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Irrigation in dose assessments models

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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Abstract

SKB has carried out several safety analyses for repositories for radioactive waste, one of which was SR 97, a multi-site study concerned with a future deep bedrock repository for high-level waste. In case of future releases due to unforeseen failure of the protective multiple barrier system, radionuclides may be transported with groundwater and may reach the biosphere.

Assessments of doses have to be carried out with a long-term perspective. Specific models are therefore employed to estimate consequences to man. It has been determined that the main pathway for nuclides from groundwater or surface water to soil is via irrigation. Irrigation may cause contamination of crops directly by e.g. interception or rain-splash, and indirectly via root-uptake from contaminated soil. The exposed people are in many safety assessments assumed to be self-sufficient, i.e. their food is produced locally where the concentration of radionuclides may be the highest. Irrigation therefore plays an important role when estimating consequences.

The present study is therefore concerned with a more extensive analysis of the role of irrigation for possible future doses to people living in the area surrounding a repository.

Current irrigation practices in Sweden are summarised, showing that vegetables and potatoes are the most common crops for irrigation. In general, however, irrigation is not so common in Sweden.

The irrigation model used in the latest assessments is described. A sensitivity analysis is performed showing that, as expected, interception of irrigation water and retention on vegetation surfaces are important parameters. The parameters used to describe this are discussed.

A summary is also given how irrigation is proposed to be handled in the international BIOMASS (BIOsphere Modelling and ASSessment) project and in models like TAME and BIOTRAC. Similarities and differences are pointed out. Some numerical results are presented showing that surface contamination in general gives the dominating contribution to resulting concentrations of radionuclides in vegetation due to irrigation.

Finally a proposal is given how to model irrigation in future assessments by using an expression taking into account the leaf area index (LAI) and a specific storage capacity. In addition differentiation of retention on vegetation surfaces for various elements is proposed due to information in the literature. It has been stated that cations are retained more effectively than anions.

Most radioecological models describe migration of radionuclides in soils by an expression including advection and bioturbation as main processes. A sensitivity and uncertainty analysis was performed for the expression used in SR 97 and SAFE to describe this. The results show, as expected, that for immobile radionuclides bioturbation causes a higher transport than advection, while for mobile radionuclides bioturbation is negligible.

Irrigation is important from an exposure point of view. The importance varies due to element and consumption rates. Interception on vegetation surfaces and subsequent retention give the highest contamination for elements with low bioavailability.

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1 Introduction

SKB has carried out several safety studies for repositories for radioactive waste. SR 97 /SKB, 1999/ was a multi-site study concerned with a future deep bedrock repository for high-level waste. Presently, SKB is performing site studies for a deep repository in Oskarshamn (Kalmar County) and Forsmark (Uppsala County). The SAFE project /SKB, 2001/ made an updated safety analysis for the shallower Final Repository for Radioactive Operational Waste (SFR) in Forsmark. In case of future releases due to unforeseen failure of the protective multiple barrier system, radionuclides may be transported with groundwater and reach the biosphere.

Assessments of doses have to be carried out with a long-term perspective. The major problems are to foresee how future ecosystems act, and if and how people's behaviour will change. Therefore various ecosystems are handled and specific models are employed to estimate consequences to man. This is achieved through modelling turnover of radionuclides and uptake in various foodstuffs.

It has been determined that one main pathway for nuclides from groundwater or surface water to soil is via irrigation /Karlsson et al, 2001; Bergström et al, 1999/. Irrigation may cause contamination of crops directly by e.g. interception or rain splash and indirectly via root uptake from contaminated soil. The exposed people are in many safety assessments assumed to be self-sufficient, i.e. their food is produced locally where the concentration of radionuclides may be highest. Irrigation therefore plays an important role when estimating consequences.

The present study is concerned with a more extensive analysis of the role of irrigation for possible future doses to people living in the area surrounding a repository. We must however bear in mind that dose values obtained using biosphere assessment models can never be formally validated and should therefore be interpreted only as indicators of potential radiological impact, conditional on the various assumptions and hypotheses that underlie the assessment. We therefore examine the assumptions behind different models for calculations of doses due to irrigation.

The main objectives of this study are:

- to give a summary of present irrigation practices in Sweden,
- to further document how irrigation was modelled in SR 97 and SAFE,
- to make a sensitivity analysis of the model used for calculating the concentrations of radionuclides in foodstuffs due to irrigation,
- to investigate how irrigation has been handled in other models,
- to further document and make sensitivity and uncertainty analysis of the expressions used for describing migration in soils of radionuclides transferred to soil by irrigation,
- to more in detail illustrate the importance of irrigation as a pathway for transfer of radionuclides to man.

This report is structured as follows: In Chapter 2, a general review of irrigation practices in Sweden is presented. Chapter 3 describes in detail how irrigation was handled in the Swedish safety assessments. The chapter also presents results from a sensitivity analysis of the irrigation model dealing explicitly with interception, irrigation amounts etc. How irrigation is handled in other dose assessments models are presented in Chapter 4.

Results of calculations with an updated model for interception and retention are shown in Chapter 5.

Migration in soil is specially handled in Chapter 6. The importance of irrigation is finally shown in Chapter 7. Finally, conclusions from the study are summarised in Chapter 8.

2 Irrigation in Sweden

About 100 000 ha (3–4% of the arable land) in Sweden can be subject to irrigation. 8 000 farms have equipment for irrigation. In a very dry year a maximum of a $1 \cdot 10^8$ m^3 of water is being used. /Linnér, personal communication, 2002/.

In contrast to dryer countries, salt build-up in soil due to irrigation is not a problem in Sweden. Such salt build-up in soil has damaged one fourth of the irrigated acreage in the world. In Sweden there is an excess of precipitation causing a runoff of 200–400 mm/a. Tests have been performed on Öland using salt water for irrigation, but not even then a salt build-up was achieved. /Linnér, personal communication, 2002/

Approximately 80% of the irrigation water is drawn from lakes and rivers, 15% is groundwater (mostly in the very south: Skåne and Halland) and 5% other sources (municipal sewage water or the farmers' own water reservoirs). /Linnér, personal communication, 1997/

The two most common types of irrigation are aerial irrigation and infiltration tubing on ground. The former is the dominating technique for outdoor irrigation. Normal interval for this is 7–10 days. Fruit trees and berries are mostly irrigated from infiltration tubing on the ground. In dry periods the water is constantly on. The volumes needed depend on the evaporation, measured or calculated from meteorological data such as temperature, wind and precipitation. Evaporation in Sweden a normal day in June to August is about 3–4 mm/d. In extremely hot days it can exceed to 6–7 mm/d. /Linnér, personal communication, 2002/

The needs for irrigation are of course a result of insufficient precipitation. /Larsson-McCann et al, 2002a,b/ have compiled detailed information about meteorological data in Forsmark and Oskarshamn areas. These data show, as expected, the high difference in precipitation amounts between coast and inland. In the Forsmark area, the amount is about 170 mm less than at an inland station when using data from a meteorological station on an island. In Oskarshamn the corresponding figure is about 100 mm. The average precipitation based on 30 years statistics is shown in Table 2-1 below.

Table 2-1. Annual average precipitation and standard deviations (corrected) at the sites (1960–1999) /Larsson-McCann et al, 2002a,b/.

Area	Station	Average annual precipitation (mm/year)	Standard deviation (mm/year)
Forsmark	Örskär (island)	588	114
Forsmark	Lövsta (inland)	758	154
Forsmark	Untra (inland)	712	135
Oskarshamn	Ölands norra udde (island)	530	78
Oskarshamn	Oskarshamn (coast)	633	120
Oskarshamn	Målilla (inland)	665	95

A general water need for plants during growing season is about 3 mm water per day or as monthly average 90 to 110 mm during the summer months /Eriksson et al, 1990/. This implies that there is a higher possibility that households located on the coast will irrigate their vegetables etc.

Data for precipitation and evapotranspiration has also been compiled for the three summer months when irrigation is most common. Data were available from the stations Örskär, Målilla and Ölands norra udde.

Table 2-2. Precipitation (mm), growing season June–August and yearly 1961–1990 /Larsson-McCann et al, 2002a,b/.

	Örskär, Östhammar					**Målilla**					**Ölands norra udde**				
	Jun	**Jul**	**Aug**	**Sum**	**Year**	**Jun**	**Jul**	**Aug**	**Sum**	**Year**	**Jun**	**Jul**	**Aug**	**Sum**	**Year**
Average	39	58	79	**176**	**588**	56	72	68	**196**	**665**	38	47	54	**139**	**530**
Max	116	147	165	**428**	**865**	138	147	133	**418**	**839**	94	120	141	**355**	**675**
Min	6	8	6	**22**	**347**	14	16	19	**49**	**471**	6	9	17	**32**	**393**

Table 2-3. Potential evapotranspiration (mm), growing season June–August and yearly 1961–1990 /Larsson-McCann et al, 2002a,b/.

	Örskär, Östhammar					**Målilla**					**Ölands norra udde**				
	Jun	**Jul**	**Aug**	**Sum**	**Year**	**Jun**	**Jul**	**Aug**	**Sum**	**Year**	**Jun**	**Jul**	**Aug**	**Sum**	**Year**
Average	102	100	78	**280**	**517**	102	98	73	**273**	**468**	106	102	77	**285**	**587**
Max	120	120	91	**331**	**603**	118	124	90	**332**	**519**	126	140	98	**364**	**712**
Min	71	73	59	**203**	**429**	81	84	62	**227**	**427**	87	81	61	**229**	**508**

2.1 Horticultural plants in greenhouses and outdoor cultivation

Greenhouses are irrigated with at least 300 mm/a. Vegetables cultivated outdoors are almost always watered, normally about 100 mm/season (varies from 0–200 mm/season). Irrigation occurs 3–4 times a season, with 25–30 mm/occasion. Growing season lasts from middle of June–August. In southern Sweden, there among Kalmar County, irrigation season lasts till middle of September /Linnér, personal communication, 1997/. The areas in Table 2-4 include vegetables, berries, fruits, flowers, nursery plants and ornamental plants.

Table 2-4. Area covered by greenhouses and area under outdoor cultivation in the whole of Sweden, Uppsala County and Kalmar County 1999 /JO 36 SM 0001/.

	Sweden (ha)	**Uppsala County (ha)**	**Kalmar County (ha)**
Greenhouses (> 200 m^2)	327.3	2.6	5.5
Outdoor cultivation (> 2500 m^2)	12 233	91	869

2.2 Pasture and ley

These crops are sparsely irrigated today. Maximum yield of pasture and ley is not that important when there are many alternative ways to get fodder for the animals. The costs of irrigation are too high /Linnér, personal communication, 2002/.

2.3 Cereals

Swedish soils are some years very dry in May and June. Grain does not germinate if it's to dry, and irrigation therefore sometimes occurs early in the season. Otherwise, grain is sparsely irrigated /Linnér, personal communication, 2002/.

2.4 Sugar beets

Sugar beets are cultivated in the south of Sweden and about 10–15% of the acreage is irrigated /Linnér, personal communication, 1997/.

2.5 Potatoes

At least 70% of the potato acreage is irrigated with approximately 100 mm/season (varies between 0 and 200). Irrigation occurs normally 3–4 times a season, from end of July till end of August, with 25–30 mm/occasion. Growing season lasts from June–August (in south of Sweden till middle of September) /Linnér, personal communication 1997 and personal communication, 2002/.

2.6 Use of arable land

In Table 2-5 the amount of land used for crops mentioned in this chapter is summarised. These data are presented to give an overview of how common the different crops are in the areas studied in this report.

Table 2-5. Use of arable land the year 2002 in Sweden, Uppsala County and Kalmar County /SCB, 2003/.

	Sweden (ha)	**Uppsala County (ha)**	**Kalmar County (ha)**
Pasture and ley	985 849	35 949	64 900
Cereals (total)	1 129 300	81 874	41 684
Wheat	339 600	31 671	10 554
Barley	416 800	34 114	19 138
Oats	295 200	12 863	6 879
Sugar beets	54 800	–	1 964
Potatoes	31 731	342	1 383

3 Irrigation model in SR 97 and SAFE

In the dose modules used within SR 97 and the updated safety analysis for SFR, irrigation was included as a main path for transferring radionuclides in ground or surface waters to upper soil. The models used were made of two parts, one for calculating the dynamic behaviour of radionuclides in the compartments and one for computing human exposure /Bergström et al, 1999; Karlsson et al, 2001/.

A schematic figure of the processes considered in the assessments models is shown in Figure 3-1.

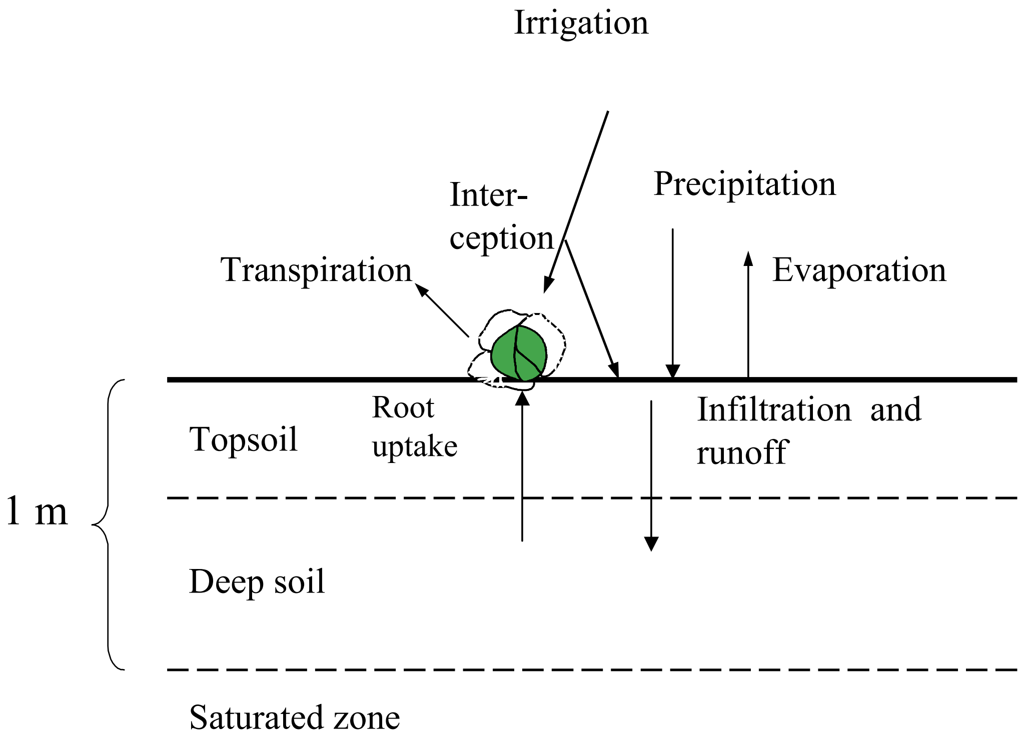

Figure 3-1. *Schematic description of water turnover atmosphere-plant-soil.*

3.1 Description

One main assumption was used in all calculations. Independent of the initial retention on vegetation surfaces, the whole amount of irrigation water was assumed to be transferred to the upper soil layer. This is in accordance with the other studies mentioned below. In addition irrigation was modelled to be used a number of times during the vegetation season.

At each irrigation occasion, part of the radionuclides in the irrigation water was assumed to remain on the vegetation surfaces, see Table 3-1 below. The resulting concentration of radionuclides in vegetation when harvested for consumption was differently calculated for different types of crops. For vegetables and pasture, which were assumed to be consumed more or less continuously, the initial concentration in vegetation from the first irrigation occasion was assumed to decrease exponentially. This was described as a weathering process, which in radioecology includes all processes like growth, grazing and effects of wind and rain, which reduce the concentration of radionuclides on vegetation. This was repeated for each irrigation occasion, causing a net build-up of radionuclides. This was described by an integral, which was solved and divided with the length of the period during which irrigation occurs in order to get an average concentration during the irrigation season, see below. In order to obtain the concentration in plants the remaining radionuclides were divided by pertinent yield values.

$$\mathrm{C_p} = \frac{\mathrm{C_w}}{Y_P} \cdot \frac{\mathrm{I}}{\mathrm{t_{tot}}} \cdot \sum_{i=1}^{Nr_{IRR}} \int_0^{t_i} e^{-\tau \cdot t} dt, \quad t_i = i \frac{t_{tot}}{Nr_{IRR}}, \quad i = 1,2,\ldots, Nr_{IRR}$$

where

C_p = Concentration of radionuclides in vegetation due to retention (Bq/kg).

C_w = Concentration of radionuclides in irrigation water (Bq/m^3).

I = Remaining water on the vegetation after each irrigation occasion (m^3/m^2 = m).

t_{tot} = Irrigation period (days).

Nr_{IRR} = Number of irrigation occasions per year.

t_n = Times between irrigation occasion and end of irrigation period (days).

τ = ln 2/T$_{½w}$ where T$_{½w}$ = weathering half-life (days).

Y_p = Annual yield of vegetables and pasturage, respectively (kg/(m^2·year)).

Values used for the parameters are given with ranges for sensitivity analysis in Table 3-1 below.

Table 3-1. General data used when calculating the effect of interception and retention.

Parameter	Unit	Best estimate	Reference
Water amount used at each irrigation event (V_{IRR})[1]	m^3/m^2	0.030	Estimated after /Linnér, personal communication, 1997/
Irrigation events (Nr_{IRR})	Number per year	5	Estimated after /Linnér, personal communication, 1997/
Irrigation period	Days	75	
Retention of irrigation water (I)	$m^3/m^2 = m$	0.003	/Persson, 1997/
Translocation factor [2]	$(Bq/kg\ ww)/(Bq/m^2)$	0.1	Default value
Weathering half-life ($T_{½w}$)	Days	15	/IAEA, 1994/
Yield values, vegetables	kg/m^2	2.0	/Karlsson et al, 2001/
Yield values, root-vegetables	kg/m^2	2.3	/Karlsson et al, 2001/

[1] Not of importance in these calculations as it only determines how much irrigation water will be transferred to soil.

[2] Translocation is an element specific process. As default the value 0.1 was used.

In this study, we looked upon the process of interception, which determines the amount of precipitation water that will not reach the ground due to the filtering effects of vegetation. The process is essential in water balance studies. Irrigation can be seen as a heavy rain. To be effective, the amount of water should be quite high per occasion. The amount of water remaining on vegetation surfaces can be modelled as a function of the leaf area index (LAI) and a specific storage capacity. In this context, LAI is defined as half the total green leaf area (one-sided area for broad leaves) in the plant canopy per unit ground area /Chen and Black, 1992/. LAI is an important parameter when describing plant interaction with the atmosphere, especially concerning radiation, energy, momentum and gas exchange /Monteith and Unsworth, 1990/. Values of the leaf area index vary with time and type of crop.

In /Persson, 1997/ various leaf areas are given as well as specific interception storage capacity. In order not to underestimate contamination, the maximum LAI of 6 (value for grass ley) was selected and a specific interception storage capacity of 0.5. More discussion about data will be given in Section 3.3 below. /Persson, 1997/ used these values in a comparison of simulated water balance for willow, spruce, grass ley and barley.

Another approach was used for cereals and root vegetables that are not harvested continuously. We then simply assumed that a fraction of the nuclides in the 6·0.5 mm water layer was translocated to edible parts of the plants at each irrigation occasion. This translocation factor is element-specific. There is however a lack of data for almost all radionuclides. The radionuclides Cs-137 and Sr-90 are the most studied due to their high importance for doses due to accidental releases from nuclear power plants. The following expression was used to estimate the concentration in cereals and root crops due to surface contamination:

$$C_r = \frac{\sum_{o}^{Nr_{IRR}} I \cdot TL_r \cdot C_w}{Y_r}$$

where

C_r = Concentration of radionuclides in root vegetables (Bq/kg dw) due to surface contamination.

Nr_{IRR} = Number of irrigation occasions.

I = Remaining water on the vegetation after each irrigation occasion ($m^3/m^2 = m$).

TL_r = Translocation from plant surface to edible parts of plant, ((Bq/kg ww)/(Bq/m^2)).

C_w = Concentration of radionuclides in irrigation water (Bq/m^3).

Y_r = Yield-values for root vegetables (kg/m^2).

Contamination due to rain-splash was not explicitly taken into account. Instead, consumption of soil due to unwashed vegetables was considered in the assessments /Bergström et al, 1999, Karlsson et al, 2001/.

3.2 Sensitivity analyses

Sensitivity analyses were performed in order to study the relative importance of the parameters for the resulting concentrations . Best estimate values (see Table 3-1 above) were used, and we assumed that all values were normally distributed with a standard deviation of 10% of their average values. The 10% were arbitrarily selected, as the main objective was to study how the model results depend on the information used, i.e. it does not matter if 1% or 10% variation in values was used. Maximum values due to the build-up during several irrigation occasions were studied in addition to the averages during irrigation. Because the actual numerical values themselves, and not only their variation, may affect the outcome, different cases were selected.

The PRISM package /Gardner et al, 1983/, developed in Studsvik, was used for the analyses. This implied that sets of parameter values were generated from given distributions of each parameter. Model results were then calculated for all of the sets. The statistical tool of the system applies regression and correlation to identify those parameters contributing most to the variation of the results. A thousand sets were used and the Spearman rank coefficient was computed.

According to Chapter 2 cereals are not irrigated in Sweden, and if so, only at the germination stage. Pasturage is not irrigated. We have therefore focused on vegetables and root crops. Assuming a concentration of 1 Bq/l in the irrigation water, the average concentration in vegetables will be 1.8 Bq/kg while the maximum concentration will be 2.5 Bq/kg. Root crops would contain 0.66 Bq/kg when a translocation factor of 0.1 is applied.

The sensitivity analysis points out the following parameters of importance, see Table 3-2 below.

Table 3-2. Sensitivity of model results to variation of parameter values.

Parameter	Contribution (%) Vegetables Average	 Max	 Root vegetables
Number of irrigation events	14	13	24
Weathering half-life	13	8	–
Retained amount	23	28	24
Time from irrigation season start to when an irrigation event occurs	12	7	–
Yield values	24	29	21
Translocation	–	–	24

Important parameters for all responses are retention on the surfaces of vegetation and yield values. The four parameters used to describe the concentration in root vegetables all contribute about equally to the results. For vegetables the exponential decrease of concentration due to weathering processes and the time during which irrigation occurs give minor contribution to the results.

If the number of irrigation occasions is increased, the concentration will increase proportional due to the assumption of the same interception and retention during the time irrigation occurs.

As it may be doubtful to include weathering as a process for decreasing the content of vegetation on the surfaces, see discussion below, we investigated what should happen if it was excluded. The concentration in vegetables will naturally increase. The increase is about a factor of three compared to the case with weathering (5.7 Bq/kg as an average value and 7.5 Bq/kg for the maximum value). Root crops are not affected at all since weathering is not included for such crops. The most sensitive parameters to the results are shown in Table 3-3 below.

Retained amount of water and yield values are the most important parameters. The results are quite understandable, because when weathering is excluded, no time dependency shows up in the calculations. The resulting concentrations are simply a sum of the retention at each irrigation event.

Table 3-3. Sensitivity of model results if weathering is excluded.

Parameter	Contribution (%) Vegetables Average	 Max	 Root-crops
Number of irrigation events per year	10	22	22
Retained amount	39	30	24
Yield values	39	30	24
Translocation	–	–	24

The expression used in SR 97 and SAFE gives a contamination of vegetation that is directly proportional to the number of irrigation events. A doubled rate of irrigation gives a doubled level of contamination both for vegetables and root vegetables. If the weathering process is taken into account the length of the time period when irrigation occurs also plays a role. If no weathering is considered, the resulting contamination on vegetation surfaces is naturally independent of time between irrigation and harvest.

3.3 Discussion

The modelling of the process of interception and initial retention and the data used are essential for the surface contamination, according to the outcome from the sensitivity analyses. Interception varies with the growth of the plant, but this was not taken into account in SR 97 or SAFE. We used only one value of the factor to describe this without taking elements properties into account. Several publications have however found that retention depends on the chemical properties of the elements /Pröhl et al, 1995; Hoffman et al, 1989/.

Regarding interception of irrigation water, leaf area index and a specific storage capacity are important parameters for describing the process of interception. It is however more useful to consider both these parameters instead of using the lumped factor as was done in SR 97 and SAFE.

The leaf area index varies with season and type of plant. In general, LAI is a function of biomass density, but also the shape of the leaves is of importance. In a study of tomato plants e.g. the interception decreased though the LAI increased /Brambilla et al, 2002/. This was explained to be due to the growth of the fruits affecting the position of the leaves. In /Pröhl and Müller, 1994/ tabulated values were given for various plants and times during growing season. These values were based on a literature survey reported in /Müller and Pröhl, 1993/. Because of the great interest in surface contamination due to accidental releases, the main focus was on cereals and grass. These are not irrigated in Sweden.

Irrigation of potatoes occurs mostly during July and August, LAI-values are then given as 4 /Pröhl and Müller, 1994/, which is somewhat lower than the maximum value of 6, which was used in SR 97 and SAFE. The corresponding value for vegetables was 5. In order to be conservative, we propose that 4 and 5 are used as LAI for potatoes and vegetables, respectively, in future dose assessments.

In addition to values of LAI, it is important to have good knowledge about the specific storage of water per LAI. In the calculations above, the maximum value of 0.6 mm water per LAI was used, according to /Persson, 1997/. He referred his value to /Johnsson and Jansson, 1991/ that referred to /Jensen, 1979/. As Jensen's study dealt with a forest model, care must be taken when using such a high value as it might be more valid for forests. A default value for specific storage capacity of 0.2 mm per LAI was found in /Jansson and Karlberg, 2001/. They present a model for the exchange of heat and mass for the soil-plant-atmosphere system. Unfortunately, no reference was given for the value. /Pröhl, 1990/ studied the specific storage capacity and recommended 0.2 mm per LAI for grass. In his study he has among others used an old reference; Horton from 1919. It seems clear from Pröhl´s study that other plants, like vegetables, have a higher specific storage capacity, about 0.3 mm per LAI. We therefore suggest that 0.3 mm per LAI should be used in the future.

What is obvious is that the properties of various elements should be considered when looking upon the resulting retention of radionuclides on the surfaces of vegetation. A lot of studies were performed after fallout due to wet deposition from the radioactive plume from the Chernobyl accident, e.g. /Pröhl et al, 1995/. In that study, retention as well as decrease due to weathering was examined. The observations confirmed that the chemical properties of the elements are of importance for retention. They showed that cations were retained more effectively than anions. This was explained by the negative charge of vegetation surfaces /Schönherr, 1977; Ertel et al, 1992/. /Hoffman et al, 1989/ also support these findings. We therefore propose that retention values according to Table 3-4 below should be used in future assessments.

Table 3-4. Retention coefficients.

Chemical form	Best estimate	Min	Max
Cations (e.g. Se, Ra, U)	2	1.5	2.5
Monovalent cations (e.g. Cs)	1	0.5	1.5
Anions (e.g. Cl, Tc-oxides, I)	0.5	0.3	0.7

The retention also depends on irrigation or precipitation intensity. It is however considered that irrigation should be effective, which leads to that a substantial amount of water is used at each occasion.

The decrease due to weathering processes is always described by a weathering half-life and an exponential decline. When this lumped parameter also contains dilution due to growth, it is not logical to use, however. That is because the yield values are used when calculating the concentration per kg crop, i.e. the biological growth of vegetation is already included. It is disputable to consider weathering at all, as it is questionable that elements retained on the surfaces due to intensive watering may be transferred away due to e.g. wind and precipitation. In general, the precipitation water is more acid than the surface water, which could lead to higher abundance of the cations present on vegetation surfaces. For anions on the other hand, ignorance of weathering may overestimate the surface contamination.

Another important parameter is yield value. In the earlier calculations a default value of 2 kg/m^2 was used for vegetables. Agricultural statistics give varying values dependent on crop, see Table 3-5 below.

The bulky vegetables have the highest yield values, about a factor of 2 higher than the default value used.

Table 3-5. Yield-values 1999 for vegetables grown on open land in Sweden /SCB, 2003/.

Crop	Cucumber	Cauli-flower	White cabbage	Head of lettuce	Iceberg lettuce	Leaf-type lettuce
Yield (kg/m^2)	4.5	1.7	4.5	1.7	2.8	1.4

4 Irrigation models in other studies

A review of the assumptions made in three other models BIOTRAC /Davis et al, 1993/, BIOMASS /IAEA, 2003/ and TAME /Klos et al, 1996/ for handling contamination due to irrigation is presented below.

4.1 Comparison of BIOTRAC, BIOMASS, TAME and SR 97

A summary of similarities and differences in the models are presented in Table 4-1. Data from SR 97 are shown as a comparison.

All models are conservatively biased when looking on redistribution of radionuclides, as they assume that all irrigation water reach ground without losses due to interception. BIOTRAC, by assuming that lack of water (obtained from daily calculations of the water balance) is replaced by irrigation water, uses the highest amounts of irrigation water. On the other hand, this model uses the lowest retention of radionuclides on vegetation surfaces, which compensate the resulting surface contamination. This value is not documented. BIOMASS shows the most complicated structure when comparing the expression for resulting concentration in vegetation. In BIOMASS fractions of retained radionuclides are transferred to other parts of vegetation, and a fraction of that is transferred to edible parts. All irrigation water is applied to vegetation at one occasion. On the other hand, BIOMASS suggests element dependent data to be used when estimating the retention of radionuclides on vegetation. Unfortunately, documentation of that data is not clear in the report. No model seems to look upon irrigation as a series of events.

It may be observed that irrigation was mostly based on assumptions of the amounts of water, and no survey has been performed upon if and what is irrigated as a base for the modelling. BIOTRAC uses a probabilistic approach when assuming irrigation to occur or not, however. It is not clear from the report how consistent this approach is, as irrigated amounts are obtained from daily water balance calculations.

Table 4-1. Compilation of basic assumptions considering irrigation in dose assessments models for safety assessments of radioactive waste.

Model			
BIOTRAC	**BIOMASS**	**TAME**	**SR 97**
Climate			
Not changed within the time of a simulation.	Long-term climate variations are ruled out on basis of low relevance to lifetime average exposure.	Different reference biospheres are included in the model.	Not changed within the time of a simulation.
Exposure group			
All food consumed is grown locally.	A small farming community living of local products.	A closed agricultural community.	A self-supporting critical group.
Irrigated crops			
Vegetables and forage crops.	Root vegetables, green vegetables, grain and pasture.	Root vegetables, green vegetables, grain and pasture.	Root vegetables, green vegetables, (grain and pasture, due to scenario).
Irrigation water source			
Well or lake with equal probability for the garden, lake water for the forage field.	Well. Natural surface water bodies excluded from the biosphere system.	Local wells or surface water.	Local wells or surface water.
Irrigation amount			
Variable about 0.6 m^3/m^2 and year. Calculated as the amount that needs to be added to keep soil water content at field moisture capacity.	0.3 m^3/m^2 and year, indicative range 0.2–0.4 m^3/m^2 and year.	No data presented in the report.	Average 0.15 m^3/m^2 and year.
Continuous process			
Irrigation at one occasion.	Irrigation at one occasion.	Not specified.	At specific occasions.
Duration of irrigation			
Irrigation lasts for 100 years (GM) (50–10 000 years). (Probability watering gardens 0.9, forage fields 0.02).	Assessment context $1 \cdot 10^6$ years.	Not specified.	Assessment context 10 000 years.
Irrigation season			
May–September.	July–August (60 days).	No data in the report.	May–July.
Soil depth			
Probabilistic or distributed. Less than 0.5 m treated as a single, well-mixed compartment.	0.3 m	No data in the report.	Average 0.3 m
Interception fraction of irrigation water			
0.05 (all food types). Fix parameter.	See “resulting interception factor” below.	Included, no data presented in the report.	0.1

Model			
BIOTRAC	**BIOMASS**	**TAME**	**SR 97**
Retention, element specific			
No	Yes	Yes	No
Resulting interception factor			
	0.3 I-129 0.1 Tc-99 0.5 Np-237 0.5 Nb-94		
Translocation			
No	0.01–1 Element- and crop dependent.	Included in the interception factor.	Element and crop dependent.
Evapotranspiration			
Calculated via daily averaged values of net solar radiation, wind speed, vapour pressure and air temperature. Average leaf length, LAI, root cross-sectional area, root distribution with depth and surface resistance to water flow.	No	Varies with assumed climate.	Considered for estimating resulting run-off.
Weathering			
Yes, half-time 12 days all crops.	18/year Includes mechanic weathering, wash-off and leaf fall. Nuclide- and crop independent Applies only after irrigation has ended.	Included, no data presented in the report.	Yes, half-time 15 days all crops.
Loss due to preparation of foodstuffs			
Yes	Yes	Yes	No
Transfer to soil			
	When calculating the concentration in soil, all the activity in the water, used for irrigation, is assumed to enter the soil.	Radionuclides removed from plant by weathering or harvesting is transferred to the soil.	When calculating the concentration in soil, all the activity in the water, used for irrigation, is assumed to enter the soil.
Rain-splash			
Yes	Yes	No	No
Daughter nuclides taken into consideration			
Yes	No	Yes	No

4.2 Results of BIOTRAC, BIOMASS and SR 97

Some results from the models described above were compiled in Table 4-2. They are normalised to a unit concentration of 1 Bq/m^3 in the water used for irrigation. Table 4-2 shows total dose from all sources, dose from ingestion of irrigated crops and the contribution from contamination of plant surface. However the values are not directly comparable as the number of exposure pathways varies as well as a lot of parameter values concerning consumption and element specific values etc also vary.

A sample BIOTRAC calculation shows that the largest dose from Tc-99 is received through the soil/plant/man pathway (Table 4-2). The air/plant/man pathway involving irrigation, and the water/man pathway are the next most important pathways, but they result in doses more than two orders of magnitude less than the soil/plant/man pathway.

The results from BIOMASS indicate that irrigation gives an important contribution to total dose. Drinking water and consumption of animal products are other important pathways, especially for I-129 and Tc-99. For Nb-94 external exposure from soil is the most important pathway, followed by milk consumption. The values for BIOMASS represent a critical group consisting of "arable farmers".

Except for Tc-99 and Nb-94 the surface contamination dominates the contamination of crops for the samples given below. However, the percentage contribution varies between the models, where the results from BIOMASS show the highest percentage contribution to plant contamination by surface contamination.

Table 4-2. Total dose (Sv/y), percentage contribution from intake of irrigated crop and percentage of contamination pathway for crops, according to BIOTRAC, BIOMASS and SR 97.

MODEL Crop	Nuclide	Total dose from all pathways considered Sv/year	Dose from consumption of irrigated crop (% of total dose)	Contribution from contamination of plant surfaces (% of dose from irrigated crops)
BIOTRAC All crops included	Tc-99	$1.5 \cdot 10^{-7}$	99.3	
BIOMASS Grain	Nb-94	$1.7 \cdot 10^{-6}$	0.2	46
	Tc-99	$4.5 \cdot 10^{-9}$	41	53
	I-129	$7.1 \cdot 10^{-7}$	56	99
	Np-237	$4.3 \cdot 10^{-7}$	20	93
BIOMASS Green vegetables	Nb-94	$1.7 \cdot 10^{-6}$	0.2	99
	Tc-99	$4.5 \cdot 10^{-9}$	10	46
	I-129	$7.1 \cdot 10^{-7}$	16	96
	Np-237	$4.3 \cdot 10^{-7}$	44	92
SR 97 Green vegetables	Nb-94	$2.7 \cdot 10^{-7}$	1.6	91
	Tc-99	$2.1 \cdot 10^{-9}$	49	16
	I-129	$2.3 \cdot 10^{-7}$	20	23
	Np-237	$1.7 \cdot 10^{-7}$	8.2	87

5 Updated interception model

During this study the importance of interception led us to develop an updated interception model.

Some calculations were performed in order to estimate the importance for the surface contamination due to the proposed changing of parameter values, according to the discussion in Chapter 3. The parameters with ranges are given in Table 5-1. In similarity to the former models, irrigation is described as summation of retention at each occasion; see the expression below for vegetables. Note that in this example the maximum level in vegetation is handled.

$$C_p = Nr_{IRR} \cdot \frac{LAI \cdot StoCap \cdot Kret \cdot C_w}{Y_p}$$

where

C_p = Concentration of radionuclides in plants due to retention (Bq/kg).

Nr_{IRR} = Number of irrigation events per year.

LAI = Leaf Area Index (m^2/m^2).

StoCap = Water storage capacity in vegetation due to interception (m^3/m^2).

Kret = Element dependent retention factor (–).

C_w = Concentration in water (Bq/m^3).

Y_p = Yield values (kg/m^2).

For root crops the expression above is multiplied with an element dependent translocation factor.

Table 5-1. Parameter values, triangularly distributed.

Parameter		Unit	Best estimate	Min value	Max value
Nr_{IRR}		–	4	3	5
LAI, vegetables		m^2/m^2	5	4	6
LAI, root crops		m^2/m^2	4	3	5
StoCap, vegetables		m^3/m^2	$3 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Yield, vegetables		kg/m^2	2	1.5	4
Yield, root vegetables		kg/m^2	2.0	1.9	2.3
Kret	Anions	–	0.5	0.3	0.7
	Cs		1.0	0.5	1.5
	Cations		2.0	1.5	2.5

Ranges for LAI were subjectively selected but should be valid for summer months when irrigation is most common. As the yield values are at harvest the LAI and yield-values should be coherent. Minimum value for storage capacity per LAI was the one that represents grass while the maximum value corresponds to the maximum value found in /Pröhl, 1990.

The yield values used for vegetables are 2.0 kg/m^2, varying from 1.5 to 4.0, due to the yield-values presented in Table 3-5. Yield value relevant for potatoes in Forsmark area is 2.03 kg/m^2 according to /Berggren and Kyläkorpi**,** 2002/. Value for Kalmar County is 2.02 kg/m^2. Ranges used are 1.9–2.3 kg/m^2. The minimum value of 1.9 kg/m^2 represents yield from Dalarna, a county in west Sweden at the same latitude as the Forsmark area. Statistics about agricultural practices do not give specific values for Uppland where the Forsmark area is located. The maximum value represents an average yield 1999 for forest districts in central Sweden /SCB, 2002/. Data show that the potatoe yield decreases with time /SCB, 1999, 2002/.

The calculations show that for e.g. Cs the mean resulting concentration in vegetation will be 2.5 Bq/kg if the added water has a concentration of 1 Bq/l. For cations and anions the corresponding value will be 5 and 1.3 Bq/kg, respectively. The values for cations are about a factor 2 higher than when using the old data and not considering any loss due to weathering. If weathering would be considered the values would decrease to about a third.

6 Migration in soils

In the models adopted for SR 97 and SAFE soils were divided into two compartments, one upper where plants grow, and one deeper layer from which radionuclides leaked to groundwater for discharge to wells or surface waters /Bergström et al, 1999, Karlsson et al, 2001/. Radionuclides transferred from above by irrigation water were exchanged between these compartments due to processes like advection and bioturbation. Erosion from upper soil caused a loss of radionuclides from the system. This report focuses on how the migration rate constants were obtained, and which parameters influenced them the most.

6.1 Description

It was assumed that nuclides transferred to soil by irrigation water migration due to advective processes and bioturbation. This was expressed in the models as a transfer coefficient (TC, y^{-1}) from top soil to deep soil, see below. The expression for retention considers that the soluble part of the elements follow the infiltration of water in soils. The fraction attached to particles is transported due to earthworms' consumption and following excretion of soil (bioturbation):

$$TC = \frac{R}{\varepsilon_t \cdot D_{ts} \cdot RET} + \frac{BioT}{D_{ts}(1-\varepsilon_t) \cdot \rho_p}$$

where

$$RET = 1 + K_d \cdot \rho_p \cdot \frac{(1-\varepsilon_t)}{\varepsilon}$$

and

R = Runoff (Precipitation – Evapotranspiration) ($m^3/(m^2 \cdot year)$).

ε_t = Porosity of topsoil (m^3/m^3).

D_{ts} = Depth of topsoil (m).

BioT = Transport due to bioturbation ($kg/(m^2 \cdot year)$).

ρ_p = Density of soil particles (kg/m^3).

K_d = Distribution factor, concentration of an element on solids relative to dissolved (m^3/kg).

The factor *RET* above originates from a study of transport of radionuclides in water/mineral systems /Andersson et al, 1982/. It gives the relation between retention of an element and its K_d-value for transport in a column. This expression for retention is used in most dose assessments models /Klos et al, 1996; IAEA, 2003/. An exception is BIOTRAC /Davies et al, 1993/, using a much more complex soil model.

The value for soil retention is then used together with the water turnover in soil in order to obtain turnover rates. This may be performed differently in various models. In our case we looked upon the annual runoff from the area of interest and the pore volume available for keeping water in upper soil. This implies that all runoff is handled as ground-water runoff, and that there is no surface water runoff. Others, like BIOMASS, suggest an infiltration rate of water to be used. Other ways are to use the permeability rate in upper soil layers, dividing with pertinent soil layer. Due to high variability of permeability, however, and the fact that we were looking for annual exposure values we preferred to use annual runoff values. On the other hand, it is verified in many hydrology studies that groundwater runoff is the major part of the annual runoff; a fraction may be surface water, especially during spring season and snow melt. This fraction is on the other hand also dependent on topography of the area of interest.

The rates for bioturbation were obtained from an annual transport of soil, divided by soil masses /Müller-Lemans and van Dorp, 1996/.

6.2 Sensitivity analysis

A sensitivity analysis was performed on the expression used for obtaining migration rates. All parameters were assumed to be normally distributed and 10% of their best estimates were taken as standard deviations, see Table 6-1 below. The PRISM-package from EBS biosphere system was used here as well, see Section 3.2.

Table 6-1. General parameter values used in the sensitivity analysis.

Parameter	Unit	Best estimates	Standard deviation	Reference
Runoff	m^3/m^2	0.25	0.025	/Lindborg and Schüldt, 1998/
Depth of top soil layer (D_{ts})	m	0.25	0.025	/Haak, 1983/
Soil particle density (ρ_p)	kg/m^3	2 650	265	/Hillel, 1980/
Soil porosity, top soil (ε_t)	m^3/m^3	0.5	0.05	/Wiklander, 1976/
Bioturbation (BioT)	kg/m^2	2	0.2	/Müller-Lemans and van Dorp, 1996/

Because K_d-values vary over substantial ranges it was necessary to study the expression for a range of K_d-values; see Table 6-2 below where the results are presented.

Table 6-2. Sensitivity of transfer coefficient to variation of parameter values.

K_d	Migration	Percentage contribution					
(m^3/kg)	(y^{-1})	K_d	Run-off	Bioturbation	Soil depth	Soil density	Soil porosity
10	$6.41 \cdot 10^{-3}$	0	0	24	26	17	25
1	$7.13 \cdot 10^{-3}$	0	0	21	27	18	26
0.1	$1.43 \cdot 10^{-2}$	8	8	5	27	19	25
0.05	$2.22 \cdot 10^{-2}$	13	13	2	24	18	23
0.01	$8.31 \cdot 10^{-2}$	19	19	0	22	15	18
0.005	$1.54 \cdot 10^{-1}$	19	21	0	22	14	16
0.001	$5.74 \cdot 10^{-1}$	17	29	0	30	11	6
0.0005	$8.90 \cdot 10^{-1}$	12	36	0	36	8	0
0.0001	$1.61 \cdot 10^{0}$	2	38	0	39	2	13
0.00001	$1.99 \cdot 10^{0}$	0	32	0	32	0	30

For strongly sorbing nuclides (high K_d-value), the comparatively even distribution between the four parameters included shows that the bioturbation contributes more to migration than the advection. As K_d decreases to 0.1 the advection contributes as well and K_d and runoff begin to matter. Soil depth, porosity and density, which are part of both terms, are the parameters for which the results are most sensitive.

With a K_d-value of 0.05 or lower, bioturbation is of much less importance. The contribution from K_d and runoff increases significantly due to the greater fraction in solution that moves downward with the infiltrating water. The influence of soil density decreases as well, as low K_d-values results in low fraction of particulate matter, and the product of K_d and density grow less important. The results are most sensitive for parameters that describe the water turnover for elements with high mobility.

6.3 Uncertainty analysis

An uncertainty analysis was also performed for the transfer coefficient described above. Our intention was to use data from the Forsmark area. At present such data was not available, however. We therefore estimated the parameter values according to a description of the type of soil at the Forsmark area given by /Berggren and Kyläkorpi, 2002/. Loam and sandy loam dominate in the area. We used data for particle densities and porosities from a large compilation of such data for various types of soil, given by /Schaap and Leij, 1998/. They have investigated a number of data sets for soils in order to estimate soil hydraulic properties from parameters such as e.g. texture, bulk density and water. They used three large data sets to analyse these data. Statistical values of bulk densities, volumes of hydroscopic bound water and porosities are shown from their analysis in Table 6-3.

Table 6-3. Bulk densities (Bd), volume of hydroscopic bound water (θ_r) and soil porosities (θ_s), from /Schaap and Leij, 1998/. Mean values and standard deviations (in parentheses).

Class	N[a]	Parameters Bd g/cm^3	θ_r cm^3/cm^3	θ_s cm^3/cm^3
Sand	308	1.53 (0.12)	0.053 (0.029)	0.375 (0.055)
Loamy sand	205	1.52 (0.19)	0.049 (0.042)	0.390 (0.070)
Loam	249	1.37 (0.25)	0.061 (0.073)	0.399 (0.098)
Sandy loam	481	1.46 (0.26)	0.039 (0.054)	0.387 (0.085)
Silt loam	332	1.28 (0.27)	0.065 (0.073)	0.439 (0.093)
Sandy cl. loam	181	1.57 (0.18)	0.063 (0.078)	0.384 (0.061)
Silty cl. loam	89	1.32 (0.18)	0.090 (0.082)	0.482 (0.086)
Clay loam	150	1.42 (0.19)	0.079 (0.076)	0.442 (0.079)
Silt	6	1.33 (0.09)	0.050 (0.041)	0.489 (0.078)
Clay	92	1.39 (0.20)	0.098 (0.107)	0.459 (0.079)
Sandy clay	12	1.59 (0.10)	0.117 (0.114)	0.385 (0.046)
Silty clay	29	1.36 (0.15)	0.111 (0.119)	0.481 (0.080)

[a] Number of samples per textural class.

The values used with ranges are summarised in Table 6-4 below and results are shown in Table 6-5. In similarity to the sensitivity analysis various mean values of K_d-values were used. The ranges were also used in the dose assessment for the safety analysis of SFR /Karlsson et al, 2001/.

Table 6-4. Values and distributions used in the uncertainty analysis of the influence of K_d-value on migration. Values representative for the Forsmark area.

	K_d (m^3/kg)	Runoff (m^3/(m^2,year))	Bioturbation (kg/(m^2,year))	Soil depth (m)	Particle density (kg/m^3)	Soil porosity (–)
Value	Varies	0.25	2	0.25	2545	0.45
Distr	Log Triangular	Triangular	Triangular	Triangular	Normal	Normal
Stand dev					0.25	0.1
Min/max	A factor 10	0.2/0.3	1.0/3	0.2/0.3	1000/3500	0.1/1

Table 6-5. Percentage contribution of the parameters to the uncertainty in the transfer coefficient, various K_d-values.

K_d (m^3/kg)	Migration (y^{-1})	K_d %	Runoff %	Bioturbation %	Soil depth %	Particle density %	Soil porosity %
1	$7.10 \cdot 10^{-3}$	16	0	33	7	0	33
0.1	$1.72 \cdot 10^{-2}$	80	1	3	2	0	10
0.01	$1.09 \cdot 10^{-1}$	93	1	0	0	0	4
0.001	$6.32 \cdot 10^{-1}$	94	2	0	1	0	0

The uncertainty analysis clearly shows that bioturbation and soil porosity are the parameters that have the greatest influence on migration for strongly sorbing elements (high K_d-values). When K_d increases a minor part of the elements is found in the water fraction and the soil related parameters therefore loose their great influence. The uncertainty is totally dominated by K_d for values 0.1 $m^3 kg^{-1}$ and lower. These results are similar to the results from the uncertainty analyses, pointing out K_d as a high contribution to the uncertainty for migration of relatively mobile elements.

6.4 Physical parameters

A literature survey was made for the physical soil parameters, porosity, water amount and particle density. Minerogenic soils may be divided into classes due to their structure, see Table 6-3. /Schaap and Leij, 1998/ investigated a number of data sets for soils in order to estimate soil hydraulic properties from parameters such as texture, bulk density and water among other things. They used three large data sets for analysing. A final table from their analysis is shown in Table 6-3. As can be seen from the table, the porosity expressed as percent varies due to the texture of the soils. The most fine-grained soils, such as clay, have the highest porosity and therefore the lowest bulk density. No soils with a considerable amount of organic material were encompassed in the study. In general the organic matters in soils have a density of 0.9 kg/dm^3. The default value of 0.5 used in safety assessments of SR 97 and SAFE seems according to this information to overestimate the soil porosity. An overestimation of the value for this parameter leads to somewhat lower migration rates. This is however a parameter that is site specific and the site investigations would give information about values to be applied. In addition the high variability of K_d-values overwhelms the importance of soil porosity.

All references so far have given 2 650 kg/m^3 as an average value for soil particle density. If soils consist of heavier minerals or high presence of iron oxides the particle density will increase /Hillel, 1980/.

A compilation of physical soil parameters used in various assessments is shown in Table 6-6. No great attention has been paid to these parameters as they are site-dependent and studied in the siting programme.

Table 6-6. Soil physical parameters.

		/NV, 1997/	/Wiklander, 1976/	/Hillel, 1980/	/FitzPatrick, 1980/
Organic carbon content (%)	Middle	2			
	Min	0.5			
	Max	5			
Bulk density (kg/m^3)	Middle	$1.5 \cdot 10^3$		$1.3–1.35 \cdot 10^3$	1.3
	Min			$1.1 \cdot 10^3$	0.55
	Max			$1.6 \cdot 10^3$	2
Soil particles density (kg/m^3)	Middle		$2.65 \cdot 10^3$	$2.6–2.7 \cdot 10^3$	$2.650 \cdot 10^3$
	Min		$2.53 \cdot 10^3$		$2.6 \cdot 10^3$
	Max		$3.40 \cdot 10^3$		$5.2 \cdot 10^3$
Water content (dm^3/dm^3)		0.3			
Air content (dm^3/dm^3)		0.2			
Soil porosity (m^3/m^3)	Middle		0.5		
	Min		0.4	0.3	
	Max		0.6	0.6	

7 Irrigation as a pathway – discussion

For comparison of the irrigation exposure pathway with others, some simple calculations can be used for estimation of the contamination due to interception and retention. The surface contamination can be expressed as a volume of water taken in per kg vegetables according to the earlier findings. For the elements with the highest retardation this will be 13 litres of water per kg vegetables for a unit concentration of 1 Bq/litre of water. In the latest assessment the water consumption for adults was 600 l per year, implying that these exposure pathways give the same dose if about 46 kg vegetables are consumed. Consumption two and four times higher should give the same exposure for cesium and anions, respectively. Such estimations are of course valid if it is assumed that the same water is used for consumption and irrigation. That is not always the case, however. Due to the closeness of garden plots to surface water like small streams, people might use such water for irrigation but not for consumption.

The importance of root uptake in comparison to surface contamination was also studied. We looked on the general behaviour of radionuclides when employing various values for root uptake and K_d. Example calculations were performed for the radionuclides Cl-36, Se-79, Tc-99, I-129, Cs-135, Ra-226, Pa-231, Np-237, U-238 and Pu-239. These nuclides were selected due to their importance for exposure in safety assessments for high-level waste /Pinedo et al, 2003/.

The model for surface contamination according to Chapter 5 was used in the calculations, which means considering LAI, specific storage capacity and retention due to the properties of the elements. The general parameter values used are shown in Table 7-1.

Table 7-1. General parameter values, triangularly distributed.

Parameter	Unit	Best estimate	Min value	Max value
Total irrigation volume	$m^3/(m^2, year)$	0.1	0.09	0.11
Nr_{IRR}	Number	4	3	5
LAI, vegetables	m^2/m^2	5	4	6
LAI, root vegetables	m^2/m^2	4	3	4
StoCap	m^3/LAI	$3 \cdot 10^{-4}$	$2 \cdot 10^{-2}$	$4 \cdot 10^{-4}$
Yield-values, vegetables	kg/m^2	2	1.5	4
Yield values, root vegetables	kg/m^2	2.03	1.9	2.3

The element-specific values used in the calculation are shown in Tables 7-2 to 7-5 below.

Table 7-2. Element specific distribution coefficients K_d for soil ((Bq/kg soil)/(Bq/m^3 water)), from /Karlsson and Bergström, 2002/.

Element	Distribution coefficient (m^3/kg)			
	Best estimate	Distribution	Low	High
Cl	$1 \cdot 10^{-3}$	LT	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$
Se	$1 \cdot 10^{-2}$	LT	$1 \cdot 10^{-3}$	$1 \cdot 10^{-1}$
Tc	$5 \cdot 10^{-3}$	LT	$1 \cdot 10^{-3}$	$1 \cdot 10^{-2}$
I	$3 \cdot 10^{-1}$	LT	$1 \cdot 10^{-1}$	$1 \cdot 10^{0}$
Cs	$1 \cdot 10^{0}$	LT	$1 \cdot 10^{-1}$	$1 \cdot 10^{1}$
Ra	$5 \cdot 10^{-1}$	LT	$1 \cdot 10^{-2}$	$1 \cdot 10^{0}$
Pa	$1 \cdot 10^{1}$	LT	$1 \cdot 10^{0}$	$1 \cdot 10^{2}$
U	$1 \cdot 10^{-1}$	LT	$1 \cdot 10^{-2}$	$1 \cdot 10^{0}$
Np	$1 \cdot 10^{-1}$	LT	$1 \cdot 10^{-2}$	$1 \cdot 10^{0}$
Pu	$5 \cdot 10^{0}$	LT	$1 \cdot 10^{-1}$	$1 \cdot 10^{1}$

Table 7-3. Element specific root uptake factors for vegetables ((Bq/kg w.w. vegetable)/(Bq/kg d.w. soil)), from /Karlsson and Bergström, 2002/.

Element	Vegetables (dry soil/fresh veg)			
	Best estimate	Distribution	Low	High
Cl	$3 \cdot 10^{0}$	T	$1 \cdot 10^{0}$	$1 \cdot 10^{1}$
Se	$2 \cdot 10^{0}$	LT	$1 \cdot 10^{-1}$	$3 \cdot 10^{0}$
Tc	$2 \cdot 10^{1}$	LT	$1 \cdot 10^{-1}$	$8 \cdot 10^{1}$
I	$3 \cdot 10^{-2}$	LT	$3 \cdot 10^{-3}$	$3 \cdot 10^{-1}$
Cs	$2 \cdot 10^{-2}$	LT	$2 \cdot 10^{-3}$	$2 \cdot 10^{-1}$
Ra	$5 \cdot 10^{-3}$	LT	$3 \cdot 10^{-4}$	$1 \cdot 10^{-1}$
Pa	$3 \cdot 10^{-4}$	LT	$3 \cdot 10^{-5}$	$3 \cdot 10^{-3}$
U	$1 \cdot 10^{-3}$	LT	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$
Np	$4 \cdot 10^{-3}$	LT	$4 \cdot 10^{-4}$	$4 \cdot 10^{-2}$
Pu	$2 \cdot 10^{-5}$	LT	$2 \cdot 10^{-6}$	$2 \cdot 10^{-4}$

Table 7-4. Element specific root uptake factors for root crops ((Bq/kg w.w. root crop)/(Bq/kg d.w. soil)).

Element	Root crops (dry soil /fresh veg)			
	Best estimate	Distribution	Low	High
Cl	$6 \cdot 10^{0}$	T	$2 \cdot 10^{0}$	$2 \cdot 10^{1}$
Se	$4 \cdot 10^{0}$	LT	$2 \cdot 10^{-1}$	$6 \cdot 10^{0}$
Tc	$5 \cdot 10^{-2}$	LT	$5 \cdot 10^{-3}$	$5 \cdot 10^{-1}$
I	$1 \cdot 10^{-2}$	LT	$1 \cdot 10^{-3}$	$1 \cdot 10^{0}$
Cs	$2 \cdot 10^{-2}$	LT	$2 \cdot 10^{-3}$	$2 \cdot 10^{-1}$
Ra	$4 \cdot 10^{-3}$	LT	$4 \cdot 10^{-4}$	$2 \cdot 10^{-2}$
Pa	$6 \cdot 10^{-4}$	LT	$6 \cdot 10^{-5}$	$6 \cdot 10^{-3}$
U	$3 \cdot 10^{-3}$	LT	$3 \cdot 10^{-4}$	$3 \cdot 10^{-2}$
Np	$2 \cdot 10^{-3}$	LT	$2 \cdot 10^{-4}$	$2 \cdot 10^{-2}$
Pu	$3 \cdot 10^{-5}$	LT	$3 \cdot 10^{-6}$	$3 \cdot 10^{-4}$

Table 7-5. Element specific translocation factors from surface to edible part of cereals and root crops ((Bq/kg w.w.)/(Bq/m^2)), triangularly distributed.

Element	Translocation factors (m^2/kg)		
	Best estimate	Min	Max
Cl	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
Se	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
Tc	$1 \cdot 10^{-1}$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-2}$
I	$1 \cdot 10^{-1}$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-1}$
Cs	$2 \cdot 10^{-1}$	$1 \cdot 10^{-1}$	$3 \cdot 10^{-1}$
Ra	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
Pa	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
U	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
Np	$1 \cdot 10^{-1}$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-1}$
Pu	$2 \cdot 10^{-2}$	$1 \cdot 10^{-2}$	$3 \cdot 10^{-2}$

7.1 Element-specific calculations

The same model as above was used, but ranges of all parameter values were considered. Values for the element-specific parameters such as K_d, root uptake factors and translocation factors were taken from /Karlsson and Bergström, 2002/, except the translocation factor for Tc-99. In /Karlsson *et al,* 2001/ a very low value for translocation of technetium was given. The value was much lower than the values of elements known to be much less biologically available than technetium. Therefore, we used a higher value in these calculations. An annual irrigation rate of 0.1 m^3 was used for irrigation during a period of 10 000 years.

The calculations show that initial retention on vegetation surfaces is very important for elements with low bioavailability and high adsorption to soil. As can be seen from Figure 7-1, surface contamination gives dominant contribution to the concentration except for Cl-36, Tc-99, I-129 and Cs-135. These radionuclides have a high bioavailability leading to high root uptake factors. Chlorine is also an anion, leading to low retention on vegetation surfaces. This also explains the lower contribution to total concentration for I-129. It is worth mentioning that inhalation usually is a main pathway for actinides. Drinking water is also important for uptake of the actinides due to their low bioavailability. On the other hand it might happen that water might be used for irrigation but not as drinking water. The same pattern is valid for root crops, see Figure 7-2.

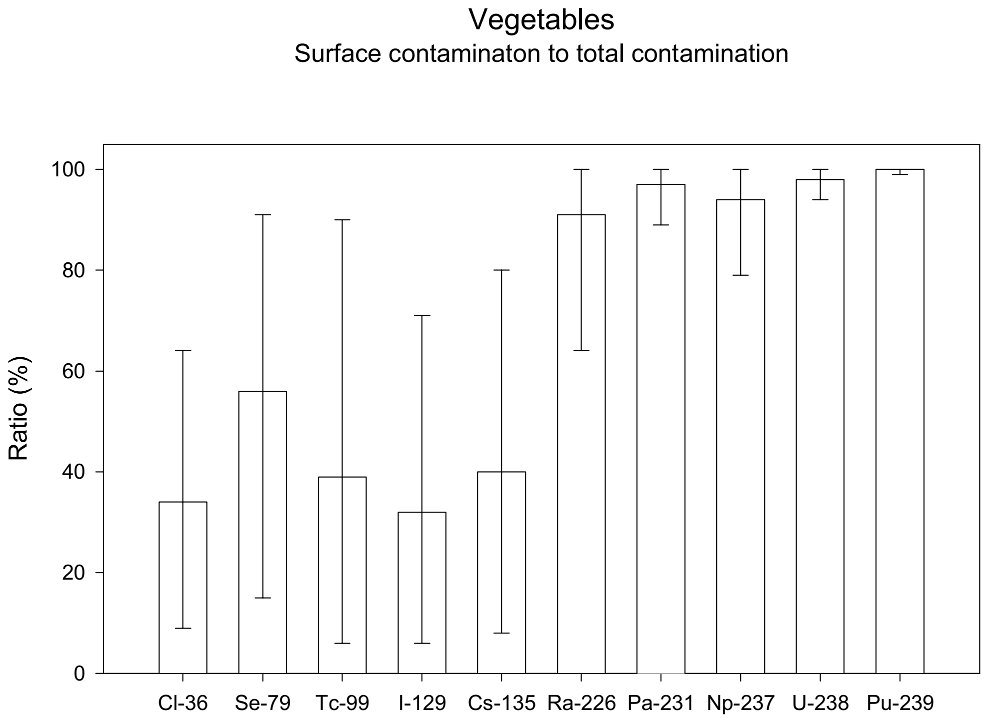

Figure 7-1. *Ratios (in percentage) of contamination on surfaces and total concentration in vegetables, mean and 90% confidence interval.*

The importance of surface contamination is however lower for root crops than for vegetables because only a fraction of the retained radionuclides is transferred to the edible parts (translocation). Consequently, the percentage contamination due to surface retention is lower for root crops than for vegetables, see Figure 7-2.

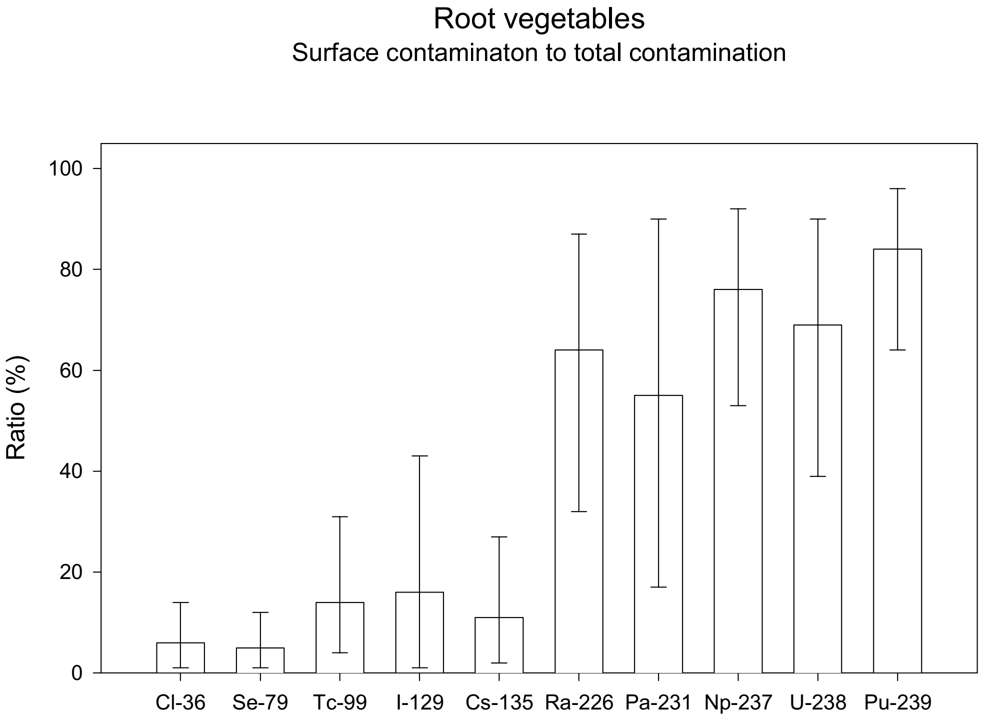

Figure 7-2. *Ratios (in percentage) of the concentration in root crops due to surface contamination and total concentration, mean and 90% confidence interval.*

8 Conclusions

Irrigation is not very common in Sweden. Around 3–4% of the cultivated land may be subject for irrigation during dry years. Potatoes and vegetables are the crops that are most often irrigated. Cereals are seldom irrigated, and if so only once, at germination. Pasturage is not irrigated. This implies that interception of irrigation water should not need to be considered for contamination of cereals and pasturage.

The way of handling irrigation varies considerably in the studied models, from a simple element-independent fraction retained to element-specific fractions based on an initial retention determined by the leaf surface area. The amounts used also vary considerably between 600 mm per year to about 200 mm per year. The various ways of handling irrigation caused a difference between model results in the relative contribution to exposure from irrigation. It also led to that the importance of interception contra root-uptake as contamination pathway varied from zero up to about 99%.

The sensitivity analysis performed on the expression used in the safety analysis SR 97 and SAFE shows that the intercepted fractions of water in combination with the number of irrigation events are important factors. It is recommended that an expression taking into account the leaf area index (LAI) and a specific storage capacity should replace the lumped parameter used earlier.

Values that enable differentiation of retention on vegetation surfaces for various elements were found in the literature. It has been stated that cations are retained more effectively than anions. Monovalent ions' behaviour are something in between these extremes. We therefore propose that in coming studies this should be considered employing values according to Table 8-1 below.

Table 8-1. Retention coefficients for intercepted ions.

Chemical form	Best estimate	Min value	Max value
Anions	0.5	0.3	0.7
Monovalent cations (Cs)	1.0	0.7	1.3
Cations	2.0	1.5	2.5

The sensitivity and uncertainty analyses performed for the expression used for describing migration in soils show, as expected, that for immobile radionuclides bioturbation causes a higher transport than advection, while for mobile radionuclides bioturbation is negligible. Values of K_d are the ones contributing most to the uncertainty in the expression for elements having K_d-values of 0.1 m^3/kg and lower, see Table 8-2 below.

Table 8-2. Percentage contribution of the parameters to the uncertainty in the transfer coefficient, various K_d-values.

K_d (m^3/kg^{-1})	Migration (y^{-1})	K_d %	Runoff %	Bioturbation %	Soil depth %	Particle density %	Soil porosity %
1	$7.10 \cdot 10^{-3}$	16	0	33	7	0	33
0.1	$1.72 \cdot 10^{-2}$	80	1	3	2	0	10
0.01	$1.09 \cdot 10^{-1}$	93	1	0	0	0	4
0.001	$6.32 \cdot 10^{-1}$	94	2	0	1	0	0

Studying values for soil porosity from a large database over minerogenic soils, porosity values were lower than the values used earlier.

Irrigation is important from an exposure point of view. The importance varies due to element and consumption rates. Interception on vegetation surfaces and subsequent retention give the highest contamination for elements with low bioavailability.

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