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CHERNOBYL DYKE ON THE PRIPYAT RIVER: COLLECTIVE DOSE REDUCTION AND COST-BENEFIT ANALYSIS

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ABSTRACT

The rise of the water level of the Pripyat river – particularly during spring flooding – as well as erosion associated with ice-jam events, has led to the periodic inundation of the area surrounding the Chernobyl power plant. The immersion of contaminated ground results in the re-suspension and dissolution of radioactive particles which were deposited at the time of the accident in 1986 and which are still present in the upper layers of the soil.

The radioactivity eroded from the flood plain, where the density of radioactive contamination remains extremely high – the ground contamination can reach values around 17,000 kBq.km^{-2} for ^{90}Sr and around 36,000 kBq.km^{-2} for ^{137}Cs –, is then released into the Pripyat river and enters the Dnieper river through the Kiev reservoir. This radioactivity is then transported through the Dnieper down to the Black Sea. This secondary re-contamination of the Dnieper is a significant source of exposure for the Ukrainian population living along the river.

To reduce this radiological impact, the construction of a dyke on the right bank of the Pripyat river close to the Chernobyl power plant was proposed to complement an already existing protective dyke built in 1993 on the left bank. In order to provide elements for evaluating the pertinence and effectiveness of this project, Bonnard & Gardel Consulting Engineers Ltd. (BG) – Lausanne, Switzerland – and the CEPN have been awarded a contract by the Geneva office of the United Nation to perform an evaluation study. In this context, the CEPN performed a dose assessment as well as a cost-benefit analysis.

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1. INTRODUCTION

1.1. Position of the Problem

The radioactive particles deposited in the plain around the Chernobyl Nuclear Power Plant (ChNPP) after the accident are still a major source of contamination of the water of Pripyat and Dnieper rivers. A protective dyke is under design on the right bank of the Pripyat river to mitigate the consequences of the erosion and dissolution of the radioactive particles deposited on the ground in the exclusion zone of the Chernobyl nuclear power plant (Figure 1.1 and 1.2).

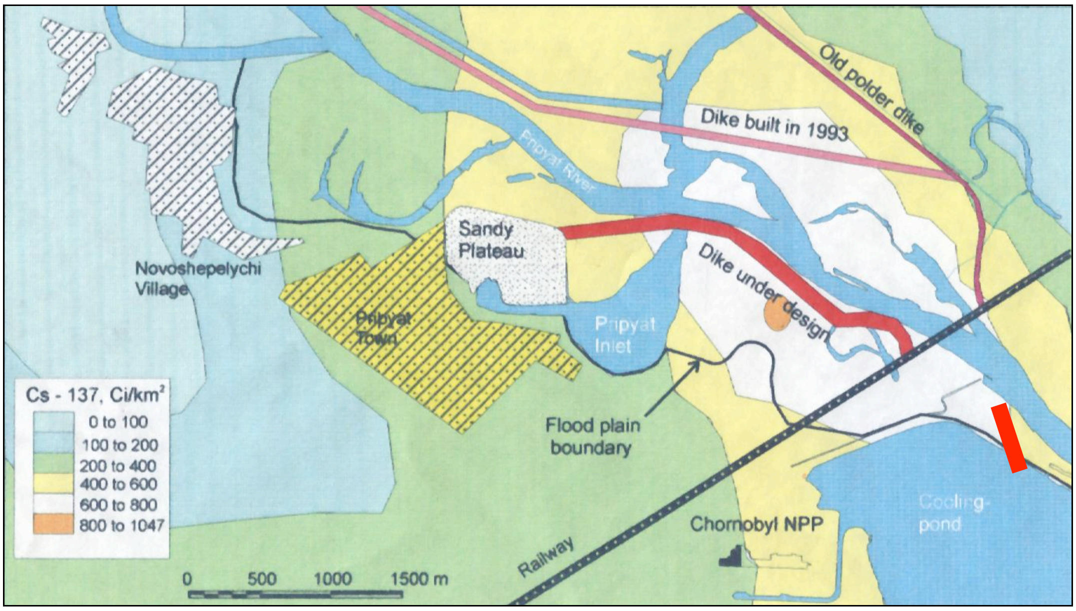

Figure 1.1 ^{137}Cs ground contamination of the Chernobyl flood plain

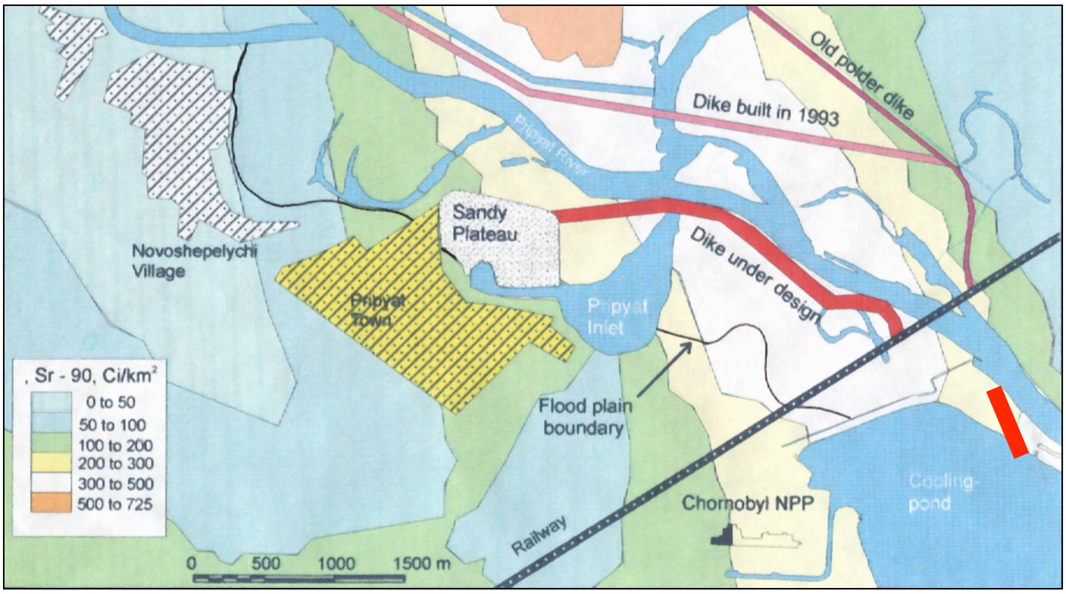

Figure 1.2 ^{90}**Sr ground contamination of the Chernobyl flood plain**

Spring flooding and winter ice-jams of the Pripyat river lead to a secondary contamination of the river waters through the erosion and dissolution of contaminated solid materials from the flood plain (Figure 1.3 a and b).

Figure 1.3a **Chernobyl flood plain and backwater; the CNPP is on the right**

Figure 1.3b Chernobyl flood plain and backwater; the CNPP is at the back

The radioactivity eroded from the flood plain, where the density of radioactive contamination remains extremely high – the ground contamination of the flood plain can reach values around 17,000 kBq.km^{-2} for ^{90}Sr and values around 36,000 kBq.km^{-2} for ^{137}Cs (Figure 1.1 and 1.2) –, is then released into the Pripyat river and enters the Dnieper river through the Kiev reservoir. This radioactivity is then transported through all the Dnieper reservoirs down to the Black Sea (Figure 1.4).

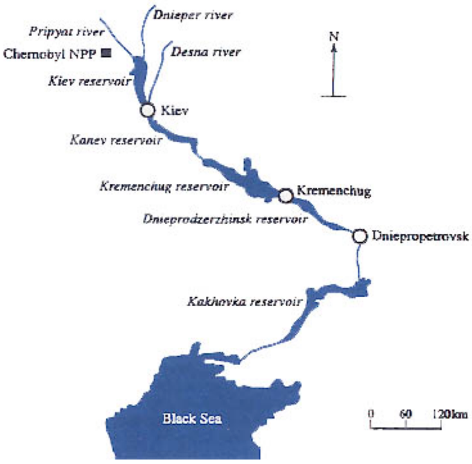

Figure 1.4 The Dnieper cascade

The contamination of the water of Dnieper reservoirs remains a problem in terms of radiological exposure of the populations living along the river cascade, used to make an intensive usage of the river water (for direct consumption, for the irrigation of agricultural products, for fishing, etc.).

Thus, the project of construction of a right bank dyke is aiming at reducing the collective dose associated with this secondary contamination of the Dnieper water.

1.2. Objective of the Study

Bonnard & Gardel Consulting Engineers Ltd. (BG) and the Centre d'étude sur l'Evaluation de la Protection dans le domaine Nucléaire (CEPN) have been awarded by the United Nations Office at Geneva to perform an evaluation of this project of construction of the right-bank dyke, i.e.:

- To evaluate the effectiveness of the dyke in terms of collective dose reduction,
- To examine the technical options that have been proposed,
- To perform a cost-benefit analysis.

In a first stage, after the analysis of the hydrological situation of the Chernobyl flood plain and the Pripyat river, BG performed an evaluation of the effectiveness of the proposed dyke. They calculated the amount of radioactivity dissolved and eroded from the contaminated plain during a 70-year period of flooding events, according to the local hydrological and soil contamination conditions. The flooding Sequences were simulated with a Monte Carlo analysis, leading to a set of 1,000 Sequences of 70-year period radioactive releases into the Kiev reservoir, with and without the right-bank dyke.

In a second stage CEPN performed an evaluation of the collective dose reduction associated with the construction of the dyke, which served as a basis for the cost-benefit analysis of the right-bank dyke construction project. This report presents the methodology and the results from this second stage.

This study has been conducted in close co-operation with the Ukrainian Ministry of Chernobyl Affairs (EMERCOM), the Scientific Centre for Radiation Medicine, the Ukrainian Hydro-meteorological Research Institute, the Institute of Geological Sciences, and the Institute of Mathematical Machine and Systems Problems (IPMMS), in Kiev.

1.3. Methodology

Collective dose calculations were performed for a reference time period of 70 years of operation of the dyke. Based on the Monte-Carlo simulation of flooding events during this 70 year reference time period [2], a set of nine Sequences of annual radioactive discharges of ^{137}Cs and ^{90}Sr – resulting from the dissolution and the erosion of the contaminated flood plain into the Kiev reservoir – was considered for dose calculations.

The first step of the study aimed at evaluating the effectiveness of the dyke in terms of collective dose reduction. The assessment of the radiological consequences of the radioactive releases into the Pripyat–Dnieper river system was performed with the RIPARIA computer code developed at CEPN [3]. Collective doses were computed for major ingestion routes of exposure, taking account of the direct consumption of water and fish from the successive Dnieper reservoirs, the ingestion of food products irrigated with the Dnieper water (green and root vegetables, cereals) as well as milk produced on irrigated pastures. A sensitivity analysis was performed on the main parameters of the dose assessment modelling to better estimate the variability of the results.

The second step of the study was devoted to the monetary valuation of both the costs of the right bank dyke – construction and maintenance – and the expected benefits on dose reduction. Costs of the dyke were expressed as "one-off" costs for construction and annual costs for operating and maintenance of the dyke during the considered return time period (70 years). The cost of the dyke and its side works have been analysed in the "Dyke design and cost analysis" report [4].

Costs were calculated on the basis of Ukrainian prices, expressed in Hrivnyas (UHA) and were then converted into US $ for the cost-benefit analysis, assuming that all construction expenses were invested at the beginning of the construction. A discount rate was considered for annual operating and maintenance costs. A basic value of the man-sievert was calculated, derived from the Ukrainian gross domestic product in 1997 – GDP per capita – ("Human Capital" approach). To better cope with the local situation and taking into account social aspects, an adjustment of this basic value was proposed for the general population, based on recent theoretical developments in the monetary value of the man-sievert.

Given the dyke construction and operating costs and the associated expected dose reduction, a cost-benefit ratio was finally calculated, taking into account the variability in dose reduction estimates. The robustness of this cost-benefit ratio was also tested by considering significant variations in the different parameters of the calculation modelling.

2. COMPUTERIZATION OF THE DOSE-ASSESSMENT MODELLING

2.1. General Presentation of RIPARIA

Collective dose assessments were performed with RIPARIA, a “box-modelling” computer code for assessing the radiological consequences of radioactive releases into rivers. This code was developed and tested by CEPN for the French Rhône river, and its parameters were adjusted to better cope with the specificity of the Dnieper cascade. The modelling of the sedimentation processes was modified for this study, on the basis of the European Methodology report RP72 [5].

The major assumptions inherent to this box modelling are the homogeneity of each reservoir with respect to its parameters (i.e. suspended sediment load, sedimentation rate, depth, etc.), and an equal distribution of the activity within the volume of the reservoir. Exchanges between reservoirs are expressed in terms of an average annual transferred volume of water. Seasonal variations (of water flows for example) are not considered in the modelling. The impacts of such seasonal variations of water flows were estimated and considered in the variability study of dose assessment results.

2.2. Principles for Radionuclide Dispersion Modelling

The Dnieper river-reservoirs system represents the main water-supply system of Ukraine. It crosses the Ukrainian territory from its border with the Russian Federation and the Republic of Belarus in the north to the Black Sea coast in the south.

The Dnieper river-reservoirs system is made up of six large artificial reservoirs: Kiev, Kanev, Kremenchug, Dnerprodzerdzin, Zaporozhye and Kakhov. The Pripyat and the Dnieper rivers are the main tributaries of the Kiev reservoir (Table 2.1).

Table 2.1. **Main characteristics of the reservoirs composing the Dnieper cascade**[1]

Reservoir	Volume (m^3)	Length (m)	Width (m)	Depth (m)	Outflow (m^3/an)	Bed sediment depth[2] (m)
Kiev	3.70×10^9	1.10×10^5	8.40×10^3	4	3.18×10^{10}	1
Kanev	2.64×10^9	1.23×10^5	5.50×10^3	3.9	5.14×10^{10}	1
Kremench.	1.35×10^{10}	1.49×10^5	1.51×10^4	6	5.71×10^{10}	1
Dneprodz.	2.50×10^9	1.14×10^5	5.10×10^3	4.3	4.90×10^{10}	1
Zaporozhye	3.30×10^9	1.29×10^5	3.20×10^3	8	5.16×10^{10}	1
Kakhov	1.82×10^{10}	2.30×10^5	9.30×10^3	8.5	3.98×10^{10}	1

[1] Average values, from [3], [4]

[2] Depth of the sediment layer where exchanges of radionuclides (diffusion, bioturbation) are taken into account

Each reservoir is modelled as a box made up of different layers. The first layer corresponds to the water column. The processes of dispersion of the radionuclides into the river system refer to mechanisms of transport by water exchanges between each compartment (water outflow). The second layer corresponds to the bed sediments. The sediment processes result from three phenomena: depletion of suspended materials in equilibrium with the water phase activity, diffusion of radioactivity between the water column and the bed sediment layer, and bioturbation, modelled as a diffusive process between layers too.

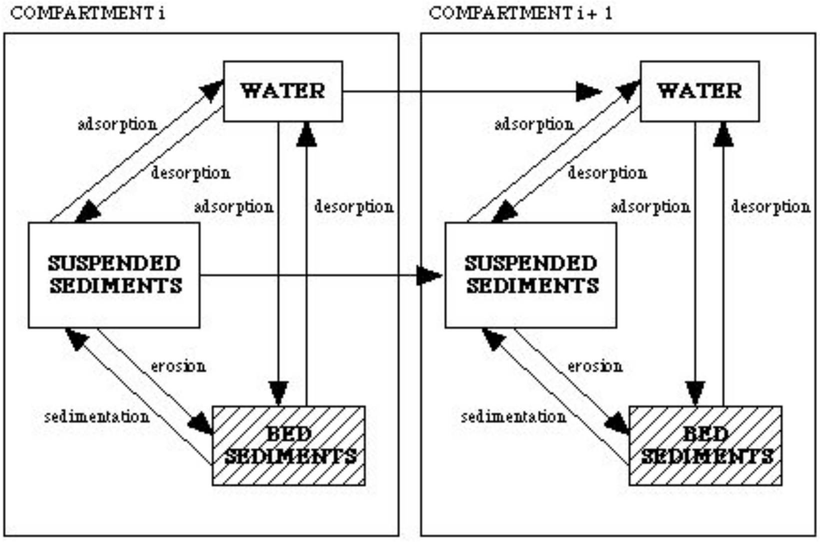

Figure 2.1 **Modelling of the radionuclide dispersion and sedimentation processes**

The equations of the time evolution of the activity concentration in both water columns and bed sediment layers are written for each compartment i [5], [7]:

$$\frac{dC_{i,w}}{dt} = \frac{k_{i-1,i}}{V_i} \cdot C_{i-1,w} - \frac{k_{i,i+1}}{V_i} \cdot C_{i,w} - (\lambda_1 + \lambda) \cdot C_{i,w} + \lambda_2 \cdot \frac{e_i}{h_i} \cdot C_{i,sed} + Q_w$$

$$\frac{dC_{i,sed}}{dt} = -(\lambda_2 + \lambda) \cdot C_{i,sed} + \lambda_1 \cdot \frac{h_i}{e_i} \cdot C_{i,w} + Q_{sed}$$

where:

$C_{i,w}$: activity concentration in water column (in Bq.m^{-3}) – unfiltered water,
$C_{i,sed}$: activity concentration in bed sediments (in Bq.m^{-3}) – wet sediments,
$K_{i-1,i}$: water flow from compartment i-1 (upstream) to compartment i (in m^{3}.y^{-1}),
V_i: volume of compartment i (in m^{3}),
λ: radioactive decay constant (in y^{-1}),
e_i: depth of bed sediment (in m),
h_i: depth of water column (in m),
Q_w: release rate in dissolved form (normalised by the volume of the release compartment – in Bq.m^{-3}.y^{-1}),
Q_{sed}: release rate in adsorbed form (normalised by the volume of the release compartment – in Bq.m^{-3}.y^{-1}).

Activity in the water column is lost to bed sediments through sorption onto suspended particulates which then settle out. The transfer from the water column to the bed sediment layer is given by λ_1 while the return of activity from bed sediments to the water column is given by λ_2.

$$\lambda_1 = \frac{K_d \cdot S}{h(1 + K_d \cdot SS)} + \frac{1}{R} \cdot \frac{D}{h \cdot e} + \frac{(R-1)}{R} \cdot \frac{B}{h \cdot e}$$

$$\lambda_2 = \frac{1}{R} \cdot \frac{D}{e^2} + \frac{(R-1)}{R} \cdot \frac{B}{e^2}$$

with :

$$R = 1 + (1 - \varepsilon)\frac{\rho}{\varepsilon} \cdot K_d$$

where:

K_d: concentration factor for sediments (in Bq.kg^{-1} per Bq.m^{-3}),

S: sedimentation rate (in kg.m^{-2}.y^{-1}),

h: depth of water column (in m),

e: depth of bed sediments (in m),

SS: suspended sediment load (in kg.m^{-3}),

ε: porosity of sediments (dimensionless)

ρ: density of sediments – dry weight (in kg.m^{-3}),

D: diffusion coefficient (in m^2.y^{-1}),

B: bioturbation coefficient (in m^2.y^{-1}).

R: retardation coefficient (dimensionless) which is used to distinguish between activity held on the sediments and activity in the water; R^{-1} is the proportion of activity held in the sediment pore water.

Average suspended sediment loads in all reservoirs of the system are given in Table 2.2.

Table 2.2. Average suspended sediment load in the reservoirs [6]

Reservoir	Sediment load (mg/L)
Kiev	6 - 10
Kanev	6
Kremenchug	9 - 10
Dneprodzerzhinsk	6
Zaporozhye	5
Kakhovka	4

A sedimentation rate of 0.5 $kg.m^{-2}.y^{-1}$ was considered for all reservoirs of the cascade. Diffusion and bioturbation (treated as a diffusive process) coefficients were respectively fixed to $3.15x10^{-2}$ and $3.6x10^{-5}$ $m^2.y^{-1}$.

A density of bed sediment of 2.6 $t.m^{-3}$ and a porosity of 0.75 were considered.

The activity concentrations in filtered water and in dry sediments are given by:

$$C_{i,w}^{filtered} = \frac{1}{1 + K_d \cdot SS} \cdot C_{i,w}$$

$$C_{i,sed}^{dry} = \frac{K_d}{R \cdot \varepsilon} \cdot C_{i,sed}$$

2.3. Principles for Collective Dose Calculations

Collective doses are calculated for different routes of exposure on the basis of the time-integrated activity concentration in unfiltered water, hereafter referred as IC(t).

$$IC(t) = \int_0^t C_{i,w} \cdot dt$$

The routes of exposure considered in the calculations were the direct consumption of water and fish from the successive Dnieper reservoirs, the ingestion of food products irrigated with the Dnieper water (green and root vegetables, cereals) as well as milk produced on irrigated pastures.

Collective doses are derived from IC as given in the following equations.

$$D_{fish} = 0.5 \times F_c \cdot IC \cdot K_d^{fish} \cdot Q_{fish} \cdot \exp^{(-\lambda \cdot d)}$$

$$D_{water} = 0.5 \times F_c \cdot IC \cdot Q_{water} \cdot \exp^{(-\lambda \cdot d)}$$

$$D_{irrigatedproducts} = F_c \cdot IC \cdot \left(Q_{irr}^p \cdot S_{irr}^p\right) \cdot \left(K_p \cdot \frac{P^p}{S_{irr}^p}\right) \cdot \exp^{(-\lambda \cdot d)}$$

where:

D: collective dose for the considered route of exposure,

F_c: dose factor for ingestion for the considered radionuclide (in $Sv.Bq^{-1}$),

K_d^{fish}: fish concentration factor, i.e. the ratio of the activity concentration in fish (in

Bq.kg^{-1}) and the activity concentration in the environment water (in Bq.m^{-3}), assuming an equilibrium state,

Q_{fish}: the annual amount of fish caught in the river (in kg.year^{-1})

Q_{water}: the annual amount of water collected from the river for direct consumption (in m^3.year^{-1}),

Q_{irr}^{p} : the irrigation rate of the culture p (in m^3.ha^{-1}),

S_{irr}^{p} : the irrigated surface of culture p (in ha),

P^p: the production rate of culture p (in kg.year^{-1}),

K_p: the transfer factor of activity between the water used for irrigation of the culture p (pastures for milk production) and the product p (in Bq.kg^{-1} per Bq.m^{-2}.year^{-1}),

d: delay for consumption of the considered product (in days).

A multiplying factor of 0.5 was applied to activity concentrations for water consumption and fish ingestion, to take into account filtering processes for « drinking water » and the edible fraction of fish for « fish consumption ».

2.4. Radionuclide Dependent Data

The radionuclide dependent concentration factors K_d for sediments and fish – which represent the ratio between radionuclide concentrations on sediments/fish and in solution at equilibrium – considered for this study are presented in Table 2.3.

Table 2.3. Concentration factors for sediments and fish (Bq.kg^{-1} per Bq.m^{-3})

Radionuclide	Sediments	Fish
^{137}Cs	20	1
^{90}Sr	0.2	0.03

The dose factors considered for dose assessments were taken from the ICRP Publication N° 72 (dose factors by ingestion for adults). Activity concentrations in food products due to the irrigation of cultures and pastures by unit deposition rate of water were calculated by using the FARMLAND database [8] (Table 2.4).

Table 2.4. Dose factors and activity concentration in food products after

irrigation

	Ingestion dose factor[1] (Sv.Bq^{-1})	Activity concentration of food products associated with a unit deposition rate of radionuclides (Bq.kg^{-1} per Bq.m^{-2}.y^{-1})			
Radionuclide	Adult	Green vegetables	Root vegetables	Cereals[2]	Milk (cow)
^{137}Cs	1.3x10^{-8}	4.72x10^{-3}	4.42x10^{-3}	1.67x10^{-2}	5.68x10^{-3}
^{90}Sr	2.8x10^{-8}	2.39x10^{-2}	3.57x10^{-3}	1.64x10^{-2}	4.51x10^{-3}

[1] From ICRP Publication 72, Vol. 26, No. 1, 1996

[2] Preparation losses included [8]

2.5. Validation of the Parameters of the Modelling

The adjustment of sedimentation parameters was performed making comparisons between predicted values from RIPARIA code and from another computer code for river dispersion modelling (WATOX), developed by a Ukrainian institute [9]. The results were also compared with measurements performed into the Kiev reservoir between 1987 and 1993. Conclusions are presented on Figures 2.2 to 2.4.

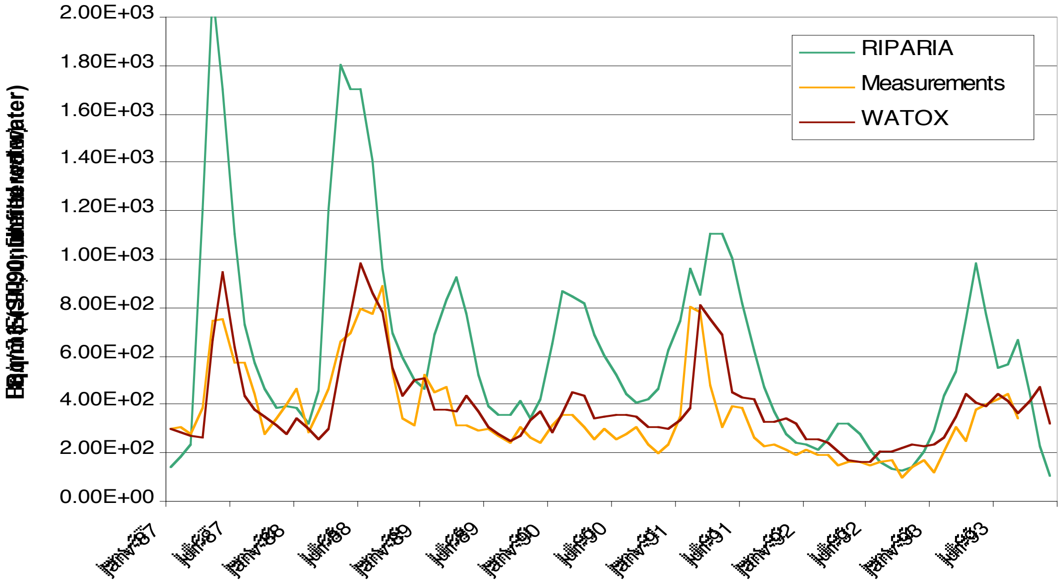

Figure 2.2 Comparison between predicted and measured ^{90}Sr activities in the Kiev reservoir during the period 1987-1993

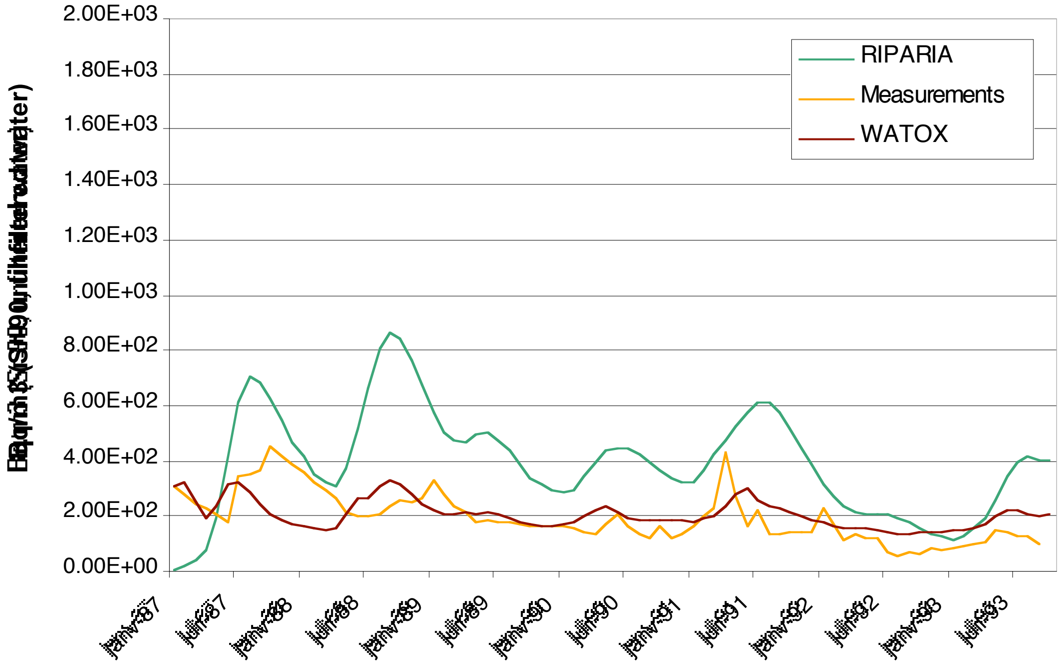

Figure 2.3 Comparison between predicted and measured ^{90}Sr activities in the Dneprodzerzhinsk reservoir during the period 1987-1993

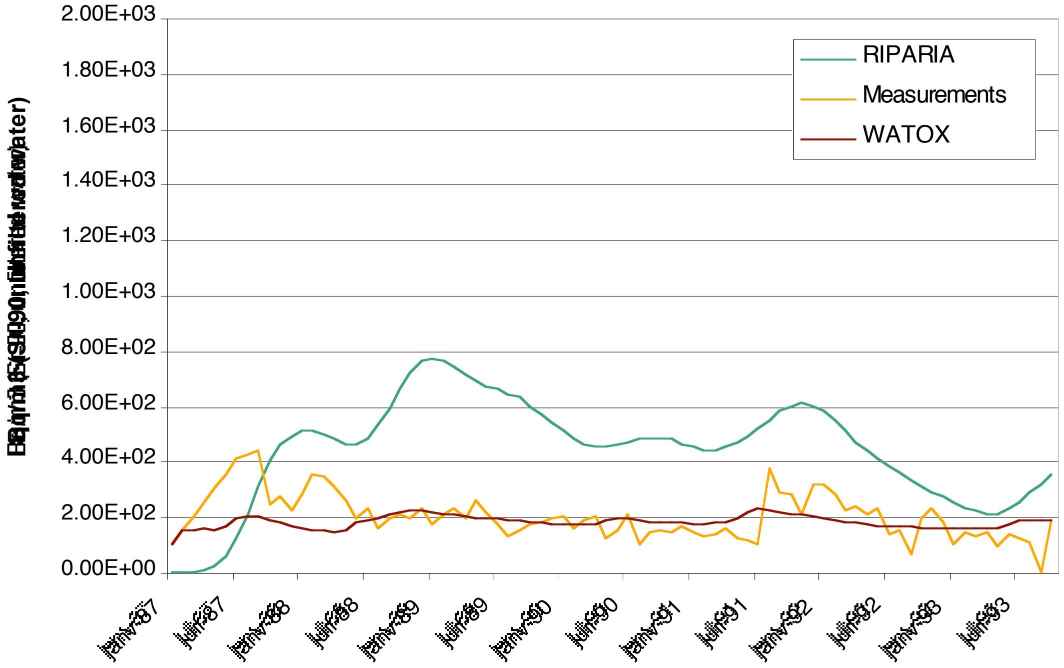

Figure 2.4 Comparison between predicted and measured ^{90}Sr activities in the Kakhov reservoir during the period 1987-1993

Predicted and measured activity concentration values in the different reservoirs of the Dnieper cascade are in a rather good accordance. Differences between predicted and measured values can reach a factor 4. These differences can be partly explained by the fact that seasonal variations of water flows are not taken into account in the RIPARIA modelling (but taken into account in WATOX), keeping in mind that these water flow variations can reach a factor about 3 within on year in the Kiev reservoir for example [6].

2.6. Water Usage and Agricultural Data

The water from the Dnieper cascade is very much used through direct consumption by the population living in the Dnieper basin and through irrigation and fishery. About 1.8 million hectares of productive farming lands are irrigated by the Dnieper cascade water. About 40% of the irrigated lands are used for the production of fodder for farm animals. The others are used for production of rice and grain. Vegetable and fruit production represent less than 10% of the total irrigated lands [10], [11].

A compilation of data from different sources was performed, with some major assumptions to cope with the structure of the dose module of RIPARIA, to estimate the exposure of the population through the usage of the Dnieper waters.

Given the total surface of irrigated products, the following distribution was considered: green vegetables represent 10% of irrigated lands, while root vegetables represent 20%, cereals 20% and pastures 50%. All irrigated pastures were considered to be dedicated to milk production. A synthesis of the agricultural data considered in the present study is given in Table 2.5.

Table 2.5. Irrigated surfaces of agricultural land

Origin reservoir	Irrigated areas of agricultural land (ha)	Irrigated areas of pastures (cow milk) (ha)	Irrigated areas of green vegetables (ha)	Irrigated areas of root vegetables (ha)	Irrigated areas of cereals (ha)
Kiev	5.80×10^4	2.90×10^4	5.80×10^3	1.16×10^4	1.16×10^4
Kanev	5.80×10^4	2.90×10^4	5.80×10^3	1.16×10^4	1.16×10^4
Kremenchug	1.79×10^5	8.95×10^4	1.79×10^4	3.58×10^4	3.58×10^4
Dneprod.	8.50×10^4	4.25×10^4	8.50×10^3	1.70×10^4	1.70×10^4
Zaporozhe	8.50×10^4	4.25×10^4	8.50×10^3	1.70×10^4	1.70×10^4
Kakhovka	1.40×10^6	7.00×10^5	1.40×10^5	2.80×10^5	2.80×10^5

For pastures, green and root vegetables, an irrigation rate of 1000 $m^3.ha^{-1}$ was considered; for cereals: 1500 $m^3.ha^{-1}$. A production of 13 $t.ha^{-1}$ was assumed for green vegetables,

24 $t.ha^{-1}$ for root vegetables, 2.7 $t.ha^{-1}$ for cereals and 3.6 $t.ha^{-1}$ for milk. A delay for consumption of products was also considered: 2 days for direct water consumption, 7 days for green vegetables, 180 days for root vegetables, 300 days for cereals, 1 day for fish and 2 days for milk.

It was assumed that a total amount of fish of 25,000 t was annually caught in the Dnieper cascade. The catches in each reservoir of the cascade were assumed to be directly proportional to the population consuming water from the Dnieper cascade (third column of Table 2.6), with an average annual consumption of 3.1 $kg.y^{-1}$ of fish per capita. The volume of water directly consumed by the population was calculated on the basis of an average consumption of 1.5 $L.day^{-1}$ per capita.

Table 2.6. Population, water consumption and fish catches in the Dnieper cascade

Origin reservoir	Total population in the Dnieper basin	Population consuming water from the Dnieper cascade	Consumption of water ($m^3.y^{-1}$)	Fish catches (kg/y)
Kiev	$2.25x10^6$	$3.75x10^5$	$2.05x10^5$	$1.16x10^6$
Kanev	$2.25x10^6$	$3.75x10^5$	$2.05x10^5$	$1.16x10^6$
Kremenchug	$4.40x10^6$	$9.00x10^5$	$4.93x10^5$	$2.79x10^6$
Dniprod.	$1.27x10^7$	$3.40x10^6$	$1.86x10^5$	$1.05x10^7$
Zaporozhe	$1.30x10^6$	$7.00x10^5$	$3.83x10^5$	$2.17x10^6$
Kakhovka	$8.20x10^6$	$2.50x10^6$	$1.37x10^5$	$7.75x10^6$

3. COLLECTIVE DOSE CALCULATIONS

Collective doses were calculated over a reference period of 70 years, starting from the year 2000, assumed to be the beginning of the dyke operation, for nine Sequences of releases. The releases of ^{137}Cs and ^{90}Sr associated with the flooding events (ice-jams included) are considered as an input of radioactivity into the first reservoir of the Dnieper cascade, i.e. the Kiev reservoir. All radioactive discharges were entered as dissolved discharges only, since the impact of the release form on final dose results was estimated to be not significant[1].

3.1. Input of Radioactivity into the Kiev Reservoir

Dose assessments were performed on the basis of the annual radioactive discharges associated with different flooding Sequences simulated for the considered 70 year reference period [2]. Since radiological impacts integrated over this long time period are strongly affected by the time distribution of the flooding events, given their magnitude and time of occurrence, a set of nine flooding Sequences was extracted from the complete data set of 1000. Criteria of selection of these nine Sequences assumed to be representative of the most probable "best" and "worst" cases are described on Table 3.1.

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[1] The influence of the release form on the collective dose was estimated for the 30-days 1994 flooding. In that case, a 100 % dissolved release of 3.54 TBq (^{90}Sr) overestimates the total collective doses by a factor ≈ 1.7, compared with the same amount of radioactivity released on a mixed form (1.47 TBq adsorbed + 2.07 TBq dissolved); i.e. in terms of doses: $D_{100\%\ dis}(70\ years) \approx 1.7 \times D_{mixed}(70\ years)$.

Table 3.1. **Criteria of selection of the 5 flooding Sequences**

Occurrence of the “highest” magnitude flooding events in the Sequence	Magnitude		
	Mean	Low	High
Uniformly distributed on the time period	Sequence 1	Sequence 4	Sequence 7
Distributed at the end of the time period	Sequence 2	Sequence 5	Sequence 8
Distributed at the beginning of the time period	Sequence 3	Sequence 6	Sequence 9

Figures 3.1 to 3.9 show the distribution of flooding events of the nine Sequences. Table 3.2 proposes a synopsis of the main characteristics of these Sequences. Upper bars correspond to ice-jams events; bottom bars indicate the magnitude of the flood discharge (in m^3s^{-1}).

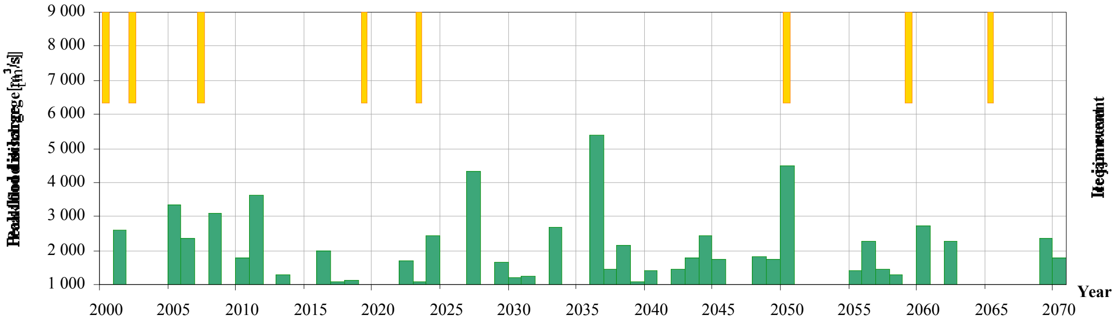

Figure 3.1 Distribution of flooding events for Sequence 1

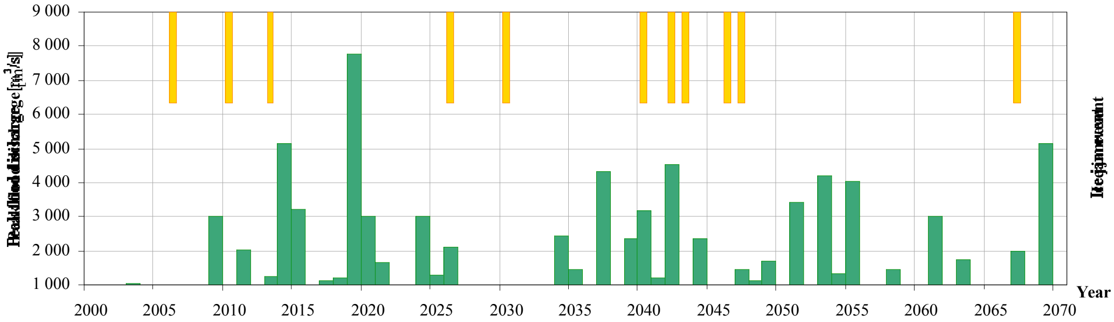

Figure 3.2 Distribution of flooding events for Sequence 2

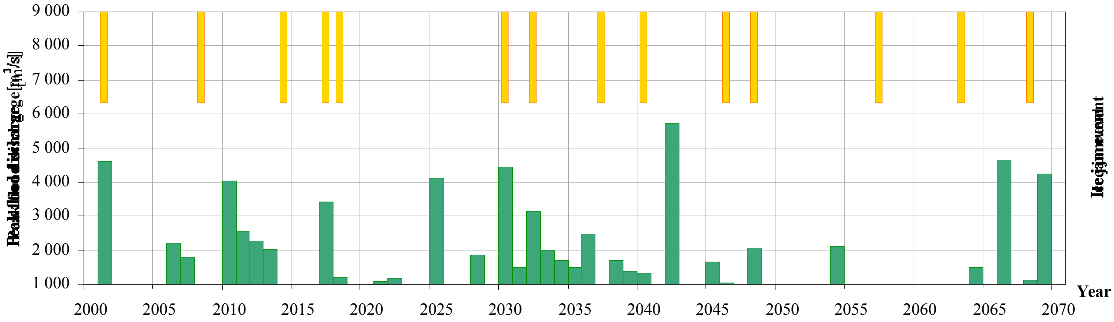

Figure 3.3 Distribution of flooding events for Sequence 3

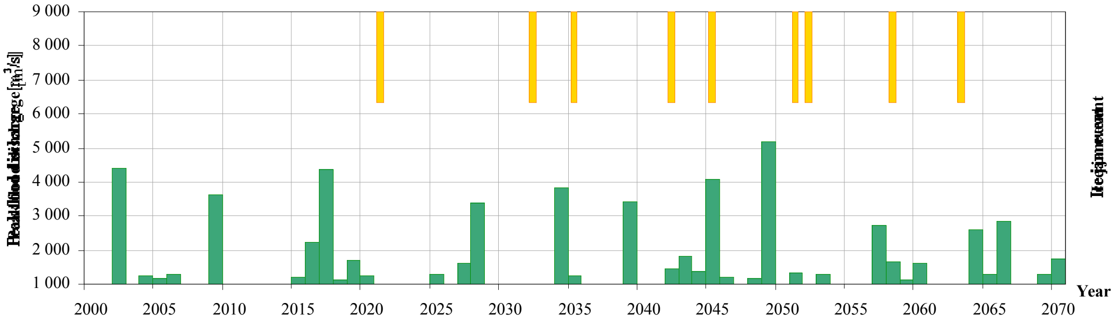

Figure 3.4 Distribution of flooding events for Sequence 4

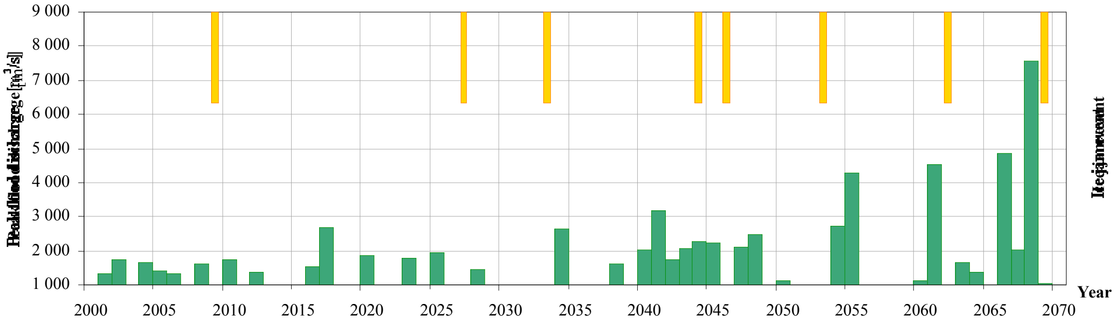

Figure 3.5 Distribution of flooding events for Sequence 5

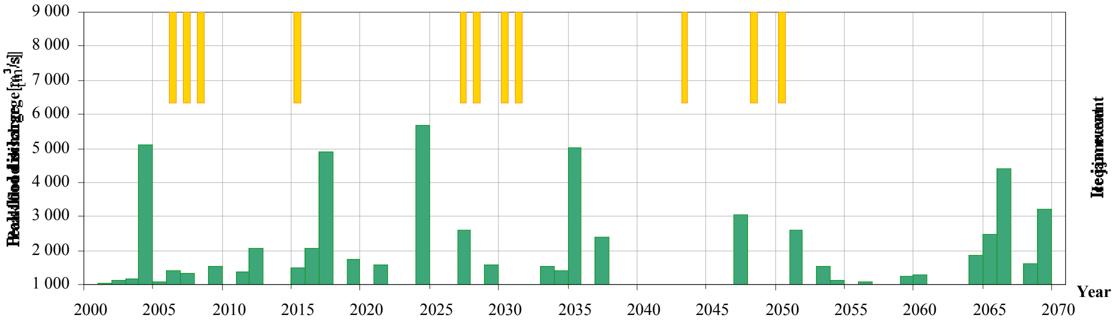

Figure 3.6 Distribution of flooding events for Sequence 6

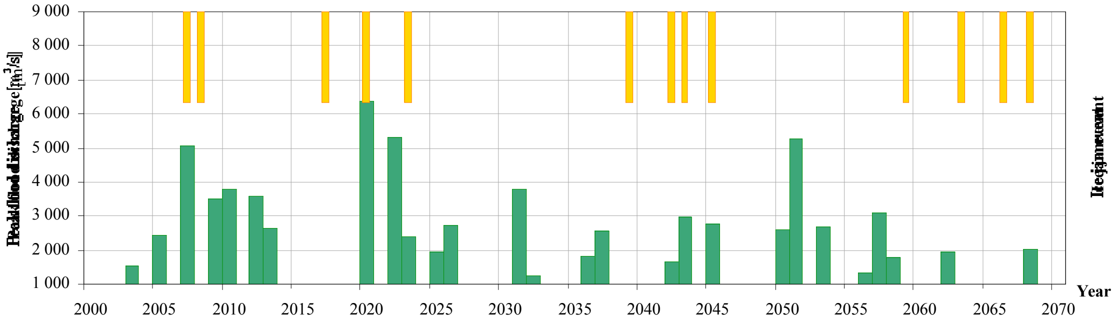

Figure 3.7 Distribution of flooding events for Sequence 7

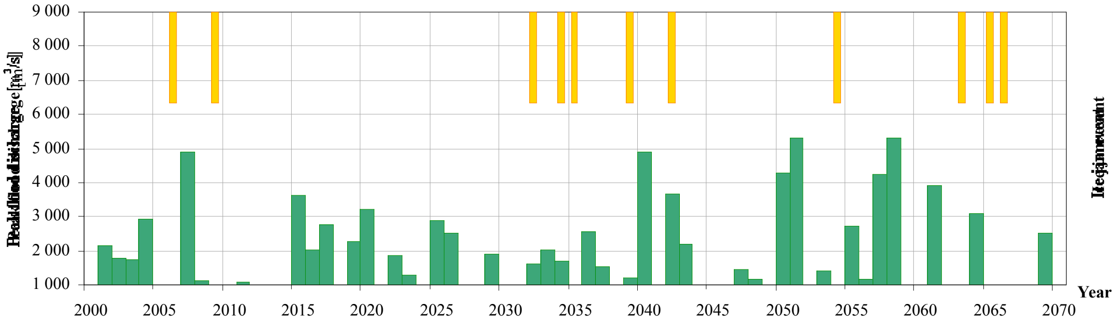

Figure 3.8 Distribution of flooding events for Sequence 8

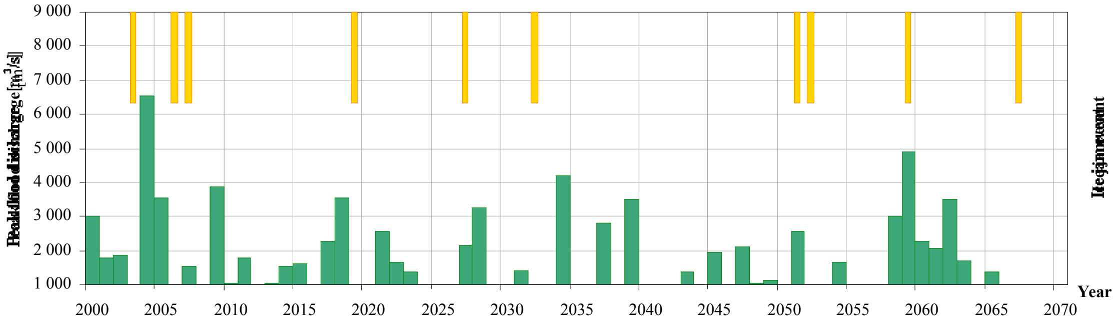

Figure 3.9 Distribution of flooding events for Sequence 9

For Sequence 2, Sequence 5, Sequence 7 and Sequence 9 the maximum water discharge rate can exceed 6000 $m^3.s^{-1}$ (once during the whole time period). For these years, it was assumed that the dyke would be completely flooded and consequently inefficient in the reduction of radio-contamination of waters. Thus the radioactive releases considered in these particular cases were the release rates in the absence of the dyke.

Annual releases averaged over the 70-year period without the right bank dyke are in the range of 0.22 – 0.37 $TBq.y^{-1}$ for ^{137}Cs and 0.9 – 1.9 $TBq.y^{-1}$ for ^{90}Sr. Maximum annual discharge values for the nine Sequences are respectively 2.3 $TBq.y^{-1}$ and 21 $TBq.y^{-1}$ for ^{137}Cs and ^{90}Sr (both observed in Sequence 9).

Table 3.2. Synopsis of the releases

	Mean annual release (Bq.y^{-1})			
	^{137}Cs		^{90}Sr	
	Without Dyke	With Dyke	Without Dyke	With Dyke
Sequence 1	3.15x10^{11} (max 1.6x10^{12})	1.51x10^{11} (max 9.6x10^{11})	1.43x10^{12} (max 1.1x10^{13})	1.13x10^{12} (max 9.2x10^{12})
Sequence 2	3.03x10^{11} (max 1.6x10^{12})	1.61x10^{11} (max 1.6x10^{12})	1.56x10^{12} (max 1.5x10^{13})	1.28x10^{12} (max 1.5x10^{13})
Sequence 3	3.15x10^{11} (max 2.3x10^{12})	1.45x10^{11} (max 1.1x10^{12})	1.46x10^{12} (max 1.4x10^{13})	1.15x10^{12} (max 1.1x10^{13})
Sequence 4	2.18x10^{11} (max 1.7x10^{12})	1.13x10^{11} (max 1.0x10^{12})	1.11x10^{12} (max 1.3x10^{13})	8.83x10^{11} (max 1.0x10^{13})
Sequence 5	2.31x10^{11} (max 9.3x10^{11})	1.03x10^{11} (max 5.0x10^{11})	8.95x10^{11} (max 5.2x10^{12})	7.20x10^{11} (max 4.7x10^{12})
Sequence 6	2.51x10^{11} (max 1.7x10^{12})	1.08x10^{11} (max 9.6x10^{11})	1.07x10^{12} (max 1.3x10^{13})	8.16x10^{11} (max 1.0x10^{13})
Sequence 7	3.47x10^{11} (max 2.0x10^{12})	1.86x10^{11} (max 1.82x10^{12})	1.8x10^{12} (max 1.4x10^{13})	1.45x10^{12} (max 1.4x10^{13})
Sequence 8	3.66x10^{11} (max 1.6x10^{12})	1.82x10^{11} (max 9.1x10^{11})	1.82x10^{12} (max 1.2x10^{13})	1.44x10^{12} (max 8.9x10^{12})
Sequence 9	3.7x10^{11} (max 2.3x10^{12})	1.92x10^{11} (max 2.3x10^{12})	1.85x10^{12} (max 2.1x10^{13})	1.54x10^{12} (max 2.1x10^{13})

3.2. Results of Dose Calculations

3.2.1. Annual Collective Doses

The annual collective doses associated with the releases of the nine Sequences are presented on figures 3.10 to 3.18.

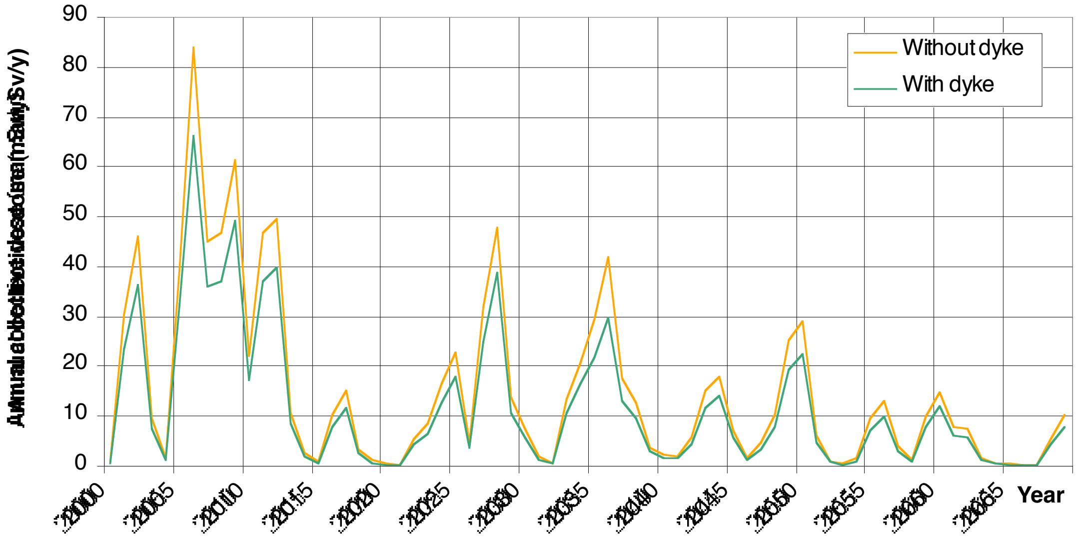

Figure 3.10 Estimated annual collective doses for Sequence 1

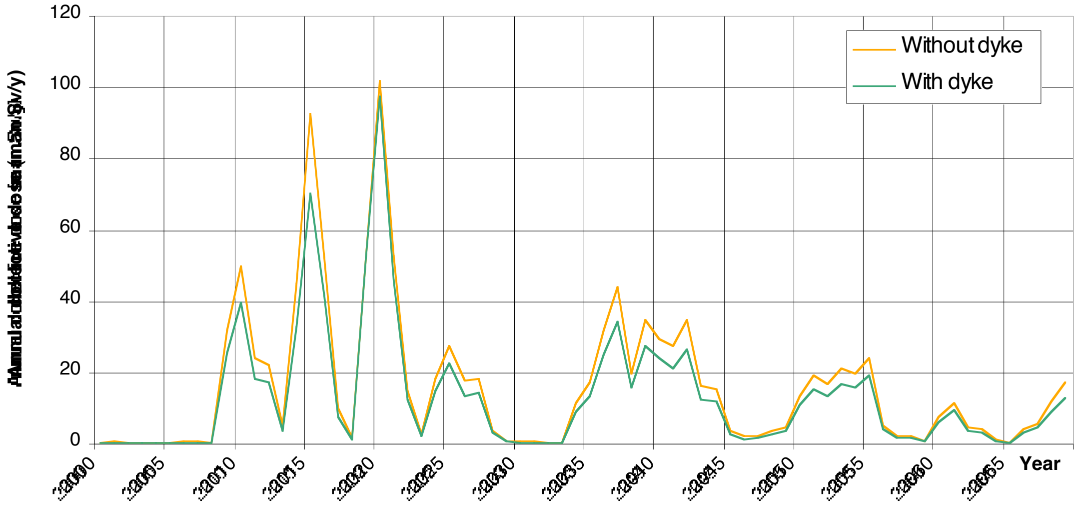

Figure 3.11 Estimated annual collective doses for Sequence 2

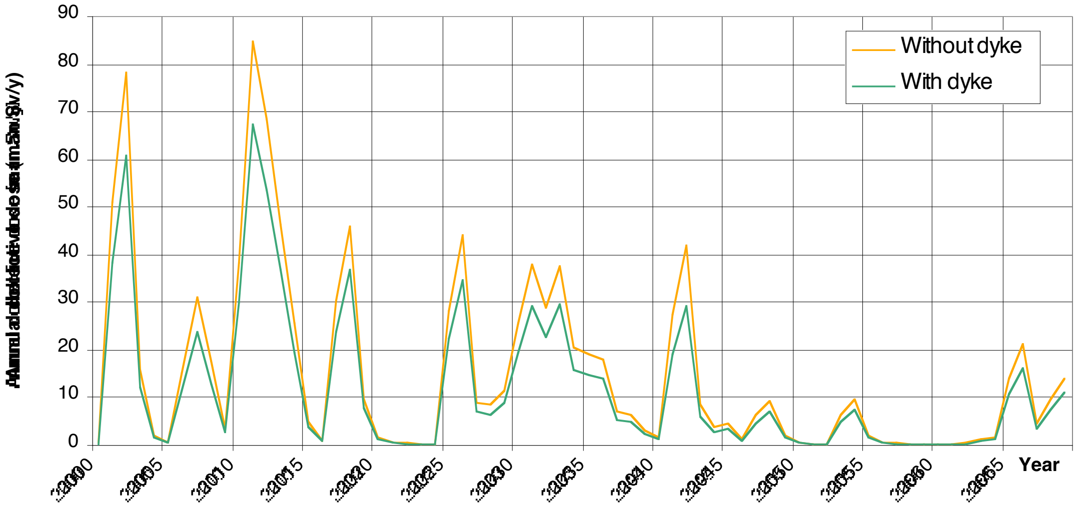

Figure 3.12 Estimated annual collective doses for Sequence 3

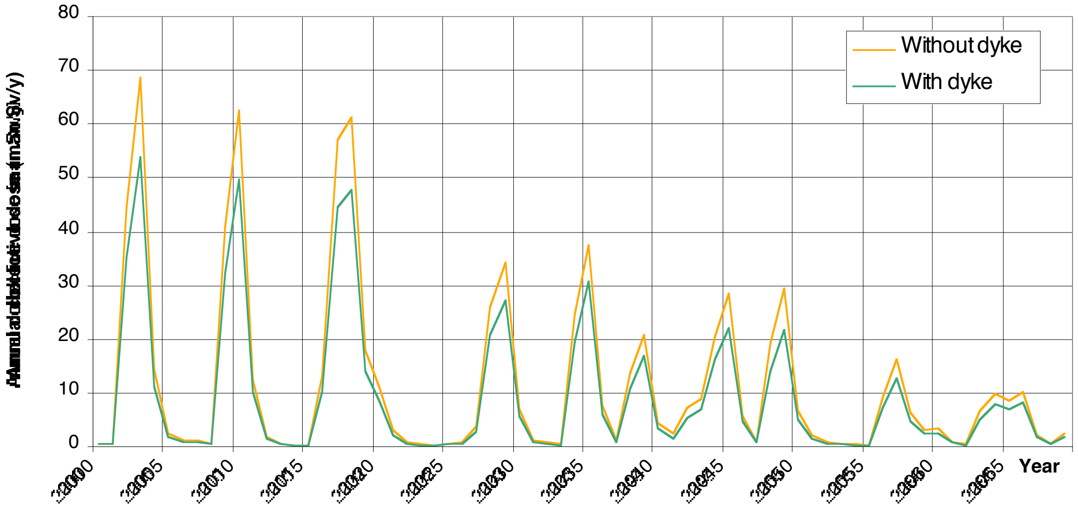

Figure 3.13 Estimated annual collective doses for Sequence 4

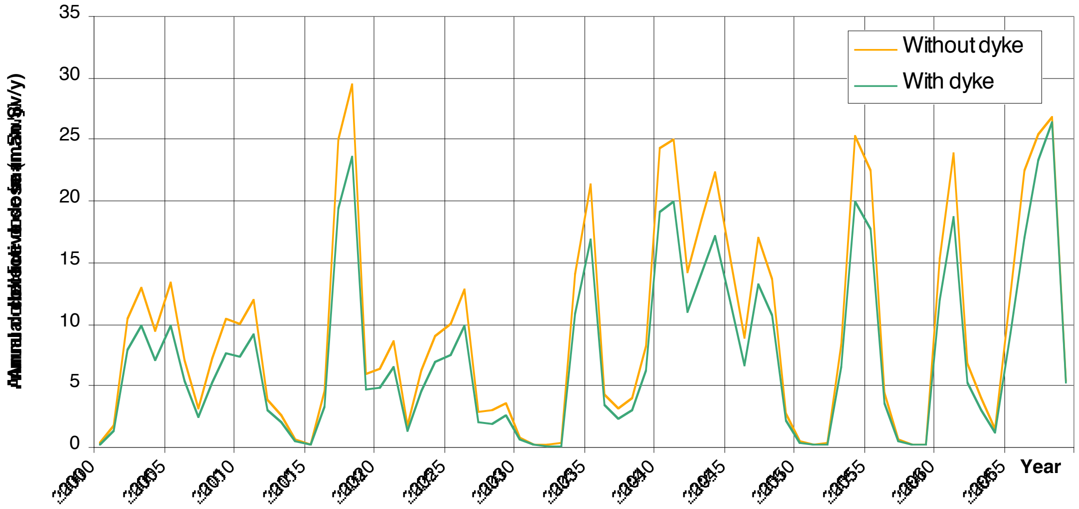

Figure 3.14 Estimated annual collective doses for Sequence 5

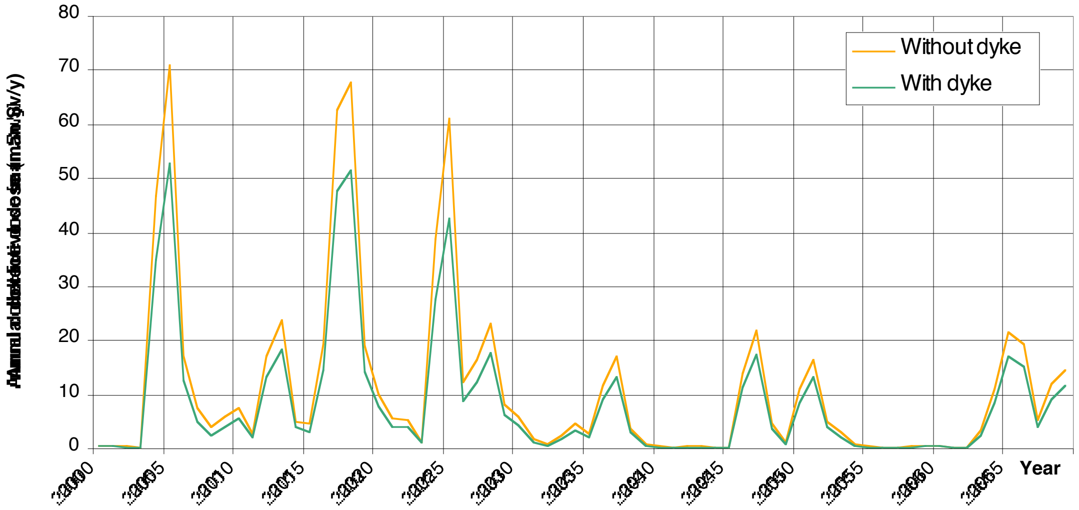

Figure 3.15 Estimated annual collective doses for Sequence 6

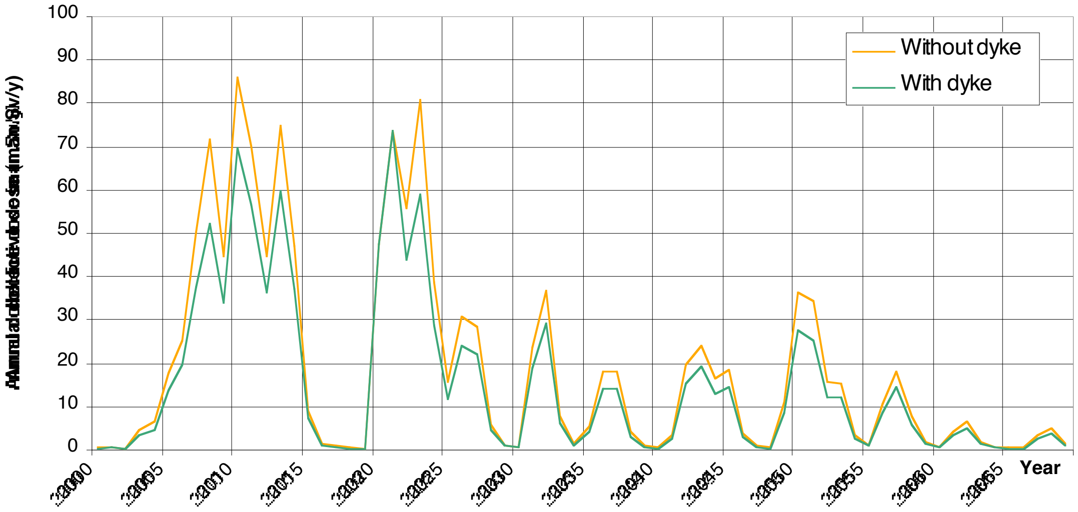

Figure 3.16 Estimated annual collective doses for Sequence 7

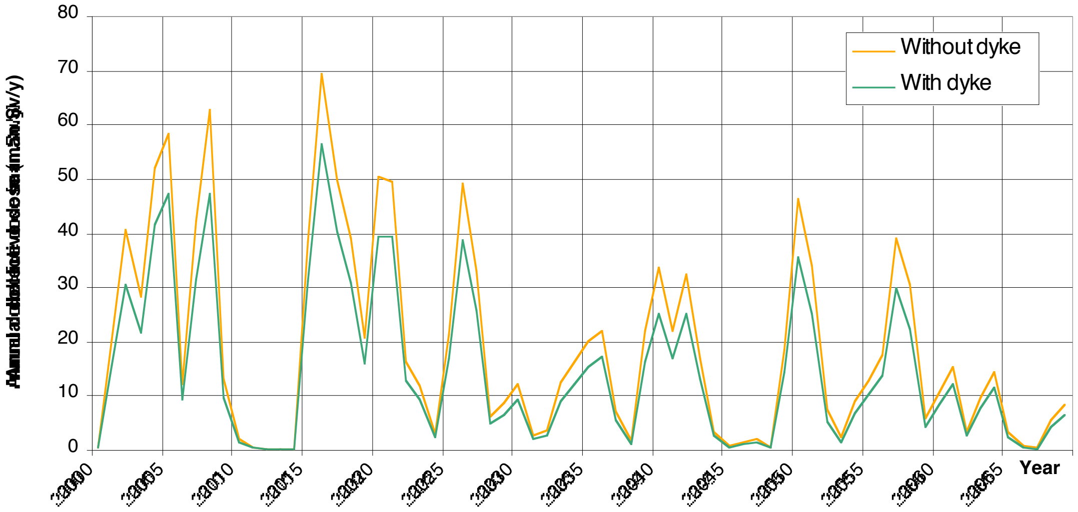

Figure 3.17 Estimated annual collective doses for Sequence 8

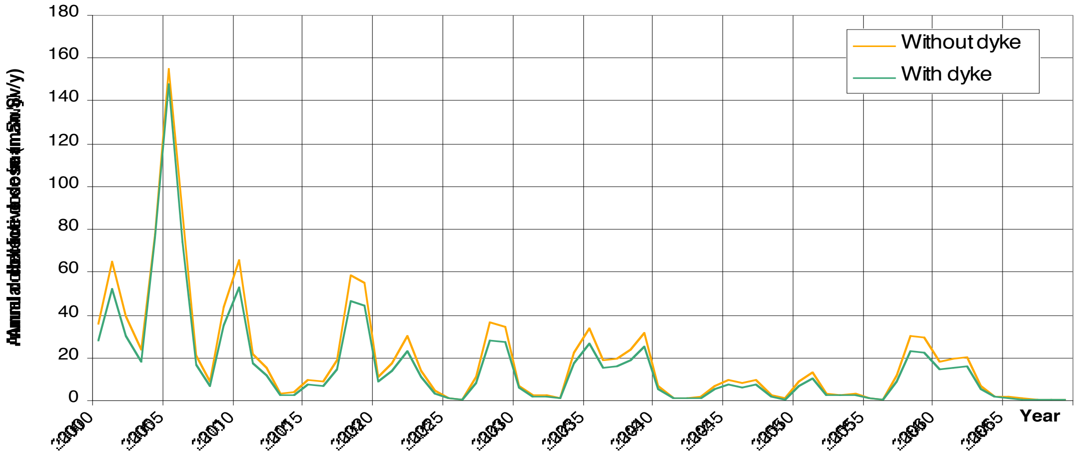

Figure 3.18 Estimated annual collective doses for Sequence 9

The maximum annual collective dose is observed for Sequence 9 and reaches the maximum value of ≈160 man.Sv for one year.

3.2.2. Cumulated Collective Doses

Table 3.3 as well as Figure 3.19 present the estimated collective doses associated with the different Sequences and the expected dose reduction after the construction of the right bank dyke.

Table 3.3. Estimated dose reduction associated with the right bank dyke construction

Sequence	**Cumulated collective dose (man.Sv)**		
	Without dyke	With dyke	Reduction
Sequence 1	1030	800	230
Sequence 2	1120	910	210
Sequence 3	1060	810	250
Sequence 4	800	620	180
Sequence 5	660	510	150
Sequence 6	770	570	200
Sequence 7	1300	1030	270
Sequence 8	1320	1020	300
Sequence 9	1340	1090	250

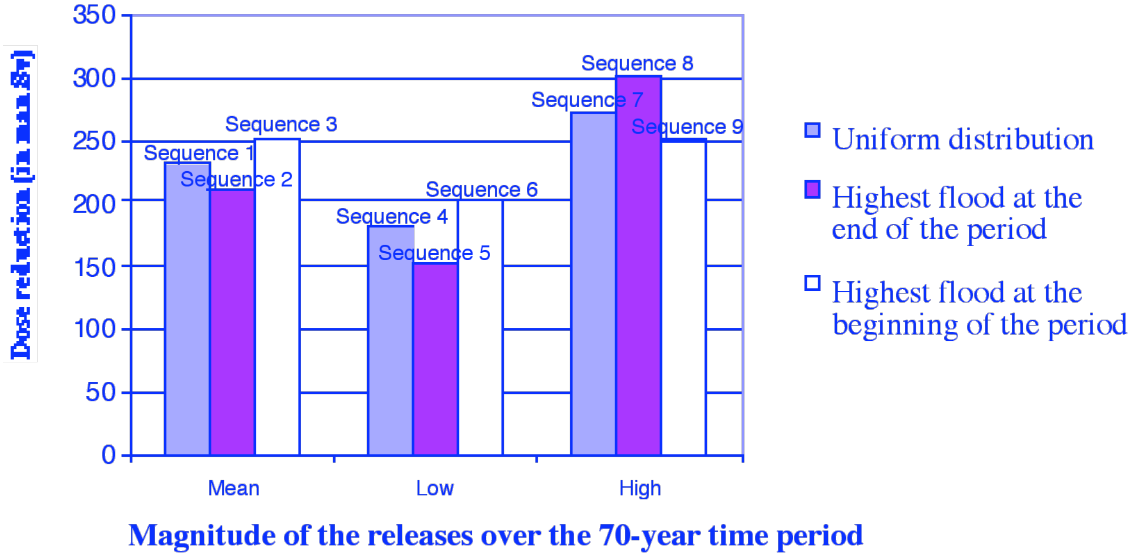

Figure 3.19 **Estimated collective dose reduction associated with the right bank dyke construction for nine flooding Sequences over a 70-year period**

The estimated dose reduction associated with the construction of the right bank dyke is in the range of 150 – 300 man.Sv for the considered 70 years period. Figure 3.20 shows the time evolution of the dose reduction for each considered Sequence. One can notice that, depending on both the magnitude of the highest flooding events and their temporal distribution within the period (concentrated at the beginning or at the end of the time period), the return time needed to reach a certain level of dose reduction can vary from several years to several decades. For example, the time needed to reach a dose reduction of 50 man.Sv varies from 6 years (Sequence 9) to 25 years (Sequence 5).

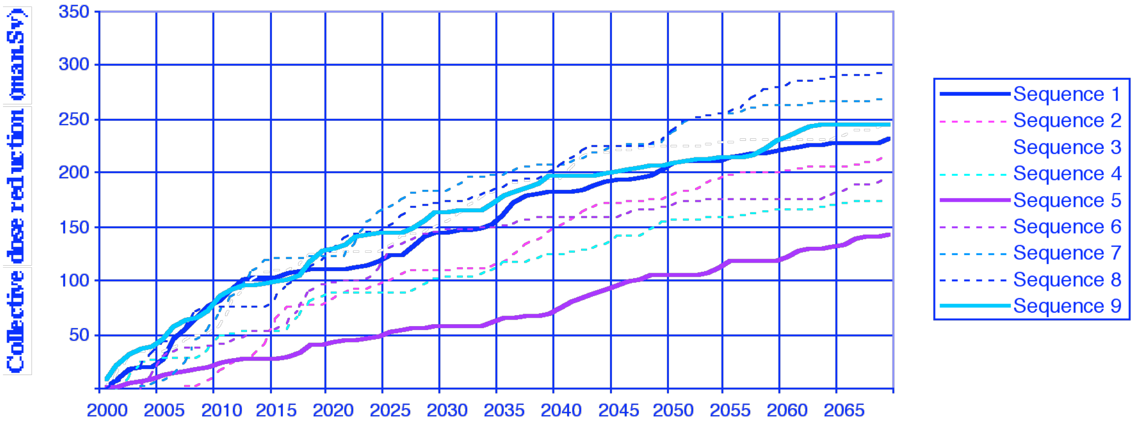

Figure 3.20 **Time evolution of the estimated dose reduction for nine flooding Sequences**

Figure 3.21 shows the collective dose reduction 20 years after the beginning of the period, for each flooding Sequence. One can notice that the estimated dose reduction during the 20 first years of the reference period represents from 28 % (Sequence 5) to 52 % (Sequences 3 and 9) of the total dose reduction over a 70 years period. These results show that whatever the flooding Sequence considered – assuming that the nine considered Sequences are representative of « probable cases », worst and best situations included –, the benefit of the dyke reaches about 50 % of its total value within the 20 first years.

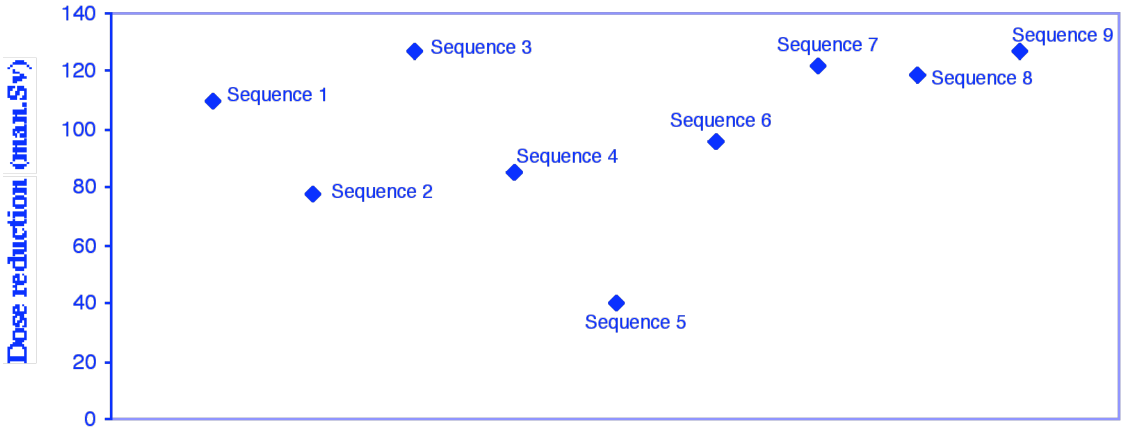

Figure 3.21 **Estimated dose reduction reached during the 20 first years after the dyke construction (reference year 2000)**

3.2.3. Relative Contribution of the Different Routes of Exposure

Table 3.4 presents the relative contribution of ^{137}Cs and ^{90}Sr to the collective dose, for each route of exposure.

Table 3.4. Relative contribution of the different routes of exposure to the total collective dose

	Relative contribution (%)		
	^{137}Cs	^{90}Sr	Total
Drinking water	1	13	14
Fish	2	1	3
Green vegetables	0	35	35
Root vegetables	1	20	21
Cereals	1	15	16
Cow milk	1	10	11
Total	**6**	**94**	**100**

The main exposure is associated with ^{90}Sr, which leads to about 94% of the total cumulated dose. This can be partly explained by two major radionuclide dependent factors :

- The ingestion dose factor for ^{90}Sr (about two times higher than the one for ^{137}Cs) ;
- The activity concentration in green vegetables for ^{90}Sr (about 50 times higher than the one for ^{137}Cs).

Furthermore, the contribution of the irrigation of agricultural land for food production is estimated to more than 80% of the total dose (about 10% for cow milk), the main route being the green vegetables.

It is interesting to note that, contrary to other routes, the relative contribution of the fish ingestion route is higher for ^{137}Cs. This is mainly due to the fact that the concentration factor for fish is about two orders of magnitude higher for ^{137}Cs than for ^{90}Sr. It may influence the contribution of fish ingestion on the total dose when the releases of ^{137}Cs become relatively more important than those of ^{90}Sr, as shown in Figure 3.22 for the beginning of the period and for the years 2030 (fish ingestion can lead to about 40% of the dose of these years).

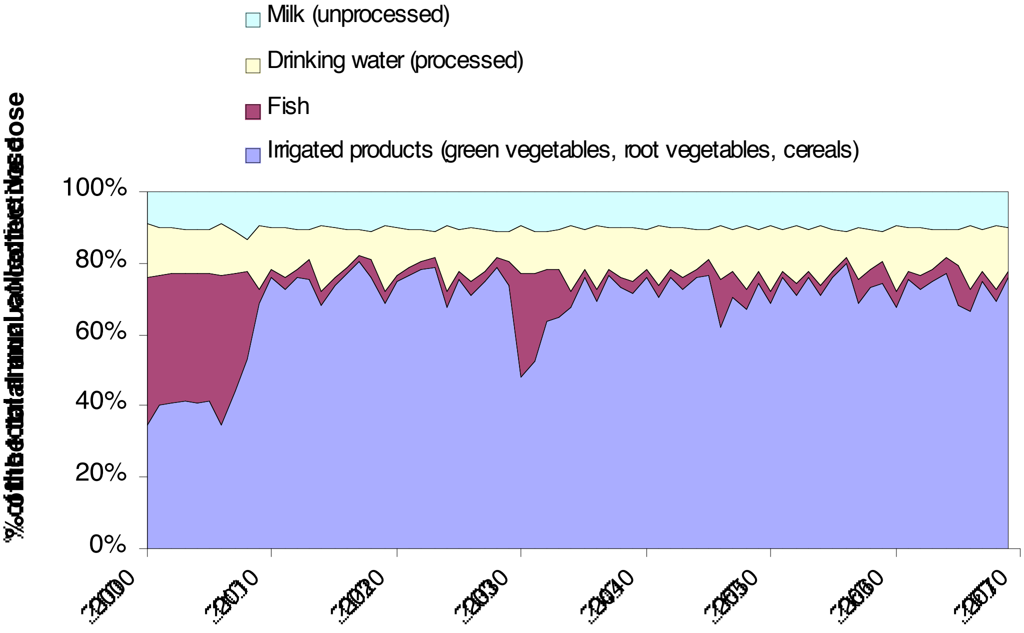

Figure 3.22 Evolution of the relative contribution of the different routes of exposure (Sequence 2) to the collective dose

3.2.4. Sensitivity of the Results with key Modelling Parameters

Most of the parameters used in the modelling of the radionuclide dispersion and dose calculations are characterised by large uncertainties and variability with the local situation, and the precision of the results, due to the large space and time scale of the calculations, can be strongly affected. For example, radionuclide dependent factors found in the literature, such as K_d values, can vary by several orders of magnitude.

An attempt was made to assess the effects of a significant variation of the values of major key parameters of the dose calculation modelling, and the results are presented in Table 3.5 and discussed below.

Table 3.5. **Sensitivity analysis on major key parameters of the modelling**

Parameter	**Assumption**	**Effect on collective doses**
Release form adsorbed/dissolved phase	A 100% dissolved release compared with a mixture 40% adsorbed on sediments + 60% dissolved – 30 day release at the beginning of the 70 year reference period (data from 1994 flooding event)	Multiplication by a factor ≈ 1.5
Fish concentration factors K_d[2]	For Sequence 1 – ^{90}Sr and ^{137}Cs ; Multiplication by a factor 10 of the fish K_d values	Multiplication by a factor ≈ 1.3
Sediment concentration factor K_d[3]	For Sequence 1 – ^{90}Sr only ; Multiplication by a factor 10 of the sediment K_d value of ^{90}Sr	Division by a factor ≈ 1.1
Water flow rates of the reservoirs of the cascade	For Sequence 1 ; Division by a factor 3 of all flow rates	Multiplication by a factor ≈ 3

Diminishing the flow rates by a factor 3 multiplies the cumulated dose by a factor about 3, and it also strongly impacts on the temporal distribution of annual doses in time, as shown on Figure 3.23.

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[2] Equilibrium ratio between activity concentration in fish and in water (in Bq/kg per Bq/m^3).

[3] Equilibrium ratio between activity concentration in sediments and in water (in Bq/kg per Bq/m^3).

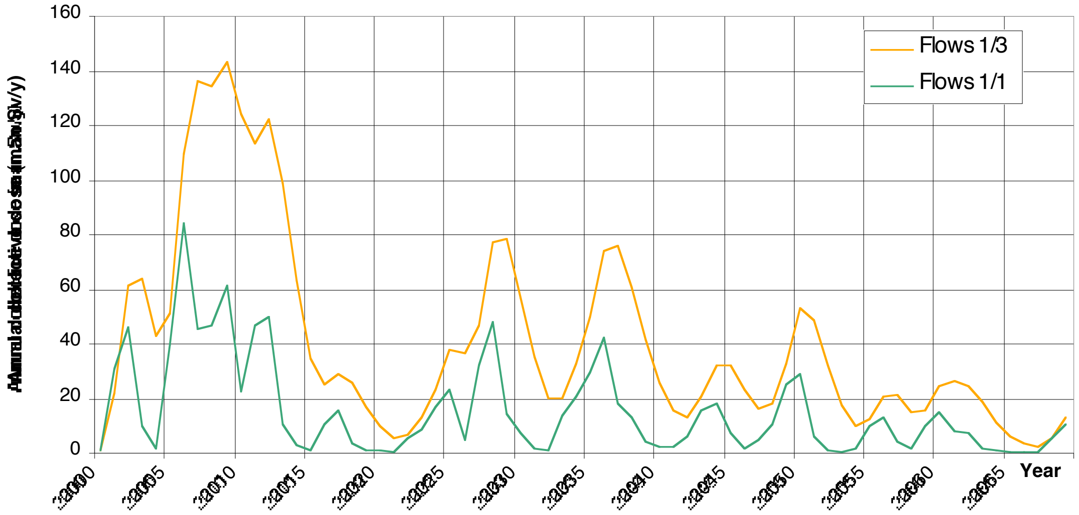

Figure 3.23 Effect of a flow rate division by a factor 3 on annual collective doses

Considering a multiplication by a factor 10 of fish concentration factors, the relative contribution of fish ingestion on the formation of the collective dose can reach 85 % on certain years (Figure 3.24 ; to be compared with Figure 3.22).

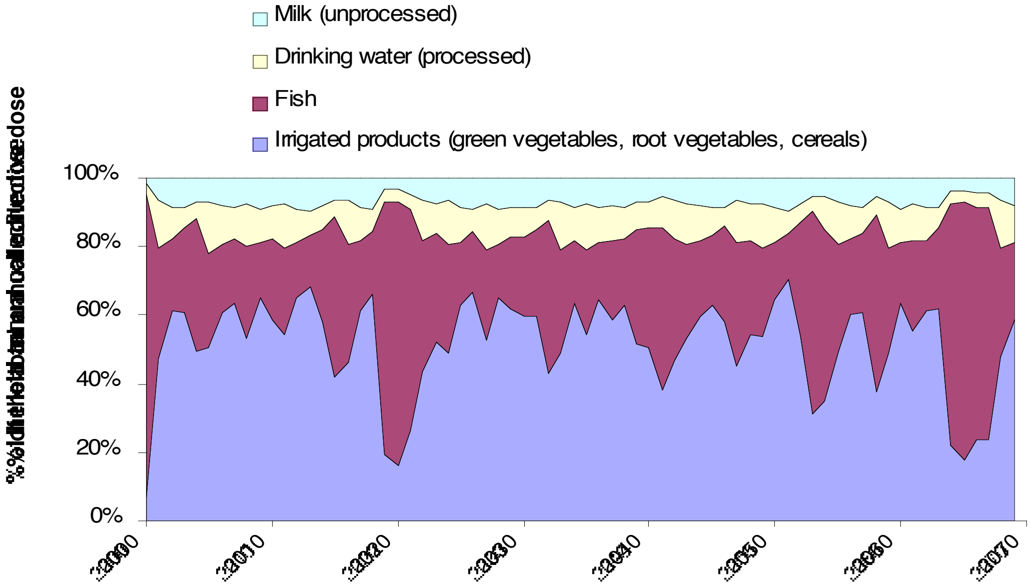

Figure 3.24 Relative contribution of the different routes of exposure to the collective dose when multiplying fish concentration factor by a factor 10 (Sequence 2)

4. COST-BENEFIT ANALYSIS

The cost-benefit analysis was performed on the basis of the dose reduction calculations presented in Section 3. Contrary to the assumptions adopted for the calculations of radioactivity released in the Pripyat, the permeability of the dyke is not total. Seepage through the dyke will contribute to decrease its efficiency by about 18 % [4]. Thus, a multiplicative correction factor of 0.82 was applied directly to the dose reduction to take into account this phenomenon.

For simplification, the reference date for the dyke operation is assumed to be the beginning of 2000. Construction and annual operating costs were evaluated on the basis of 1999 data, in Ukrainian Hrivnyas – UHA –, then converted into US $.

4.1. Evaluation of the Costs of the Project

The costs of the right bank dyke were separated into two types: the direct investment costs – « one off » costs associated with the construction of the dyke (Table 4.1) –, and the annual costs for operation and maintenance of the dyke (Table 4.2) [4].

Table 4.1. “One-off” costs of the right bank dyke project

Item	Quantity	Unit price	Total/item	
		UHA	10^3 UHA	10^3 US \$
Basic costs				
Topographical survey during execution			5	1
Dyke (m^3)	1 200 000	1.42	1 700	425
Pumping station			18	5
Drainage (dam n°3 and Yanov bridge)			34	9
Sub-total basic costs			**1 757**	**439**
(including 17% for overhead and 30% for planned development of contractor)				
Building and energy costs				
Energy equipment for construction			4	1
Temporary buildings for construction			87.5	22
Sub-total costs for energy and building			**91**	**23**
Other expenses				
Extra cost for winter works			11	3
Extra cost for working in exclusion zone			87	22
Transportation of workers			27	7
Compensation for economic variations (contractor)*			*2300*	*575*
Sub-total other expenses			**125**	**31**
Supervision and engineering				
Site supervision			87	22
Survey before works			14	4
Engineering costs			100	25
Controlling			10	3
Sub-total supervision-engineering			**211**	**53**
Reserve fund for economic variations (client)*			*2800*	*700*
TOTAL*			**2 184**	**546**
Unforseen expenses (15%)			328	82
Total without VAT			**2 512**	**628**

* Funds for economic variations were not taken into account in this study [4]

Table 4.2. **Maintenance and operating costs of the right bank dyke**

Item	Annual costs	
	UH.y^{-1}	US $.$y^{-1}$
TOTAL	**200 000**	**50 000**

When dealing with long term protection investments, it is necessary to take a discount rate into account. The discount rates to be considered depend on the country (based on the financial market) and on the type of investment. In France, the value retained by the "Commissariat Général au Plan" was 8 % in 1992, ranging from 8 to 10 % within the period 1970–1992 [14]. Values of 5 % and 8 % were respectively proposed in this study [12], [13]. They were applied to operating and maintenance costs of the dyke. Figure 4.1 shows the evolution of annual costs of the right bank dyke project for the selected discount rates, assuming a period of 70 years for dyke operation. The first-year costs include the "one-off" costs.

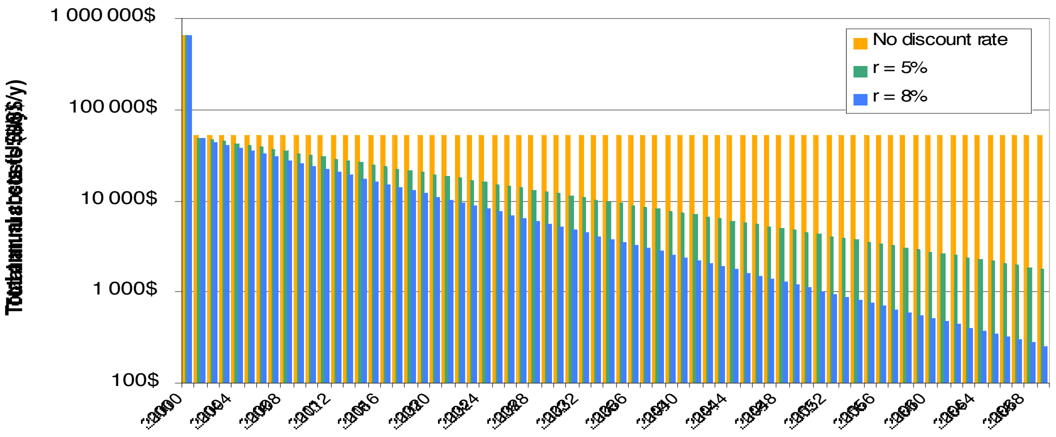

Figure 4.1 **Evolution of total annual costs of the project (70-year period of dyke operation) for different discount rates**

For different reasons (economic, uncertainties on dose assessments, etc.), a period of 70 years is very long for dyke operation. A sensitivity analysis on this parameter is also proposed, the results being calculated for a reference time of 20 years (value generally retained in France for such investments).

4.2. Monetary Value of the man-sievert for the Public

The evaluation of the cost – the benefit, expressed in monetary value – associated with the dose reduction of the dyke construction relies on the adoption of a monetary value of the man-sievert, adapted to the population of concern. A basic approach is to consider a constant monetary value of the man-sievert (α) for the whole reference time period, derived from the gross domestic product (GDP) of the considered country (« Human Capital » approach).

$$\alpha = GDP \cdot LL \cdot p$$

where α is the monetary value of the man-sievert (the so-called *alpha* value), GDP the gross domestic product per capita, LL the loss of life expectancy due to a radiation induced cancer (in years) and p the probability of radiation induced cancer for the general population (lifetime risk), associated with a collective dose of one man-sievert.

According to the International Commission on Radiological Protection (ICRP), for the general population a value of lifetime risk of 7.3×10^{-2} per man.Sv is recommended [15]. The loss of life expectancy associated with a radiation induced cancer is taken to be 16 years in agreement with the calculations from ICRP. A rounded value of US $ 1 200 was retained for the Ukrainian GDP per capita in 1997[4].

That leads to a basic α value of US $ 1 400 $(\text{man.Sv})^{-1}$. In fact, this value is a basic one which is rather more adapted to workers. For the general population, there exists a higher willingness to pay for their protection against exposures to ionising radiation than for workers, mainly because of the non-existence of a compensation system. For the population, given the lower individual level of exposure than for the workers, it is generally difficult to develop a compensation system. Thus workers who may be concerned by future cancers would be compensated for this, while the general population would probably not. A multiplying factor of 6 is proposed to take account of these social aspects in the monetary evaluation of human life. The estimation of this correction factor value for public is based on the conclusions from a recent study conducted in France [15]. That leads to a corrected value of the man-sievert of US $ 8 400.

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[4] Source: Banque Mondiale. From “Conjoncture 2000: Le nouveau bilan économique, politique et social du monde”, Institut Cédimes, Les Echos, Bréal, 1999.

Furthermore, the discounting of the value of human life does not seem reasonable in that case, especially in a country where it would be better to consider a positive trend for long term gross domestic product evolution, which would rather increase the monetary value of human life. Moreover, Ukraine – as well as other countries of the CIS affected by the contamination of the Chernobyl accident – are currently in a process of revising their national regulatory limit values concerning the contamination of the environment, to protect better the exposed populations from radioactivity. This strategy is mainly based on the strong concern of the populations living in contaminated territories about long term uncertainties on the health effects of the continuous exposure to radioactivity, and a general willingness to develop efforts for preserving the health. Consequently, an absence of discounting of the value of the man-sievert was assumed for this specific study, and the alpha value of US $ 8 400 was finally retained. Table 4.3 gives different values generally recommended by authorities in other countries for such evaluations [12].

Table 4.3. Monetary values of man-sievert recommended in various countries

National authority	Situation	α value (US $ per man-sievert)
United Kingdom NRPB – 1993	Public Workers Patients: children Patients: adults Patients: the elderly	30 000 75 000 150 000 75 000 15 000
Scandinavian countries (Radiation Protection Authorities) – 1991	All situations	100 000
Unites States (NRC) – 1993	Public – workers	100 000

4.3. Results of the Cost-Benefit Analysis

Given the estimated α value of US $ 8 400 and considering a discount rate of the annual costs of 8 %, the cost-benefit ratio of the right bank dyke project was calculated for the nine 70-year flooding Sequences. Table 4.4 gives a synthesis of the dyke costs (construction, operation and maintenance) for different discount rates, for a reference time period of 70 years as well as for a reference period of 20 years.

Table 4.4. Dyke costs (Total, 10^6 US $)

Reference period	Discount rate		
	r = 8 %	r = 5 %	r = 0 %
70 years	1.25	1.59	4.08
20 years	1.11	1.23	1.58

A factor 6 (multiplying) was finally applied to all ratios to take into account the uncertainties on the major parameters of the modelling for dose calculations, as discussed in section 3. This uncertainties factor is represented as vertical bars on all the cost-benefit ratios presented in the different figures hereafter.

Figure 4.2 shows the results of the estimated cost-benefit ratios for flooding Sequences (1, 5 and 9). Sequence 5 and Sequence 9 were selected to be representative of two « extreme » cases of flooding profiles within the 70-year reference period, while Sequence 1 represents the « most probable » situation. Results are also presented for a reference time period of 20 years in Figure 4.3.

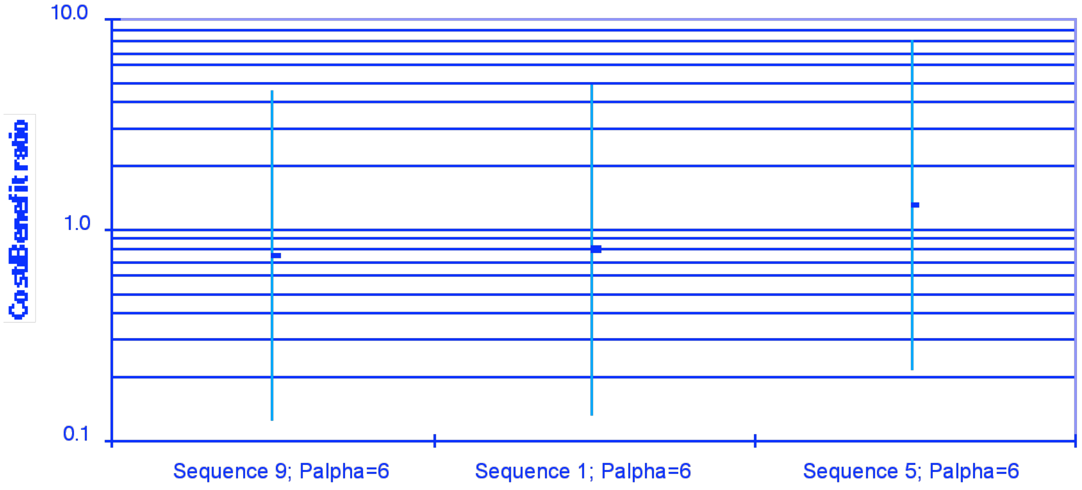

Figure 4.2 **Cost-benefit ratios for three flooding Sequences for a 70-year reference period**

As shown in Figure 4.2, cost-benefit ratios are rather in the range of 0.7 to 1.2. Given the uncertainties on the results on dose calculations, values in the range of 0.1 to 8 could be expected in most of the Sequences.

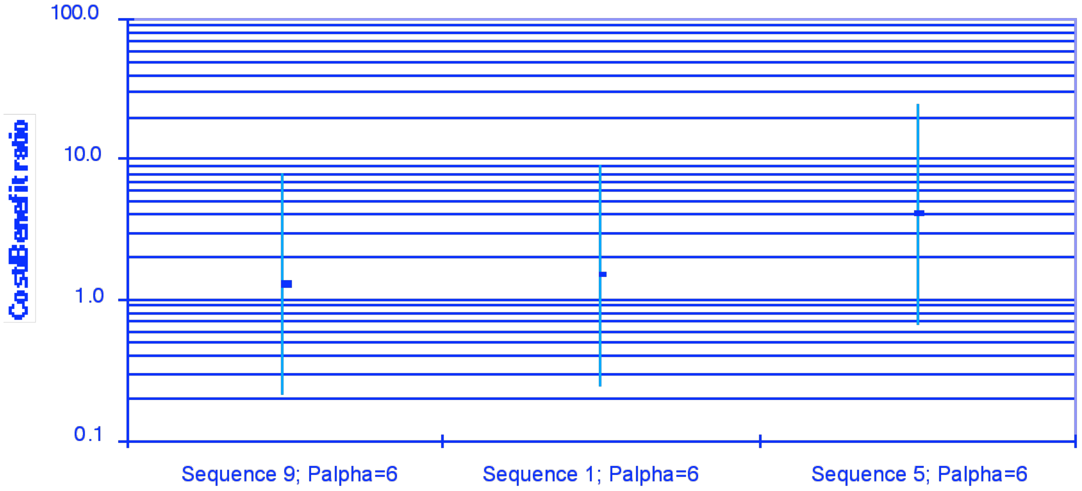

Figure 4.3 **Cost-benefit ratios for three flooding Sequences for a 20-year reference period**

Compared with Figure 4.2, Figure 4.3 shows that the cost-benefit ratio is not too much affected by reducing the reference time from 70 years to 20 years, especially for Sequence 9 where high flooding events occur at the beginning of the reference period, the economic efficiency of the dyke being almost entirely demonstrated within the first 20 years.

4.4. Sensitivity Analysis

A sensitivity analysis is proposed to test the resistance of the calculated cost-benefit ratios with any variation of some of the parameters.

For example Figure 4.4 shows the results when considering a lower monetary value of the man-sievert. The multiplying factor P_{alpha} = 6, representing the public willingness to better protect themselves from the contamination of the environment, was decreased to a value of P_{alpha} = 3.

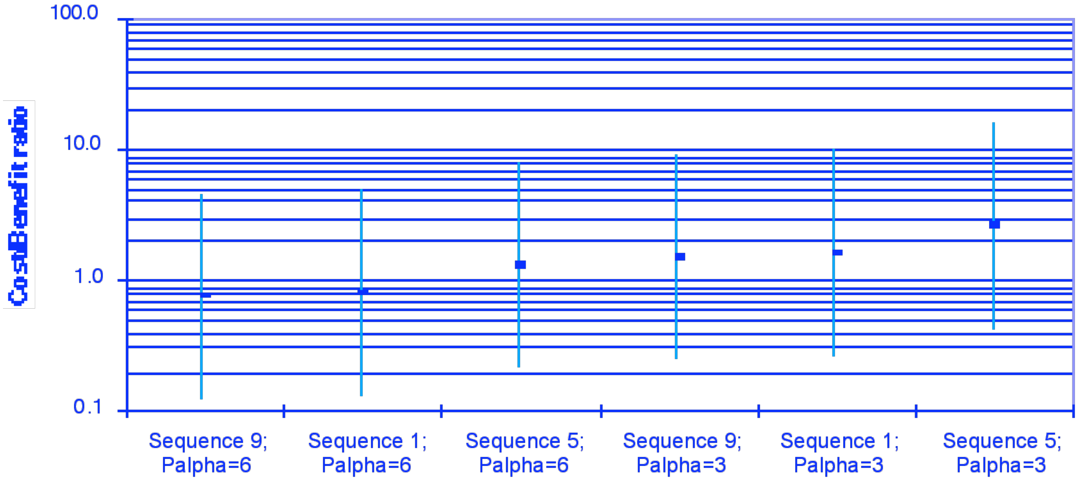

Figure 4.4 **Cost-benefit ratios for three flooding Sequences and two monetary values of the man-sievert (P_{alpha} = 3 and P_{alpha} = 6)**

Even if the dyke could be still economically justified for Sequence 9 events – high releases and flooding events at the beginning of the reference period –, one can notice that the construction of the dyke, for Sequence 5 events where cost-benefit ratios start to be rather above 1 – between 1 and 3 –, could not be justified if we reduce the analysis to a strict radiological and economic dimension. Nevertheless, this project also enters in the scope of general environmental development projects, and that should enhance any strictly radiologically-based judgement.

5. CONCLUSIONS

All results presented in section 4 were voluntarily given with a high degree of variability, to point out the difficulties associated with the modelling of long term radionuclides dispersion into the environment and the difficulty to estimate « one » monetary value of the human life when dealing with radiological risks and future generation health protection.

There is an aspect which was not considered in this study – because of the absence of available quantitative information – and which deals with the possible deterioration and therefore reduction of efficiency of the existing left-bank dyke, as a consequence of the construction of the right-bank one. If this problem happened for extremal floods[5], it would call for further assessment of the consequences in terms of water re-contamination, and that may finally put the present right-bank dyke project benefit into question.

Considering only radiological and economic criteria, the results obtained in this study show that the expected benefits associated with the construction of the right-bank dyke tend to just compensate the estimated investments and maintenance costs of the project: the cost-benefit ratio is around unit (in the range 0.6–1 with factor 6 of variability), which is rather favourable. Actually, the annual operating costs remain extremely high for such a type of construction, mainly due to some administrative constraints on the budget elaboration, which are specific to this country. If the annual maintenance costs were reduced to US$ 12 600.year^{-1}, e.g. 2% of construction costs –maintenance costs for this type of construction is expected to be less than 5 % of construction costs –, cost-benefit ratios presented in Figure 4.2 would be rather in the range 0.5–0.8.

Moreover, recent achievements in the field of social management of radiological risk [16] have demonstrated that the sustainable development of living conditions in contaminated territories could not be reduced to radiological or economic analyses only, but should rather be based on a complex management allowing to deal with all dimensions of life – radiological, economic, social, health, education, ethical, aesthetic, etc. –, and based on the strong involvement of the actors concerned – local population

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[5] According to our information, the left bank dyke has been designed for the 100 years return period flood taking into account the future right bank dyke.

directly confronted with the radiological risk, local and regional production centres, local, regional and national authorities, etc. [17]. It is important to notice that there are some side benefits which are expected from this project. These benefits are related to the averted radio-contamination of waters associated with flooding of the zone where many contaminated materials were buried after the Chernobyl accident. Due to the lack of information about the detailed inventory of these materials and about their contamination levels, the assessment of these benefits with a sufficient degree of precision was impossible in the context of this study, but should be taken into consideration for any justification judgement. Finally it appears that this project – initiated more than 12 years after the Chernobyl accident – may be more justified in the perspective of a long term improvement of living conditions and not solely on a radiological criteria basis.

Thus, given the estimated collective dose reduction and its associated economic benefit – based on data available at the time of this evaluation –, the project of the construction of the right-bank dyke, seems to be a general project for the rehabilitation of contaminated territories, which benefits extend beyond the collective radiological impact. In that case, the expected side effects of the project would probably justify the part of the investments costs which could be above the dose reduction benefit only.

REFERENCES

[1] BONNARD & GARDEL, **Site visit and data analysis**, Report, 1999.

[2] BONNARD & GARDEL, **Hydraulic washout study**, report, 1999.

[3] RAFFESTIN D., LEPICARD S., MICHOU P., **RIPARIA : Logiciel d'évaluation de l'impact radiologique associé au relâchement de matières radioactives en milieu fluvial**, Rapport CEPN n° 237, 1995.

[4] BONNARD & GARDEL, **Dyke design and cost analysis**, report, 1999.

[5] EUROPEAN COMMISSION, **Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment**, RP 72, EUR 15760, 1995.

[6] IPMMS, Personal Communication.

[7] RAFFESTIN D., LEPICARD S**., POSEIDON Version 2.0, Logiciel d'évaluation des impacts radiologiques associés aux rejets de matières radioactives en milieu marin**, Note CEPN NTE/96/24, 1997.

[8] PC-CREAM 97**, PC System for assessing the radiological impact of routine releases**, National Radiological Protection Board, Report EUR 17791 EN, NRPB-SR296, June 1997.

[9] ZHELEZNYAK M., SHEPELEVA T., SIZONENKO V., MEZHUEVA, I., **Simulation of countermeasures to diminish radionuclide fluxes from the Chernobyl zone via aquatic pathways**, Radiation Protection Dosimetry, Vol. 73, Nos. 1–4, 181–186, 1997.

[10] BERKOVSKI V., RATIA G., NASVIT O**., Internal doses to Ukrainian populations using Dnieper river water**, Health Physics, Vol. 71, No. 1, 37-44, 1996.

[11] BERKOVSKI V., VOITSEKHOVITCH O., NASVIT O., ZHELEZNIAK M., SANSONE, U., **Exposures from aquatic pathways,** In: Proceedings of the First International Conference on the Radiological Consequences of the Chernobyl Accident, EUR 16544 EN, 1996.

[12] LEFAURE C., **The man-sievert value: concept, models, status and practices**, European Commission/International Atomic Energy Agency ALARA Training Course, Prague, September 1997.

[13] GOLLIER C., **Discounting an Uncertain Future**, GREMAQ and IDEI, University of Toulouse, France, May 1997.

[14] SCHIEBER C., SCHNEIDER T., EECKHOUDT L., **Valeurs monétaires de l'homme.sievert et prise en compte du temps**, CEPN Rapport No. 214, 1993.

[15] EECKHOUDT L., SCHIEBER C., SCHNEIDER T., GODFROID P., **Monetary value of the man-sievert for public exposure versus worker exposure**, CEPN Rapport No. 262, 1999.

[16] HERIARD-DUBREUIL G., et al., **Post-accident management: the ETHOS project**, Health Physics, Vol.77, No. 4, pp. 361–372, 1999.

[17] ROLEVITCH I.V., et al., **Une démarche de réhabilitation des conditions de vie dans les territoires contaminés : le projet ETHOS en Belarus**, Responsabilité et Environnement - Annales des Mines, Avril, pp. 5-11, 1999.