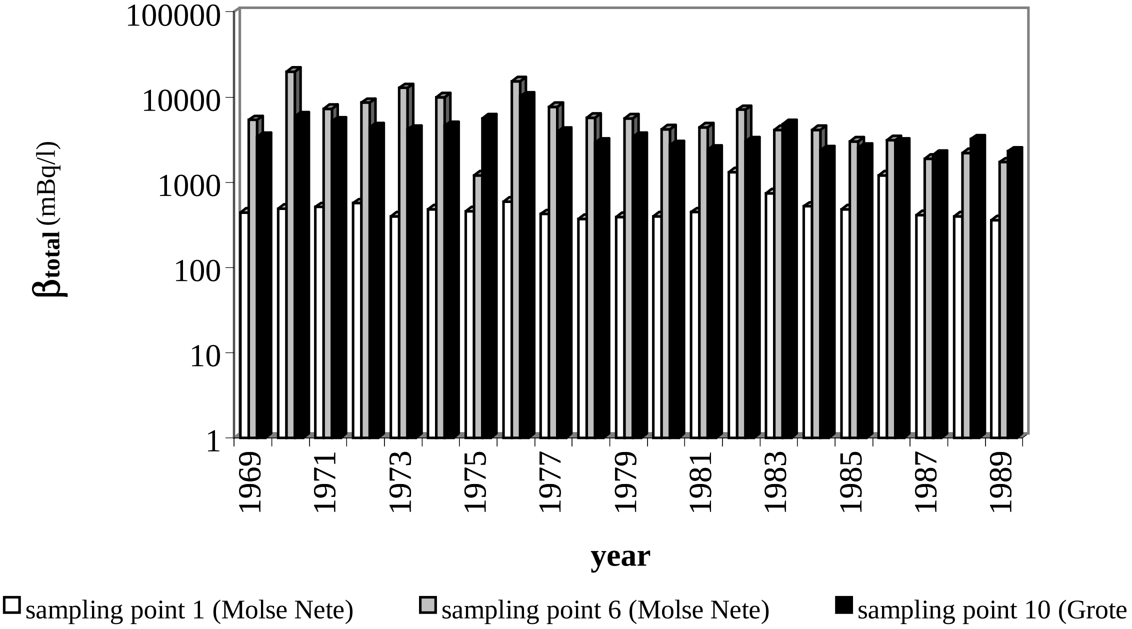

Figure 9: *Annual averages of the total β radioactivity (mBq L^{-1}) at three different locations during the period 1969 - 1989 (Deworm et al., 1990)*

The β activity in the Molse Nete varies between 0.4 and 1.3 Bq L^{-1} upstream the discharge point and between 1.7 and 12.8 Bq L^{-1} downstream the discharge point. The major source for the β radioactivity in the section upstream the discharge point is the presence of naturally occuring radionuclides (mainly ^{40}K and daughter products of ^{226}Ra), in the section downstream the discharge point the β activity is mainly due to the discharged nuclides ^{60}Co, ^{90}Sr, ^{131}I, ^{134}Cs and ^{137}Cs as shown in section 3.3.1. In the Grote Nete downstream the confluence with the Grote Laak, the β activity lies between 2.1 and 6.5 Bq/l and the daughter products of ^{226}Ra discharged into the Grote Laak and the β activity discharged into the Molse Nete are the main sources. The highest levels of β activity were observed in the Molse Nete during the 1970's. Since then the discharges declined rapidly and the β activity of the Grote Nete, downstream the Grote Laak became more important.

Distribution coefficients for suspended matter have been determined *in-situ*, in a few sampling campaigns, at the watermill (Molse Nete) and in the Grote Nete (Zeevaert *et al.*, 1987). The results are shown in Table 15.

Table 15: *Distribution coefficients of suspended matter (L kg^{-1}) (Zeevaert et al., 1987)*

	Distance to the discharge point (km)	
	+ 3.6	*+ 17.7*
^{60}Co	2E+04	2E+04
^{137}Cs	5E+04	3E+04
^{90}Sr	9E+02	2E+03
Pu	2.5E+05	1E+05
^{241}Am	1.0E+06	8E+05

3.3.2.2 Radiocontamination of the bed sediment

As stated previously, a part of the radionuclides released into the Molse Nete will stay in the liquid phase, the other part will adsorb on the suspended matter and sediment.

As noted in section 3.2.2, the sediment was only sampled intermittently. Sampling was carried out at the 10 sampling points (Figure 1). To measure the radioactivity, the cores were cut in slices of 10 or 20 cm and dried at 105°C. The radioactivity levels of the most important radionuclides are shown in Table 16 for different depths.

The radioactivity of the bed sediment changes with time, due to the subsequent dredging operations and its downstream movement and also the changes in discharge rates. The data show that the maximum radioactivity levels of the bed sediment are reached in the vicinity of the water mill, about 3.7 km downstream the discharge point. Just before the water mill the river becomes wider, slowing down the water flow and leading to a higher sedimentation, which allows the finer particles (higher specific activity) to settle in considerable amounts.

Comparison of the data obtained for 0-10 cm, 20-30 cm, respectively 20-40 cm depth demonstrate that the radioactivity concentrations decrease with depth. Also, in accordance with the discharges, the contamination of bed sediment decreases with time.

Table 16: *^{60}Co, ^{137}Cs, ^{241}Am and Pu (α) concentrations in the bed sediment of the Molse Nete(Bq kg^{-1} dry)*

Nuclide	*Year*	*Depth (cm)*	*Distance to the discharge point (km)*								
			-2.2	*+0.05*	*+0.9*	*+2.5*	*+3.7*	*+5.3*	*+6.4*	*+7.0*	*+ 18.0*
^{60}Co	1977	0 - 10			529	892		377			
		10 - 20			42.9	19.6					
		20 - 30			28.9			<18.5			
	1978	0 - 20	<2.22		$677/555^a$		$248/2516^a$				
		20 - 40	<2.44		$15.2/7.4^a$		$7.4/252^a$				
	1979	0 - 10		114	503	245	6327	352		45.1	192/252
		10 - 20		30.0	485	8.51	2312	570		13.7	
	1980	0 - 10		201	681	314	2501		3.33	25.2	120
		10 - 20		159	61.7	178	234				
	1983	0 - 10	<2.29		50.7		588	97.3			
		10 - 20	<1.33		4.07		127	92.1			
		20 - 40	<2.29		5.18		50.7	34.9			
	1986	0 - 20			73.7		28.3				
		20 - 40			5.00		6.40				
	1991				140		430				
^{137}Cs	1977	0 - 10			71.0	622		733			
		10 - 20			<25.9	19.6		230			
		20 - 30				<1.3		10.0			
	1978	0 - 20	3.5		$142/660^a$	$200/3219^a$					204/222
		20 - 40	2.6		$5.6/18^a$	$10.0/355^a$					
	1979	0 - 10	3.7	153	470	340	4588	459		163	
		10 - 20		28.5	222	12.2	1661	485		81.0	
	1980	0 - 10	2.1	261	725	363	2002		1.3	115	295/244
		10 - 20	1.7	216	770	300	2882		4.0	110	
	1983	0 - 10	2.4		163		544	365			
		10 - 20	<1.3		12.2		122	267			
		20 - 40	<1.3		7.0		54.4	54.8			
	1986	0 - 20	1.7		148		62.9	21.1			
		20 - 40	1.1		6.7		17.8	4.1			
	1991				162		825				

Nuclide	*Year*	*Depth (cm)*	*Distance to the discharge point (km)*								
			-2.2	*+0.05*	*+0.9*	*+2.5*	*+3.7*	*+5.3*	*+6.4*	*+7.0*	*+ 18.0*
^{241}*Am*	1977	0 - 10			21.8	337					
		10 - 20			8.5	18.5					
		20 - 30			16.7	15.2					
	1978	0 - 20	8.5		270		78/581[a]				11.8
		20 - 40			11.8						
	1979	0 - 10		71	207	120	2190	195		14.1	
		10 - 20		28	176	15.5	1188	114			
	1980	0 - 10		35.5	188	98	877			9.3	8.9
		10 - 20		27.4	209	46.6	614				
	1983	0 - 10	≤5.2		15.5		98.4	25.5			
		10 - 20	≤5.2		≤5.2		23.3	42.9			
		20 - 40	≤5.2		≤5.2		13.7	26.6			
	1986	0 - 20	≤5	≤5		20.6		6.1	8.1		
		20 - 40	≤5	≤5		9.0		≤5	≤5		
	1991				31		101				
Pu (α)	1977	0 - 10			127						
		10 - 20			145						
		20 - 30			38.5						
	1978	0 - 20	13		252	96/692[a]					20
		20 - 40			13.3						
	1979	0 - 10		118	266	137	2978	219		38.5	
		10 - 20	17.8	53.3	256	19.2	1251	124		34.7	
	1980	0 - 10		65.1	356	128	1769		14.8	28.8	20
		10 - 20		79.9	314	68	1021		53.3	16.7	15
	1983	0 - 10	20.7		15.9		195	34.0			
		10 - 20	≤5		5.6		21.5	38.1			
		20 - 40	10.4		≤5		20.0	32.9			
	1986	0 - 20	16.3	5.7		21.2		35.5	21.1		
		20 - 40	≤5	16.9		6.6		22.9	48.8		
	1991				116		768				

[a] north bank/south bank

3.3.2.3 Radiocontamination of the river banks

The frequent removal of dredged sediment has led to a noticeable radiocontamination of the terrestrial environment.

Until 1978, dredging was performed annually, only at the bends (or points with high depositions), normally during the months of September or October. From 1978, dredging is also performed over whole sections (not only bends) and since 1983, only over whole sections. Two sections are distinguished ; section 1 from sampling point 1 to 6 (water mill) and section 2 from sampling point 6 to the confluence with the Grote Nete.

Dredgings performed from 1978 until 1993 :

1978 : section 1 - only bends
section 2 - completely
1979 : sections 1 and 2 - only bends
1980 : section 1 - only bends
section 2 - completely
1981 : section 1 - completely
section 2 - only bends
1982 : sections 1 and 2 - only bends
1983 : section 2
1984 : section 1
1985 : no dredging
1986 : section 2
1987 : section 1 (between discharge point and water mill)
1988 : section 1(between sampling point 1 & discharge point)
1989 : no dredging
1990 : section 2
1991 : section 1
1992 : no dredging
1993 : no dredging

Due to the fact that bed sediment is removed regularly and deposited on the river banks, the radioactivity measured on these banks will reflect the former radiocontamination of the bed sediment. The dredged sediment was mainly put on the south bank, where it was not easily accessible. Sediment can also be found on the north bank. At this moment, the contamination level of the banks is generally higher than that of the bed sediment, reflecting the higher discharges in the past (Table 17). The highest concentrations are found for ^{137}Cs.

Table 17: *Radioactivity concentrations of soil samples (Bq kg^{-1}) from the banks of the Molse Nete.*

Distance to the discharge point (km)	*^{60}Co*	*^{137}Cs*	*^{241}Am*	*Pu*
1989-1990				
+ 0.05	210	610	157	
+ 0.65	560	1120	450	250
+ 0.80	49	152	20	
+ 1.05	610	1290	104	
+ 1.65	69	96	18	
+ 2.30	380	890	710	550
+ 2.40	17.1	58	2	
+ 3.35	0.56	230		
+ 3.70	685	1200	190	140
1991				
+ 0.90	148	700	350	861
+ 2.30	18.7	193	22	
+ 3.35	850	2400	1820	

The local dose rates on the river banks are measured annually with fixed TLD dosimeters placed 1 m above groundlevel. In Table 18, the annual averages of the dose rate are given for the period 1982 - 1995.

The highest dose rates are observed on the banks of the depositing zone of the Molse Nete, where the highest sediment levels are found. The background level is about 70 nSv h^{-1}.

In 1993, an extensive monitoring campaign was carried out. The dose rate was measured for each 10 m, from 50 m upstream of the discharge point to 100 m downstream of the water mill. Measuring points were taken at the middle of the river and at 4 m, 4.5 m, 6 m and every 2 m up to 14 m distance from the middle on both banks. Figure 10 shows the results from the south bank for every 150 m of this stretch of the river, beginning at the discharge point. The results for the south bank are also summarised in Table 19 . The dose rate on the south bank varies between 80 and 1000 nSv h^{-1}. The background level in the Campines is about 70 - 80 nSv h^{-1}. The current averages of the dose rate are about two times higher. On the north bank, the radioactivity is lower, a dose rate range of 80 to 300 nSv h^{-1} is observed.

Table 18: *External gamma dose rate (nSv/h) on the banks of the river Molse Nete.*

Year	*Distance to discharge point (km)*						
	-2.2	*+ 0.9 south*	*+ 0.9 north*	*+ 3.0*	*+ 3.7 south*	*+ 3.7 north*	*+ 7.0*
1982	58	271	216	505	103	336	103
1983	68	242	204	502	96	395	111
1984	58	200	131	446	89	437	108
1985	68	179	105	390	107	340	107
1986	71	124	89	209	80	202	77
1987	71	120	79	180	81	168	77
1988	76	119	94	206	86	137	78
1989	66	114	83	186	79	140	64
1990	62	92	73	160	74	125	61
1991	64	100	74	160	79	120	66
1992	66	94	84	145	86	110	66
1993	68	89	75	156	84	100	72
1994	62	80	73	142	81	90	65
1995	62	76	66	134	80	90	64

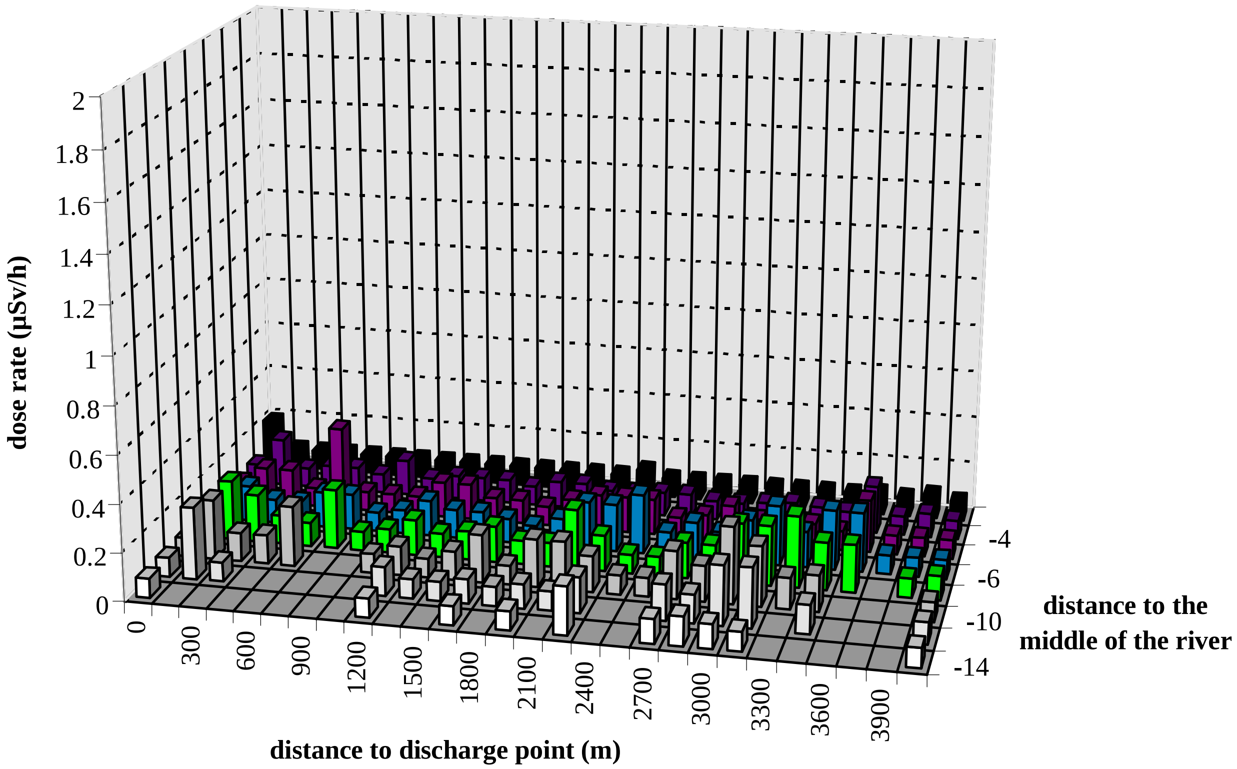

***Figure 10 :** Dose rate measurement on the south bank of the Molse Nete*

***Table 19 :** Average dose rates (µSv h^{-1}) on south bank of the Molse Nete (monitoring campaign of 1993). Number of measuring points is given in parentheses (Slegers, 1994).*

distance from discharge point	distance from water side							
	10 m	8 m	6 m	4 m	2 m	0.5 m	0 m	above water
0 - 175 m	0.08 (1)	0.17 (4)	0.2 (15)	0.21 (17)	0.20 (17)	0.24 (17)	0.19 (17)	0.09 (17)
175 - 2240 m	0.11 (95)	0.12 (147)	0.12 (196)	0.13 (205)	0.13 (203)	0.12 (203)	0.10 (206)	0.08 (206)
2240 - 2450 m	0.13 (13)	0.14 (19)	0.17 (22)	0.19 (22)	0.21 (22)	0.20 (22)	0.11 (22)	0.08 (22)
2450 - 3090 m	0.10 (48)	0.12 (61)	0.16 (64)	0.16 (64)	0.15 (64)	0.12 (64)	0.09 (64)	0.08 (64)
3100 - 3640 m	0.16 (23)	0.17 (36)	0.19 (50)	0.24 (53)	0.23 (54)	0.15 (55)	0.11 (55)	0.08 (55)
3640 - 4050 m	0.08 (3)	0.1 (3)	0.19 (5)	0.08 (27)	0.08 (40)	0.1 (40)	0.1 (40)	0.08 (40)
minimum	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
maximum	0.35	0.30	1.0	0.50	0.50	0.80	0.40	0.15
average	0.12	0.13	0.15	0.15	0.15	0.13	0.10	0.08

3.3.2.4 Radiocontamination of aquatic flora and faune

There are only few fish in the Molse Nete. The water life consists mainly of freshwater plants, insects like fly larvae, bugs, water mites and worms. The most abundant species of water plants *Potamogeton pectinatus* L. and *Potamogeton natans* L were collected occasionally from different locations, mostly chosen at random. The species are separated and dried at 105 °C. The results for samples taken in June

1979 and June 1980 from 9 sampling points (Figure 1) are summarised in Table 20. The activity varies widely, but it appears that the highest activities occur near the discharge point with a second maximum near the area of maximum sediment activity. The activity in *Potamogeton pectinatus* is usually 1.5 to 2 times higher than in *Potamogeton natans*.

Benthic samples have been collected in 1980 (Konings *et al.*, 1980). The two main radionuclides detected are ^{60}Co and ^{137}Cs. The mean ^{60}Co activity in 9 samples taken in 1980 was 0.33 mBq g^{-1} dw per Mbq released (range 0.074 - 1.11 mBq g^{-1} dw per MBq released). The mean ^{137}Cs levels were to 10 times lower.

Table 20: *Radioactivity levels in aquatic plants (Metayer-Piret et al., 1982)*

site	year	^{60}Co		^{137}Cs		Pu	
		P. Pectinatus	*P. natans*	*P. Pectinatus*	*P. natans*	*P. Pectinatus*	*P. natans*
1	1979	≤ 1.5	≤ 2.2	n.d.	n.d.	≤ 3.8	≤ 3.7
	1980	0.8	4.1	4.1	10.0	1.4	2.7
2	1979	5.6	22.2	70.7	138	9.6	8.5
	1980	31.2	54.0	902	1980	48.4	116
4	1979	5.2	31.1	49.6	123	5.2	7.6
	1980	9.8	60.9	159	503	13.8	173
5	1979	15.9	30.3	85.8	139	23.5	22.4
	1980	15.1	29.9	189	259	26.8	66.7
6	1979	27.4	35.5	110	158	23.7	37.7
	1980	33.5	/	311	/	48.1	/
7	1979	9.6	35.1	61.4	103	18.9	13.0
	1980	11.8	/	96.2	/	14.0	/
8	1979	9.2	10.4	61.0	63.2	11.5	12.7
	1980	2.7	/	70.3	/	12.7	/
9	1979	12.2	/	33.3	/	13.3	/
	1980	/	/	/	/	/	/
10	1979	19.6	17.0	178	85.8	14.8	18.9
	1980	/	/	/	/	/	/

n.d. not detected

4. Restoration options

As stated earlier the current radiological situation of the site at the Molse Nete river is characterised by radioactive contamination of the bed sediment, originating mainly from past discharges. This has also caused contamination of the river banks and of some fields and pastures along the river due to dredging of bed sediment from the river. Irrigation with water from the river has brought about some minor additional contamination of nearby fields or pastures. Nowadays the radioactive releases into the river are much lower than they were ten or more years ago, causing the contamination levels in the upper soil and sediment levels to diminish. However, this is not reflected in the dose assessments that were based on discharge levels and concentration values of some ten years ago and earlier. Moreover, it has been assumed that river sediment was applied onto agricultural land over an unrealistically large surface area. This conservatism has to be borne in mind when evaluating restoration options for this site.

Before restoring the site a first measure should be the stopping of radioactive discharges into the river, or the reduction of them to negligible values. This is not a restoration measure since it does not counteract the radiological consequences of the radionuclides already present at the site but only prevents further radioactivity from being released into the environment. However it is a first logical step before the restoration of the site and is indicated as the basecase A (see further). Nevertheless, without remediation, the differences in the collective doses between the discharges stopped and the discharges continuing are very small (in the order of a few percent), because of the high contribution of earlier discharges of ^{239}Pu and of ^{241}Am to the total dose.

The best-estimate values of the characteristics of the restoration techniques applied to the site of the Molse Nete are given in Table 21. They are derived from the ranges indicated in Technical Deliverable 3+4 (Zeevaert and Bousher, 1998). Performance indicators (efficacies), unit costs (i.e. costs per unit volume soil/sediment to be treated or surface area to be covered) and unit labour volumes (exposure times of restoration workers) are included.
The unit costs are estimated to be relatively high due to the site circumstances (bad accessibility of the site). This is also the case for the unit labour volumes or exposure times of the restoration workers.

A first category of restoration techniques to be considered is the removal of radioactive sources (soil and sediment). This is obviously an effective measure, but implies the disposal of large volumes of soil and sediment as radioactive contaminated waste, which is very costly. The costs are reduced to reasonable values by only removing soils from fields and pastures that were assumed to have been contaminated with river sediment, and not those that were contaminated through irrigation with river water only. Moreover only the upper layers (a few tens of cm thick) of the soil, i.e. the root zone layers of fields and pastures, and the upper sediment layers were removed and disposed of. This reduction of volumes to be removed will bring about a slight decrease of the efficacy (decontamination factor, DF) of the restoration technique, but this is negligible with respect to the changes in economical costs.
The replacement of the removed soil by clean, fertile soil makes it again suited for agricultural activities and increases the cost only by a negligible amount.

The volumes of contaminated soil and sediment to be disposed of can be reduced further by the application of separation techniques on the excavated material. This is at the cost of a higher concentration of radionuclides in the waste remaining for disposal and consequently of a higher unit price of waste disposal. However, in this case the considerable reduction of volume of waste to be disposed of, more than counterbalances the higher unit cost of the waste disposal. The separation techniques taken into consideration are a physical one, soil washing and a chemical one, chemical solubilization.

***Table 21**: Characteristics of restoration techniques for the site of the Molse Nete river : Site-specific values.*

		Performance	*Cost* (1) *(EUR* m^{-3}*)*	*Labour Volume Exposure Times (manh* m^{-3}*)*
A	Basecase Discharges into river stopped	/	/	/
B	Removal: soil sediment	Co : DF = 7 Cs, Pu, Am : DF = 10	125 (4) 150 (5)	0.8 0.9
C_1	Physical Separation Soil Washing : soil sediment	 Co : DF = 4 Cs, Pu, Am : DF = 6	 350 + 125 (6) 350 + 150 (6)	 0.95 1.05
D_1	Chemical Separation Solubilisation : soil sediment	 DF = 10	 400 + 125 (6) 400 + 150 (6)	 2.3 2.4
E_1	Containment Capping: soil sediment	 $k = 10^{-10}$ m s^{-1}	 40 (2) 45 (2)	 0.25 (3) 0.28 (3)
F_1	Physical Immobilisation *Ex-situ*: soil sediment	 Reduction of Mobility: factor = 15	 100 + 125 100 + 150	 0.95 1.05
F_2	Physical Immobilisation *In-situ*: soil sediment	 Reduction of Mobility: factor = 15	 200 250	 0.30 0.35
G_1	Chemical Immobilisation *Ex-situ*: soil sediment	 Reduction of Mobility: factor = 10	 180 + 125 180 + 150	 0.95 1.05
G_2	Chemical Immobilisation *In-situ*: soil sediment	 Reduction of Mobility: factor = 10	 200 250	 0.30 0.35

(1) Without waste disposal
(2) EUR m^{-2}
(3) manh m^{-2}
(4) waste disposal: 700 EUR m^{-3}
(5) waste disposal: 800 EUR m^{-3}
(6) waste disposal: 2500 EUR m^{-3}

A third category of restoration techniques that can be applied is containment.

The capping of the contaminated soil and river sediment with asphalt concrete, or a hot asphalt mix yields a very effective barrier against water infiltration. Additionally, the major advantage of this technique is its low over-all cost. The dose to the population will be reduced to a negligible value but at the cost of a surface soil, that is no longer suited for agricultural practices. As a consequence the drawback of this technique is the loss of income (social attribute) and taxes (economical attribute) from agricultural activities. The application of only a layer of fertile soil would not suffice to make the soil again suited for agricultural activities, as it would in the case of soil removal.

The application of subsurface barriers, another containment technique is obviously not suited for this site.

A last category of restoration techniques to be considered is immobilisation; cement-based (physical) and polymer-based (chemical) immobilisation can be applied.
Although immobilisation has not such a drastic influence on the soil water balance as capping has, the soil will not be suited for agricultural practices after treatment. Whether the application of a fertile soil layer will suffice for making the soil again usable for agricultural purposes, is questionable.
As a consequence, the advantage of the reduction of the collective doses to negligible values is at the cost of the drawbacks of a loss of income (social attribute) and a loss of taxes (economical attribute) as for capping.
The immobilisation, physical as well as chemical, can be carried out *in-situ* or *ex-situ*. The cost of the *ex-situ* immobilisation is for both techniques (physical and chemical) higher than the cost of the *in-situ* immobilisation. This is due to the cost of excavation and transport prior to immobilisation for the *ex-situ* technique, although the cost of the physical immobilisation itself is lower by a factor of two for the *ex-situ* relative to the *in-situ* technique.

5. Radiological impact assessments

5.1 Compartment scheme

The compartment scheme for the Molse Nete river (Figure 11) is based on the site description in chapter 3. It has been developed in WP4 (Risk Assessments). The dose assessments are explained in TD 6 (Stiglund and Nordlinder, 1999)

The source originates from low-level radioactive effluents from a nuclear waste treatment facility that are released into the river and transported further downstream. About 7 km further down the river reaches the confluence with the Grote Nete river. This distance is quite far and this is the reason for dividing the river into two boxes, i.e. an upper and lower part. The soil is also divided into two compartments for the same reason.

Since releases have been going on for over forty years a lot of activity can be found in the sediments and in the soil next to the river. The river is dredged every five years and the sediment is then put on the banks. Some of the dredged sediment is subsequently applied onto agricultural soil. Irrigation of fields and pastures with water from the river is occurring a few times every year.

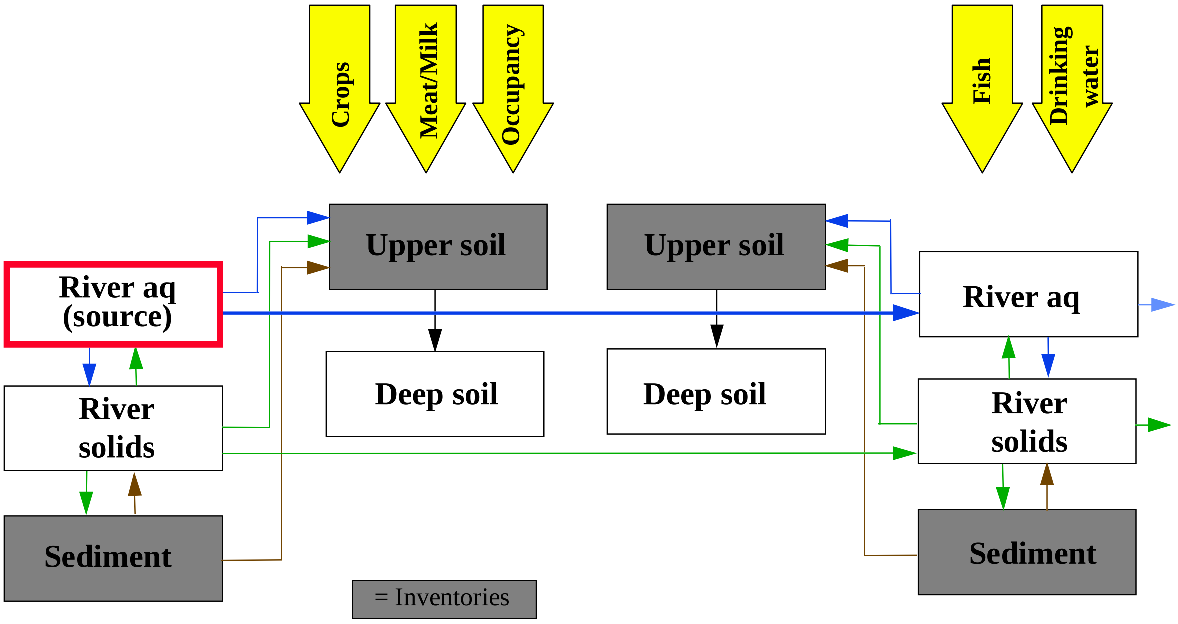

Figure 11: *Compartment structure for the Molse Nete river and considered exposure pathways*

5.2 Exposure pathways

The exposure pathways considered are schematically shown in Figure 11. They include:

- consumption of river water
- consumption of milk and meat through the watering of cattle at the river

- consumption of milk and meat contaminated through the pasture eaten by cattle. The soil has been irrigated with river water and amended with sediment from the river bed
- consumption of fish from the river
- consumption of cereals, potatoes and vegetables. The soil has been irrigated with river water and amended with sediment from the river bed
- inhalation of dust from the soil
- external irradiation from contaminated fields

5.3 Critical nuclides

The most important radionuclides, discharged into the Molse Nete are ^{60}Co, ^{137}Cs, ^{239}Pu and ^{241}Am. Over the period 1961 to 1990, about 130 GBq a^{-1} ^{60}Co, 37 GBq a^{-1} ^{137}Cs, 1.3 GBq a^{-1} ^{239}Pu and 0.68 GBq a^{-1} ^{241}Am were released. The discharges of radionuclides are, nowadays, much lower.

5.4 Critical groups

The critical group consists of farmers living in the neighbourhood. They are eating locally produced meat and drink milk from cows that graze nearby the river Molse Nete. All food crops are produced locally. Allfish are captured in the local river. The drinking water is taken from the river but it is filtrated before drinking. The water used for irrigation is not filtered.

5.5 Doses

Collective and individual doses have been assessed.
The individual doses concerned are the annual effective doses to average members of the critical group, before restoration (at year 1).

The collective doses assessed are collective effective dose commitments to the population truncated at the time periods of 100 and 500 years, and the collective effective doses to the restoration workers. The collective dose to the population has been derived from production data and the nuclide concentrations in the various media. The collective doses to the restoration workers were derived from the labour volumes and activity levels on the contaminated site.

5.5.1 Individual doses to critical group: base case year 1

The results of the individual dose calculations at year 1 are shown in
Table *22*.

The contribution to the total dose from different pathways is graphically depicted in Figure 12.

For ^{239}Pu and ^{241}Am the consumption of root crops are the dominant exposure pathways, while for ^{60}Co external irradiation is dominant. Usually the dominating exposure pathway from contaminated soil for ^{241}Am and especially for ^{239}Pu is inhalation of resuspended particles. In this case, due to a high value for the root uptake factor, the ingestion of different crops is the dominant exposure pathway. For ^{137}Cs the ingestion of tubers and vegetables dominates but also ingestion of meat and external irradiation play an important role.

Table 22: *Individual dose (Sv a^{-1}) at Molse Nete River at year 1*

Exposure pathway	Year	^{60}Co Mean	^{137}Cs Mean	^{239}Pu Mean	^{241}Am Mean	Total Mean
Water	1	1.6E-07	2.8E-07	1.7E-07	7.5E-08	6.8E-07
Fish	1	5.9E-07	5.4E-06	8.4E-08	1.2E-07	6.2E-06
Milk	1	3.8E-10	2.6E-08	2.8E-11	2.2E-10	2.7E-08
Meat	1	8.8E-08	6.4E-05	2.6E-07	1.0E-06	6.6E-05
Root crops	1	1.2E-06	2.5E-05	1.9E-04	3.5E-05	2.59E-04
Tubers	1	7.9E-07	1.0E-04	6.8E-06	3.2E-06	1.1E-04
Vegetables	1	4.7E-07	6.0E-05	3.3E-06	5.4E-06	6.9E-05
Ext.Exposure	1	3.8E-05	3.9E-05	6.0E-32	1.3E-07	7.7E-05
Inhalation	1	1.2E-09	8.5E-10	1.5E-05	5.4E-06	2.0E-05
Total dose	1	4.1E-05	2.9E-04	2.1E-04	5.1E-05	5.9E-04

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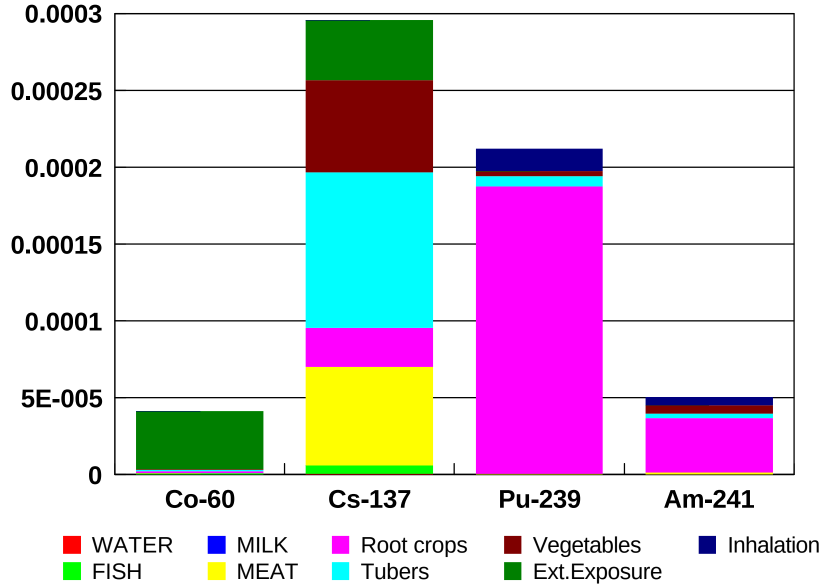

Figure 12: *The contributions to the individual dose (Sv a^{-1}) from different pathways.*

5.5.2 *Collective doses to public over 100 years and 500 years and to the restoration workers*

The results of the collective dose calculations for the public over 100 and 500 years and for the restoration workers are shown in
Table *23*. The restoration options considered are listed in Table 21 (chapter 4).

As shown in Table 23 ^{239}Pu gives the largest contribution to the total collective dose to the population. The dose to the workers is on the other hand dominated by ^{60}Co and ^{137}Cs.

In Figure 13 the collective dose committment for the public and the restoration workers is graphically depicted for ^{239}Pu for the different restoration options at 100 and 500 years.

Table 23: *Collective doses, (manSv), at the Molse Nete river*

		Time year	Co-60 Mean	Cs-137 Mean	Pu-239 Mean	Am-241 Mean	Total Mean
A	Farmers	100	7.3E-03	3.2E+00	1.1E+01	2.0E+00	1.6E+01
		500	7.3E-03	3.6E+00	4.1E+01	6.7E+00	5.1E+01
B	Farmers	100	1.0E-03	3.2E-01	1.1E+00	2.0E-01	1.6E+00
		500	1.0E-03	3.6E-01	4.1E+00	6.7E-01	5.1E+00
	Workers		4.0E-04	1.6E-04	4.0E-05	1.0E-05	6.1E-04
C1	Farmers	100	2.0E-03	9.0E-01	3.0E+00	5.5E-01	4.5E+00
		500	2.0E-03	1.0E+00	1.1E+01	1.9E+00	1.4E+01
	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03
D1	Farmers	100	7.0E-04	3.2E-01	1.1E+00	2.0E-01	1.6E+00
		500	7.0E-04	3.6E-01	4.1E+00	6.8E-01	5.1E+00
	Workers		1.0E-03	5.0E-04	1.0E-04	4.0E-05	1.6E-03
E1	Workers		1.0E-03	1.1E-03	4.0E-04	1.0E-04	2.6E-03
F1	Workers		4.0E-03	2.0E-03	6.0E-04	1.0E-04	6.7E-03
F2	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03
G1	Workers		4.0E-03	2.0E-03	6.0E-04	1.0E-04	6.7E-03
G2	Workers		1.0E-03	6.0E-04	2.0E-04	4.0E-05	1.8E-03

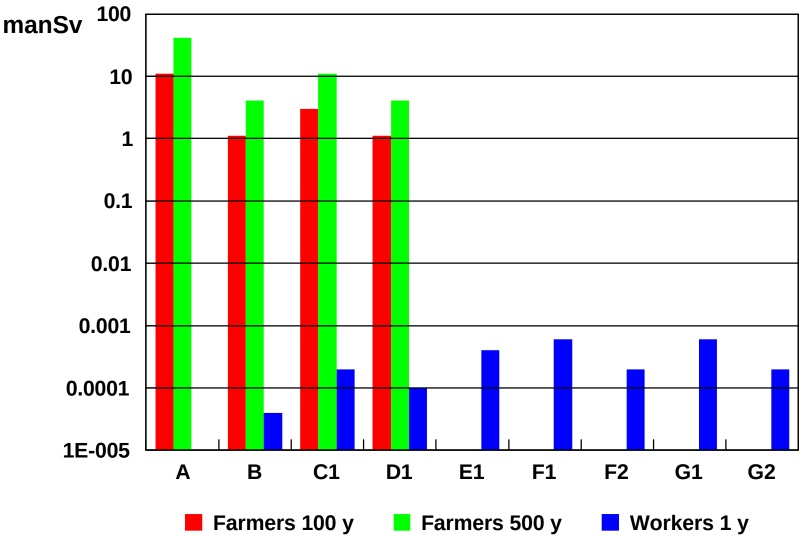

Figure 13: *The total collective dose of Pu-239 (manSv) for the restoration options at 100 and 500 years*

Uncertainty analysis

The results of the uncertainty analysis of the collective dose to the population are shown for all relevant restoration options in Table 24.

The concentration factors for uptake from soil to plants dominate the uncertainty in in the collective dose commitment for all nuclides and all restoration options concerned.
The distribution coefficient for soil is the next important parameter in this respect.

Table 24: *Collective doses (man Sv). Uncertainty analysis.*

Basecase : no remediation

		Co-60			Cs-137			Pu-239			Am-241		
Exposure pathway	Year	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile
Water	100	4.7E-09	1.7E-09	9.7E-09	4.4E-08	1.5E-08	9.7E-08	4.0E-06	1.3E-06	8.8E-06	5.1E-07	1.7E-07	1.1E-06
Fish	100	2.3E-06	8.3E-07	4.8E-06	1.1E-04	3.6E-05	2.2E-04	1.9E-05	5.0E-06	4.4E-05	2.3E-05	7.0E-06	4.9E-05
Milk, from water	100	9.8E-07	2.7E-08	3.6E-06	3.2E-05	9.4E-07	1.2E-04	2.2E-07	6.2E-09	8.3E-07	5.5E-07	1.6E-08	2.1E-06
Meat, from water	100	1.4E-08	4.9E-10	5.3E-08	5.0E-06	1.6E-07	2.0E-05	1.3E-07	3.8E-09	5.2E-07	1.6E-07	5.0E-09	6.7E-07
Milk, from soil	100	3.2E-07	1.1E-08	1.2E-06	1.5E-04	3.8E-06	5.6E-04	4.3E-07	1.7E-08	1.7E-06	2.7E-06	1.0E-07	1.1E-05
Meat, from soil	100	1.6E-07	4.8E-09	6.0E-07	7.7E-04	1.9E-05	3.0E-03	8.2E-06	3.1E-07	3.1E-05	2.7E-05	1.1E-06	9.9E-05
Root crops	100	3.8E-03	4.9E-04	1.3E-02	5.5E-01	7.1E-02	1.8E+00	1.1E+01	1.4E+00	3.4E+01	1.7E+00	2.2E-01	5.5E+00
Tubers	100	1.9E-03	2.5E-04	6.2E-03	1.6E+00	2.1E-01	5.2E+00	2.8E-01	3.6E-02	9.1E-01	1.1E-01	1.4E-02	3.6E-01
Vegetables	100	1.3E-03	1.7E-04	4.1E-03	1.1E+00	1.4E-01	3.5E+00	1.6E-01	2.1E-02	5.0E-01	2.1E-01	2.8E-02	6.9E-01
Farmers, ext exposure	100	2.6E-04	2.1E-04	3.1E-04	1.8E-03	1.4E-03	2.1E-03	6.9E-30	5.2E-30	8.4E-30	1.3E-05	1.1E-05	1.4E-05
Farmers, inhalation	100	8.3E-09	1.1E-09	2.7E-08	3.8E-08	4.9E-09	1.2E-07	1.7E-03	2.1E-04	5.3E-03	5.2E-04	6.8E-05	1.7E-03
Total	**100**	**7.3E-03**	**2.3E-03**	**1.7E-02**	**3.3E+00**	**9.4E-01**	**7.4E+00**	**1.1E+01**	**1.8E+00**	**3.5E+01**	**2.0E+00**	**4.6E-01**	**5.7E+00**
Water	500	4.7E-09	1.7E-09	9.7E-09	4.4E-08	1.5E-08	9.7E-08	4.0E-06	1.3E-06	8.8E-06	5.1E-07	1.7E-07	1.1E-06
Fish	500	8.3E-06	1.1E-06	2.7E-05	3.8E-05	4.9E-06	1.2E-04	1.7E+00	2.1E-01	5.3E+00	5.2E-01	6.8E-02	1.7E+00
Milk, from water	500	9.8E-07	2.7E-08	3.6E-06	3.2E-05	9.4E-07	1.2E-04	2.2E-07	6.2E-09	8.3E-07	5.5E-07	1.6E-08	2.1E-06
Meat, from water	500	1.4E-08	4.9E-10	5.3E-08	5.0E-06	1.6E-07	2.0E-05	1.3E-07	3.8E-09	5.2E-07	1.6E-07	5.0E-09	6.7E-07
Milk, from soil	500	3.2E-07	1.1E-08	1.2E-06	1.6E-04	4.2E-06	6.3E-04	1.6E-06	5.9E-08	6.4E-06	9.2E-06	3.7E-07	3.6E-05
Meat, from soil	500	1.6E-07	4.8E-09	6.0E-07	8.4E-04	2.1E-05	3.3E-03	3.1E-05	9.0E-07	1.2E-04	9.2E-05	3.4E-06	3.4E-04
Root crops	500	3.8E-03	4.9E-04	1.3E-02	6.0E-01	7.8E-02	2.0E+00	4.0E+01	4.6E+00	1.3E+02	5.7E+00	7.4E-01	1.8E+01
Tubers	500	1.9E-03	2.5E-04	6.2E-03	1.8E+00	2.3E-01	5.7E+00	1.1E+00	1.2E-01	3.6E+00	3.8E-01	4.6E-02	1.2E+00
Vegetables	500	1.3E-03	1.7E-04	4.1E-03	1.2E+00	1.5E-01	3.8E+00	5.8E-01	6.1E-02	2.0E+00	7.2E-01	9.2E-02	2.3E+00
Farmers, ext exposure	500	2.6E-04	2.1E-04	3.1E-04	1.9E-03	1.5E-03	2.3E-03	2.6E-29	1.0E-29	3.8E-29	4.2E-05	3.0E-05	5.0E-05
Farmers, inhalation	500	8.3E-09	1.1E-09	2.7E-08	4.1E-08	5.3E-09	1.3E-07	6.3E-03	7.4E-04	2.1E-02	1.8E-03	2.3E-04	5.7E-03
Total	**500**	**7.3E-03**	**2.3E-03**	**1.7E-02**	**3.6E+00**	**1.0E+00**	**8.2E+00**	**4.1E+01**	**5.8E+00**	**1.3E+02**	**6.8E+00**	**1.5E+00**	**2.0E+01**

Table 24: *Collective doses (manSv). Uncertainty analysis. (continued)*

Case B : Removal of soil & sediment

		Co-60			Cs-137			Pu-239			Am-241		
Exposure pathway	Year	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile
Water	100	6.6E-10	2.4E-10	1.4E-09	4.4E-09	1.5E-09	9.7E-09	4.0E-07	1.3E-07	8.8E-07	5.1E-08	1.7E-08	1.1E-07
Fish	100	3.3E-07	1.2E-07	6.8E-07	1.1E-05	3.6E-06	2.2E-05	1.9E-06	5.0E-07	4.4E-06	2.3E-06	7.0E-07	4.9E-06
Milk, from water	100	1.4E-07	3.9E-09	5.2E-07	3.2E-06	9.4E-08	1.2E-05	2.2E-08	6.2E-10	8.3E-08	5.5E-08	1.6E-09	2.1E-07
Meat, from water	100	2.1E-09	7.0E-11	7.6E-09	5.0E-07	1.6E-08	2.0E-06	1.3E-08	3.8E-10	5.2E-08	1.6E-08	5.0E-10	6.7E-08
Milk, from soil	100	4.6E-08	1.5E-09	1.7E-07	1.5E-05	3.8E-07	5.6E-05	4.3E-08	1.7E-09	1.7E-07	2.7E-07	1.0E-08	1.1E-06
Meat, from soil	100	2.2E-08	6.9E-10	8.5E-08	7.7E-05	1.9E-06	3.0E-04	8.2E-07	3.1E-08	3.1E-06	2.7E-06	1.1E-07	9.9E-06
Root crops	100	5.5E-04	7.0E-05	1.8E-03	5.5E-02	7.1E-03	1.8E-01	1.1E+00	1.4E-01	3.4E+00	1.7E-01	2.2E-02	5.5E-01
Tubers	100	2.8E-04	3.5E-05	8.8E-04	1.6E-01	2.1E-02	5.2E-01	2.8E-02	3.6E-03	9.1E-02	1.1E-02	1.4E-03	3.6E-02
Vegetables	100	1.9E-04	2.4E-05	5.8E-04	1.1E-01	1.4E-02	3.5E-01	1.6E-02	2.1E-03	5.0E-02	2.1E-02	2.8E-03	6.9E-02
Farmers, ext exposure	100	3.7E-05	3.0E-05	4.4E-05	1.8E-04	1.4E-04	2.1E-04	6.9E-31	5.2E-31	8.4E-31	1.3E-06	1.1E-06	1.4E-06
Farmers, inhalation	100	1.2E-09	1.6E-10	3.8E-09	3.8E-09	4.9E-10	1.2E-08	1.7E-04	2.1E-05	5.3E-04	5.2E-05	6.8E-06	1.7E-04
Total	**100**	**1.1E-03**	**3.3E-04**	**2.4E-03**	**3.3E-01**	**9.4E-02**	**7.4E-01**	**1.1E+00**	**1.8E-01**	**3.5E+00**	**2.0E-01**	**4.6E-02**	**5.7E-01**
Water	500	6.6E-10	2.4E-10	1.4E-09	4.4E-09	1.5E-09	9.7E-09	4.0E-07	1.3E-07	8.8E-07	5.1E-08	1.7E-08	1.1E-07
Fish	500	1.2E-06	1.6E-07	3.8E-06	3.8E-06	4.9E-07	1.2E-05	1.7E-01	2.1E-02	5.3E-01	5.2E-02	6.8E-03	1.7E-01
Milk, from water	500	1.4E-07	3.9E-09	5.2E-07	3.2E-06	9.4E-08	1.2E-05	2.2E-08	6.2E-10	8.3E-08	5.5E-08	1.6E-09	2.1E-07
Meat, from water	500	2.1E-09	7.0E-11	7.6E-09	5.0E-07	1.6E-08	2.0E-06	1.3E-08	3.8E-10	5.2E-08	1.6E-08	5.0E-10	6.7E-08
Milk, from soil	500	4.6E-08	1.5E-09	1.7E-07	1.6E-05	4.2E-07	6.3E-05	1.6E-07	5.9E-09	6.4E-07	9.2E-07	3.7E-08	3.6E-06
Meat, from soil	500	2.2E-08	6.9E-10	8.5E-08	8.4E-05	2.1E-06	3.3E-04	3.1E-06	9.0E-08	1.2E-05	9.2E-06	3.4E-07	3.4E-05
Root crops	500	5.5E-04	7.0E-05	1.8E-03	6.0E-02	7.8E-03	2.0E-01	4.0E+00	4.6E-01	1.3E+01	5.7E-01	7.4E-02	1.8E+00
Tubers	500	2.8E-04	3.5E-05	8.8E-04	1.8E-01	2.3E-02	5.7E-01	1.1E-01	1.2E-02	3.6E-01	3.8E-02	4.6E-03	1.2E-01
Vegetables	500	1.9E-04	2.4E-05	5.8E-04	1.2E-01	1.5E-02	3.8E-01	5.8E-02	6.1E-03	2.0E-01	7.2E-02	9.2E-03	2.3E-01
Farmers, ext exposure	500	3.7E-05	3.0E-05	4.4E-05	1.9E-04	1.5E-04	2.3E-04	2.6E-30	1.0E-30	3.8E-30	4.2E-06	3.0E-06	5.0E-06
Farmers, inhalation	500	1.2E-09	1.6E-10	3.8E-09	4.1E-09	5.3E-10	1.3E-08	6.3E-04	7.4E-05	2.1E-03	1.8E-04	2.3E-05	5.7E-04
Total	**500**	**1.1E-03**	**3.3E-04**	**2.4E-03**	**3.6E-01**	**1.0E-01**	**8.2E-01**	**4.1E+00**	**5.8E-01**	**1.3E+01**	**6.8E-01**	**1.5E-01**	**2.0E+00**

Table 24: *Collective doses (manSv). Uncertainty analysis. (continued)*

Case C1 : Soil washing

		Co-60			Cs-137			Pu-239			Am-241		
Exposure pathway	Year	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile
Water	100	1.6E-09	5.7E-10	3.2E-09	1.2E-08	4.2E-09	2.7E-08	1.1E-06	3.7E-07	2.4E-06	1.4E-07	4.7E-08	3.1E-07
Fish	100	7.8E-07	2.8E-07	1.6E-06	3.0E-05	1.0E-05	6.2E-05	5.2E-06	1.4E-06	1.2E-05	6.2E-06	1.9E-06	1.4E-05
Milk, from water	100	3.3E-07	9.1E-09	1.2E-06	9.0E-06	2.6E-07	3.4E-05	6.1E-08	1.7E-09	2.3E-07	1.5E-07	4.3E-09	5.7E-07
Meat, from water	100	4.8E-09	1.6E-10	1.8E-08	1.4E-06	4.5E-08	5.6E-06	3.5E-08	1.1E-09	1.4E-07	4.5E-08	1.4E-09	1.9E-07
Milk, from soil	100	1.1E-07	3.5E-09	3.9E-07	4.1E-05	1.1E-06	1.6E-04	1.2E-07	4.7E-09	4.7E-07	7.6E-07	2.8E-08	3.0E-06
Meat, from soil	100	5.2E-08	1.6E-09	2.0E-07	2.1E-04	5.2E-06	8.2E-04	2.3E-06	8.7E-08	8.5E-06	7.6E-06	3.0E-07	2.7E-05
Root crops	100	1.3E-03	1.6E-04	4.2E-03	1.5E-01	2.0E-02	5.0E-01	2.9E+00	3.8E-01	9.6E+00	4.6E-01	6.0E-02	1.5E+00
Tubers	100	6.4E-04	8.2E-05	2.1E-03	4.5E-01	5.8E-02	1.4E+00	7.8E-02	1.0E-02	2.5E-01	3.1E-02	4.0E-03	1.0E-01
Vegetables	100	4.3E-04	5.6E-05	1.4E-03	3.0E-01	3.9E-02	9.6E-01	4.3E-02	5.7E-03	1.4E-01	5.9E-02	7.8E-03	1.9E-01
Farmers, ext exposure	100	8.6E-05	7.0E-05	1.0E-04	4.9E-04	3.9E-04	5.9E-04	1.9E-30	1.4E-30	2.3E-30	3.5E-06	3.0E-06	3.9E-06
Farmers, inhalation	100	2.8E-09	3.6E-10	8.9E-09	1.1E-08	1.4E-09	3.4E-08	4.7E-04	5.9E-05	1.5E-03	1.5E-04	1.9E-05	4.6E-04
Total	**100**	**2.4E-03**	**7.7E-04**	**5.6E-03**	**9.0E-01**	**2.6E-01**	**2.1E+00**	**3.0E+00**	**5.0E-01**	**9.7E+00**	**5.5E-01**	**1.3E-01**	**1.6E+00**
Water	500	1.6E-09	5.7E-10	3.2E-09	1.2E-08	4.2E-09	2.7E-08	1.1E-06	3.7E-07	2.4E-06	1.4E-07	4.7E-08	3.1E-07
Fish	500	7.8E-07	2.8E-07	1.6E-06	3.0E-05	1.0E-05	6.2E-05	5.3E-06	1.4E-06	1.2E-05	6.2E-06	1.9E-06	1.4E-05
Milk, from water	500	3.3E-07	9.1E-09	1.2E-06	9.0E-06	2.6E-07	3.4E-05	6.1E-08	1.7E-09	2.3E-07	1.5E-07	4.3E-09	5.7E-07
Meat, from water	500	4.8E-09	1.6E-10	1.8E-08	1.4E-06	4.5E-08	5.6E-06	3.5E-08	1.1E-09	1.4E-07	4.5E-08	1.4E-09	1.9E-07
Milk, from soil	500	1.1E-07	3.5E-09	3.9E-07	4.5E-05	1.2E-06	1.7E-04	4.5E-07	1.7E-08	1.8E-06	2.6E-06	1.0E-07	9.9E-06
Meat, from soil	500	5.2E-08	1.6E-09	2.0E-07	2.3E-04	5.8E-06	9.0E-04	8.6E-06	2.5E-07	3.4E-05	2.6E-05	9.3E-07	9.5E-05
Root crops	500	1.3E-03	1.6E-04	4.2E-03	1.7E-01	2.2E-02	5.5E-01	1.1E+01	1.3E+00	3.6E+01	1.6E+00	2.1E-01	5.1E+00
Tubers	500	6.4E-04	8.2E-05	2.1E-03	4.9E-01	6.3E-02	1.6E+00	3.0E-01	3.2E-02	9.9E-01	1.1E-01	1.3E-02	3.3E-01
Vegetables	500	4.3E-04	5.6E-05	1.4E-03	3.3E-01	4.3E-02	1.1E+00	1.6E-01	1.7E-02	5.6E-01	2.0E-01	2.5E-02	6.5E-01
Farmers, ext exposure	500	8.6E-05	7.0E-05	1.0E-04	5.3E-04	4.1E-04	6.5E-04	7.3E-30	2.9E-30	1.1E-29	1.2E-05	8.3E-06	1.4E-05
Farmers, inhalation	500	2.8E-09	3.6E-10	8.9E-09	1.2E-08	1.5E-09	3.7E-08	1.8E-03	2.0E-04	5.7E-03	4.9E-04	6.3E-05	1.6E-03
Total	**500**	**2.4E-03**	**7.7E-04**	**5.6E-03**	**9.9E-01**	**2.9E-01**	**2.3E+00**	**1.2E+01**	**1.6E+00**	**3.7E+01**	**1.9E+00**	**4.1E-01**	**5.4E+00**

Table 24: *Collective doses (manSv). Uncertainty analysis. (continued)*

Case D1 : Capping

		Co-60			Cs-137			Pu-139			Am-241		
Exposure pathway	Year	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile	Mean	5%tile	95%tile
Water	100	4.7E-10	1.7E-10	9.7E-10	4.4E-09	1.5E-09	9.7E-09	4.0E-07	1.3E-07	8.8E-07	5.1E-08	1.7E-08	1.1E-07
Fish	100	2.3E-07	8.3E-08	4.8E-07	1.1E-05	3.6E-06	2.2E-05	1.9E-06	5.0E-07	4.4E-06	2.3E-06	7.0E-07	4.9E-06
Milk, from water	100	9.8E-08	2.7E-09	3.6E-07	3.2E-06	9.4E-08	1.2E-05	2.2E-08	6.2E-10	8.3E-08	5.5E-08	1.6E-09	2.1E-07
Meat, from water	100	1.4E-09	4.9E-11	5.3E-09	5.0E-07	1.6E-08	2.0E-06	1.3E-08	3.8E-10	5.2E-08	1.6E-08	5.0E-10	6.7E-08
Milk, from soil	100	3.2E-08	1.1E-09	1.2E-07	1.5E-05	3.8E-07	5.6E-05	4.3E-08	1.7E-09	1.7E-07	2.7E-07	1.0E-08	1.1E-06
Meat, from soil	100	1.6E-08	4.8E-10	6.0E-08	7.7E-05	1.9E-06	3.0E-04	8.2E-07	3.1E-08	3.1E-06	2.7E-06	1.1E-07	9.9E-06
Root crops	100	3.8E-04	4.9E-05	1.3E-03	5.5E-02	7.1E-03	1.8E-01	1.1E+00	1.4E-01	3.4E+00	1.7E-01	2.2E-02	5.5E-01
Tubers	100	1.9E-04	2.5E-05	6.2E-04	1.6E-01	2.1E-02	5.2E-01	2.8E-02	3.6E-03	9.1E-02	1.1E-02	1.4E-03	3.6E-02
Vegetables	100	1.3E-04	1.7E-05	4.1E-04	1.1E-01	1.4E-02	3.5E-01	1.6E-02	2.1E-03	5.0E-02	2.1E-02	2.8E-03	6.9E-02
Farmers, ext exposure	100	2.6E-05	2.1E-05	3.1E-05	1.8E-04	1.4E-04	2.1E-04	6.9E-31	5.2E-31	8.4E-31	1.3E-06	1.1E-06	1.4E-06
Farmers, inhalation	100	8.3E-10	1.1E-10	2.7E-09	3.8E-09	4.9E-10	1.2E-08	1.7E-04	2.1E-05	5.3E-04	5.2E-05	6.8E-06	1.7E-04
Total	**100**	**7.3E-04**	**2.3E-04**	**1.7E-03**	**3.3E-01**	**9.4E-02**	**7.4E-01**	**1.1E+00**	**1.8E-01**	**3.5E+00**	**2.0E-01**	**4.6E-02**	**5.7E-01**
Water	500	4.7E-10	1.7E-10	9.7E-10	4.4E-09	1.5E-09	9.7E-09	4.0E-07	1.3E-07	8.8E-07	5.1E-08	1.7E-08	1.1E-07
Fish	500	2.3E-07	8.3E-08	4.8E-07	1.1E-05	3.6E-06	2.2E-05	1.9E-06	5.0E-07	4.4E-06	2.3E-06	7.0E-07	4.9E-06
Milk, from water	500	9.8E-08	2.7E-09	3.6E-07	3.2E-06	9.4E-08	1.2E-05	2.2E-08	6.2E-10	8.3E-08	5.5E-08	1.6E-09	2.1E-07
Meat, from water	500	1.4E-09	4.9E-11	5.3E-09	5.0E-07	1.6E-08	2.0E-06	1.3E-08	3.8E-10	5.2E-08	1.6E-08	5.0E-10	6.7E-08
Milk, from soil	500	3.2E-08	1.1E-09	1.2E-07	1.6E-05	4.2E-07	6.3E-05	1.6E-07	5.9E-09	6.4E-07	9.2E-07	3.7E-08	3.6E-06
Meat, from soil	500	1.6E-08	4.8E-10	6.0E-08	8.4E-05	2.1E-06	3.3E-04	3.1E-06	9.0E-08	1.2E-05	9.2E-06	3.4E-07	3.4E-05
Root crops	500	3.8E-04	4.9E-05	1.3E-03	6.0E-02	7.8E-03	2.0E-01	4.0E+00	4.6E-01	1.3E+01	5.7E-01	7.4E-02	1.8E+00
Tubers	500	1.9E-04	2.5E-05	6.2E-04	1.8E-01	2.3E-02	5.7E-01	1.1E-01	1.2E-02	3.6E-01	3.8E-02	4.6E-03	1.2E-01
Vegetables	500	1.3E-04	1.7E-05	4.1E-04	1.2E-01	1.5E-02	3.8E-01	5.8E-02	6.1E-03	2.0E-01	7.2E-02	9.2E-03	2.3E-01
Farmers, ext exposure	500	2.6E-05	2.1E-05	3.1E-05	1.9E-04	1.5E-04	2.3E-04	2.6E-30	1.0E-30	3.8E-30	4.2E-06	3.0E-06	5.0E-06
Farmers, inhalation	500	8.3E-10	1.1E-10	2.7E-09	4.1E-09	5.3E-10	1.3E-08	6.3E-04	7.4E-05	2.1E-03	1.8E-04	2.3E-05	5.7E-04
Total	**500**	**7.3E-04**	**2.3E-04**	**1.7E-03**	**3.6E-01**	**1.0E-01**	**8.2E-01**	**4.1E+00**	**5.8E-01**	**1.3E+01**	**6.8E-01**	**1.5E-01**	**2.0E+00**

6. Ranking of restoration options at the Molse Nete river.

In this section the multi-attribute utility (MAU) analysis is resumed, that has been carried out for ranking the remediation options envisaged for the site of the Molse Nete in TD8 (Hedemann Jensen, 1999). Cost-benefit analysis has also been applied to evaluate if the remediation options are justified on economic grounds. Moreover, annual individual doses to critical groups before implementation of remedial measures have been assessed for comparison with the clean-up criteria recommended by IAEA.

6.1 Evaluation of remediation options (MAU analysis)

6.1.1 Attributes

The attributes that has been considered in this study includes:

- ☐ *Health attributes*
    - collective doses to population
    - doses to remediation workers
    - non-radiological health factors
- ☐ *Economic attributes*
    - costs of remedial actions (incl. costs of labour and monitoring)
    - costs of monitoring of remedial options
    - costs of disposal of generated waste (in broad categories)
    - loss/gain of taxes due to loss/gain of income
- ☐ *Social attributes*
    - reassurance of the public
    - discomfort, disturbance and anxiety from the remedial action
    - loss/gain of income

The restoration options included for the Molse Nete site have been identified in Chapter 4 (Table 21). The economical and radiological data for quantifying the various attributes for each of those options are shown in Table 25.

6.1.2 Utilities

Utility functions for the attributes *monetary costs* and *radiation doses* have been calculated from the figures in Table 25 on monetary cost components and residual collective doses after remediation. Linear (risk neutral) utility functions have been used.

Table 25: *Remediation costs and collective doses to population and workers for different restoration strategies at the Molse Nete River site.*

Restoration strategy	Collective dose to population [man Sv]		Collective dose to workers	Monetary costs of restoration [kEUR]				Fraction of activity left on-site	Waste volume (m^3)
	100 y	500 y	[man·Sv]	Remediation	Monito-ring	Waste disposal	Inc. loss		
							Tax loss		
A	16	51	0	0	3,200	0	0	1	0
							0		
B	1.6	5.1	$6.1 \cdot 10^{-4}$	3,570	1,000	19,580	0	0.1	26,520
							0		
C1	4.5	14	$1.8 \cdot 10^{-3}$	12,870	2,000	13,260	0	0.3	5,300
							0		
D1	1.6	5.1	$1.6 \cdot 10^{-3}$	13,970	2,000	13,260	0	0.1	10,600
							0		
E1	negli.	negli.	$2.6 \cdot 10^{-3}$	4,250	3,200	0	68	1	0
							1,360		
F1	negli.	negli.	$6.7 \cdot 10^{-3}$	6,220	3,200	0	68	1	0
							1,360		
F2	negli.	negli.	$1.8 \cdot 10^{-3}$	5,810	3,200	0	68	1	0
							1,360		
G1	negli.	negli.	$6.7 \cdot 10^{-3}$	8,340	3,200	0	68	1	0
							1,360		
G2	negli.	negli.	$1.8 \cdot 10^{-3}$	5,810	3,200	0	68	1	0
							1,360		

6.1.2.1 Utility functions for monetary costs

Utility functions have been determined for remediation costs (including labour costs), waste disposal costs (including transport costs), monitoring costs and loss of taxes due to loss of income:

$$u_{\mathrm{remedia}}(x) = 100 \cdot \left(1 - \frac{x}{13{,}970}\right) \quad \text{for } 0 \le x \le 13{,}970 \text{ kEUR}$$

$$u_{waste}(x) = 100 \cdot \left(1 - \frac{x}{19{,}580}\right) \quad \text{for } 0 \le x \le 19{,}580 \text{ kEUR}$$

$$u_{tax}(x) = 100 \cdot \left(1 - \frac{x}{1{,}360}\right) \quad \text{for } 0 \le x \le 1{,}360 \text{ kEUR over 100 y}$$

$$u_{monitor}(x) = 100 \cdot \left(1 - \frac{x}{3{,}200}\right) \quad \text{for } 0 \le \mathrm{x} \le 1{,}000 \text{ kEUR over 100 y}$$

6.1.2.2 Utility functions for health factors

The following utility functions for the radiological health components have been determined for the exposed population and workers implementing the remedial actions. Only radiological health factors are considered for the Molse Nete River site as no heavy metals are found.

$$u_{\text{dose, pop,100}}(x) = 100 \cdot \left(1 - \frac{x}{16}\right) \text{ for } 0 \le x \le 16 \text{ man Sv}$$

$$u_{\text{dose, pop,500}}(x) = 100 \cdot \left(1 - \frac{x}{51}\right) \quad \text{for } 0 \le x \le 51 \text{ man Sv}$$

$$u_{\text{dose, work}}(x) = 100 \cdot \left(1 - \frac{x}{0.0067}\right) \quad \text{for } 0 \le x \le 0.0067 \text{ man Sv}$$

6.1.2.3 Utility functions for social factors

The utility function u_{reas} for reassurance would be linked to both the residual dose and the fraction of activity remaining on the site after the remedial measure has been implemented. However, the residual dose and remaining activity are not necessarily correlated. A remedial measure that has left all the activity on site in a contained form (capping, surface barriers etc.) might give a substantial dose reduction and thus a low value of the residual doses. Detailed information on how social factors like reassurance are linked with individual doses and activity concentration on site is not available. Therefore, utility functions for 100 years and 500 years integration time have been proposed which gives a low value only when both sub-utilities have low values:

$$u_{\text{reas,100}}(x,y) = 100 \cdot \left(\frac{1}{2} \cdot \left(1 - \frac{x}{16}\right)_{\text{dose}} + \frac{1}{2} \cdot \left(1 + \frac{0.1 - y}{1.0 - 0.1}\right)_{\text{activity}}\right)$$

for $0 \le x \le 16$ man Sv and $0.1 \le \mathrm{y} \le 1$

$$u_{\text{reas,500}}(x,y) = 100 \cdot \left(\frac{1}{2} \cdot \left(1 - \frac{x}{51}\right)_{\text{dose}} + \frac{1}{2} \cdot \left(1 + \frac{0.1 - y}{1.0 - 0.1}\right)_{\text{activity}}\right)$$

for $0 \le x \le 51$ man Sv and $0.1 \le y \le 1$

where y is the fraction of activity remaining on site after the remedial measures has been implemented. The value of the utility function u_{reas} will be 100 for a residual dose of 0 man Sv and a remaining fraction of the initial activity of 0.1 (best strategy) and 0 for a residual dose of 16 (51) man Sv and a remaining activity fraction of 1.0 (worst strategy).

The utility function u_{distur} for disturbance has been related to the volume of soil and sediment waste to be transported to the waste disposal site:

$$u_{distur}(x) = 100 \cdot \left(1 - \frac{x}{26{,}520}\right) \quad \text{for } 0 \le x \le 26{,}520 \text{ m}^3$$

For the remedial option C1 the waste volume is 26,520 m^3 and for the options D1 and D2 it is 5,300 m^3. No waste is produced for all other options.

The utility function u_{loss} for loss of income due to loss of agricultural production facilities can be determined from the specific agricultural production pattern per unit area weighted with the market price of the production.

The income loss has been determined to be about 1 $\text{EUR}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$. It is, however, very likely that the farmers soon would find other income. The loss is therefore assumed to last only for two years, which will give the following utility function:

$$u_{loss}(x) = 100 \cdot \left(1 - \frac{x}{68}\right) \quad \text{for } 0 \le x \le 68 \text{ kEUR over 2 years}$$

6.1.3 Weighting factors

Weighting factors are scaling factors that reflect the relative importance of each of the attributes. The weighting factors assigned to the different attributes at the same hierarchy level can be either the ratio of value ranges, *R*, of the attributes or by assigning values to the ratio of the weighting factors at that level. Both methods have been used here.

6.1.3.1 Weighting factors for major attributes

The major weighting factors considered in this study include those for monetary costs, health and social factors. The sum of these weighting factors should respect the following conditions:

$$w_{health} + w_{economic} + w_{social} = 1$$

The assessment of the weighting factors is discussed in TD8 where conversion/scaling constants between weighting factors for the major attributes has been expressed as:

$$C_1 = \frac{w_{economic}}{w_{health}} \cong \frac{w_{economic}}{w_{dose,pop}} = \frac{R_{economic}}{\alpha \cdot R_{dose,pop}}$$

$$C_2 = \frac{w_{social}}{w_{health}} \approx \frac{r_{psy}}{r_{rad}}$$

C_1 can be determined for a 100 and 500 years integration time for the collective dose from the values given in Table 25. The value of C_2 is more difficult to assess but a value of 0.2 - 0.3 has been argued for in TD8. From these values C_1 and C_2 the weighting factors for health, economic and social factors have been calculated as shown in Table 26. The values indicated in the left of the double columns are for an integration time of 100 years for the collective dose; the values in the right are for an integration time of 500 years.

Table 26: *Weighting factors for attributes and sub-attributes applied in the ranking of remediation options.*

Health factors			Economic factors		Social factors	
0.057	0.157		0.929	0.803	0.014	0.039
Dose population	1	1	Remediation costs	0.37	Reassurance	0.63
Dose workers	0	0	Waste disposal costs	0.51	Disturbance	0.11
Non -radiation	-	-	Monitoring costs	0.084	Loss / gain of income	0.26
			Loss / gain of taxes	0.036		

6.1.3.2 Weighting factors for health sub-attributes

The weighting factors for health sub-attributes include those of radiation induced stochastic health effects to the affected population and workers and non-radiation induced stochastic health effects to the affected population. The sum of these weighting factors should respect the following conditions:

$$w_{dose,pop} + w_{dose,work} + w_{non-rad} = 1$$

The conversion/scaling constant, *C*, for the health attributes can according to TD8 be expressed as:

$$w_{dose,pop} = C \cdot R_{dose,pop} \cdot l \cdot r_{rad} \cong C \cdot R_{dose,pop}$$

$$w_{dose,work} = C \cdot R_{dose,work} \cdot l \cdot r_{rad} \cong C \cdot R_{dose,pop}$$

$$w_{non-rad,pop} = C \cdot R_{non-rad,pop} \cdot l \cdot r_{non-rad}$$

Exposure to heavy metals is not relevant for the Molse Nete River site and $R_{non\text{-}rad}$ is therefore zero. The value of *C* is given by:

$$C = \frac{1}{R_{dose,pop} + R_{dose,work}}$$

From the calculated values of C_{100} and C_{500} (for 100 and 500 years integrating time for the collective dose) the weighting factors for collective population and worker doses have been calculated as shown in Table 26.

6.1.3.3 Weighting factors for economic sub-attributes

The weighting factors for economic sub-attributes include those for cost of remediation, cost of waste disposal, costs of monitoring and loss/gain of taxes. The sum of these weighting factors should respect the following conditions:

$$w_{remedia} + w_{waste} + w_{monitor} + w_{tax} = 1$$

The conversion/scaling constant, *C*, for the economic attributes can according to TD8 be expressed as:

$$w_{remedia} = C \cdot R_{remedia}$$

$$w_{waste} = C \cdot R_{waste}$$

$$w_{monitor} = C \cdot R_{monitor}$$

$$w_{tax} = C \cdot R_{tax}$$

The conversion/scaling constant, *C*, for the economic sub-attributes can be determined from the cost ranges in Table 6.1 and the weighting factors for remediation costs, waste disposal costs and monitoring costs have been calculated as shown in Table 26

6.1.3.4 Weighting factors for social sub-attributes

The weighting factors include those for reassurance, disturbance and loss/gain of taxes. The sum of these weighting factors should respect the following conditions:

$$w_{distur} + w_{reas} + w_{loss} = 1$$

The conversion/scaling constants for the social sub-attributes can according to TD8 be expressed as:

$$C_1 = \frac{w_{reas}}{w_{distur}} \text{ and } C_2 = \frac{w_{loss}}{w_{distur}}$$

In TD8 it is argued that $w_{reas} > w_{loss} > w_{distur}$ and that $C_1 \approx 5 - 7$ and $C_2 \approx 2 - 3$. From these values the weighting factors for disturbance, reassurance and tax loos/gain have been calculated as shown in Table 26.

It should be emphasized that value setting of weighting factors is the crucial issue of any optimisation because subjective judgements inevitably will enter the process.

6.2 Results

IAEA has proposed clean-up criteria in terms of individual doses (International Atomic Energy, 1997). The individual doses assessed at the Molse Nete River site are of the order of 600 μSv·a^{-1} at the time of decision to introduce remediation (year 1). According to the IAEA criteria, clean-up is usually needed for an individual dose range of 0.1 - 1 mSv·a^{-1} if a constraint for controlled practices is applied. Even without the application of a constraint, IAEA suggests that for individual doses of 0.1 - 1 mSv·a^{-1} clean-up might sometimes be needed. Based on these recommendations it can therefore be concluded that some kind of remediation would almost always be justified for the Molse Nete River site.

In a cost-benefit approach, the monetary costs, X, of the remediation strategies are compared with the benefit of the collective dose reduction, ΔS. The net benefit, ΔB, is given as:

$$\Delta B = \alpha \cdot \Delta S - (\alpha \cdot S_{work} + X_{remedia} + X_{waste} + X_{tax} + X_{monitor})$$

None of the remedial options are justified on economical grounds alone when only the central estimates of collective dose are used together with an α-value of 100,000 EUR·manSv^{-1} (Swedish Radiation Protection Institute, 1991). A higher value of α (*e.g.* 200,000 EUR·manSv^{-1}) and more extreme values from the calculated collective dose distribution (*e.g.* the 95th percentile (see TD6)) would make the options E1, F1, F2, G1 and G2 economically justified when the avertable collective dose is taken over 100 years. Similarly, the options B, E1, F1, F2, G1 and G2 would be economically justified for an integration time of 500 years and more extreme values of the collective doses. It should be emphasized that the dose assessments are based on conservative assumptions concerning the habits of the affected population and the usage of the contaminated sediments. More realistic assumptions would have resulted in much lower doses.

In the multi-attribute approach, overall scores, U_i, of the remediation options i has been determined from the weighted sum of utilities for each of the attributes considered:

$$\begin{aligned} U_i &= \sum_{j=1}^{3} w_j \cdot u_{ij} \\ &= w_{health} \cdot (w_{dose,pop} \cdot u_{dose,pop} + w_{dose,work} \cdot u_{dose,work}) \\ &+ w_{economic} \cdot (w_{waste} \cdot u_{waste} + w_{remedia} \cdot u_{remedia} + w_{monitor} \cdot u_{monitor} + w_{tax} \cdot u_{tax}) \\ &+ w_{social} \cdot (w_{distur} \cdot u_{distur} + w_{reas} \cdot u_{reas} + w_{loss} \cdot u_{loss}) \end{aligned}$$

The weighting factors above have all been sampled in a triangular distribution between 0.67 - 1.5 times the most probable value given in Table 26. Similarly, the values of all the utilities, $u(x)$, are determined from the utility functions in which the values of x are sampled in a triangular distribution between 0.67 - 1.5 times the central values of x given in Table 25. Negative correlation between collective doses and remediation costs has been applied with a correlation coefficient of – 0.8. The evaluation of the different strategies has been made with the forecasting and risk analysis program CRYSTAL BALL. Latin Hypercube Sampling technique was used and the number of trials were 10,000. The results for the scores, U_i, for the options A - G2 are shown in Figure 14. The error bars represent the 5% and 95% percentiles of the distributions of U_i. The left picture shows the results for an integration time of 100 years for the collective dose; the right picture for an integration time of 500 years.

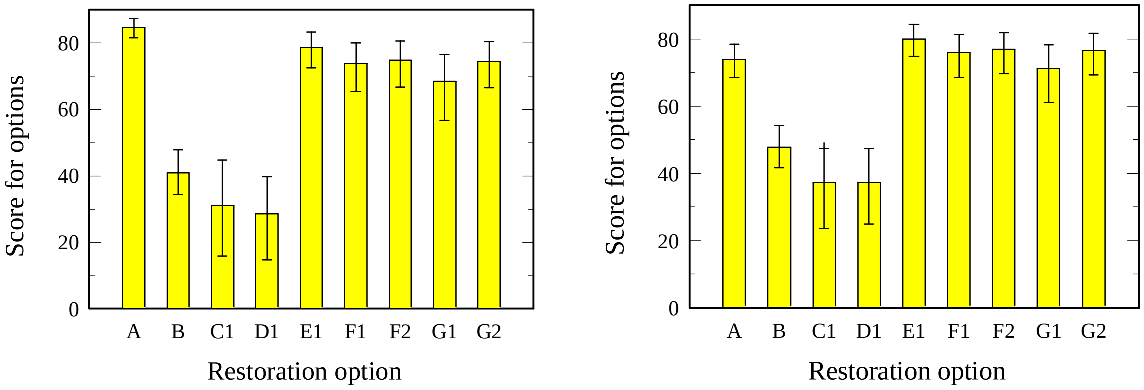

Figure 14: *Overall evaluation of scores for the remediation strategies considered.*

It appears from this figure that there is practically no difference between the scores for an integration time of 100 and 500 years due to the low weight of the health attributes although the score for option A is somewhat lower for the longer integration time. The options A, E1, F1, F2, G1 and G2 have practically an equal score which makes it rather difficult to distinguish which is the optimum. For a 500-years integration time the option E1, capping, has the highest score, and this option can therefore be considered as the optimum.

The ranking of the different remedial measures using multi-attribute utility analyses allows the inclusion of factors that are not easy to quantify in monetary terms as is required in cost-benefit analysis. The weighting factors assigned to the different attributes have been determined by use of scaling factors in terms of weighting factor ratios, and their values were sampled around a most probable value. Notwithstanding this advantage of the multi-attribute method there are difficulties with the determination of weighting factors for the different attributes. Without any terms of reference for the weighting between attributes, value settings by a decision maker could lead to ‘optimised’ results that might be useless because of a subjective bias of the decision maker in the selection of weighting factors. Therefore, the outcome of any multi-attribute analysis, including the present study, should be judged very carefully in the light of the values assigned to the weighting factors before any firm conclusions could be drawn.

7. Conclusions

In this technical deliverable the example site of the Molse Nete river has been characterised in detail for the purpose of demonstrating the applicability of the methodology for ranking for restoration techniques, developed in the RESTRAT project. A list of potentially relevant restoration techniques has been drawn up and the ranking of the techniques carried out.

Concerning the outcome of the ranking procedure, “no remediation” has been shown to be the optimal solution, when the radiological impact is integrated over 100 year and “capping” followed by immobilisation techniques when the radiological impact is integrated over 500 years. This outcome is due to the high economic costs associated with restoration, resulting in a weighting factor of 0.93 (100 years) or 0.80 (500 years radiological impact) for those costs. Within the economic costs, the costs for waste disposal play a very important role and this explains why options producing no waste, are ranked higher than those in which important quantities of contaminated soil or sediment are to be disposed of.

However, the outcome indicated above is only valid if a deterministic assessment with central values is carried out. If the uncertainties associated with weighting factors and utility values of the attributes are taken into account, relatively large uncertainties as to the ranking of the restoration techniques arise. The conclusion of the ranking procedure would then be that six of the nine remediation options considered are equivalent (e.g. not significantly different). Only the options, in which radioactive waste had to be disposed of, are then ranked significantly lower.

With respect to the way how the attributes considered have been quantified, the radiological impact on the population has been assessed through very conservative assumptions as far as the “no remediation” and removal and separation techniques are concerned. More realistic exposure conditions would have led to lower dose values for those options and a lower weighting factor for this attribute.

The social factors, being very difficult to quantify, have been replaced by objective measures, such as activity left on site, residual dose and waste transport. Their weighting factor has been determined rather arbitrarily, based on experience in situations, that were totally different from those of the Molse Nete river. Determination of the weighting factor on another basis, with participation of the interested groups of the public and of competent authorities, may lead to a much higher value and a higher influence of social factors on the outcome of the ranking procedure.

8. References

Bladt A., Byloos J., Demaree G. And Van der Beken A. Hydrologische balansen in : Grondwaterbeleid in de provincie Antwerpen. Eindverslag voor het Deelcontract 7 PIDPA-VUB juni 1976-november 1977, 1977.

Bodemkaart van België. Kaartblad en verklarende tekst van Meerhout 46W (schaal 1:20 000). Comité voor het opnemen van de Bodemkaart en de Vegetatiekaart van België, Gent, 1969.

Cnudde J.P. Hydrologische studie van het plassengebied van Mol. R.U.G., Leerstoel Toegepaste Geologie.

Deworm J.P., Govaerts P. De impakt van de lozing van vloeibare radioactieve effluenten op de Molse Nete en haar omgeving. ES-7-13, SCK. September 1990.

Fieuw G., Deworm J.P., Govaerts P., Marlein J., Slegers W. Bilan van de geloosde radioactieve gasvormige en vloeibare effluenten. SKV 87-490/F119, 1987.

Geologische kaart van België - Vlaams gewest. Kaartblad 17 : Mol (schaal 1:50 000). Ministerie van Economische zaken. Belgische Geologische dienst, 1995.

Hedemann Jensen P. Methodology for ranking restoration options., RESTRAT Technical Deliverable 8. Risoe National Laboaratory, Roskilde, Denmark, 1999.

International Atomic Energy Agency. Application of radiation protection principles to the clean-up of contaminated areas. IAEA-TECDOC-987 (1997).

Konings J., Kirchman R., Dupont J.C., Breugelmans M. Behavior of radionuclides and heavy metals in the Nete river (N. Belgium). Part I: Radionuclides. Progress report of a research program under the sponsorship of I.U.R. Project B.T.K. 8159. December 1980.

Metayer-Piret M., Gerber G.B., Konings J., Colard J., Koch G. Behaviour of long-lived radionuclides released into a small river by a nuclear installation at Mol, Belgium. Environmental migration of long-lived radionuclides, p. 517 - 524. Proceedings of an international symposium on migration in the terrestrial environment of long-lived radionuclides from the nuclear fuel cycle. IAEA, 1982.

Metayer-Piret M., Kirchmann R, Konings J. Etude radioecologique des sites Molse Neet et Witte Neet. Etat d'avancement des travaux effectués durant la période du 1/1/1979 au 31/12/1979. SCK rapport, Decembre 1980.

Metayer-Piret M., Kirchmann R. Etude radioecologique des sites Molse Neet et Witte Neet. Etat d'avancement des travaux effectués durant la période du 1/1/1978 au 31/12/1978. Volume I: Sediments. SCK rapport, Janvier 1979.

Metayer-Piret M., Kirchmann R. Etude radioecologique des sites Molse Neet et Witte Neet. Etat d'avancement des travaux effectués durant la période du 1/1/1978 au 31/12/1978. Volume II: Eaux, matières en suspension et sédimentées. SCK rapport, Novembre 1979.

Piret M., Kirchman R., Hospied M. Etude radioecologique des sites Molse Neet et Witte Neet. Etat d'avancement des travaux effectués durant la période du 1/1/1977 au 31/12/1977. SCK rapport, Fevrier 1978.

Slegers W. Meting van het stralingsniveau langs de Molse Nete. Verslag van metingen uitgevoerd door SCK•CEN en B.P. SCK rapport, Onderzoekseenheid Stralingsbescherming, Dienst Stralings-kontrole SKV/94-242. April, 1994.

Stiglund Y., Nordlinder S. Risk assessment model for use in site restoration. General methodology and site-specific aspects., RESTRAT Technical Deliverable 6. Studsvik Eco & Safety, Nyköping, Sweden, 1999.

Swedish radiation Protection Institute. The monetary value of collective dose reduction (alfa value). Statement from meeting of the Nordic Radiation Protection Authorities (Denmark, Finland, Iceland, Norway and Sweden) at Reykjavik, 14 June 1991. Stralskyddsnytt 4/91. Swedish radiation Protection Institute (1991)

Van de Voorde N. De rol van riviersedimenten bij de reconcentratie van effluentenradioaktiviteit. Proefschrift tot het bekomen van de licentie in Radioprotectie, K.U.L, 1968.

Wemaere I., Marivoet J. Geological disposal of conditioned high-level and long-lived radioactive waste. Updated regional hydrogeological model for the Mol site (The north-eastern Belgium model). Report to NIRAS/ONDRAF, R-3060, February 1995.

Zeevaert Th., Fieuw G., Kirchman R., Koch G., Vandecasteele C.M. Assessment of the dose to man from the sediments of a river receiving radioactive effluents released by a waste treatment facility. Annalen van de Belgische vereniging voor stralingsbescherming, 12, n° 2-3, 1987.

Zeevaert Th., Bousher A. Restoration Techniques : Characteristics and Performances., RESTRAT Technical Deliverable 3+4. SCK•CEN, Mol, Belgium - Westlakes S.C., Moor Row, Cumbria, UK., 1998.

Appendix 1 : Determination of waste volumes and activity left on site

1. Quantities of contaminated sediment and soil contaminated through application of bed sediment

Amount of bed sediment dredged out from the Molse Nete river onto the banks
Net sedimentation rate: 1.8 mg/m²/s
Surface area of the Molse Nete downstream discharge point: 5x6,800 = 34,000 m²
Quantity of sediment dredged out annually to prevent filling up: 1,930 tonne/y = 1,300 m³/y
(for a density of 1.6)
Quantity of bed sediment dredged out over 30 years: 39,000 m³

Surface area of agricultural soil contaminated through sediment
Arabale land is estimated to be present over 5% at one border of the Molse Nete
Pasture is estimated to be present over 20% at one border
Assuming that 1/5 of them receives sediment over 100m width, yields:
Contaminated surface area of arable land = 6,800 m²
Contaminated surface area of pasture = 27,200 m²

Amounts of agricultural soil contaminated through sediment
Estimated application rate of sediment on arable land:16 kg/m² every 5 year = 0.002 m/y
Estimated application rate of sediment on pasture: 8 kg/m² every 5 year = 0.001 m/y
Total amount of sediment applied on arable land: 6,800x0.002 = 13.6 m³/y
Total amount of sediment applied on pasture: 27,200x0.001 = 27.2 m³/y

Assuming that the contamination of the fields is mixed over 0.30 m, the volume of arable land that is contaminated, amounts to: 2,040 m³
Assuming that the contamination of the pasture is mixed over 0.15 m, the volume of pasture soil that is contaminated, amounts to: 4,080 m³
Total amount of contaminated agricultural soil: 6,120 m³

Amount of sediment left on the banks
Quantity of bed sediment left on the banks: 1,300 - 40 = 1,260 m³/y
Quantity accumulated over 30 years: 37,800 m³
(assuming that this sediment is spread out at one border of the river over the entire length and 5 m width, the thickness of this layer is approx. 1 m.)

Amount of contaminated sediment left on the river bed
Estimated thickness of contaminated sediment layer: 0.30 m
Amount of contaminated bed sediment in the Molse Nete: 10,200 m³

2. Quantities of soil contaminated through irrigation

Surface area of agricultural soil contaminated through irrigation
Assuming that all pastures and arable land along the Molse Nete are irrigated with water from the Nete, the surface areas that are contaminated amount to: 34,000 m² of arable land; and
136,000 m² of pasture.
Of this surface areas 6,800 m² arable land and 27,200 m² pasture are also contaminated through application of sediment.

Amounts of agricultural soil contaminated through irrigation

Assuming a thickness of 0.30 m for the contaminated soil layer of arable land, yields a contaminated volume of 10,200 m³ contaminated arable land. From this volume 2,040 m³ is also contaminated through sediment.
Assuming a thickness of 0.15 m for the contaminated soil layer of pasture, yields a contaminated volume of 20,400 m³ contaminated pasture soil. From this volume 4,080 m³ is also contaminated through sediment.

Appendix 2 : Determination of cost factors

1. Unit costs

The costs calculated in this chapter refer to the restoration techniques applied (including labour costs!), excavation for ex-situ treatments (including transport), and waste disposal (including transport). The unit cost values applied are derived from (Zeevaert and Bousher, 1998), taking into account the site-specific conditions for determining the best-estimate values.

B. Soil and sediment removal

Relatively high costs for excavation, because of bad accessibility of the terrain

Soil scraping not taken into account

- *Soil excavation* (also to be taken into account for the ex-situ separations afterwards)

Excavation costs including transport (soil - bed sediment)	125 - 150 EUR / m^3
Excavation costs including transport and RCRA disposal (soil - bed sediment)	700 - 800 EUR / m^3
(this type of disposal could be assumed for disposal of the total contaminated soil)	
Disposal cost for radioactive waste including transport	2500 EUR / m^3
(this type of disposal could be assumed for disposal of the most contaminated fraction, after separation)	

C. Physical Separation (ex-situ)

Transport and disposal of the most contaminated fraction afterwards not taken into account

- *Soil washing*

excavation and transport of the soil - sediment (prior to washing)	125 - 150 EUR/m^3
soil washing costs	350 EUR/m^3

D. Chemical Separation (ex-situ)

Transport and disposal of the most contaminated fraction afterwards not taken into account

- *Chemical solubilization*

excavation and transport of the soil - sediment (prior to solubiliz.)	125 - 150 EUR/m^3
solubilization costs	400 EUR/m^3

E. Containment

Subsurface barriers not feasible

- *Capping*

asphalt concrete capping costs of soil - bed sediment	40 - 45 EUR/m^2

F. Physical Immobilization

- *ex-situ*

excavation and transport of the soil - sediment (prior to immobiliz.)	125 - 150 EUR/m^3
ex-situ immobilization costs	100 EUR/m^3

- *in-situ*

in-situ immobilization costs	soil	200 EUR/m^3
	bed sediment	250 EUR/m^3

G. Chemical Immobilization

- *ex-situ*

excavation and transport of the soil - sediment (prior to immobiliz.)	125 - 150 EUR/m^3
ex-situ immobilization costs	180 EUR/m^3

- *in-situ*

in-situ immobilization costs	soil	200 EUR/m^3
	bed sediment	250 EUR/m^3

2. Total costs

The costs indicated are related to the actions considered in the dose assessments. This means that only the soils and riverbeds contaminated with sediment have been considered for remedial actions and not the soils that were only contaminated through irrigation (too high costs for too low dose effects).

For soil removal, it can be assumed that the amount of soil removed has to be replaced by clean soil. Since the costs related to this would be of the order of 8 EUR/m^3 for agricultural soil and 4 EUR/m^3 or less for other soils, they are not added in the estimates (negligible).

For the contaminated river banks (contaminated over approx. 1 m), the amount of soil to be replaced or treated is assumed to be a 0.3 m thick layer, resulting in a volume of 10,200 m^3.

For the wastes to be disposed of in the B, C and D options, it is assumed that for bulk soil/sediment removal (option B) the cost would be related to RCRA disposal, whilst for soil/sediment for which only the higher contaminated fraction is disposed of (options C and D), the cost would be related to radioactive waste disposal (low- level)

B. Soil and sediment removal

Soil: agricultural soil to be removed: 6,120 m^3
soil on banks to be removed: 10,200 m^3
Sediment: bed sediment to be removed: 10,200 m^3

Excavation (+ transport):	soil:	16,320 x 125 EUR =	2,040 kEUR	
	sediment:	10,200 x 150 EUR =	1,530 kEUR	
Waste disposal (+ transport):	soil:	16,320 x 700 EUR =	11,424 kEUR	(RCRA)
	sediment:	10,200 x 800 EUR =	8,160 kEUR	

C.1 Physical separation (soil washing)

Excavation (+transport) prior to treatment: 2,040 + 1,530 = 3,570 kEUR (see B)

Waste disposal (+transport) of contaminated fraction (considered to be 20% of total amount):
26,520 x 0.20 x 2,500 EUR = 13,125 kEUR

Washing costs (incl. labour): 26,520 x 350 EUR = 9,282 kEUR

D.1 Chemical separation (solubilisation)

Excavation (+transport) prior to treatment: 3,570 kEUR (see C.1)

Waste disposal (+transport): 13,125 kEUR (see C.1)

Separation costs (incl. labour): 26,520 x 400 EUR = 10,608 kEUR

E.1 Capping

Soil: surfaces agricultural soil to be capped: 34,000 m²
surfaces banks to be capped: 34,000 m²
Sediment: surfaces bed sediment to be capped: 34,000 m²

Cost of capping (incl. labour): soil: 68,000 x 40 EUR = 2,720 kEUR
bed sediment: 34,000 x 45 EUR = 1,530 kEUR

F.1 Physical Immobilization (ex-situ)

Excavation (+transport) prior to treatment: 3,570 kEUR (see C.1)

Cost of immobilization (incl. labour): 26,520 x 100 EUR = 2,652 kEUR

F.2 Physical Immobilization (in-situ)

Cost of immobilization: soil: 16,320 x 200 EUR = 3,264 kEUR
(incl. labour) bed sediment: 10,200 x 250 EUR = 2,550 kEUR

G.1 Chemical Immobilization (ex-situ)

Excavation (+transport) prior to treatment: 3,570 kEUR (see C.1)

Cost of immobilization (incl. labour): 26,520 x 180 EUR = 4,774 kEUR

G.2 Chemical Immobilization (in-situ) see F.2

Cost of immobilization: soil: 16,320 x 200 EUR = 3,264 kEUR
(incl. labour) bed sediment: 10,200 x 250 EUR = 2,550 kEUR